A new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector

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PREFACE

An **article-based** approach has been followed for the compilation and completion of this thesis. A total of three peer-reviewed journal articles have been published. Each individual article was compiled and submitted to the *South African Journal of Industrial Engineering* for publication and underwent a double-blind peer-review process. In addition to the three journal articles, a conference paper was presented at the annual conference of the *South African Institute for Industrial Engineering.* The outcomes of all publications logically support one common research objective, namely the development of a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. Proper permission was obtained for the publication of the articles listed in this thesis. Permission was also obtained to include excerpts from the listed articles in this thesis.

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The Lord has given me, through His infinite mercy and grace, the ability and opportunity to further my studies. For this, I am most grateful.

I would like to express my gratitude to:

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ABSTRACT

Title: A new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector

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Keywords: South African mining industry; Industry 4.0; Wide-area wireless communication; Network Quality of Service; Data availability

Industry 4.0 initiatives aim to increase and maintain the operational efficiency of existing manufacturing methods and processes, as well as to enhance existing automation methods and technologies. Established heavy industries, such as the mining and steelmaking industry, water distribution schemes and power utilities, have been less proactive in adopting Industry 4.0 initiatives and methods. Machine-to-Machine communication and wireless networks form the backbone of the Industry 4.0 network layer. The aim of this thesis is to illustrate the current limitations present in wide-area wireless communications and to present a new telemetry monitoring system to address these limitations in the South African heavy industry sector.

In the first article, listed in Appendix B, a clear architectural description is presented that can be used to guide heavy industry players in the adoption of key Industry 4.0 principles in practice. An input-output methodological approach was followed to deconstruct the Industry 4.0 paradigm into two parts, namely the digital framework and the digital toolbox, with both

terms being coined in this article. Together, these two components form a roadmap that can be utilised to navigate the tides of Industry 4.0 adoption in the heavy industry sector.

In the second article, listed in Appendix C, a new software-based system is developed that actively monitors the network layer vital signs of a wide-area wireless telemetry system. The proposed monitoring system was implemented on a wide-area wireless telemetry network utilised by multiple industrial facilities within South Africa. The system successfully monitored more than 80 remote sites, with communication failures being detected immediately. The average connection uplink time was also increased by more than 25%.

In the third article, listed in Appendix D, the proposed monitoring system is integrated into existing real-time information systems. This integration allowed for the introduction of enhanced troubleshooting and maintenance procedures that can be followed on-site to rectify any network anomalies. Positive impacts were made on condition-based maintenance agreements between an energy services company and a South African gold mining company. The aim of the third article is to emphasise the value of the developed telemetry monitoring system in industry.

In the conference paper, listed in Appendix E, the value of an information and asset management system for the management of subscriber identification module (SIM) cards utilised in heavy industry is emphasised. The paper aims to analyse and present the current architecture of existing industrial information systems and discuss key challenges that contribute to communication disruptions. The paper introduces a new information and asset management system to address the challenges presented. The system is validated, and the results reflect the value of such a system in industry, with a communication cost reduction of 62%.

LIST OF ARTICLES

This thesis serves to logically present and summarise the technical and academic work described in the articles listed below. The articles are numbered in consecutive order with Roman numerals. These numerals will be used as a reference to the relevant articles in this thesis. Conference papers are also listed below. Permission has been obtained from all relevant parties to allow for appendices, with Appendix A containing a valid co-author statement. The journal guidelines for authors can be viewed in Appendix F.

I. J. Prinsloo, J. C. Vosloo, and E. H. Mathews, "Towards Industry 4.0: A roadmap for the South African heavy industry sector," *South African Journal of Industrial Engineering*, vol. 30, no. 3, pp. 174–186, Nov. 2019.
Article DOI number: https://doi.org/10.7166/30-3-2237
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II. J. Prinsloo, M. Mathews, J. du Plessis, and J. Vosloo, "Development of a software-based monitoring and information system for industrial telemetry applications," *South African Journal of Industrial Engineering*, vol. 30, no. 1, pp. 54–68, May 2019.
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III. J. Prinsloo, M. J. Mathews, and J. C. Vosloo, "The value of a telemetry monitoring system in sustaining the operational performance of industrial information systems," *South African Journal of Industrial Engineering*, vol. 31, no. 2, pp. 129–142, Aug. 2020.

Article DOI number: https://doi.org/10.7166/31-2-2200

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Published conference papers:

- J. Prinsloo, M. J. Mathews, J. N. du Plessis, and J. C. Vosloo, "An information systems approach to the proactive management of subscriber identification modules in industry," in *SAIIE29 Proceedings*, 2018, pp. 127–138.

The candidate, J. Prinsloo, executed all research for the listed articles above and, therefore, claims responsibility for the technical and academic content of all articles. A more detailed discussion on the contributions of the co-authors can be viewed in Appendix A. The candidate also obtained permission from the co-authors, M.J. Mathews, J.C. Vosloo, J.N. du Plessis, and E.H. Mathews, to submit this thesis.

Additional research outputs are being planned for future publications in the form of conference papers. These outputs are listed below:

- J. Prinsloo, J.C. Vosloo, E.H. Mathews, "Results from implementing a monitoring and information system on industrial telemetry applications," in *SAIIE32 Proceedings*, 2021.

- J. Prinsloo, "Sustaining the operational performance of industrial information systems through wireless telemetry," in *SAIIE33 Proceedings*, 2022.

- J. Prinsloo, "A wireless telemetry monitoring approach for enabling Industry 4.0 initiatives in the South African heavy industry sector," in *SAIIE34 Proceedings*, 2023.

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LIST OF ABBREVIATIONS

CPS	Cyber-Physical Systems
EMIS	Energy Management Information System
ESCo	Energy Services Company
GSM	Global System for Mobile communication
GUI	Graphical User Interface
ICMP	Internet Control Message Protocol
ICT	Information and Communication Technology
IETF	Internet Engineering Task Force
IoT	Internet of Things
IIoT	Industrial Internet of Things
IP	Internet Protocol
M2M	Machine-to-Machine
MSISDN	Mobile Station International Subscriber Directory Number
QoS	Quality of Service
RMMS	Remote Monitoring and Maintenance Systems
SCADA	Supervisory Control and Data Acquisition
SIM	Subscriber Identification Module
SQL	Structured Query Language
TIA	Telecommunications Industry Association
VPN	Virtual Private Network

CHAPTER 1

INTRODUCTION

This section aims to provide a brief introduction into the background and need for this study.

1.1 BACKGROUND

Since the inception of mechanical production and manufacturing, the industrial realm has experienced three major technological revolutions. These revolutions lifted manufacturing and production to new heights by introducing unique methods and technologies for increasing production and optimising production efficiency [1].

Advances in the underlying principles and methods of production and manufacturing had a profound effect on the nature of industry, directing global economic growth and scalability towards an ever-increasing upward trend [2], [3].

The first industrial revolution focused primarily on the implementation of sophisticated mechanical production and manufacturing procedures [4]. These procedures enhanced economic productivity and growth, which stimulated development and production [5], [6].

Assembly line production and mass labour were introduced by the second industrial revolution, categorised as Industry 2.0 [7]. Reduced cost and production time, coupled with increased production efficiency, led to an increase in supply, which further stimulated economic growth [8].

The establishment of Industry 2.0 in the manufacturing and industrial sector introduced several challenges. Production competitiveness, efficiency, and optimisation, as well as other factors such as cost reduction and energy consumption, presented new areas of concern, which inevitably led to the inception of the third industrial revolution, coined Industry 3.0 [9].

The third industrial revolution is categorised by the introduction of industrial automation. Electronic engineering and communication, in combination with industrial automation, aims to

address the social and economic challenges present by increasing production uptime and efficiency whilst reducing production costs [10].

Significant advances in the Information and Communication Technology (ICT) field pave the way for the next industrial revolution, coined Industry 4.0, which is currently in its development phase. The term Industry 4.0 was first established at the Hannover Trade Fair in 2011 and is an initiative spearheaded by the German government [11].

The concept of Industry 4.0 was first established to combat economic and industrial growth challenges due to a decline in a stable workforce. The Industry 4.0 vision aims to increase manufacturing output and competitiveness by digitising factories and promoting digital collaboration between systems [12].

The main objectives of Industry 4.0 are to increase and maintain the operational efficiency of existing manufacturing methods and processes, as well as to enhance existing automation methods and technologies [13]. To achieve these objectives, Industry 4.0 aims to form an interconnected ecosystem between various technological concepts, standards, and frameworks. Cyber-physical systems (CPS), the Internet of Things (IoT), cloud manufacturing, knowledge integration, and information exchange [12], [14], [15], as highlighted in [16], all form part of the Industry 4.0 vision.

The end result of a successfully implemented Industry 4.0 ecosystem is the establishment of smart factories, smart products, smart cities, and smart services in society [17]. Examples of an Industry 4.0 ecosystem include self-organising factories, automatic supply and demand matching on production lines, and intelligent power grid systems that can adjust the demand for electricity based on grid activity.

By extending the Industry 4.0 paradigm into the heavy industry sector, complex systems can be optimised, which can result in significant production output capabilities. The importance of extending Industry 4.0 into the heavy industry sector is further emphasised by the constraints placed on heavy industry through external factors, such as government policies, economic volatility, and increased competitiveness [18], [19].

1.2 RESEARCH PROBLEM AND STUDY OBJECTIVE

Established heavy industries, such as the mining and steelmaking industry, water distribution schemes, and power utilities, have been less proactive in adopting Industry 4.0 initiatives and methods [20], [21]. Production costs, capital expenditure, safety, and security are the primary factors that hinder Industry 4.0 adoption [21].

Additional constraints, such as the distribution of facilities over wide geographical areas and harsh working environments, also contribute to this slow adoption rate [22]. Due to the slow Industry 4.0 adoption rate, most of the heavy industry realm cannot yet be classified as “smart” industry and is currently operating at traditional best-effort service level [20], [23].

Real-time information systems do exist in industry but cannot be classified as fully functional Industry 4.0 systems due to the lack of automation and “self-reliance” present in these systems. Real-time information systems do, however, have a significant impact on the effectiveness of industrial facilities. Large industrial plants usually comprise multiple operationally interconnected systems and span a wide geographical area.

The need-to-know forms a critical part of the daily industrial optimisation process. In the context of the heavy industry realm, real-time information systems play a crucial role in data processing and display [24]. Efficiencies in the industrial sector can be achieved by viewing

operations and processes on a holistic level. This is, however, only possible with the integration of communication between different operational areas and sectors [25].

System interoperability is considered to be one of the crucial points for any industrial IoT ecosystems [26]. The quality of service (QoS) levels of wireless communication systems are considered to be paramount in sustaining the performance and effectiveness of an interoperable system [26]. The reliability and availability of wireless communication services, such as the GSM network, must therefore be ensured in order to allow industrial IoT applications to reach their full potential.

The use of existing third-party infrastructure implies that no control can be exercised over the network. The end-user of the network must, therefore, cater for potential communication disruptions over which they have no control. Disruptions in communication can result in data loss, which can have a negative impact on the performance of industrial processes and systems.

Enabling Industry 4.0 in the heavy industry sector will allow for the development of modular, standalone systems that facilitate wireless communication and wireless data transfer. These net-centric applications are enabled by wireless communication technologies, such as the Global System for Mobile communication (GSM) network.

Wide-area wireless telemetry networks, such as the GSM network, play an important role in facilitating accessibility and allow for real-time monitoring and data transmission over wide geographical distances. In remote areas, communication between interconnected systems is usually poor to non-existent, which can hamper the operational status of real-time information systems [22].

Several industrial information systems investigated in the literature rely heavily on a stable communication network [27]–[30]. Should the existing cellular communication network experience disruptions in communications, these systems would become unreliable and have no benefit for industrial clients.

In addition to limited or intermittent connectivity, challenges such as limited bandwidth and potential security threats can also hamper the effectiveness of real-time information systems, which can, in turn, have a negative impact on production [31]. The challenges discussed above can have a considerable effect on the Quality of Service (QoS) of industrial communication systems.

The communication network and its underlying infrastructure are considered to be the limiting factors for industrial IoT applications. The remoteness and layout of some industrial sites require that wide-area wireless communications be used as the predominant method for data transmission.

Failure to communicate effectively nullifies all benefits that are provided by an integrated Industry 4.0 ecosystem, which makes Industry 4.0 adoption infeasible [32]. Ineffective communication can also have a negative impact on the traditional model of centralisation currently used in industry. Communication failure can result in damage to existing infrastructure and can also lead to a potential loss of life [33].

The quality and stability of the network layer form a crucial part of an optimal Industry 4.0 ecosystem. Machine-to-Machine (M2M) communication and wireless networks form the backbone of the Industry 4.0 network layer [34], and limitations in wireless networks directly affect the adoption of Industry 4.0 principles and methods in the heavy industry sector.

The focus must, therefore, be placed on a guaranteed QoS. If Industry 4.0 is to successfully extend into the domain of heavy industry players, connectivity disruptions and accessibility must be addressed.

From the discussion above, a clear gap in the current knowledge spectrum has been identified. This gap is formulated as a single statement below:

There is a gap in addressing the challenges of maintaining optimal Quality of Service in wide-area wireless communication networks. Failure to address these challenges directly affects the reliability of Industry 4.0 solutions, which further affects the adoption rate of Industry 4.0 principles in the South African heavy industry sector.

Having defined a clear gap in the current knowledge spectrum above, an original research problem can be formulated and is stated below:

The Industry 4.0 paradigm currently experiences slow adoption within the South African heavy industry sector. Guaranteed Quality of Service in the network layer is the primary factor that hinders the adoption potential of Industry 4.0 principles.

From the original research problem stated above, a clear need and study objective can be formulated and is stated below:

There is, therefore, a need to develop a new telemetry monitoring system to enhance the Quality of Service in the network layer hence enabling Industry 4.0 initiatives in the South African heavy industry sector. Hence, this thesis aims to emphasise the current limitations present in wide-area wireless communications and present a novel telemetry monitoring system to address these limitations in the South Africa heavy industry sector.

1.3 RESEARCH METHODOLOGY

To solve the original research problem stated above, this thesis outlines a four-step methodology that focuses on context analysis, system development, system evaluation, and financial impact. These steps correspond to the motivation and objectives of the research articles completed by the candidate. Each step is discussed below.

I. Context analysis – Article I

The first step comprises a detailed review of the current Industry 4.0 landscape. The goal of this review is to identify shortcomings in the South African mining sector and to provide a detailed Industry 4.0 roadmap for the South African heavy industry context.

II. System development and verification – Article II

The roadmap presented in step I allows for current limitations to be identified. The goal of step II is to isolate a specific limitation and provide a solution to the identified problem. To bring heavy industrial players into the Industry 4.0 realm, it is important to address the QoS issues of

communication networks which can hamper the overall effectiveness of an Industry 4.0 ecosystem.

III. System evaluation, validation, expansion and integration – Article III

Disruptions in accessibility and connectivity can nullify the advantages of an Industry 4.0 ecosystem. If Industry 4.0 is to successfully extend into the domain of heavy industry players, accessibility and connectivity disruptions must be addressed. With a new system developed and verified in the previous step to address this issue, the goal of step III is to assess and evaluate the value of the proposed telemetry monitoring system.

IV. Cost reduction methodology – Conference Paper

With system evaluation conducted in step III, the final step focuses on an analysis of mobile network costs. The mismanagement of underlying network assets and infrastructure can, however, result in excessive communication costs. This, in turn, hampers the effectiveness of wireless data transmission. A comprehensive information and asset management system to assist with overall SIM card management is proposed.

1.4 NOVEL CONTRIBUTIONS

The novel contributions of this thesis are presented below. Each contribution listed below aims to illustrate the significance of the research articles completed by the candidate.

I. Context analysis – Article I

In Article I, a clear architectural description is presented that can be used to guide heavy industry players in the adoption of key Industry 4.0 principles in practice. An input-output methodological approach was followed to deconstruct the Industry 4.0 paradigm into two parts.

The input model labelled as the digital framework serves as the chief enabler of the output model, labelled as the digital toolbox. Together these two components form a roadmap that can be utilised to navigate the tides of Industry 4.0 adoption in the heavy industry sector.

II. System development and verification – Article II

In Article II, a new software-based system that actively monitors the network layer vital signs of a wide-area wireless telemetry system is proposed. This monitoring system can be deployed remotely for IIoT applications.

Literature has identified existing monitoring systems, but these systems only focus on small-scale networks. The scope and reach of the proposed system are of a national scale, which makes this monitoring system unique within the context of industrial communication networks.

III. System evaluation, validation, expansion and integration – Article III

The proposed system in Article II was expanded and integrated into existing industrial information systems with the aim of increasing the operational performance of these systems. This expansion and integration also result in enhanced troubleshooting procedures that can be followed on-site to rectify any network communication anomalies.

IV. Cost reduction methodology – Conference Paper

In the conference paper, the value of an information and asset management system for the management of SIM cards utilised in heavy industry is emphasised. The paper aims to analyse and present the current architecture of existing industrial information systems and discuss key challenges that contribute to communication disruptions.

The paper introduces a new information and asset management system to address the challenges presented. The system is validated, and the results reflect the value of such a system in industry, with a communication cost reduction of 62%.

1.5 THESIS OVERVIEW

The outline of this thesis is presented below. The objective of this outline is to provide a logical structure to the completed research articles.

Chapter 1: Introduction – This section aims to provide an overview of the need for this study. Several study objectives have been presented that highlight the motivation of this study, and a holistic problem statement is compiled from the study motivation, followed by a thesis outline.

Chapter 2: Towards Industry 4.0 – Chapter 2 aims to summarise the research objectives and outcomes of Article I. A definition of the article objectives followed by a literature survey is presented to establish the context. A summary of Article I is given, which highlights the findings of the research, and the section concludes with a discussion of the findings.

Chapter 3: Monitoring and information system development – Chapter 3 aims to summarise the research objectives and outcomes of Article II. A definition of the article objectives is once again presented. A literature survey is then provided, followed by a summary of the findings. This section concludes with a short discussion of the findings.

Chapter 4: The value of a telemetry monitoring system – Chapter 4 aims to summarise the research objectives and outcomes of Article III. The article objectives are presented, followed by a literature survey. The article is summarised, and a discussion on the findings serve as a conclusion to this section.

Chapter 5: Proactive management of infrastructure – Chapter 5 aims to summarise the research objectives of one conference paper. The objectives of the conference paper are provided, followed by a literature survey. The article is summarised, and the section concludes with a short discussion of the findings.

Chapter 6: Discussion – Chapter 6 aims to provide a detailed discussion of the findings of this study. Each article is discussed, and the novel contributions highlighted. The value of this study to industry is also discussed in depth. The potential for future research is presented with the aim of expanding this study.

Chapter 7: Conclusion – This section concludes this thesis. In summary, this thesis focuses on identifying and addressing challenges that inhibit the adoption of the Industry 4.0 vision, strategy, and underlying methods.

CHAPTER 2

ARTICLE 1: TOWARDS INDUSTRY 4.0

This section provides a detailed discussion on the objectives and outcomes of Article I.

2.1 PREAMBLE

The aim of this thesis is to address the challenge of developing a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. To address this aim, a holistic view of the Industry 4.0 paradigm must be obtained.

With no clear roadmap presented in literature, it is necessary to present standards, technologies, and overall guidelines that facilitate Industry 4.0 adoption in the heavy industry sector. An Industry 4.0 implementation roadmap is presented to bring heavy industry players into the Industry 4.0 domain.

By looking at Industry 4.0 holistically, it is determined that there is a need for the development of a novel telemetry monitoring system to allow for reliable communication to take place over wide geographical distances. Article I can be found in Appendix B and was published in the *South African Journal of Industrial Engineering* [16].

2.2 ARTICLE OBJECTIVES

In response to the holistic problem statement, Article I aims to provide a detailed Industry 4.0 implementation roadmap that will guide heavy industry players in adopting the Industry 4.0 vision [16]. The objectives of Article I are to:

- Define and present the key underlying technologies of Industry 4.0.
- Propose a framework from which Industry 4.0 can be implemented in the heavy industry sector.
- Discuss current challenges that might hinder Industry 4.0 adoption in the heavy industry sector.

The objectives defined above aim to provide clarity and remove uncertainty in establishing new methods and technologies in the heavy industry sector.

2.3 METHODOLOGY

In response to the article objectives listed in the previous section, a summary of the methodological approach for Article I is provided below:

- A detailed literature review was conducted in order to determine the state of the art of the key underlying technologies of Industry 4.0.
- More than one hundred journal articles were investigated. This number was reduced based on the current Industry 4.0 landscape.
- From the reduced articles, the underlying technologies could be identified and included in the roadmap.
- The extensive literature survey highlighted the fundamental components of Industry 4.0. The candidate then proceeded to compile a logical structure of the technologies and value drivers, with the end result being a comprehensive framework to guide industry players on the road to Industry 4.0 adoption.
- From the literature survey discussed in the first point above, several articles were earmarked that focused on key challenges. These articles were included in the discussion on the challenges that might hinder Industry 4.0 adoption.

An input-output methodological approach was followed to deconstruct the Industry 4.0 concept into two parts. The first part serves as the input model for Industry 4.0 and is labelled the ‘Industry 4.0 digital framework’.

The main objective of the digital framework is to introduce various concepts, models, and technologies that are underlying components that are required for Industry 4.0. The second

part serves as the output model for Industry 4.0 and is labelled the ‘Industry 4.0 digital toolbox’. The objective of the digital toolbox is to present various enabling tools and methodologies that can be used to embed the Industry 4.0 vision in the industrial and manufacturing sector.

The methodology in Article I aims to present a detailed roadmap for the implementation of Industry 4.0 methods in the South African mining sector. A digital framework and toolbox are presented to address current gaps in this sector.

2.4 LITERATURE STUDY

Efficiency and profitability are key factors that prove to be challenging in the South African mining industry [35]. Critical factors such as market-related pressures and government policies force the industry to new and alternative methods of sustainable mining operations [29].

One of the primary methods for remaining profitable is the reduction of capital expenditure on existing operations. Key focus points that have a direct impact on sustainable mining operations include energy usage profiles, asset management strategies, and remote monitoring and maintenance strategies [27], [36], [37].

Current Industry 4.0 strategies focus primarily on wireless communication and IoT-based solutions for real-time transmission and decentralised collaboration [38]. This is a major concern since mining systems are usually separated by large geographical distances both on a horizontal and vertical level [35].

The geographical nature of deep-level mining operations creates limitations in wireless communication network operation. Additionally, limited access to mining equipment and assets, as well as ageing infrastructure, further hampers Industry 4.0 adoption.

The challenges mentioned above directly affect the ability of deep-level mines to implement Industry 4.0 methods and applications. Several IoT-related applications have, however, been incorporated into the mining environment. These applications aim to address the focus points mentioned above, with the primary objective to increase operational efficiency and sustainability.

Energy management information systems (EMIS) and automated electricity bill analysis systems focus primarily on supporting mining efficiency by providing line-of-site solutions to energy management and utilisation [29], [36].

In addition to systems focusing on energy management, several systems exist that aim to improve the operational efficiency of mining operations. These systems include condition-based maintenance systems and real-time monitoring and information systems [27], [30], [39], [40], and utilise existing Supervisory Control and Data Acquisition (SCADA) systems for real-time data retrieval. The collected data is transmitted via wide-area wireless telemetry networks to central database systems, where it is stored and processed.

The utilisation of SCADA systems for real-time data retrieval is an acceptable method for retrieving data due to the infrastructure challenges present in mining operations. It should, however, be noted that the quality and extensibility of SCADA networks can hamper the outcomes of these systems [41].

The South African mining environment still uses the traditional industry model of centralisation [42]. Equipment is monitored and controlled from a central point, usually an industrial SCADA system, and all information is distributed via a wired telemetry system to various industrial endpoints.

To allow Industry 4.0 practices to be adopted in the mining sector, a push for decentralisation and wireless interconnection must be made. The facilitation of interconnected modular systems, which allow virtualisation to take place, will effectively allow for a virtual copy of mining operations to be made. This virtual copy, referred to as a digital twin, can be considered the next step in managing mining operations [43].

Wired telemetry still allows real-time capabilities, such as rapid responses to service delivery and production, but these capabilities are limited to local mining operations. For expert condition-based maintenance strategies to be implemented, big data and decentralised computing must be incorporated into the current operational infrastructure context [43].

Mining operations can be improved and optimised by incorporating intelligent systems, sensors, and other IoT-related technologies into the existing infrastructure. The next step would be to incorporate predictive maintenance strategies into existing EMIS infrastructures to increase operational efficiency methodologies further. The expansion and incorporation of wireless sensor networks into the heavy industry realm has already been proposed, and solutions that actively focus on the improvement of mining operations and safety have been presented [44]–[46].

Key elements of Industry 4.0 that have not been integrated into South African mining operations include wireless communication technologies, decentralisation, virtualisation, and modularity of systems. The aim of Article I is, therefore, to address the mentioned gaps by

providing a strategic roadmap to guide South African mining operations into the next phase of digital operations.

2.5 SUMMARY OF ARTICLE

The outcome of Article I is two-fold. Firstly, Article I aims to provide an architectural framework to accurately represent the Industry 4.0 vision in industry. Secondly, Article I aims to apply the proposed framework to a theoretical case study with the objective of identifying the gaps currently present in the heavy industry sector. Article I presented a deconstructed model of the Industry 4.0 paradigm. The deconstructed model consists of two parts, and an input-output methodological approach was followed [16].

The proposed input model is labelled as the Industry 4.0 digital framework. The objective of the Industry 4.0 digital framework is to identify concepts and technologies that are foundational building blocks and underlying components of Industry 4.0. The output model is labelled as the Industry 4.0 digital toolbox [16].

The objective of the Industry 4.0 digital toolbox is to identify tools and methodologies that can be utilised to establish the Industry 4.0 vision in the heavy industry sector. The terms *digital framework* and *digital toolbox* are both introduced in Article I. A detailed discussion of each term can be viewed in Appendix B.

The concepts, models and technologies identified in the digital framework act as key enabling components for the tools and methodologies present in the Industry 4.0 digital toolbox. Figure 1 below illustrates a deconstructed model of the Industry 4.0 paradigm. Several applications and examples are provided to illustrate the scope of each model. An extensive and detailed literature review was conducted to compile the deconstructed model depicted in

Figure 1 below. From the literature review, the deconstructed model was also expanded into a detailed architectural model. The expanded model can be viewed in Article I in Appendix B.

Firstly, the proposed digital framework was partitioned into two subsections that focus on key technologies and principles. The primary technologies that enable the framework are CPS, IoT, decentralised computing, and wireless networks [13], [47]–[49]. These technologies are core enabling technologies that form the foundation of any Industry 4.0 ecosystem [16].

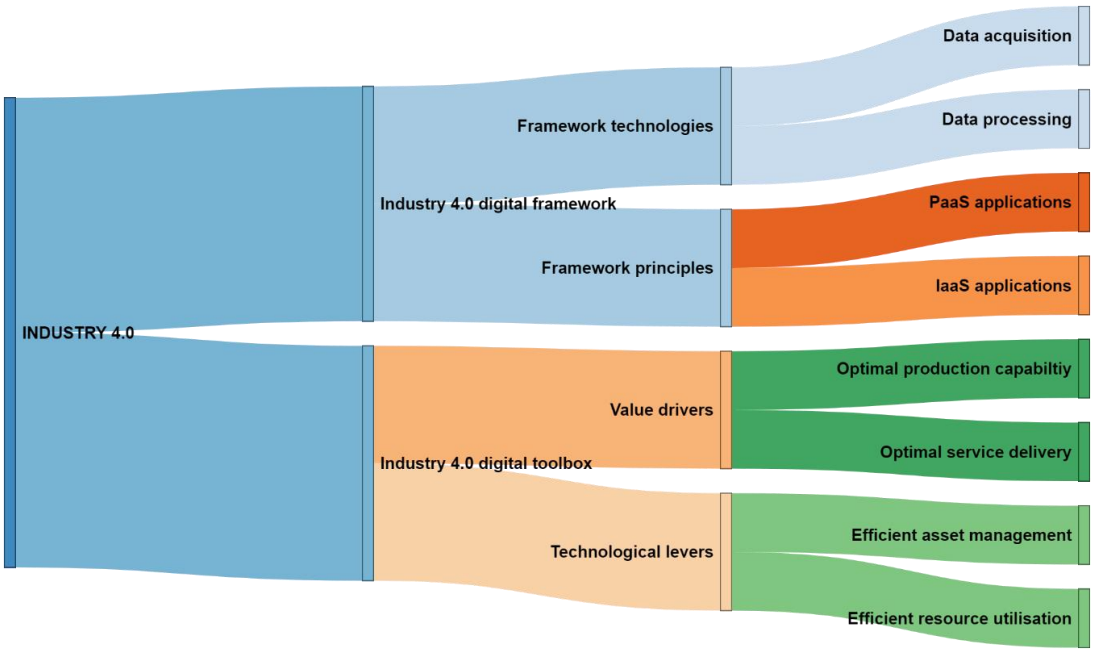


Figure 1: A top-down deconstruction of the Industry 4.0 paradigm [16]

Framework principles include decentralisation, real-time capability, modularity, interoperability and virtualisation [13], [48], [50]–[52]. These five principles serve as classifiers and must be present if a successful Industry 4.0 system is to be implemented [16].

Secondly, the proposed digital toolbox was partitioned into two subsections which are labelled as *key value drivers* and *technological levers*. The digital framework discussed above facilitates the use of the digital toolbox. By implementing technological levers such as remote

monitoring and control [39], predictive maintenance [42], and supply-chain optimisation [8], Industry 4.0 can be successfully integrated into industrial systems [16].

Finally, several key challenges have been investigated that can hamper the adoption of Industry 4.0 methods in the heavy industry sector. The challenges have been divided into two main categories, namely physical challenges and psychological challenges [16].

Physical challenges include system interoperability challenges [53], accessibility challenges [54], [55], and issues regarding security and privacy [38], [56]. Psychological challenges include the impact on labour relations [57], the need for better technical skill-sets [57], and education and financial implications [15].

2.6 DISCUSSION

The traditional industry model of centralisation is still being utilised in the South African mining sector [35]. Mining assets and equipment are monitored and controlled from a centralised point which is usually an industrial SCADA system. Information from equipment is relayed via a wired telemetry system to the SCADA from which control can be exercised [16].

To promote the adoption of Industry 4.0 applications in the mining sector, the implementation of decentralised methods and wireless telemetry must be prioritised. By facilitating interconnected and decentralised systems that are modular, virtualised environments can be created in which entire mining environments can be recreated and modelled. This virtual copy often referred to as the digital twin, is the next step for managing mining operations [16].

The shift from wired telemetry to wireless telemetry networks is a crucial factor for Industry 4.0 applications. Wired telemetry networks still allow for real-time capabilities to be implemented; however, these capabilities are limited to localised mining environments and local operations due to infrastructure constraints [16]. The implementation of expert condition-based maintenance systems relies heavily on big data applications and decentralised computing [16].

The incorporation of intelligent systems, sensors, and other IoT-related technologies can have a significant impact on the improvement and optimisation of mining operations [16]. The incorporation of these technologies enables the next stage of condition-based maintenance systems, which is the implementation of predictive maintenance strategies. The expansion of EMIS platforms by incorporating predictive maintenance strategies can further increase operational efficiency methodologies [16].

The incorporation of wireless sensor networks into the heavy industry sector has already been proposed. Existing solutions from literature that focus on the improvement of mining operations and safety have been proposed in [44]–[46]. These solutions can only serve as examples of how the Industry 4.0 paradigm can be manifested in the heavy industry sector if stable and reliable network communication is present [16].

2.7 CONCLUSION

Article I presented a detailed architectural study of Industry 4.0. A brief excerpt is provided from Article I below to conclude this chapter [16]: *"The main objective of the article was to propose an architectural framework that clearly highlights key areas of importance that must first be addressed before Industry 4.0 adoption can take place. To illustrate the value of the proposed framework, a theoretical case study was developed.*

In the context of the South African mining industry, a methodological shift must first be made from traditional centralised approaches of operation to decentralised operations. This, together with the implementation of wireless sensor networks and wireless telemetry, will pave the way for the adoption of Industry 4.0."

CHAPTER 3

ARTICLE 2: TELEMETRY MONITORING

SYSTEM DEVELOPMENT

This section aims to provide a detailed discussion on the objectives and outcomes of Article II.

3.1 PREAMBLE

The aim of this thesis is to address the challenge of developing a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. The communication network in IoT-based industrial applications has been identified as the limiting factor that can hamper QoS.

The QoS of wireless communication networks is paramount in sustaining the performance of interoperable Industry 4.0 systems. The detailed literature review in Article I determined that there is a need for the development of a novel telemetry monitoring system to allow for reliable communication to take place over wide geographical distances. Article II documents the development of such a system. Article II can be found in Appendix C and was published in the *South African Journal of Industrial Engineering* [58].

3.2 ARTICLE OBJECTIVES

In response to the holistic problem statement, Article II aims to propose a new software-based monitoring system that actively monitors the status of industrial wide-area wireless telemetry systems [58]. The objectives of Article II are to:

- Provide an overview of the general IoT architectural model within the context of the heavy industry sector.
- Highlight the challenges and limitations present in existing IoT applications that utilise wireless communication methods.
- Propose, implement, and verify a new software-based monitoring and information system for wide-area wireless telemetry networks on a national scale.

The objectives listed above aim to address QoS issues that are currently present in wide-area wireless telemetry networks in the heavy industry sector.

3.3 METHODOLOGY

In response to the article objectives listed in the previous section, a summary of the methodological approach for Article II is provided below:

- An extensive literature review was conducted on the state of the art of the IoT architectural model in the heavy industry sector. From the literature survey, gaps and limitations were identified and prioritised.
- Each area of limitation was investigated, and site visits were conducted to verify the impact of the limitation.
- The most significant areas of concern were highlighted. In Article II, the reliability and QoS of wide-area wireless communications were highlighted as the primary limitation and cause for concern.
- A new system was then proposed, developed, and verified, as discussed in Article II.
- The system was divided into three subsections, with each subsection being completed and tested before starting development for the next subsection.
- The monitoring software routine was first developed and tested. Testing was done by means of actively probing existing IP addresses on a VPN network.
- The database design was then completed using MySQL workbench as the chosen tool for design and implementation. The monitoring subsection was then connected to the database.
- Finally, the graphical user interface was designed, implemented, and deployed.

In summary, by implementing a remote server and mobile communication router at an industrial facility, the facility can be connected to the web, which would allow for the implementation of IoT applications such as remote monitoring and maintenance. This

connection is facilitated by mobile communication routers, and it allows for critical data to be transferred wirelessly over large distances.

3.4 LITERATURE STUDY

The rapid expansion of the Internet into more facets of everyday life paves the way for the establishment of new research and development fields. One such field is the Internet of Things (IoT) which, while relatively new, proves set to become a major component of connectivity and communication in the modern era. The term 'Internet of Things' is defined as a paradigm that focuses on the incorporation of existing technologies to achieve interconnected environments, where physical products are connected to the Internet [59].

By extending the Internet and Web into the physical realm, everyday objects can be made 'smart'. With the further interconnection of these various smart objects, new applications can be developed to provide solutions to existing challenges [60].

By extending IoT applications into the industrial sector, interconnected systems and processes can be maintained and optimised; this, in turn, may add massive value in production output capabilities by improving efficient production. This is especially important due to the constraints placed on heavy industry by external factors such as government policies, economic volatility, and increased competitiveness [18].

Established heavy industries, such as mining, steel production, water distribution, and power utilities, have been slow in adopting IoT practices and applications [61]. Much of this hesitance to incorporate IoT methods into existing processes is derived from legitimate concerns, such as safety, security, and costs [61].

Most of the heavy industry realm cannot yet be classified as ‘smart’ industries — they are still operating at a traditional ‘best-effort’ service level [23]. Heavy industrial facilities are also typically spread over wide geographical areas (such as water pumping schemes) and operate under adverse conditions (such as mines).

However, it is still possible to bring this sector into the realm of IoT by using existing technologies. With the use of existing technologies such as radio-frequency identification (RFID), wide-area wireless communications such as the global system for mobile communication (GSM) network (including long-term evolution (LTE) networks), and the global positioning system (GPS), it is possible to convert existing industrial processes and operations into ‘smart heavy industries’ [26].

System interoperability is a critical factor for the operation of any Industrial Internet of Things (IIoT) ecosystem [26]. The reliability and availability of wireless communication services, such as the GSM network, must be maintained to ensure that IIoT applications can be utilised to their full potential.

To promote system interoperability, various initiatives and organisations have been established. These initiatives include the Internet Engineering Task Force (IETF) and the Telecommunications Industry Association (TIA). The main objective of these organisations is to maintain a global standard on the implementation and utilisation of communication protocols [26].

Studies from literature have shown that resource-intensive IoT applications can hamper the performance of mobile communication networks [62], [63]. Several models and methods have been proposed. Large-scale IIoT applications that utilise the GSM network can

experience cellular access limitations due to high network traffic [64]. Methods such as network access overload control, network access overhead reduction, and network access deadlines all aim to prevent access limitations [65].

A review of existing Industry 4.0 applications in the heavy industry sector showed that most IIoT applications focus on maintaining the operational status of critical facilities, such as water pumping schemes and mine ventilation and cooling. Typical IIoT applications include real-time energy management systems, EMIS, condition-based maintenance systems, and remote monitoring and maintenance systems (RMMS) [27], [29], [37], [39], [66].

From the systems listed above, it was found that raw data is usually obtained via the integrated SCADA system on the industrial site. Data is then transmitted wirelessly to a centralised storage environment where processing can be done. The processed data is then used by the systems listed above to perform system-specific tasks. A critical observation that was made from these systems is that a stable wireless communication channel is always assumed.

Other IoT applications that do not fit in the context of industrial systems were also investigated from literature. These systems focus on sociological challenges, such as vehicle location monitoring and tracking [59], patient health monitoring [67], and mobile battlefield casualty monitoring systems [68].

These systems rely heavily on a stable communication network to perform real-time analyses. Once again, these systems assume that a stable network backbone will always be present; therefore, network layer monitoring capabilities were not incorporated into these systems.

Reliable IoT solutions, both in the industrial environment and the social environment, are of the utmost importance; hence ensuring network reliability and stability must be considered as a top priority [69]. The need, therefore, exists to develop a system to maintain QoS specifically for heavy IIoT applications.

3.5 SUMMARY OF ARTICLE

Most IIoT applications make use of the GSM network to relay information to off-site servers for data processing. To establish a secure connection between the remote industrial site and the data storage end-point, a Virtual Private Network (VPN) is utilised [58].

With the use of a VPN, each industrial site can be configured with a unique Internet Protocol (IP) address for wireless communication purposes [22]. To enable GSM network communication, a mobile GSM router is required on-site.

The proposed system is designed to monitor the status of the communication network between a mobile GSM router and existing cloud infrastructure [58]. Two techniques were identified from literature for communication network monitoring, namely active procedures and passive procedures [70].

An active measurement approach has been chosen as the preferred method for monitoring the status of the communication network [58]. Active probing entails the transmission of Internet Control Message Protocol (ICMP) packets across the network to the remote end-point, which is the industrial site.

The system proposed by Article II can be divided into three subsystems. Subsystem 1 consists of the software routines that actively monitor the uplink status of network equipment, which is the GSM routers used for real-time data transmission.

Vital parameters that are retrieved include uplink status, measured as an average percentage value; mobile data usage, measured in Megabytes; and router signal strength, measured in decibels. The reason for monitoring these parameters, as well as the system capabilities, are addressed in Chapter 4 of this thesis. Article II mainly focuses on the monitoring of the network uplink.

Subsystem 2 focuses on the storage of the network information retrieved by Subsystem 1. A relational database has been designed and implemented to facilitate data storage. Subsystem 3 consists of a graphical user interface (GUI), as well as event logging capabilities. Information stored by Subsystem 2 is displayed in real-time, allowing for rapid response to communication failures [58]. Figure 2 below provides an overview of the main software flow of the network monitoring system.

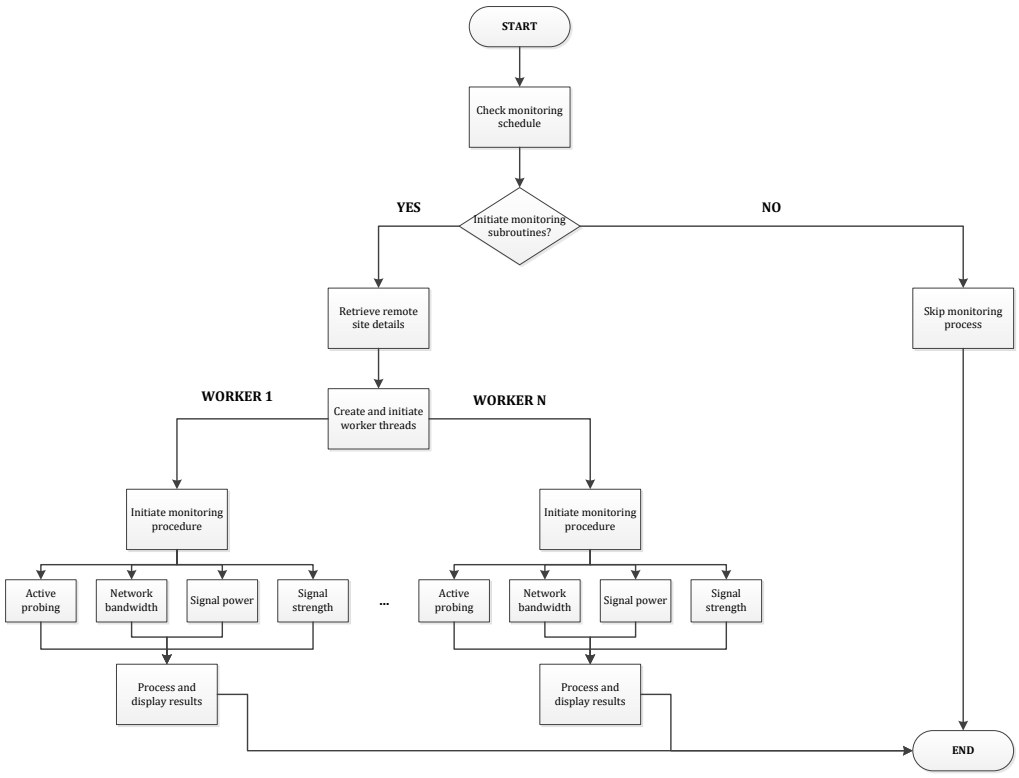
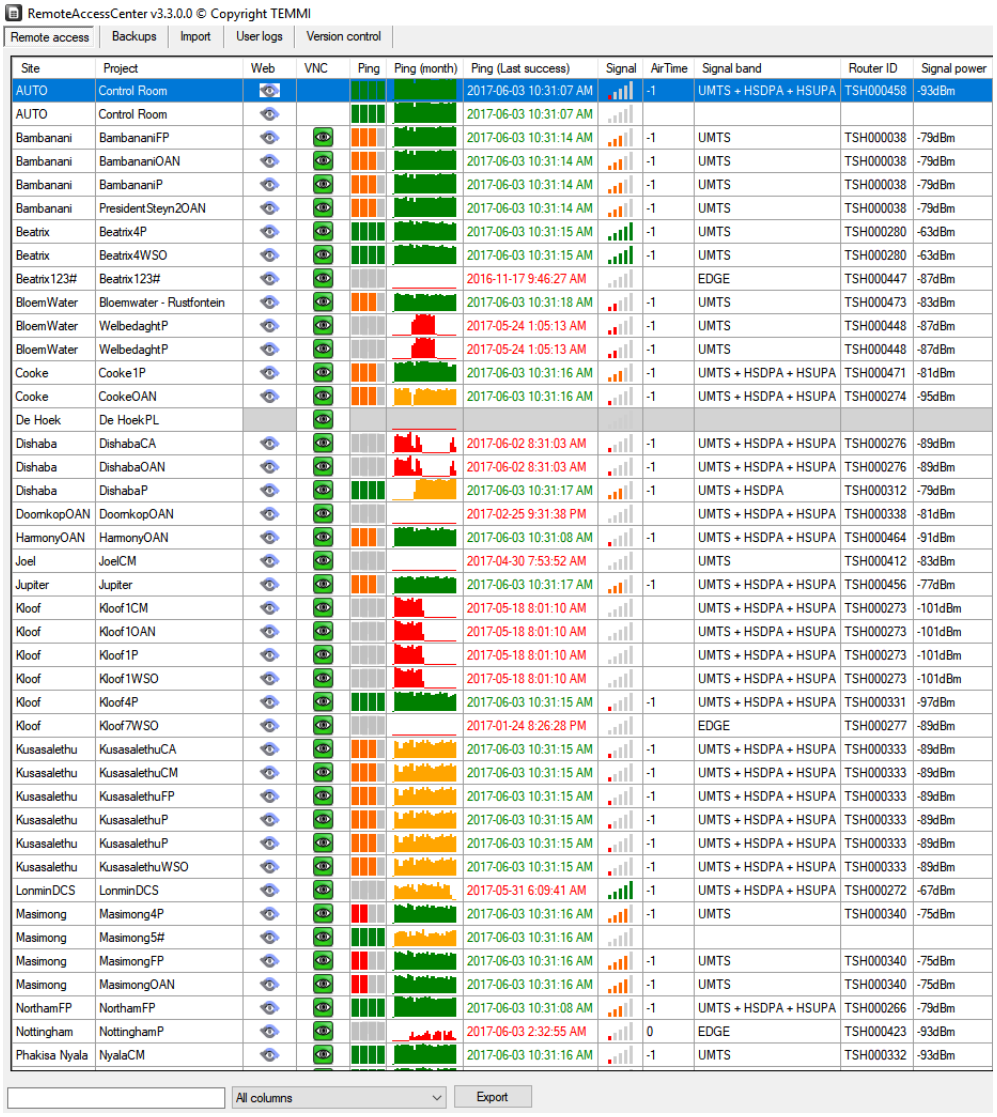


Figure 2: A software routine flow diagram to illustrate system operation [71]

The main software routine executes on a periodic basis, and upon execution, various subroutines are triggered. These subroutines are executed in a multithreading environment, which allows for any number of remote industrial sites to be monitored. The main objective of the subroutines is to retrieve the values of the network parameters defined above [58].

After retrieval, the acquired information needs to be stored and processed. A Structured Query Language (SQL) relational database system has been implemented to facilitate data storage [58]. Two data tables have been designed to accommodate raw data storage and processed data storage. The processed data comprises daily averages for all remote end-points.

Finally, all processed information is relayed to maintenance personnel via visual dashboards. In addition to vital network monitoring information, site-specific data are also displayed. This includes the site IP address, the port number that is required for remote access, and the details of the engineer that is responsible for maintaining site operations [58]. The information mentioned above is relevant since it aids in performing proactive maintenance. Figure 3 below illustrates the layout of the summary visual dashboard.



Site	Project	Web	VNC	Ping	Ping (month)	Ping (Last success)	Signal	AirTime	Signal band	Router ID	Signal power
AUTO	Control Room					2017-06-03 10:31:07 AM		-1	UMTS + HSDPA + HSUPA	TSH000458	-93dBm
AUTO	Control Room					2017-06-03 10:31:07 AM					
Bambanani	BambananiFP					2017-06-03 10:31:14 AM		-1	UMTS	TSH000038	-79dBm
Bambanani	BambananiOAN					2017-06-03 10:31:14 AM		-1	UMTS	TSH000038	-79dBm
Bambanani	BambananiP					2017-06-03 10:31:14 AM		-1	UMTS	TSH000038	-79dBm
Bambanani	PresidentSteyn2OAN					2017-06-03 10:31:14 AM		-1	UMTS	TSH000038	-79dBm
Beatrix	Beatrix4P					2017-06-03 10:31:15 AM		-1	UMTS	TSH000280	-63dBm
Beatrix	Beatrix4WSO					2017-06-03 10:31:15 AM		-1	UMTS	TSH000280	-63dBm
Beatrix123#	Beatrix123#					2016-11-17 9:46:27 AM			EDGE	TSH000447	-87dBm
BloemWater	Bloemwater - Rustfontein					2017-06-03 10:31:18 AM		-1	UMTS	TSH000473	-83dBm
BloemWater	WelbedaghtP					2017-05-24 1:05:13 AM		-1	UMTS	TSH000448	-87dBm
BloemWater	WelbedaghtP					2017-05-24 1:05:13 AM		-1	UMTS	TSH000448	-87dBm
Cooke	Cooke1P					2017-06-03 10:31:16 AM		-1	UMTS + HSDPA + HSUPA	TSH000471	-81dBm
Cooke	CookeOAN					2017-06-03 10:31:16 AM		-1	UMTS + HSDPA + HSUPA	TSH000274	-95dBm
De Hoek	De HoekPL										
Dishaba	DishabaCA					2017-06-02 8:31:03 AM		-1	UMTS + HSDPA + HSUPA	TSH000276	-89dBm
Dishaba	DishabaOAN					2017-06-02 8:31:03 AM		-1	UMTS + HSDPA + HSUPA	TSH000276	-89dBm
Dishaba	DishabaP					2017-06-03 10:31:17 AM		-1	UMTS + HSDPA	TSH000312	-79dBm
DoornkopOAN	DoornkopOAN					2017-02-25 9:31:38 PM			UMTS + HSDPA + HSUPA	TSH000338	-81dBm
HarmonyOAN	HarmonyOAN					2017-06-03 10:31:08 AM		-1	UMTS + HSDPA + HSUPA	TSH000464	-91dBm
Joel	JoelCM					2017-04-30 7:53:52 AM			UMTS	TSH000412	-83dBm
Jupiter	Jupiter					2017-06-03 10:31:17 AM		-1	UMTS + HSDPA + HSUPA	TSH000456	-77dBm
Kloof	Kloof1CM					2017-05-18 8:01:10 AM			UMTS + HSDPA + HSUPA	TSH000273	-101dBm
Kloof	Kloof1OAN					2017-05-18 8:01:10 AM			UMTS + HSDPA + HSUPA	TSH000273	-101dBm
Kloof	Kloof1P					2017-05-18 8:01:10 AM			UMTS + HSDPA + HSUPA	TSH000273	-101dBm
Kloof	Kloof1WSO					2017-05-18 8:01:10 AM			UMTS + HSDPA + HSUPA	TSH000273	-101dBm
Kloof	Kloof4P					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000331	-97dBm
Kloof	Kloof7WSO					2017-01-24 8:26:28 PM			EDGE	TSH000277	-89dBm
Kusasalethu	KusasalethuCA					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
Kusasalethu	KusasalethuCM					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
Kusasalethu	KusasalethuFP					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
Kusasalethu	KusasalethuP					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
Kusasalethu	KusasalethuP					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
Kusasalethu	KusasalethuWSO					2017-06-03 10:31:15 AM		-1	UMTS + HSDPA + HSUPA	TSH000333	-89dBm
LonminDCS	LonminDCS					2017-05-31 6:09:41 AM		-1	UMTS + HSDPA + HSUPA	TSH000272	-67dBm
Masimong	Masimong4P					2017-06-03 10:31:16 AM		-1	UMTS	TSH000340	-75dBm
Masimong	Masimong5#					2017-06-03 10:31:16 AM					
Masimong	MasimongFP					2017-06-03 10:31:16 AM		-1	UMTS	TSH000340	-75dBm
Masimong	MasimongOAN					2017-06-03 10:31:16 AM		-1	UMTS	TSH000340	-75dBm
NorthamFP	NorthamFP					2017-06-03 10:31:08 AM		-1	UMTS + HSDPA + HSUPA	TSH000266	-79dBm
Nottingham	NottinghamP					2017-06-03 2:32:55 AM		0	EDGE	TSH000423	-93dBm
Phakisa Nyala	NyalaCM					2017-06-03 10:31:16 AM		-1	UMTS	TSH000332	-93dBm

Figure 3: The summary visual dashboard of the telemetry monitoring system [58]

The immediate detection of communication network anomalies was facilitated by the monitoring system. As stated in Article II [58]: *"The primary objective of the proposed system was to actively monitor the vital signs of a GSM-based telemetry system. The system thus monitored and displayed the status of a mission-critical telemetry system on a real-time basis. Unstable connections were successfully identified and troubleshot. This clearly illustrates the benefits of implementing such a system on existing industrial IoT applications to ensure optimum service delivery."*

The telemetry monitoring system has been designed and implemented as a stand-alone cloud-based software system implemented with the Microsoft .NET framework, which can operate independently from existing Industry 4.0 applications [58]. Figure 4 below shows the scope of wide-area wireless communication, as well as the strategic importance of the proposed system.

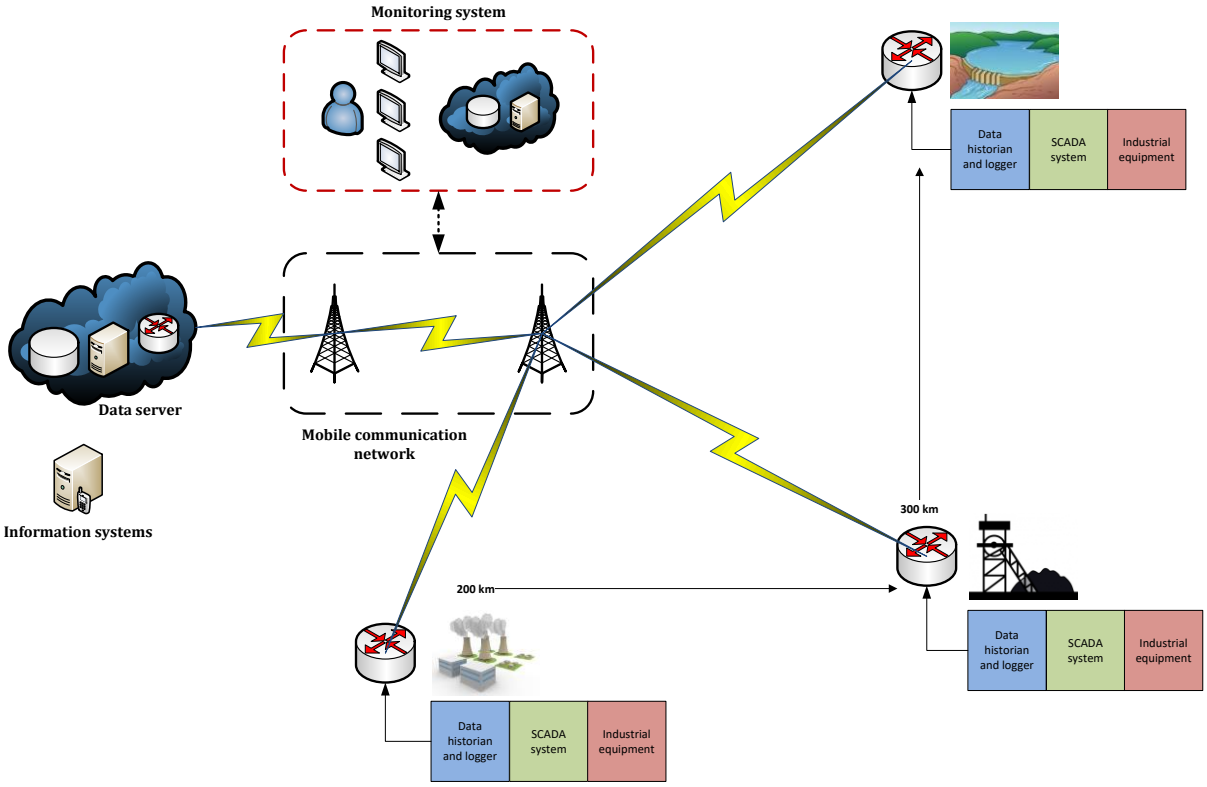


Figure 4: The scope and context of the proposed telemetry monitoring system [71]

The main challenge in the current methodology is that the monitoring and maintenance systems utilise the same communication network to relay monitoring information. QoS degradation in the communication network will, therefore, directly affect the monitoring and information systems on-site [58].

An independent system that is not integrated into an existing IIoT ecosystem ensures that the system itself will not be affected by anomalies that might have a negative impact on other subsystems [58]. The interaction between the telemetry monitoring system and an existing IIoT ecosystem is, however, required. The solution is to package the system as a cloud-based application with the ability to access the ecosystem via the network layer.

By expanding an IIoT ecosystem, as described above, it is possible to probe the network layer and monitor vital network layer parameters without the danger of compromising the system due to weaknesses present in the ecosystem [58]. This is a significant improvement to the current methodology of remote monitoring and maintenance systems in the heavy industry sector, where systems are usually implemented on an actual server on-site [13].

3.6 DISCUSSION

The system proposed in Article II was implemented on an existing mobile communication network utilised by an Energy Services Company (ESCo) to implement EMIS. Currently, the ESCo actively maintains energy projects across seven of the nine provinces in South Africa [58].

A brief overview is provided as an excerpt from Article II to illustrate the effect of the system in practise [58]: *"A total of 80 remote industrial sites were incorporated into the system. The remote sites include platinum mines, gold mines, processing plants, and several water distribution schemes.*

The underlying industrial equipment used on these sites includes compressors, pumps, fridge plants, fans, actuators, bulk air coolers, and various measurement devices. With the

monitoring of 80 industrial sites, the total number of heavy industrial equipment being monitored is well over a thousand individual components."

During the implementation phase of the system, it was found that active probing on an hourly basis gave an accurate account of the network status whilst keeping the load on the communication router within an acceptable range [58].

It should, however, be noted that the active probing interval is subjected to the utilisation of the network itself. If industrial end-points need to transmit data on a half-hourly basis, the network monitoring interval must be adjusted to an appropriate time interval to ensure effective use of the system [58].

System verification was obtained by first connecting several remote end-points to the system. A small area chart is present for every site to indicate the status of each site for a historical period of thirty days. After it was established that the system accurately monitors remote end-points, additional end-points were added to expand the reach of the monitoring system [58].

The first three months after system implementation were used as the baseline to evaluate the operation of the system. Calculation of the average active probing success rate per day for a period of three months was used to determine the baselines for all monitored sites [58]. The results of the system can be viewed in Article II [58].

3.7 CONCLUSION

In conclusion of this chapter, an excerpt is given from Article II [58].

"An extensive study on existing mission-critical systems showed that network-layer monitoring is seldom incorporated into the designs of industrial IoT systems. Therefore, a

proactive monitoring system that monitors the communication uplink status of remote wide-area wireless communication end-points was developed.

The objective of this study was to develop and integrate this system into existing industrial IoT infrastructure to improve the robustness of existing infrastructure. The proposed system has been designed and implemented on existing energy management projects of an established ESCo.

A total of 80 remote end-points, encompassing over a thousand individual components, were incorporated into the system for monitoring purposes. Unstable connections were successfully flagged and marked for investigation. Necessary steps were then taken to rectify the issues.

The achieved results demonstrate that real-time monitoring of mission-critical end-points was successfully achieved. The integration of this system further improved the robustness of industrial IoT infrastructure. The results of two independent remote end-points using this system found that unstable connections were identified within one hour of operation. It is believed that the incorporation of the proposed system will serve as motivation to incorporate IoT solutions and applications in the heavy industry realm."

With a novel telemetry monitoring system developed and verified, the next step is to illustrate the value of such a system in the heavy industry sector. Article III documents the value of the developed system, and the findings are discussed in the next chapter.

CHAPTER 4

ARTICLE 3: THE VALUE OF A TELEMETRY MONITORING SYSTEM

This section aims to provide a detailed discussion on the objectives and outcomes of Article III.

4.1 PREAMBLE

The aim of this thesis is to address the challenge of developing a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. The aim of Article II was to verify the proposed network telemetry monitoring system.

With system verification established, Article III aims to emphasise the value of the proposed system in industry. The quality and stability of existing mobile communication networks can hamper the effectiveness of industrial information systems and should, therefore, be monitored and maintained on a constant basis. Article III can be found in Appendix D and was published in the *South African Journal of Industrial Engineering* [71].

4.2 ARTICLE OBJECTIVES

In response to the holistic problem statement, Article III aims to illustrate the value of the proposed telemetry monitoring system in sustaining the operations of industrial information systems [71]. The objectives of Article III are to:

- Establish the context in which real-time data transfer and communication is achieved in industrial operations.
- Present several case studies that emphasise the value of the proposed system in the heavy industry sector.

The objectives listed above aim to promote the system presented in Article II. Article III serves to validate the operation and value of the network monitoring system.

4.3 METHODOLOGY

In response to the article objectives listed in the previous section, a summary of the methodological approach for Article III is provided below:

- The methodological approach discussed in Chapter 3, in relation to Article II, has also been applied in the methodology of Article III. The value of the developed system is considered to be the main focus of Article III.
- System verification has been established by Article II. In order to emphasise the value of the developed system, a troubleshooting methodology has been developed. The methodology is documented in Article III.

The telemetry monitoring system consists of three main design components, which are presented and discussed below:

Component 1 - The physical layer: The first component of the system focuses on the acquisition of data. To determine the state of the communication network, data needs to be retrieved. This is done by using an active probing procedure to determine whether the communication network is online. For the proposed system, the physical layer will be the execution of active probing software routines to determine the state of the various network parameters listed in Table 1 below.

Component 2 - The data layer: The results obtained from the active probing routine then need to be processed and stored in a database. This component is categorised as the data layer of the system. Active probing procedures are invoked routinely during the day, and the data is processed to obtain daily and hourly averages. The data layer also acts as a historian that can be used as an additional tool to evaluate the performance of energy management systems. For the proposed system, the data layer will be in the form of an SQL database.

Component 3 - The application layer: The final component of the system allows the processed data to be relayed to visual dashboards for analysis and decision-making purposes.

The application layer allows trained personnel to start a troubleshooting and diagnostic process to rectify issues that might arise without the need to travel to the actual industrial site to start troubleshooting. For the proposed system, the application layer will be in the form of a graphical user interface (GUI).

A modular design approach has been followed to allow for rapid expansion if additional industrial sites need to be included for telemetry monitoring purposes. Visual dashboards are presented to personnel and serve as a graphical user interface on which telemetry status signals can be viewed.

By gaining insight into the status of the cellular network, a detailed troubleshooting methodology can be developed and used in the event of communication disruptions. Figure 5 below illustrates the proposed troubleshooting methodology, as highlighted in Article III.

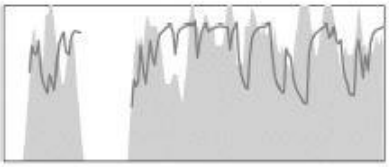
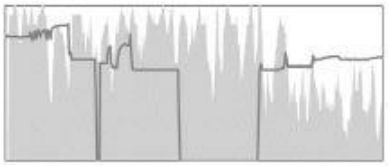
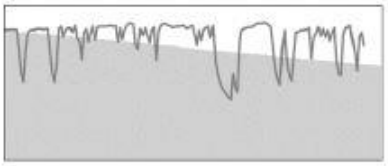
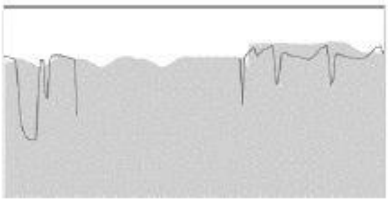
Characteristic	Illustration	Diagnosis	Troubleshoot
Network quality		Faulty network. Network downtime results in data loss. Without an active network connection, data transmission is impossible. This is illustrated by the gap in the area chart.	Network assets and infrastructure must be checked to determine whether faulty equipment results in network downtime.
		Stable network, but faulty equipment measurements. Data loss on a stable network implies that equipment measurement challenges are present on-site. An operational network can be seen in the area chart.	No troubleshooting needs to be done on the communication network if network bandwidth and signal strength are positive (see below). Investigations are required on-site to determine the cause of data loss.
Network bandwidth		Network bandwidth usage depleted. Depletion of network bandwidth results in network downtime. The area chart shows the data depletion.	Additional data bundles must be activated on the required wireless node. Data transmission routines must also be investigated on-site to determine why excessive data usage is present.
		Network bandwidth usage stable. Enough bandwidth is available to realise data transmission. This implies that equipment measurement challenges are present on-site.	No troubleshooting needs to be done on the communication network if network uplink and signal strength parameters are positive. Investigations are required on-site to determine the cause of data loss.
Equipment resilience		Network signal strength degradation. Weak signal strength results in unstable data transmission. The area chart shows the degradation in signal strength.	The geographical location of network infrastructure must be investigated and rectified to improve wireless signal reception. Faulty hardware must also be investigated.
		Network signal strength healthy. Stable network signal strength implies that equipment measurement challenges are present on-site.	No troubleshooting needs to be done on the communication network if network uplink and bandwidth parameters are positive. Investigations are required on-site to determine the cause of data loss.

Figure 5: Communication disruption diagnosis and troubleshooting [71]

4.4 LITERATURE STUDY

Cellular communication technologies and cellular infrastructure play a predominant role in facilitating real-time communication [72]. To utilise this infrastructure for real-time data transmission, minimal hardware is required to be installed. For most applications, a single industrial router is required to be installed, after which access can be obtained to the entire cellular network.

In addition to the installation of a router, mobile subscriber identification modules (SIMs) must also be incorporated to allow for wireless communication [73]. Several other applications that utilise mobile cellular networks for mobile communication can be seen in [59], [74]–[76].

The use of existing infrastructure implies that no control can be exercised over the network. The end-user that utilises the network must, therefore, cater for potential communication disruptions over which they have no control.

Disruptions in communication can result in data loss, which can have a negative impact on the performance of industrial processes and systems. Should the existing cellular communication network experience disruptions in communications, industrial information systems, as proposed by [27], [29], [39], would become unreliable and have no benefit to industrial clients.

Several network monitoring systems have been proposed in literature. Civerchia *et al.* proposed a localised IIoT monitoring system for predictive maintenance applications [77]. The main objective of the system is to facilitate the pervasive monitoring of industrial machinery.

The system proposed by Civerchia *et al.* successfully implemented the capability of monitoring industrial equipment in real-time. Emphasis was, however, placed on the equipment side and not on the monitoring of the communication network itself. The system is, therefore, unable to report on the status of the equipment if the communication network is down.

In addition to the limitation above, the proposed system was implemented locally, where direct access to equipment can be achieved with the installation and interfacing of sensor nodes. A key concern that should be noted from literature is the quality and reliability of wide-area wireless telemetry when industrial plants are separated by large geographical distances [78].

Another proposed system is the monitoring of wireless networks in smart factories. A brief excerp is given from Article III [67]: "*Gisbert et al. proposed a system that can monitor the performance of heterogeneous wireless networks within the context of local smart factories* [79]. *One key feature of the proposed system is the ability to reconfigure wireless communication nodes based on the quality of the network. The aim of the system is to help guarantee the robustness and reliability of wireless communications in the context of smart factories. The quality and reliability of wide-area wireless communication networks are, however, not addressed."*

Finally, an investigation was done into propriety network analysis tools, such as Cacti and Nagios and a number of concerns were raised. Firstly, the listed tools are not free, and licenses are required to utilise the software. Secondly, the software is incompatible with GSM communication networks. Parameters such as signal strength and bandwidth cannot be monitored by the mentioned tools for wide-area cellular communication.

Although the solutions from literature add value to the current state-of-the-art network monitoring, these systems are not appropriate in the context of wide-area wireless communications. Furthermore, literature has shown that no network monitoring solution exists within the context of the South African mining sector. There is, therefore, a need to illustrate the value of a network monitoring system in industry that facilitates network monitoring over cellular networks.

4.5 SUMMARY OF ARTICLE

Three steps must be mastered for industrial information systems to be able to accurately process and display information. The first step is to acquire the necessary data from industrial end-points. In the heavy industry sector, equipment is controlled via programming logic controllers [71].

These controllers interface with a central SCADA system, which allows for real-time monitoring and control of industrial processes and equipment. In several cases, additional control systems are required on separate servers to optimise existing control philosophies. These systems usually interface with existing SCADA systems by means of the open platform communications (OPC) server. In most cases, these systems are used to retrieve real-time raw data for information systems [71].

The second step is real-time data transmission. Most information systems utilise cloud-based infrastructure for storage and processing. This implies that a communication network is required for data transmission [58], [71].

Industrial plants and compounds are distributed across large geographical distances. To enable data transmission, the mobile cellular communication network is utilised as the

communication infrastructure. This requires the installation of industrial mobile cellular communication routers on-site to facilitate data transmission via the cellular network [71].

SIMs must be present in every router for mobile cellular communication routers to successfully transmit data. In several cases, industrial compounds serve as a hub for wireless data transmission. Data would be transmitted from other compounds to one central location from which control systems can acquire access to the data via OPC [71].

The final step is the transformation of transmitted raw data into usable information. The transmitted data is stored in a centralised or decentralised storage scheme from which calculations can be made to convey meaning. Information can then be relayed to end-users in the form of online dashboards, which are accessible from any location [71].

A critical reflection on the three steps discussed above shows that the mobile cellular communication router and mobile cellular network must be considered as a critical point in the overall architecture.

Any QoS degradation in the network will result in a failure to transmit data, which affects the overall reliability of information systems. The system proposed in this paper aims to specifically address this concern, illustrating the value of this system within the context of existing industrial information systems [71].

Article III highlights three key perspectives for maintaining the stability and operational effectiveness of an industrial wireless communication network. An excerpt from Article III is provided as discussion [71]: "*Three key perspectives that are crucial to the overall quality and stability of a wireless communication network have been identified. The first perspective is the global operational status of the wireless communication network. This perspective is*

labelled as the "line-of-site" perspective, even though wide-area wireless communications are not considered to be directional.

Software subroutines were implemented to determine the operational status of the line-of-site perspective. This entails the transmission of data packets across the network link to the receiving end-point located at an industrial facility. An operational end-point with a stable link will reply with an echo data packet in response to the active probing transmission. The responses can then be recorded and history compiled for troubleshooting purposes.

The second perspective focuses on the usage of mobile data to facilitate all network communication. Mobile data is an expensive resource and should, therefore, be monitored on a constant basis. A depletion in the mobile data bundle will also result in network downtime, which is unacceptable.

The third and final perspective focuses on the quality of the network link. The quality of a communication network can be determined by looking at the signal strength of the network. Network signal strength provides valuable insight into the current state of the network and can highlight potential issues such as coverage gaps present in remote areas as well as interference that might disrupt wireless communication over long distances."

Three major scenarios from actual case studies are presented below to illustrate the value of the system in Article III. The first scenario aims to illustrate the importance of constantly monitoring the status of the network uplink to remote industrial sites [71].

The second scenario aims to illustrate the importance of monitoring network bandwidth availability. Finally, the third scenario aims to illustrate the importance of monitoring

network signal strength [71]. Results from the three perspectives discussed are presented below, and a more detailed discussion can be found in Article III.

Figure 6 below shows the effect intermittent network connectivity has on real-time data transmission. A critical equipment measurement is presented by the line graph, whilst the area plot represents the average active probing success rate of the network uplink. From Figure 6, it can be seen that data loss occurred during two separate periods. No network uplink was available during these two periods.

The failure in the connection uplink resulted in a failure to relay all real-time data to the information system. Data transmission continued after the network connection to the remote site was restored. The telemetry system was successful in isolating the cause for data loss and aiding in effective troubleshooting.

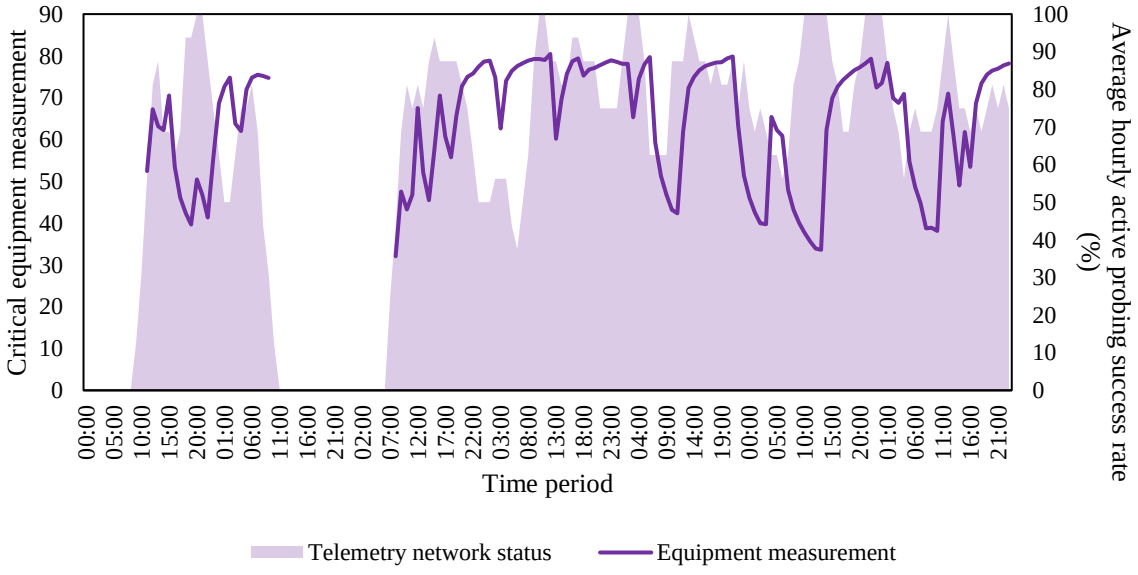


Figure 6: The effect of intermittent connectivity on data transmission [71]

Figure 7 below presents a similar scenario where a critical equipment measurement dropped to zero, indicated by the line plot. An investigation was launched to identify the cause for this measurement drop. The telemetry monitoring system indicated that the network connection to the industrial site was indeed operational. The average active probing success rate of the network connection is once again indicated by the area plot.

The findings of the investigation indicated that the on-site OPC server was offline. Real-time data acquisition via the on-site energy management system was, therefore, impossible since the OPC server facilitates communication between the energy management system and the on-site SCADA system. After the OPC server was restarted, data transmission was again operational [71].

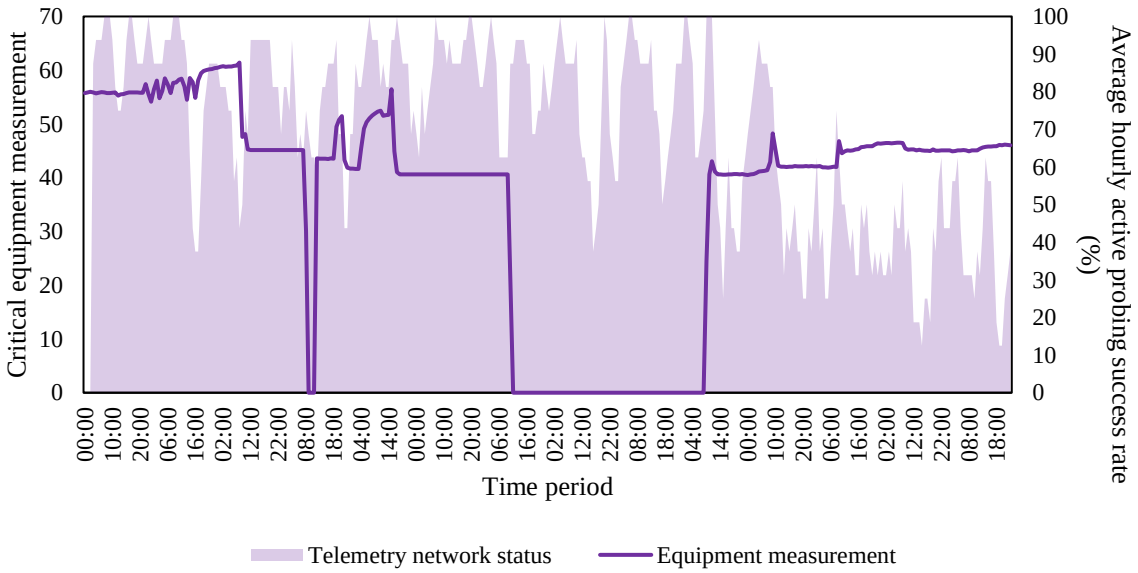


Figure 7: An example of a stable connection uplink with intermittent data [71]

Figure 8 below aims to illustrate the effect of mobile data depletion on real-time data transmission. A critical equipment measurement is once again represented by the line plot,

whilst the area plot represents the level of mobile data usage. The main observation that can be made from Figure 8 is that real-time data transmission is halted once network mobile data has been depleted.

In order to rectify the issue, mobile data needs to be manually loaded, and this can take a considerable amount of time to reflect. The telemetry monitoring system, therefore, aims to proactively prevent possible dead times due to data depletion by monitoring the real-time consumption of mobile data.

Various causes for excessive data consumption exist, namely negligence from maintenance personnel with regard to remote monitoring via remote desktop sessions and continuous retransmission of raw data from site [71], [73]. The causes for excessive data consumption can be integrated into the diagnostic and troubleshooting methodologies used by dedicated maintenance teams. The telemetry monitoring system aims to provide a reference point from which these teams can conduct troubleshooting routines [71].

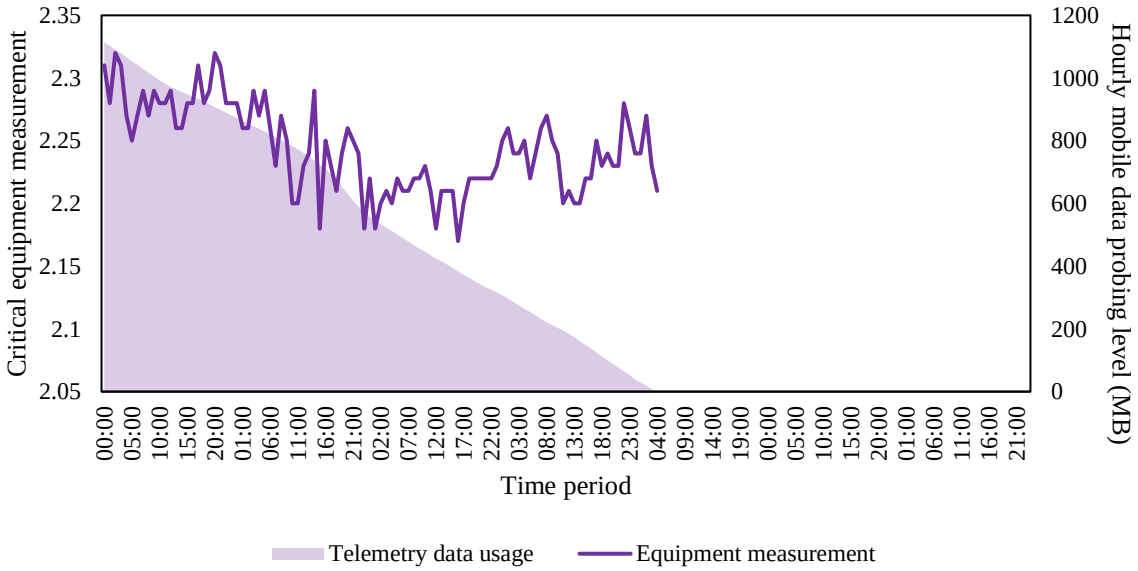


Figure 8: The effect of mobile data depletion on data transmission [71]

Signal strength levels play a vital role in sustaining maintenance agreement effectiveness [71]. Figure 9 below illustrates the effect of weak signal strength on the real-time monitoring capabilities for maintenance agreement purposes.

Figure 9 shows a clear drop in the quality of the network signal strength, which resulted in data loss. A variety of factors can influence the signal strength of wide-area wireless communications, such as electromagnetic interference and limited network coverage.

Article III provides clarity on the challenges discussed above, as well as possible intervention strategies [71]: *"The decline in the signal strength shown in Figure 9 was a result of infrastructure being moved to a different location on site. The new location experienced periodic dead times in network coverage, which resulted in occasional dead times during which no data transmission was possible. The telemetry monitoring system assisted in diagnostics and troubleshooting, and the issue was rectified by repositioning the installed infrastructure to a new position.*

To compensate for the gaps that are present in network coverage, a detailed coverage investigation must first be done to determine the state of network coverage. This information must then be used to determine a suitable location for the installation of an energy management system and the supporting infrastructure."

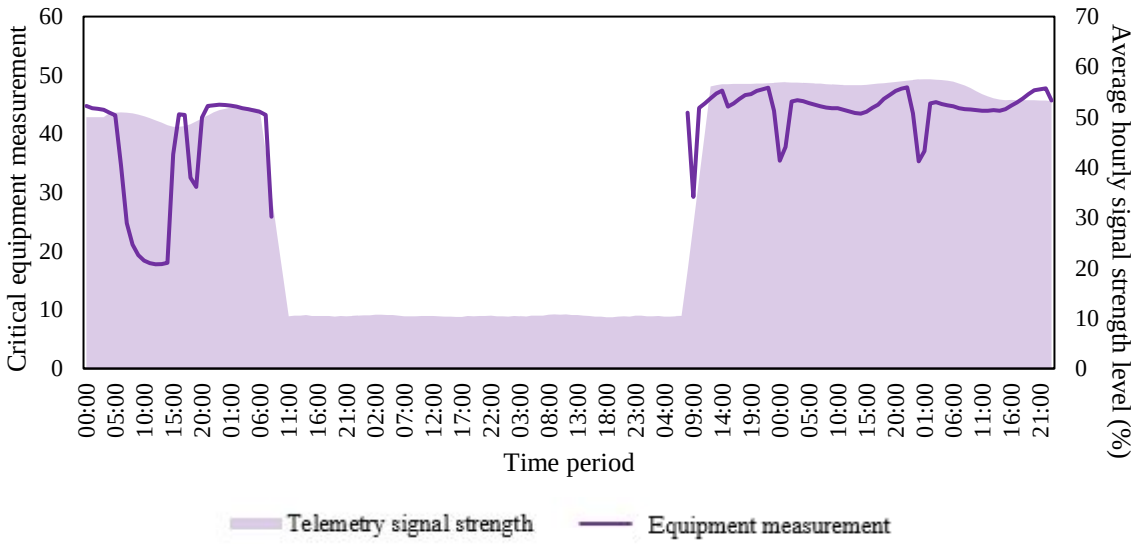


Figure 9: The effect of weak signal strength on data transmission [71]

4.6 DISCUSSION

With industry currently using existing infrastructure to achieve real-time communication and data transmission via the cellular network, there is a need to develop a telemetry monitoring system that actively monitors the status of the communication network. Since no control can be exercised on the network, QoS issues cannot be directly addressed [71].

An external monitoring system that provides insight into the status of the network was, therefore, required. As stated in Article III [71]: "*By gaining insight into the status of the cellular network, a detailed troubleshooting methodology can be developed and utilised in the event of communication disruptions. The telemetry monitoring system succeeded in providing accurate insight into the status of mobile communication networks utilised by remote industrial sites. The implementation of a telemetry monitoring system ensures that the full potential of industrial information systems can be achieved*."

The improvement and increased sustainability of QoS is made possible when telemetry between an energy services company and remote industrial sites are monitored. The proposed system also implements a novel approach to combining telemetry monitoring data with industrial information system data. By doing so, accurate and effective troubleshooting can be done to determine the cause of potential data loss present in industrial information systems [71].

Real-time data transmission, processing and display are crucial factors in condition-based maintenance systems and EMIS. Effective maintenance strategies and the need-to-know are also considered to be crucial factors in energy savings initiatives. The proposed system could assist in maintaining energy management system stability [71].

4.7 CONCLUSION

In conclusion to this chapter, an excerpt is provided from Article III below [71]:

"The performance of integrated demand-side management projects and other maintenance strategies can be greatly affected by an unstable telemetry uplink between an energy services company and a remote industrial site. An investigation into state-of-the-art Industry 4.0 applications showed that IIoT applications rely on a stable telemetry uplink but do not monitor the actual uplink itself. This implies that current IIoT systems can be unreliable if the quality of the communication network degrades.

The achieved results demonstrate the value of this system. Positive impacts were made on condition-based maintenance agreements. The system is generic and can, therefore, be applied to any IIoT ecosystem where mobile communication networks are utilised for real-time data transmission. The results obtained show that the proposed system can enhance the

robustness of existing IIoT infrastructure and this, in turn, promotes the adoption of Industry 4.0 concepts into the heavy industry sector."

The aim of Article III is to emphasise the value of a novel telemetry monitoring system in the heavy industry sector. In addition to the implementation of such a system, there is still a need to proactively manage and maintain communication infrastructure that allows for wireless communication over large geographical distances. Failure to do so would result in the accumulation of excessive network costs or even failure in network communication [71]. The next chapter addresses the management of network infrastructure to allow for effective communication to take place.

CHAPTER 5

CONFERENCE PAPER: PROACTIVE INFRASTRUCTURE MANAGEMENT

This section aims to provide a detailed discussion on the objectives and outcomes completed in the conference paper.

5.1 PREAMBLE

The aim of this thesis is to address the challenge of developing a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. With Article III emphasising the value of the proposed telemetry monitoring system in industry, the objective of the conference paper is to address additional challenges within the context of network infrastructure and costs.

The conference paper can be found in Appendix E and was published in the proceedings of the 2018 annual conference of the *South African Institute for Industrial Engineering* [73].

5.2 PAPER OBJECTIVES

In response to the holistic problem statement, the objective of this paper is to present and emphasise the value of an information and asset management system for SIM cards used by existing IIoT applications [73]. The objectives of the paper are to:

- Offer an architectural overview of industrial information systems in the context of the Industry 4.0 domain.
- Discuss critical challenges that can hamper the network layer quality and stability of industrial information systems.
- Address SIM management by introducing a comprehensive information and asset management system.
- Emphasise the value of an information and asset management system by analysing the results obtained in the field.

5.3 METHODOLOGY

In response to the article objectives listed in the previous section, a summary of the methodological approach for the paper is provided below:

- Firstly, the methodology was initiated with an extensive literature review of the current state of industrial information systems in industry. The paper highlights two systems in literature that are being used in industry that fits within the context of this paper.
- Phase 2 of the literature survey focused on identifying critical challenges that can have a profound effect on the quality and stability of industrial information systems. An investigation was done on the two systems highlighted in the paper. Site visits were first conducted to determine the exact method of operation.
- Based on the information gathered, a comprehensive information and asset management system was introduced. The application of this system, and the value thereof, is highlighted in the paper.

5.4 LITERATURE STUDY

The South African heavy industry, namely deep-level mining and steelmaking industries, still utilise traditional models focused on centralisation for the monitoring and control of production and assets [39]. The current operational architecture of the South African heavy industry sector still lacks the required infrastructure to support Industry 4.0 initiatives. A full shift to decentralised and autonomous monitoring and control is, therefore, infeasible.

An industrial information system can be divided into three main parts, namely, the physical layer, the network layer and the application layer. The collection of raw data takes place in the physical layer. Various sensors and actuators can be used to perform this task, but it is also possible to make use of an existing industrial supervisory control and data acquisition (SCADA) system to collect data.

The data obtained from industrial endpoints must then be transmitted to a decentralised storage scheme for data processing and storage. Cloud-based systems are used to allow for decentralised accessibility. Wide-area wireless communications, such as the Global System for Mobile communication (GSM), is used to transmit data to the cloud-based facility. This requires industrial GSM routers to be installed at industrial endpoints. Each router must also be fitted with a SIM card for connection to a mobile service provider network. Various works in literature emphasise the importance of wide-area wireless communications in IoT applications [64], [72], [80], [81]. Without a stable network layer, industrial information systems will be rendered inoperable.

Industry 4.0-related initiatives that mostly focus on indirect support and service delivery have, however, been proposed and implemented. The scope of these initiatives encompasses condition-based maintenance systems, automated bill analysis systems, EMIS, and remote monitoring and maintenance systems [27], [29], [30], [36].

Goosen *et al*. [29] proposed a comprehensive energy management information system with the objective of providing industry with the ability to comply with various energy management standards, legislation and incentive structures. The system facilitates data collection and storage processes, as well as data analysis methods to provide users with accurate energy reports.

Input data is provided to the system from external metering parties, the state-owned electricity utility Eskom, as well as direct input from industrial SCADA systems. Accurate energy reports are then provided as output. The energy reports can be viewed in document format, or the data can be viewed on real-time electronic dashboards.

Van Jaarsveld *et al*. [27] proposed a condition-based maintenance system with the objective of providing industry with the ability to accurately determine in real-time fashion the status of vital assets, such as pumps, compressors and fridge plant units. This system follows a similar approach to that of the EMIS proposed by Goosen *et al*. Only one source of input is used, which is the industrial SCADA system.

Various status and efficiency parameters are monitored, such as vibration characteristics, temperature levels and trip counters. Data is transmitted in a real-time fashion to a decentralised processing and storage unit, after which the processed data is relayed to visual dashboards. The transmitted data is processed for exception reporting, as well as "Safe, Caution, Risk, Failure" (SCRF) assessments.

The initiatives listed above rely heavily on mobile communication networks for real-time data transfer. Disruptions in the communication network will hamper the effectiveness and reliability of information systems that are critical to industrial operations.

Several challenges exist that inhibit the ability of industrial information systems to relay critical data in a real-time fashion. Mismanagement of SIM cards, the maladministration of mobile communication routers on-site, and general hardware failures are among the few challenges that can result in intermittent connectivity.

5.5 SUMMARY OF PAPER

In order to effectively manage SIM cards in industry, a comprehensive information and asset management system are required. Two main functional blocks form the foundation for the proposed information and asset management system. Figure 10 below provides an architectural overview of both functional blocks.

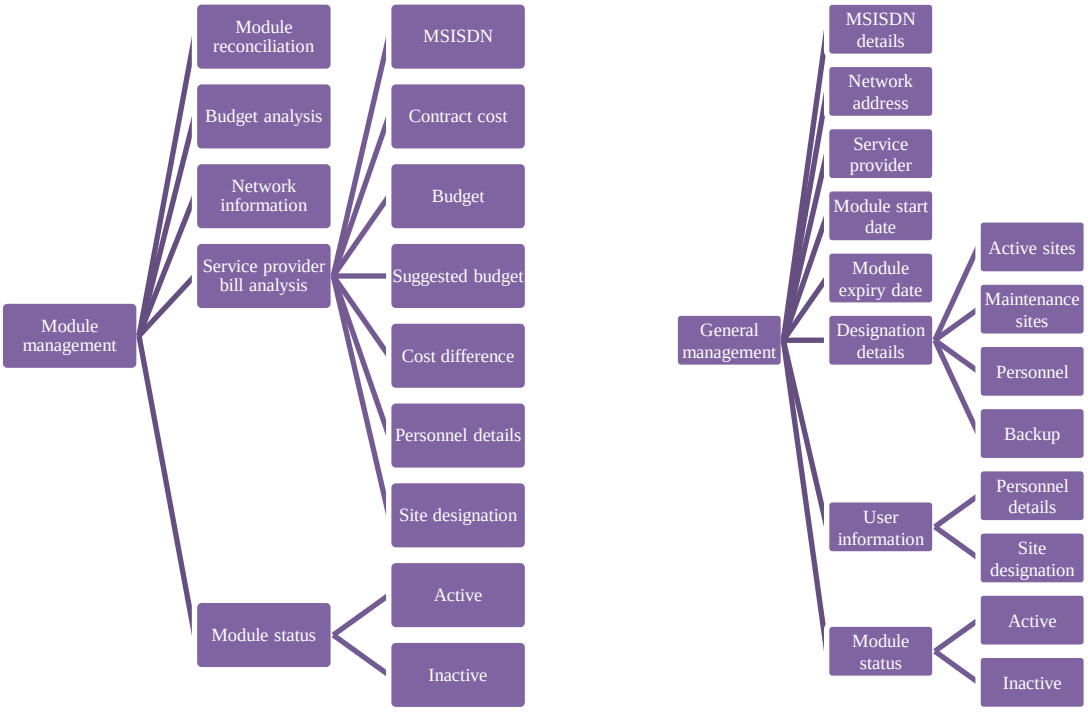


Figure 10: An architectural overview of the information and asset management system [73]

The linking of various SIM cards to individual personnel or industrial sites is facilitated by the general management block. The identification of individual SIM units is facilitated by the module management block. Administration and cost details of individual SIM cards are also provided. The module management block allows for a cost and budget analysis to be conducted [73].

The module management subsystem enables accurate cost analysis calculations to be made. The input data required to perform the cost analysis calculations must be provided in the form of data contract invoices and mobile service provider summary sheets [73].

The cost analysis functionality relies on a separate service provider bill analysis section. Data contract invoices are used as input in order to extract the SIM module mobile station

international subscriber directory number (MSISDN), as well as the monthly expense for the module. The output data obtained from the analysis functionality is compared to a suggested budget. This comparison is then used to calculate a cost difference, from which a usage profile can be compiled for a specific module [73].

The general management subsystem allows for a SIM card to be linked to a user, which can either be an industrial site or personnel. Personnel is often required to conduct remote monitoring and maintenance of site equipment and systems. To this end, SIM cards are used to facilitate remote monitoring procedures. A designated IP address linked to each SIM card gives project engineers the ability to access on-site servers from a remote location securely [73].

SIM card modules allocated to industrial sites facilitate the real-time transmission of data. These modules form an integral part in sustaining the operational ability of industrial information systems [73]. The general management subsystem lists vital module details, such as the network address, the MSISDN number, the module activation and expiry date, and the network address linked to a specific module.

A detailed cost analysis in South African Rand (R) can be viewed in Figure 11 below. The figure illustrates the costs involved in sustaining telemetry network connections to multiple industrial client groups. The actual cost per month is represented by the bar chart, and the budgeted value is illustrated by the area chart. The chart shows multiple crossover points, where the actual amount exceeded the budget value. This was caused by excessive data usage, where multiple SIM cards exceeded the stipulated data limit.

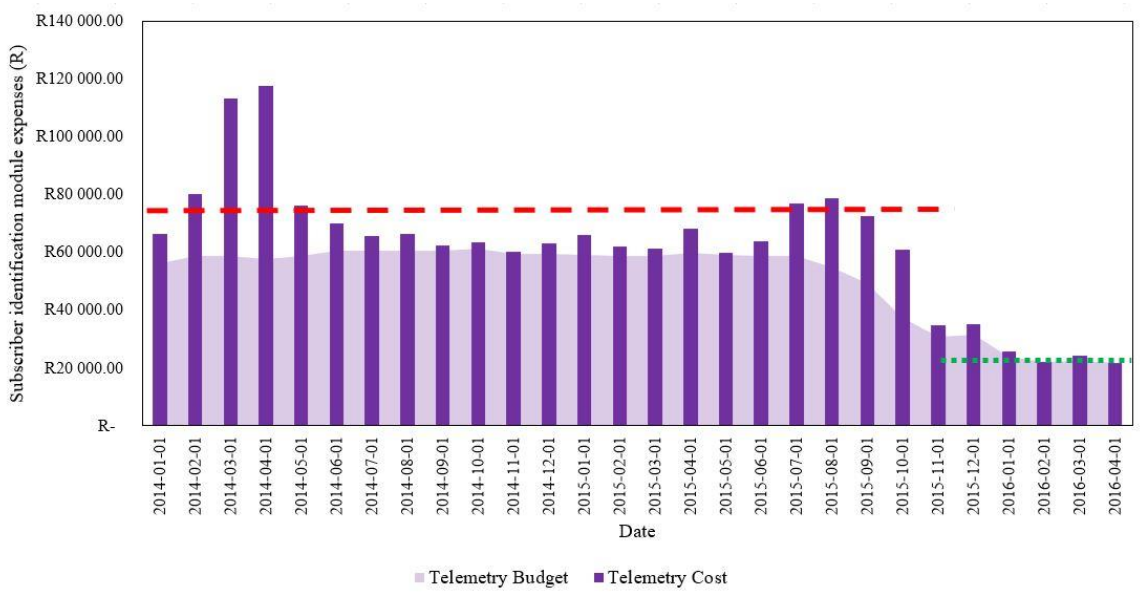


Figure 11: A cost analysis of existing SIM cards in circulation [73]

When the monthly data limit is exceeded, out-of-bundle rates come into effect. This further increases the communication costs and, if left unchecked, will result in unnecessary expenditure. The information and asset management system assisted in the identification of SIM units on industrial sites that do not require any monitoring and maintenance [73]. These SIM units were decommissioned, which led to a decrease in the overall telemetry cost illustrated in Figure 10.

The average communication cost before the intervention is illustrated by the red dashed line in Figure 10. The value equates to an amount of R71,698.93. During the intervention period, several SIM cards were decommissioned, which resulted in a drop in the average communication cost to an amount of R27,287.48 (illustrated by the green dotted line in Figure 10). This drop signifies a decrease of approximately 62% of overall communication costs [73].

5.6 DISCUSSION

Based on insight gained from literature and industry, it was determined that there is a clear need for the development of an information and asset management system. The aim of this system is to address the challenge of SIM card mismanagement in industry. The development of this system is considered to be an integral component of the network layer of any real-time information system that relies on mobile communication networks to facilitate wireless data transfer [73].

With the implementation of the asset management system, accurate cost analyses can be conducted on any mobile data contract. Billing invoices must be provided as input, and the system automatically generates the required cost profiles.

The results clearly show the advantages of the system. An excerpt from the conference paper is provided for discussion [73]: *"Automated cost analyses can provide valuable insight into the health of the network layer. The system can also identify communication anomalies that have a direct effect on the cost of maintaining a wide-area wireless telemetry uplink.*

The system presented in this paper ensures that industrial information systems such as remote monitoring and maintenance systems proposed by Yang et al. [82] *and condition-based maintenance systems proposed by Van Jaarsveld et al.* [27] *will always be able to maintain real-time communication whilst keeping communication costs at a minimum.*

The system also identified SIM cards that were subject to theft. High data costs usually point to module theft. One investigation showed that a module linked to a router that was not operational still showed high data costs. An on-site investigation revealed that an unauthorised SIM swap was done, with the replacement SIM being defective.

The system proposed in this paper approaches network layer maintenance and stability from a cost and budget point of view. Not only does this improve the quality and reliability of wide-area wireless telemetry, but it also maintains indirect expenses that are associated with industrial information system communications."

This system should be incorporated into existing information systems to increase operational and management efficiency. An example would be to integrate this system into the EMIS proposed by Goosen *et al.* [29].

Industrial client groups can also benefit from this system, should the system be integrated with other real-time information systems that have already been implemented in industry. This will additionally allow for the generation of cost analysis reports that can be distributed on an operational level. This integration will expand the reach of the system and enable clients to take responsibility for communication costs [73].

5.7 CONCLUSION

In conclusion of this chapter, an excerpt is given from the conference paper listed in Appendix E [73].

"The network layer is the backbone of any industrial information system. In the context of Industry 4.0, most information systems rely on wide-area wireless telemetry to achieve data transmission and decentralised storage and processing of data.

The GSM network is currently an acceptable method to achieve this. Challenges are, however, present that can hamper the effectiveness of industrial information systems. These challenges include the mismanagement of hardware devices, the maladministration of SIM cards, and hardware failures.

This conference paper presented an information systems approach to the management of SIM cards utilised in industry. The system consists of two main foundational blocks which allow for the calculation of automated cost analyses. These cost analyses contain actual expenses as well as budgeted values, which allows for budget comparisons to be made.

Weighted analyses are also possible, which assists in determining exceptions where communication anomalies are present."

The implementation of the proposed system allowed for an overall communication cost reduction of 62%. Average monthly network costs were reduced from approximately R72,000 to R27,000 [73].

CHAPTER 6

DISCUSSION

This section aims to summarise and discuss this study. Concluding remarks are presented.

6.1 PREAMBLE

This section aims to discuss the outcomes of this study. The novel contributions to literature of each individual article are presented. The outcomes of the articles presented in this thesis are summarised, and concluding remarks are presented. A validation strategy is also provided at the end of the chapter.

6.2 CONTRIBUTIONS TO LITERATURE

The novel contributions of each article are presented below. Each novel contribution is divided into a context section, a requirement section, and a contribution section. These novel contributions aim to satisfy the problem statement defined in the previous section. The contributions lead to improved QoS in wide-area wireless telemetry networks in the heavy industry sector.

I. Towards Industry 4.0: A Roadmap for the South African Heavy Industry Sector.

Context

The Industry 4.0 paradigm is a relatively new concept that still requires detailed investigation and discussion. Standards, technologies, and overall guidelines need to be presented if successful adoption in the heavy industry sector is to take place. Several technologies and methods exist which form the foundation of the Industry 4.0 vision, but no clear roadmap of implementation is available from literature within the context of the heavy industry domain.

Requirement

Literature has shown that no clear Industry 4.0 architectural description is available within the context of the heavy industry sector. Based on the context described above, there is a need to clearly define the Industry 4.0 paradigm within the context of heavy industry. A clear

architectural description is required for Industry 4.0 adoption. With Industry 4.0 being a relatively new concept, the required architectural description can be used as an implementational roadmap to guide heavy industry players on the road to Industry 4.0 adoption.

Contribution

In Article I, a clear architectural description is presented that can be used to guide heavy industry players in the adoption of key Industry 4.0 principles in practice. An input-output methodological approach was followed to deconstruct the Industry 4.0 paradigm into two parts.

The input model labelled as the digital framework serves as the chief enabler of the output model, labelled as the digital toolbox. Together these two components form a roadmap that can be utilised to navigate the tides of Industry 4.0 adoption in the heavy industry sector, with specific application to the South African mining sector.

The value that Industry 4.0 adds to the mining sector is illustrated by the Industry 4.0 digital toolbox. It is, however, impossible to implement the digital toolbox fully if the digital framework does not exist. Key framework technologies and principles must, therefore, be incorporated before the digital toolbox can be applied, starting with the five framework technologies: cyber-physical systems, IoT, big data, decentralised computing, and wireless networks.

Validation

Article I presented a detailed architectural study of the Industry 4.0 paradigm. The digital framework and the digital toolbox proposed in this paper clearly highlight key areas of

importance that must be addressed before Industry 4.0 adoption can take place. To illustrate the utility of the proposed architectural model, a theoretical case study was developed. In the context of the South African mining industry, a methodological shift must be made from traditional centralised operations to decentralised computing.

This, together with the implementation of wireless sensor network infrastructure, will assist in the development and advancement of asset management systems, condition-based maintenance systems, and energy management systems. The incorporation of sensors and decentralised computing will enable the incorporation of predictive maintenance strategies, which in turn will improve the operational uptime of equipment. Article I succeeded in identifying shortcomings in the South African mining sector, and it succeeded in providing a detailed Industry 4.0 roadmap for the South African heavy industry context.

II. Development of a Software-Based Monitoring and Information System for Industrial Telemetry Applications.

Context

The heavy industry sector cannot yet be classified as “smart” industry, and most players in the sector are still operating at traditional “best-effort” service levels. In addition to this, heavy industrial facilities are usually spread over wide geographical areas and operate under adverse conditions.

Due to the geographical separation of industrial plants, wide-area wireless telemetry networks are utilised to achieve real-time communication and data processing. For Industry 4.0 applications to be effective, QoS is a top priority. Challenges such as limited bandwidth, intermittent connectivity of wireless networks, and potential security threats can, however,

hamper the QoS of these telemetry networks, which makes Industry 4.0 applications ineffective.

Requirement

Literature has shown that established heavy industries such as the mining and steel manufacturing sector, water distribution schemes, and power utilities are reluctant to adopt Industry 4.0 strategies. This hesitance is due to legitimate concerns, such as safety, security, and capital expenditures.

In addition to this, the challenges mentioned in the context section above also contribute to the slow adoption rate. There is, therefore, a need to address the QoS of wide-area wireless telemetry networks to ensure that a stable communication network is provided for real-time data transmission.

Contribution

In Article II, a new software-based system that actively monitors the network layer vital signs of a wide-area wireless telemetry system is proposed. This monitoring system can be deployed remotely for IIoT applications.

Literature has identified existing monitoring systems, but these systems only focus on small-scale networks. The scope and reach of the proposed system are of a national scale, which makes this monitoring system unique within the context of industrial communication networks.

Validation

The proposed system in Article II has been designed and implemented on existing energy management projects of an established energy services company. A total of 80 remote end-

points, encompassing over a thousand individual components, were incorporated into the system for monitoring purposes. Unstable connections were successfully flagged and earmarked for investigation. Necessary steps were then taken to rectify the issues.

The results achieved demonstrate that real-time monitoring of mission-critical end-points was successfully achieved. The integration of this system further improved the robustness of industrial IoT infrastructure. It is believed that the incorporation of the proposed system will serve as motivation to incorporate IoT solutions and applications in the heavy industry realm.

Article II successfully isolated a specific limitation highlighted by Article I and provided a novel solution to the identified problem. The system developed and documented in Article II successfully achieved the need to bring heavy industrial players into the Industry 4.0 realm by addressing QoS issues in wide-area wireless communication networks.

III. The Value of a Telemetry Monitoring System on Sustaining the Operational Performance of Industrial Information Systems.

Context

Network layer quality and stability form a crucial part of an Industry 4.0 ecosystem. Methods such as M2M communication and wide-area wireless telemetry form the backbone of an interconnected industrial IoT environment.

Currently, the GSM network is utilised by heavy industry players to achieve long-range data transmission. Disruptions in communication are, however, a constant occurrence, which can hamper the functionality of real-time industrial information systems.

This, in turn, contributes to the slow Industry 4.0 adoption rate in the heavy industry sector. If Industry 4.0 is to be successfully integrated into the heavy industry domain, accessibility and connectivity disruptions must be addressed on a proactive level.

Requirement

Intermittent connectivity in wide-area wireless communications can hamper the QoS and hence the effectiveness of real-time industrial information systems. Industrial information systems will also fall short of their objectives if no input data is received from remote industrial locations.

There is, therefore, a need to develop a telemetry monitoring system that analyses all status parameters of an industrial wide-area wireless telemetry network. In addition to the development of this system, integration with existing real-time information systems is also required to promote effective troubleshooting and introduce proactive maintenance procedures on network infrastructure.

Literature has shown that existing monitoring systems do exist but are implemented on short-range communication networks that are carried out in a single building or local area. These networks do not experience the same challenges as wide-area wireless networks, and the value of existing systems is also often overlooked.

Contribution

The proposed system in Article II was expanded and integrated into existing industrial information systems with the aim of increasing the operational performance of these systems. This expansion and integration also result in enhanced troubleshooting procedures that can be followed on-site to rectify any network communication anomalies.

Validation

The results from Article III succeeded in demonstrating the value of the proposed system. Positive impacts were made on equipment monitoring in the heavy industry sector. The system is generic and can, therefore, be applied to any IIoT ecosystem where mobile communication networks are used for real-time data transmission. The results show that the proposed system can enhance the robustness of existing IIoT infrastructure, and this promotes the adoption of Industry 4.0 initiatives in the South African heavy industry sector.

IV. An Information Systems Approach to the Proactive Management of Subscriber Identification Modules in Industry.

Context

Several Industry 4.0-related systems focusing on indirect production support and service delivery have been implemented in the South African heavy industry sector. These systems utilise existing cellular communication infrastructure to facilitate real-time data transmission.

Network assets such as SIMs and network routers are required to utilise mobile communication networks. Mismanagement of these assets can result in additional capital expenditures and network instability, which can have a negative effect on the performance of industrial information systems.

Requirement

It is evident from the context described above that there is a need to ensure the effective management of underlying supporting hardware to allow for effective communication to take place. Several online platforms do exist but fail to provide a consolidated overview of industrial telemetry networks.

There is, therefore, a need to develop an information and asset management system to consolidate all information of the supporting communication infrastructure. This system will aid in troubleshooting and maintenance processes when real-time communication is disrupted.

Contribution

In the conference paper, the value of an information and asset management system for the management of SIM cards utilised in heavy industry is emphasised. The paper aims to analyse and present the current architecture of existing industrial information systems and discuss key challenges that contribute to communication disruptions.

The paper introduces a new information and asset management system to address the challenges presented. The system is validated, and the results reflect the value of such a system in industry, with a communication cost reduction of 62%.

Validation

A review of existing systems from literature and industry shows that there is a need for a comprehensive information and asset management system to address the management of SIM cards in industry. This system forms an integral part of the network layer of any Industry 4.0 information system that utilises the GSM network for real-time wireless data transfer. The information and asset management system proposed in this paper allowed for accurate cost analyses to be executed on SIM contracts.

The system automatically generates these profiles based on billing invoices provided as input. The results presented in the previous section clearly shows the value of the system. The automated cost analyses can provide valuable insight into the health of the network layer, and it can identify communication anomalies that have a direct effect on the cost of maintaining a

wide-area wireless telemetry uplink. The system proposed in the paper succeeded in reducing the overall communication costs of wide-area wireless telemetry in the South African heavy industry sector.

6.3 VALIDATION STRATEGY

In order to validate whether the outcomes of this study provide a unique solution to the complex problem statement, a validation strategy is required. A strategy consisting of five steps has been outlined and is stipulated as follows:

I. Revisit the gap in the knowledge spectrum defined in Chapter 1.

II. Revisit the original problem statement defined in Chapter 1.

III. Revisit the study objective defined in Chapter 1.

IV. Reflect on the outcomes and results of the study methodology.

V. Determine whether a solution to the original problem statement has been presented.

I. Gap in the knowledge spectrum

From Chapter 1, a clear gap in the current knowledge spectrum has been identified. This gap is formulated as a single statement below:

There is a gap in addressing the challenges of maintaining optimal Quality of Service in wide-area wireless communication networks. Failure to address these challenges directly affects the reliability of Industry 4.0 solutions, which further affects the adoption rate of Industry 4.0 principles in the South African heavy industry sector.

II. Original problem statement

Having defined a clear gap in the current knowledge spectrum, an original research problem was formulated and is re-iterated below:

The Industry 4.0 paradigm currently experiences slow adoption within the South African heavy industry sector. Guaranteed Quality of Service in the network layer is the primary factor that hinders the adoption potential of Industry 4.0 principles.

III. Need for the study and study objective

From the original research problem stated above, a clear need and study objective can be formulated:

There is, therefore, a need to develop a new telemetry monitoring system to enhance the Quality of Service in the network layer hence enabling Industry 4.0 initiatives in the South African heavy industry sector. Hence, this thesis aims to emphasise the current limitations present in wide-area wireless communications and present a novel telemetry monitoring system to address these limitations in the South Africa heavy industry sector.

IV. Reflection on methodology

The **first step** comprises a detailed review of the current Industry 4.0 landscape. The goal of this review is to identify shortcomings in the South African mining sector and to provide a detailed Industry 4.0 roadmap for the South African heavy industry context.

Article I achieved the stipulated goal by introducing a detailed architectural study of the Industry 4.0 paradigm. The digital framework and the digital toolbox proposed in this paper clearly highlight key areas of importance that must be addressed before Industry 4.0 adoption can take place.

The South African mining industry serves as an example of how the proposed framework was applied to identify Industry 4.0 adoption hurdles. The way forward is to use this framework to identify potential gaps that might hinder Industry 4.0 adoption in the heavy industry sector. After the framework has been laid down, the next step is to develop and implement the necessary tools and processes that will ensure successful Industry 4.0 adoption in the heavy industry sector.

The successful adoption of Industry 4.0 practices on a national scale — for example, in the Republic of South Africa — requires changes in current social and economic structures. For Industry 4.0 initiatives to be successful, social and economic systems must be created with the ability to respond dynamically to local and global changes.

The required infrastructure to sustain Industry 4.0 methods and frameworks must be developed and integrated into society on a national scale. Finally, Industry 4.0 awareness must be created to foster a mindset of technological advancement on a social, economic, and industrial level.

The roadmap presented in step I allows for current limitations to be identified. The goal of **step two** is to isolate a specific limitation and provide a solution to the identified problem. To bring heavy industrial players into the Industry 4.0 realm, it is important to address the QoS

issues of communication networks which can hamper the overall effectiveness of an Industry 4.0 ecosystem.

Article II achieved the stipulated goal by developing a novel monitoring system that monitors the communication uplink status of remote wide-area wireless communication end-points was developed. The objective of this study was to develop and integrate this system into existing industrial IoT infrastructure in order to improve the robustness of existing infrastructure.

The proposed system has been designed and implemented on existing energy management projects of an established energy services company. A total of 80 remote end-points, encompassing over a thousand individual components, were incorporated into the system for monitoring purposes. Unstable connections were successfully flagged and earmarked for investigation. Necessary steps were then taken to rectify the issues.

The results achieved demonstrate that real-time monitoring of mission-critical end-points was successfully achieved. The integration of this system further improved the robustness of industrial IoT infrastructure. It is believed that the incorporation of the proposed system will serve as motivation to incorporate IoT solutions and applications in the heavy industry realm.

Disruptions in accessibility and connectivity can nullify the advantages of an Industry 4.0 ecosystem. If Industry 4.0 is to successfully extend into the domain of heavy industry players, accessibility and connectivity disruptions must be addressed. With a new system developed and verified in the previous step to address this issue, the goal of **step three** is to assess and evaluate the value of the proposed telemetry monitoring system.

Article III achieved the stipulated goal of emphasising the value of a stand-alone telemetry monitoring system that can independently monitor the status and quality of a mobile

communication network. The proposed system was developed and implemented on the existing telemetry network of a South African energy services company. Around 80 sites, each with a fully functional energy management system on-site were incorporated into the scope of the monitoring system. This allowed for more than a thousand individual industrial assets to be monitored and maintained.

The results demonstrate the value of this system. Positive impacts were made on equipment monitoring in the heavy industry sector. The system is generic and can, therefore, be applied to any IIoT ecosystem where mobile communication networks are used for real-time data transmission. The results show that the proposed system can enhance the robustness of existing IIoT infrastructure, and this promotes the adoption of Industry 4.0 concepts in the heavy industry sector.

With system evaluation conducted in step III, the **final step** focuses on an analysis of mobile network costs. The mismanagement of underlying network assets and infrastructure can, however, result in excessive communication costs. This, in turn, hampers the effectiveness of wireless data transmission. A comprehensive information and asset management system to assist with overall SIM card management is proposed.

The conference paper achieved the stipulated goal by presenting an information systems approach to the management of SIM cards utilised in industry. The system consists of two main foundational blocks, which allows for automated cost analyses to be calculated. Cost analyses contain actual expenses as well as budgeted values, which allows for budget comparisons to be made. Weighted analyses are also possible, which assists in determining exceptions where communication anomalies are present. Average monthly network costs were reduced from approximately R72,000 to R27,000.

V. Conclusion

In summary, the outcomes of this study are presented in bullet form below to illustrate validation and how the solution addresses the original problem statement defined in Chapter 1:

- The outcomes of this study illustrate that this study succeeded in *emphasising the current limitations present in wide-area wireless communications,* as stipulated in the study objective.
- The outcomes of this study illustrate that this study succeeded in *presenting a novel telemetry monitoring system to address these limitations in the South Africa heavy industry sector,* as stipulated in the study objective.
- Therefore, *the need to develop a new telemetry monitoring system to enhance the Quality of Service in the network layer hence enabling Industry 4.0 initiatives in the South African heavy industry sector,* as stipulated in the study objectives, has been successfully addressed.
- The original problem statement stipulates that "g*uaranteed Quality of Service in the network layer is the primary factor that hinders the adoption potential of Industry 4.0 principles".* By successfully achieving the study objectives, this concern has been addressed.
- The study, therefore, succeeded in addressing the concern that "*The Industry 4.0 paradigm currently experiences slow adoption within the South African heavy industry sector"*, as stipulated by the original problem statement.
- Finally, by providing a novel solution to the original problem statement, the gap identified in the knowledge spectrum has been addressed and satisfied.

From the reflection on the outcomes of the study, it can be seen that the objectives of the study have been met, and the need for the study, stipulated in Chapter 1, has been addressed.

CHAPTER 7

CONCLUSION

This section aims to conclude this study.

7.1 PREAMBLE

The aim of this thesis is to address the challenges of developing a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector. The focus is on identifying and addressing challenges that inhibit the adoption of the Industry 4.0 vision, strategy, and underlying methods.

The communication network that is most commonly used in the South African heavy industry sector has been identified as the epicentre from which to start. As part of the objectives, this thesis aims to provide insight into the current scope and context of Industry 4.0 in the heavy industry sector. This section aims to reflect on the methodology, summarise the study contributions, discuss the value to industry, and finally present a short discussion on the potential future work that might be conducted to further promote the research objectives of this study.

7.2 REFLECTION ON METHODOLOGY

In response to the holistic problem statement stated in Chapter 1, this thesis presented a solution by outlining a four-step methodology focusing on context analysis, system development, system evaluation, and financial impact. Each of these steps will be presented, and a short reflection will be given on the methodology and study contributions.

I. Context analysis – Article I

The first step comprises a detailed review of the current Industry 4.0 landscape. The goal of this review is to identify shortcomings in the South African mining sector and to provide a detailed Industry 4.0 roadmap for the South African heavy industry context.

Article I achieved the stipulated goal by introducing a detailed architectural study of the Industry 4.0 paradigm. The digital framework and the digital toolbox proposed in this paper clearly highlight key areas of importance that must be addressed before Industry 4.0 adoption can take place.

The South African mining industry serves as an example of how the proposed framework was applied to identify Industry 4.0 adoption hurdles. The way forward is to use this framework to identify potential gaps that might hinder Industry 4.0 adoption in the heavy industry sector. After the framework has been laid down, the next step is to develop and implement the necessary tools and processes that will ensure successful Industry 4.0 adoption in the heavy industry sector.

The successful adoption of Industry 4.0 practices on a national scale — for example, in the Republic of South Africa — requires changes in current social and economic structures. For Industry 4.0 initiatives to be successful, social and economic systems must be created with the ability to respond dynamically to local and global changes.

The required infrastructure to sustain Industry 4.0 methods and frameworks must be developed and integrated into society on a national scale. Finally, Industry 4.0 awareness must be created to foster a mindset of technological advancement on a social, economic, and industrial level.

II. System development and verification – Article II

The roadmap presented in step I allows for current limitations to be identified. The goal of step II is to isolate a specific limitation and provide a solution to the identified problem. To bring heavy industrial players into the Industry 4.0 realm, it is important to address the QoS

issues of communication networks which can hamper the overall effectiveness of an Industry 4.0 ecosystem.

Article II achieved the stipulated goal by developing a novel monitoring system that monitors the communication uplink status of remote wide-area wireless communication end-points was developed. The objective of this study was to develop and integrate this system into existing industrial IoT infrastructure in order to improve the robustness of existing infrastructure.

The proposed system has been designed and implemented on existing energy management projects of an established energy services company. A total of 80 remote end-points, encompassing over a thousand individual components, were incorporated into the system for monitoring purposes. Unstable connections were successfully flagged and earmarked for investigation. Necessary steps were then taken to rectify the issues.

The results achieved demonstrate that real-time monitoring of mission-critical end-points was successfully achieved. The integration of this system further improved the robustness of industrial IoT infrastructure. It is believed that the incorporation of the proposed system will serve as motivation to incorporate IoT solutions and applications in the heavy industry realm.

III. System evaluation, validation, expansion and integration – Article III

Disruptions in accessibility and connectivity can nullify the advantages of an Industry 4.0 ecosystem. If Industry 4.0 is to successfully extend into the domain of heavy industry players, accessibility and connectivity disruptions must be addressed. With a new system developed and verified in the previous step to address this issue, the goal of step III is to assess and evaluate the value of the proposed telemetry monitoring system.

Article III achieved the stipulated goal of emphasising the value of a stand-alone telemetry monitoring system that can independently monitor the status and quality of a mobile communication network. The proposed system was developed and implemented on the existing telemetry network of a South African energy services company. Around 80 sites, each with a fully functional energy management system on-site, was incorporated into the scope of the monitoring system. This allowed for more than a thousand individual industrial assets to be monitored and maintained.

The results demonstrate the value of this system. Positive impacts were made on equipment monitoring in the heavy industry sector. The system is generic and can, therefore, be applied to any IIoT ecosystem where mobile communication networks are used for real-time data transmission. The results show that the proposed system can enhance the robustness of existing IIoT infrastructure, and this promotes the adoption of Industry 4.0 concepts in the heavy industry sector.

IV. Cost reduction methodology – Conference Paper

With system evaluation conducted in step III, the final step focuses on an analysis of mobile network costs. The mismanagement of underlying network assets and infrastructure can, however, result in excessive communication costs. This, in turn, hampers the effectiveness of wireless data transmission. A comprehensive information and asset management system to assist with overall SIM card management is proposed.

The conference paper achieved the stipulated goal by presenting an information systems approach to the management of SIM cards utilised in industry. The system consists of two main foundational blocks, which allows for automated cost analyses to be calculated. Cost

analyses contain actual expenses as well as budgeted values, which allows for budget comparisons to be made. Weighted analyses are also possible, which assists in determining exceptions where communication anomalies are present.

7.3 VALUE TO INDUSTRY

The quality and stability of wide-area wireless communications have been identified as crucial components for real-time data transmission across wide geographical distances. Overall, the network layer plays a critical role in an Industry 4.0 ecosystem.

The outcomes of this study illustrate that existing limitations in wireless communication networks can directly affect the adoption of Industry 4.0 strategies and methods in the South African mining sector. Successful Industry 4.0 integration in the South African heavy industry sector relies markedly on addressing current issues such as connectivity disruptions and accessibility.

The aim of Article I is to present a clear architectural methodology that can be used to guide heavy industry players in the successful adoption and incorporation of Industry 4.0 methods in practice. No clear architectural description with application on the heavy industry sector has been found from literature, and Article I, therefore, addresses the need to define a clear roadmap to Industry 4.0 adoption.

Article I presents two components to Industry 4.0 adoption, namely the Industry 4.0 digital framework and the Industry 4.0 digital toolbox. The digital framework component acts as a key enabler to the digital toolbox. Together these two components define a roadmap that can be utilised to facilitate Industry 4.0 applications in industry.

With a clear architectural description provided by Article I, Article II aims to present a new software-based monitoring system to address current challenges present in wide-area wireless telemetry networks. With wireless communication networks considered to be crucial in Industry 4.0 applications, the proposed monitoring system aims to address QoS issues that can hamper the successful integration of Industry 4.0 methods and applications.

Literature has shown that the heavy industry sector is still reluctant to adopt Industry 4.0 practices due to geographical and infrastructure constraints. An investigation into existing monitoring systems showed that only small-scale wireless networks are monitored on a constant basis. To the extent of the research, no system was found that monitored wide-area wireless communications in the heavy industry sector.

The proposed monitoring system was developed and implemented on a wide-area wireless telemetry network utilised by multiple industrial facilities within the Republic of South Africa. The system successfully monitored more than 80 remote sites, with communication failures being detected immediately. The average connection uplink time was also increased by more than 25%.

With a new software-based monitoring system presented in Article II, the objective of Article III is to emphasise the value of such a system in the heavy industry sector. The telemetry monitoring system was expanded and integrated into existing industrial information systems with the objective of increasing the operational performance of these information systems.

As discussed above, literature has shown that network monitoring systems do exist but are only implemented on small-scale networks. In addition to this, these systems are developed

as standalone troubleshooting systems. In Article III, the proposed monitoring system is integrated into existing real-time information systems.

This integration allowed for the introduction of enhanced troubleshooting and maintenance procedures that can be followed on-site to rectify any network anomalies. The results of the system showed that a positive impact was made on condition-based maintenance agreements between an energy services company and a South African gold mining company.

Mismanagement of network assets that facilitate wireless communication over wide geographical distances can result in unnecessary capital expenditures and network instability. Several online platforms do exist for network asset management, but these solutions fail to provide a consolidated overview of the status of industrial network communications.

The conference paper listed in this thesis aims to introduce a new information and asset management system with the objective to consolidate, manage, and display all network asset information. The system was implemented as a standalone asset management system and achieved an overall communication cost reduction of 62%. Average monthly network costs were reduced from approximately R72,000 to R27,000.

The studies listed in this thesis emphasise the importance of maintaining a stable communication infrastructure for the application of Industry 4.0 methods in the heavy industry sector. This thesis proves that the constant monitoring of wide-area wireless communications in the heavy industry sector does have an impact on overall operations.

It is, therefore, the author's belief that effective implementation of the proposed systems can make a positive contribution to the establishment of Industry 4.0 methods and practices in the heavy industry realm.

7.4 FUTURE RESEARCH

Expansion opportunities have been identified for the telemetry monitoring system proposed in Articles II and III. These expansion opportunities will extend the operational functionality of the system. The opportunities have also been discussed in Articles II and III and are, therefore, provided as excerpts from the articles [58], [71].

"A key expansion opportunity is to incorporate methods that would allow for the automatic generation of reports. Automatic report generation can either be included within the system, or the system can be integrated with dedicated report generation systems. By generating reports from the data, detailed analyses can be done on the state of the network infrastructure. It is believed that automatic reports can have a positive impact on telemetry QoS.

The system proposed in the listed conference paper is currently implemented as a standalone desktop system. This implies that the system can only be used locally. To increase operational and management efficiency, this system must be incorporated into existing information systems.

This would not only allow industrial client groups to view telemetry cost analyses online but it will also allow for the incorporation of these cost analyses into generated reports. This integration will expand the reach of the system and will allow clients to take responsibility for the communication costs.

The proposed system can also be implemented in the corporate world for the monitoring of company handheld devices such as cell phones, tablets and rugged smart devices. This is considered as potential future work for the expansion of the system."

In summary:

- Article I presents a clear architectural description and roadmap.
- Article I highlighted that there is a need for the development of a novel telemetry monitoring system to maintain wireless communication QoS.
- Article II presents the development of a software-based telemetry monitoring system for application in the heavy industry sector.
- Article II also aims to verify the operation of the developed system in industry.
- Article III presents the value of the developed telemetry monitoring system in industry.
- Article III aims to validate and emphasise the need for the proposed system.
- The conference paper aims to address indirect challenges in the management of network infrastructure in support of the holistic problem statement.

In conclusion:

The holistic problem statement of developing *a new telemetry monitoring system to enable Industry 4.0 initiatives in the South African heavy industry sector* has been addressed, and a novel solution has been provided.

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APPENDIX A: CO-AUTHOR STATEMENT

I, J.C. Vosloo, hereby provide consent that the articles listed below (I to IV) may be used as part of J. Prinsloo's PhD thesis.

Signature:  **Date**: 7 October 2020

I, M.J. Mathews, hereby provide consent that the articles listed below (II to IV) may be used as part of J. Prinsloo's PhD thesis.

Signature:  **Date**: 15 October 2020

I, J.N. du Plessis, hereby provide consent that the articles listed below (II and IV) may be used as part of J. Prinsloo's PhD thesis.

Signature:  **Date**: 5 October 2020

I, E.H. Mathews, hereby provide consent that the articles listed below (I) may be used as part of J. Prinsloo's PhD thesis.

Signature:  **Date**: 14 October 2020

Author contributions:

The candidate, J. Prinsloo, executed all research for the listed articles below and, therefore, claims responsibility for the technical and academic content of all articles.

Since an article-based approach was followed for this thesis, it is required that the supervisor must also be listed as an author on each article or paper. For Article I, Prof E.H. Mathews fulfilled the role of study leader. For Articles II to IV, Dr J.C. Vosloo fulfilled the role of study leader. The role of the supervisor is to provide academic oversight and to guide the candidate in writing a quality article. Prof Mathews and Dr Vosloo provided this oversight, which ensured that the articles were accepted for publication.

In addition to the listing of supervisors, the candidate was also assigned mentors for each article. For Article I, Dr J.C. Vosloo fulfilled the role of mentor and provided additional guidance on the content of the article, especially in the area of the South African mining environment. For Article III, Dr M.J. Mathews fulfilled the role of mentor and provided exceptional guidance in ensuring that the value of the academic and technical work is emphasised in Article III. For Articles II and IV, both Dr M.J. Mathews and Dr J.N. du

Plessis fulfilled the role of mentors. Dr M.J. Mathews once again assisted in the quality of the written work to ensure that the need and value is sufficiently illustrated. Dr du Plessis assisted the candidate on the technical side with the development of the proposed system. The candidate executed the design and implementation, but the technical expertise that Dr du Plessis provided, assisted the candidate in the construction of a state-of-the-art system.

Author Contributions				
Author	**Article I**	**Article II**	**Article III**	**Article IV**
J. Prinsloo	All technical and academic content	All technical and academic content	All technical and academic content	All technical and academic content
M. J. Mathews	N/A	Academic and technical writing guidance	Academic and technical writing guidance	Academic and technical writing guidance
J. N. du Plessis	N/A	Technical guidance on system implementation	N/A	Technical guidance on system implementation
J. C. Vosloo	Industry, academic and writing guidance	Academic guidance and oversight	Academic guidance and oversight	Academic guidance and oversight
E. H. Mathews	Academic guidance and oversight	N/A	N/A	N/A

Articles:

I. J. Prinsloo, J. C. Vosloo, and E. H. Mathews, “Towards Industry 4.0: A roadmap for the South African heavy industry sector,” South African Journal of Industrial Engineering, vol. 30, no. 3, pp. 174–186, Nov. 2019.

II. J. Prinsloo, M. J. Mathews, J. N. du Plessis, and J. Vosloo, “Development of a software-based monitoring and information system for industrial telemetry applications,” South African Journal of Industrial Engineering, vol. 30, no. 1, pp. 54–68, May 2019.

III. J. Prinsloo, M. J. Mathews, and J. C. Vosloo, “The value of a telemetry monitoring system in sustaining the operational performance of industrial information systems,” South African Journal of Industrial Engineering, vol. 31, no. 2, pp. 129–142, Aug. 2020.

IV. J. Prinsloo, M. J. Mathews, J. N. du Plessis, and J. C. Vosloo, “An information systems approach to the proactive management of subscriber identification modules in industry,” in SAIIE29 Proceedings, 2018, pp. 127–138.

APPENDIX B: ARTICLE I

South African Journal of Industrial Engineering November 2019 Vol 30(3) Special Edition, pp 174-186

TOWARDS INDUSTRY 4.0: A ROADMAP FOR THE SOUTH AFRICAN HEAVY INDUSTRY SECTOR

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ABSTRACT

The rapid growth and expansion of the Internet, as well as technical advances in the area of sensor technology, allow for the interconnection of physical objects for the purpose of achieving collective goals, which paves the way for the Fourth Industrial Revolution. The Industry 4.0 paradigm is a relatively new concept that still requires detailed investigation and discussion. Standards, technologies, and overall guidelines need to be presented; thus this review paper aims to address key questions to provide some clarity on navigating the tide of Industry 4.0. The key enabling technologies, and the extent to which these technologies can be applied in industry to achieve the fundamental goals of Industry 4.0, are presented and discussed. Current challenges that hinder Industry 4.0 adoption in the South African mining sector are discussed, and a short discussion on the way forward is presented. In brief, this article aims to present a detailed roadmap for the implementation of Industry 4.0 methods in the South African mining sector. From the literature, a digital framework and toolbox have been compiled to serve as a roadmap for the way forward in successful Industry 4.0 adoption. The proposed framework and toolbox are presented, with a theoretical case study.

OPSOMMING

Die vinnige groei en uitbreiding van die internet, asook tegniese vooruitgang in sensortegnologie, het die interkonneksie van fisiese voorwerp moontlik gemaak. Dit het die weg gebaan vir die Vierde Industriële Rewolusie. Die Industrie 4.0 paradigma is 'n relatiewe nuwe konsep wat diepe ondersoek en bespreking benodig. Standaarde, tegnologieë, en algehele riglyne moet aangebied word en hierdie artikel is daarop gemik om sleutelvrae met betrekking tot Industrie 4.0 te beantwoord. Die sleutel onderliggende tegnologieë, en tot watter mate die tegnologieë toegepas kan word om die fundamentele doelstellings van Industrie 4.0 te bereik, word voorgehou en bespreek. Bestaande uitdagings wat as struikelblokke vir die aanvaarding van Industrie 4.0 in die Suid-Afrikaanse mynbedryf aangetref word, word bespreek saam met 'n kort aanbieding oor die pad vorentoe. Hierdie artikel verskaf 'n gedetailleerde padkaart vir die implementering van Industrie 4.0 metodes in die Suid-Afrikaanse mynbedryf. 'n Digitale raamwerk en gereedskapkis is vanuit die literatuur saamgestel om ten einde te dien as die padkaart. 'n Gevallestudie word ter illustrasie voorgehou.

1 AN INTRODUCTION TO INDUSTRY 4.0

Industrial methods and processes are in a continuous state of evolution. The roots of the manufacturing industry, as it is known today, can be traced back to the late eighteenth to early nineteenth century [1]. Since the inception of mechanical manufacturing and the use of steam power, the manufacturing and industrial realms have experienced three major revolutions. Advances

in the underlying methods of manufacturing have not only changed the nature of industry itself, but also moulded society and directed global economic growth in a major upward trend [2], [3].

The first industrial revolution was categorised by the implementation of mechanical manufacturing procedures, with steam being the primary power driver in industry [4]. The first industrial revolution (Industry 1.0) allowed for rapid change in economic productivity and growth, with the introduction of water and steam power into society stimulating development and production [5], [6].

The advances made in the first industrial revolution were elevated to new heights in the early twentieth century with the introduction of mass labour and assembly line production. The shift to assembly line manufacturing is categorised as Industry 2.0. The implementation of conveyor-based assembly lines proved to be highly efficient, in both the time and the financial spheres, and is therefore considered to be a significant accomplishment in the manufacturing realm [7]. Electrical energy, in conjunction with mass labour production lines, played a significant role in the manufacturing industry. Reduced cost and production time, coupled with increased supply, further stimulated worldwide economic growth [8].

It can be argued that the second industrial revolution ensured the globalisation of manufacturing. Challenges such as production competitiveness, production efficiency, cost reduction, energy consumption, and production optimisation are key concerns [9]. This led to the concept of industrial automation, which is categorised as the third industrial revolution (Industry 3.0), established during the 1970s.

Industrial automation, in combination with electronic engineering and communication, aims to address social and economic challenges by increasing production uptime and efficiency while reducing production costs [10]. This ultimately improves production performance and competitiveness. Negative factors are present, however. The advent of the third industrial revolution resulted in a decline in the manual labour workforce, with many tasks being reserved for automation [11].

The term ‘Industry 4.0’ is an initiative spearheaded by the German government that was first brought to light during the Hanover Trade Fair in 2011. A decline of about 10 per cent in the European industrial share, and a decline in a stable workforce, led to the introduction of a revolutionary strategy to meet growth challenges [12]. To increase manufacturing output and competitiveness further, factories and production lines must be digitised, and digital collaboration must be promoted [13].

Revolutionary advances in the information and communication technology (ICT) field paved the way for this high-tech strategy. Rapid growth and expansion of the Internet, and technical advances in the area of sensor technology, allow for the interconnection of physical objects for the purpose of achieving collective goals [14]. The main strategy behind the Industry 4.0 initiative is to form an interconnected arena between various technological paradigms, such as cyber-physical systems (CPS), the Internet of Things (IoT), cloud manufacturing, knowledge integration, and information exchange [13], [15], [16].

The main objectives of the Industry 4.0 paradigm are to increase and maintain the operational efficiency of current manufacturing processes, and to advance current automation methodologies to new heights [17]. The implementation of underlying Industry 4.0 methods and principles will result in the establishment and incorporation of smart factories, smart products, and smart services in society as a whole [18]. Figure 1 illustrates an architectural summary of the evolution of manufacturing, starting from the first industrial revolution and ending in the current state of Industry 4.0.

The Industry 4.0 paradigm is a relatively new concept that still requires detailed investigation and discussion. This is especially important if global industrial adoption is to take place. Standards, technologies, and overall guidelines need to be presented; this review paper thus aims to address the following key questions to provide some clarity on navigating the tide of Industry 4.0:

- What is the underlying architecture of Industry 4.0?
- What are the key enabling technologies of Industry 4.0, and to what extent can these technologies be applied to achieve the defined goals of Industry 4.0?

- What are the current challenges that might hinder Industry 4.0 adoption in the South African mining industry?
- What will be the way forward?

In brief, this article aims to present a detailed roadmap for the implementation of Industry 4.0 methods in the South African mining sector. A digital framework and toolbox are presented to address current gaps in this sector.

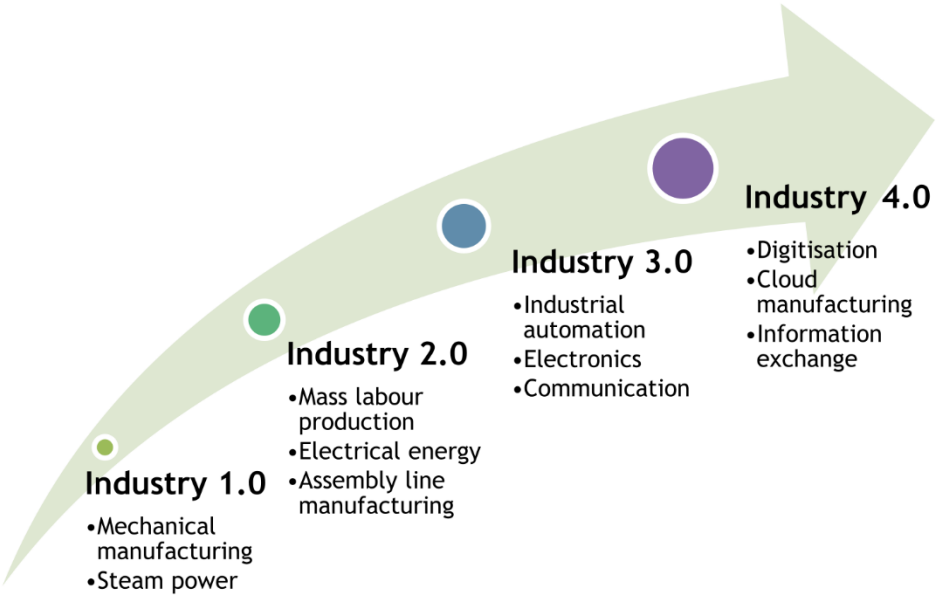


Figure 1: The history of industrial advancement

2 THE INDUSTRY 4.0 REALM: AN ARCHITECTURAL STUDY

With Industry 4.0 being a relatively new paradigm, no clear architectural description can be presented from the literature. This section aims to provide an architectural study to illustrate the value of adopting Industry 4.0 principles in practice. An input-output methodological approach was followed to deconstruct the Industry 4.0 concept into two parts.

The first part serves as the input model for Industry 4.0, and is labelled the 'Industry 4.0 digital framework'. The main objective of the digital framework is to introduce various concepts, models, and technologies that are underlying components that are required for Industry 4.0. The second part serves as the output model for Industry 4.0, and is labelled the 'Industry 4.0 digital toolbox'. The objective of the digital toolbox is to present various enabling tools and methodologies that can be used to embed the Industry 4.0 vision in the industrial and manufacturing sector.

The concepts, models, and technologies present in the digital framework serve as key enablers for the implementation of tools and methodologies present in the digital toolbox. The scope and reach of the digital toolbox will be limited if several digital framework components are removed. Figure 2 illustrates a top-down approach to deconstructing the Industry 4.0 paradigm. Several applications and examples of the digital framework and digital toolbox are presented in the final level of the Sankey diagram to emphasise the scope of the proposed framework and toolbox.

Both the framework and the digital toolbox are developed in the sections that follow. The value drivers and technological levers that form part of the Industry 4.0 digital toolbox have also been presented in previous work [13], [19], [20].

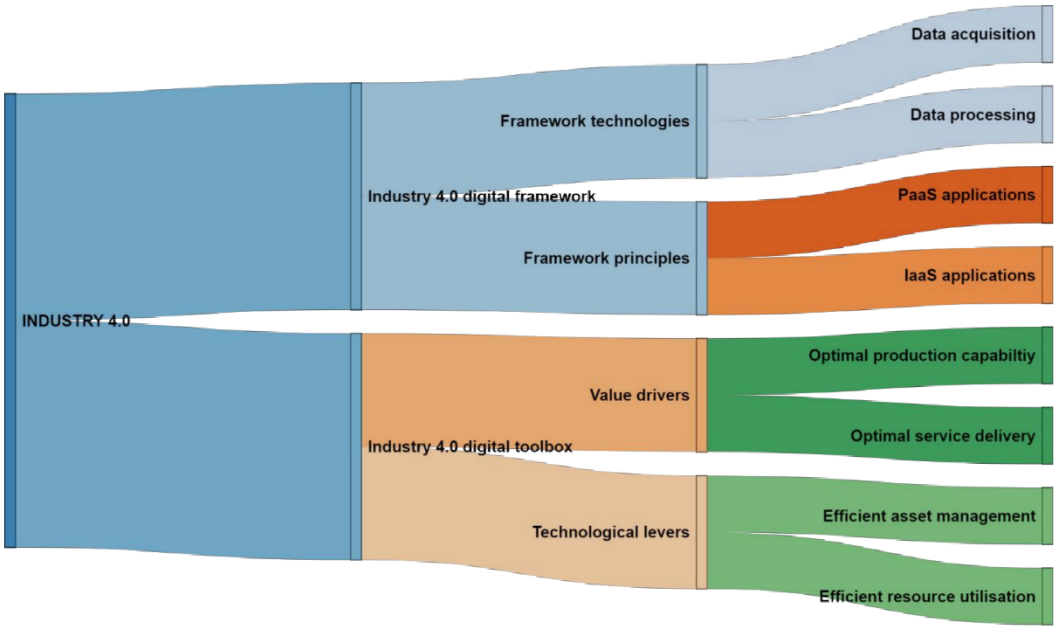


Figure 2: A deconstructed architectural view of the Industry 4.0 paradigm (see online version for colour)

2.1 The Industry 4.0 digital framework

For Industry 4.0 to be adopted into the industrial sector, various standards, methodologies, and technologies must first be introduced and incorporated into society. These all form part of a digital framework that will allow a digital toolbox to be created. The Industry 4.0 digital framework contains two main underlying components, which can be labelled as 'framework technologies' and 'framework principles'. Five key framework technologies have been identified from the literature [17], [21]–[23]. These technologies are viewed as core-enabling technologies, and are discussed in detail in Section 3 of this paper. Cyber-physical systems, the Internet of Things, big data, decentralised computing, and wireless networks form the technological backbone of the Industry 4.0 digital framework. Various published applications of these framework technologies are reported in Table 1.

Table 1: Literature survey overview of Industry 4.0 technologies and principles

Industry 4.0 digital framework			
Framework technologies	***Publications***	***Framework principles***	***Publications***
Cyber-physical systems	[24]	Decentralisation	[25]
Internet of Things (IoT)	[26]–[28]	Real-time capability	[29]
Big data	[30], [31]	Modularity	[32]
Decentralised computing	[17], [23], [33]	Interoperability	[34]
Wireless networks	[35]–[37]	Virtualisation	[38]

Cyber-physical systems can be defined as industrial automation systems that are interconnected through communication networks. This interconnection enables the performance of collective operations and the exchange of information between the physical devices and the software infrastructure [24]. Cyber-physical systems enable real-time information exchange, which can improve overall manufacturing performance. Benefits such as increased productivity, optimised energy consumption, and efficient use of production-related resources can be realised [39]. Without the implementation of cyber-physical systems, a real-time information exchange will be difficult to achieve; and this can effectively nullify the benefits underlying Industry 4.0 adoption.

The concept known as the Internet of Things is relatively new, but has already proven to be a major component in shaping the information and communication technology field. By expanding the Internet into the physical realm, individual hardware devices can be transformed into intelligent

systems operating on a collective level [40]. A lack of intelligence and collective collaboration would hamper the ability to make informed decisions, acting as a stumbling block for Industry 4.0 adoption. The rapid expansion in the implementation of cyber-physical systems and IoT applications results in massive amounts of raw data. This data must be stored and processed in a real-time fashion. The rapid expansion in raw data sets has led to the establishment of a technology known as 'big data' [41]. Large amounts of raw data prove to be challenging to process and maintain if traditional dataset methodologies are used [42]. Big data presents several methodologies that prove to be efficient for processing and storing large dataset volumes. The benefits of big data systems are increased data processing speed and efficient data storage. This, in turn, aids cyber-physical system scalability [42]. Industry 4.0 ecosystems rely on continuous information exchange; therefore, the absence of big data infrastructure and methodologies reduces the robustness and effectiveness of information exchange processes.

The realisation of cyber-physical systems, and the incorporation of these systems into existing industrial processes, inevitably leads to the generation of massive amounts of raw data. Decentralised computing encompasses technologies and fields such as artificial intelligence (AI), data analysis, and decentralised data storage. Decentralised big data storage schemes facilitate decentralised data storage; but to convey meaning from raw data, intelligent algorithms and data analysis methodologies must be developed [30].

The incorporation of decentralised computing power into the physical realm realises benefits such as self-sufficiency, self-optimisation, and autonomous decision-making. Intelligent systems can learn from the massive amounts of raw data. Decisions made by intelligent systems can be provided as inputs to cyber-physical systems [41]. This provides a feedback loop in which continuous production improvement can be sustained through continuous training. The result: a fully integrated and coordinated Industry 4.0 ecosystem that can respond and adapt to real-time changes in production [43]. The absence of decentralised computing would have a negative impact on the responsiveness and quality of service (QoS) of an Industry 4.0 ecosystem.

Wireless communication can be considered the backbone of an Industry 4.0 ecosystem [44]. It allows for real-time information flow between cyber-physical systems and decentralised storage and computing mechanisms. The absence of wireless communication methods would impair the ability of physical devices to adapt to real-time changes, and this would lead to disruptions in service. In contrast, a highly stable wireless network infrastructure results in stable communication and information exchange between cyber-physical devices and existing cloud computing services. An uninterrupted exchange of data and information results in an overall improvement in the QoS of an Industry 4.0 ecosystem [45].

While the technologies and methods discussed above are key enablers of Industry 4.0, several principles also exist to serve as classifiers. The five framework principles listed in Table 1, and established from the literature, aim to define how an Industry 4.0 ecosystem is presented [17], [22], [39], [46], [47]. These five principles must be present, and the underlying technologies must support these principles. Two of the five principles, real-time capability and decentralisation, aim to support the remaining three principles, modularity, interoperability, and virtualisation.

The two key principles that allow for real-time adoption and self-configuration are the principles of decentralisation and real-time capability. Cloud-based intelligent systems, separated from physical devices, allow for real-time decentralised decision-making to adapt to changing demands [48]. This creates flexibility and allows for the creation of smart industries that can perceive, learn, and adapt. Decentralisation allows for modularity to be incorporated into industry designs. By re-allocating various resources off-site, modular production systems that receive input from cloud-based intelligent systems can be facilitated. The key enabling technologies discussed above allow for the interconnection of various modular systems, which promotes interoperability between these systems. Remote intelligence, as well as interconnected modular systems, allows for virtualisation to take place, in which a physical copy of industrial systems is transferred to the virtual domain [29].

The principles discussed above are the key enablers spearheading digitisation, cloud manufacturing, and real-time information exchange, as illustrated by Figure 1. The adoption of Industry 4.0 practices can greatly benefit industrial systems, especially the heavy industry realm, which has been reluctant to adopt Industry 4.0 methods, technologies, and principles [49]. The Industry 4.0 digital

framework is the gateway to the incorporation and application of various technological levers in industry. Section 2.2 discusses how the Industry 4.0 digital toolbox can function with the Industry 4.0 digital framework in place.

2.2 The Industry 4.0 digital toolbox

The digital framework presented in the previous section allows for the creation of an Industry 4.0 digital toolbox. It should be noted that the Industry 4.0 digital framework discussed in the previous section facilitates the use of the proposed Industry 4.0 digital toolbox. Industry 4.0 can be incorporated into the industrial society by implementing technological levers and methodologies enabled by the digital toolbox. This will have a direct effect on existing value drivers in industry. Figure 3 gives a graphical representation of the overall Industry 4.0 architecture, divided into the Industry 4.0 framework and the Industry 4.0 toolbox.

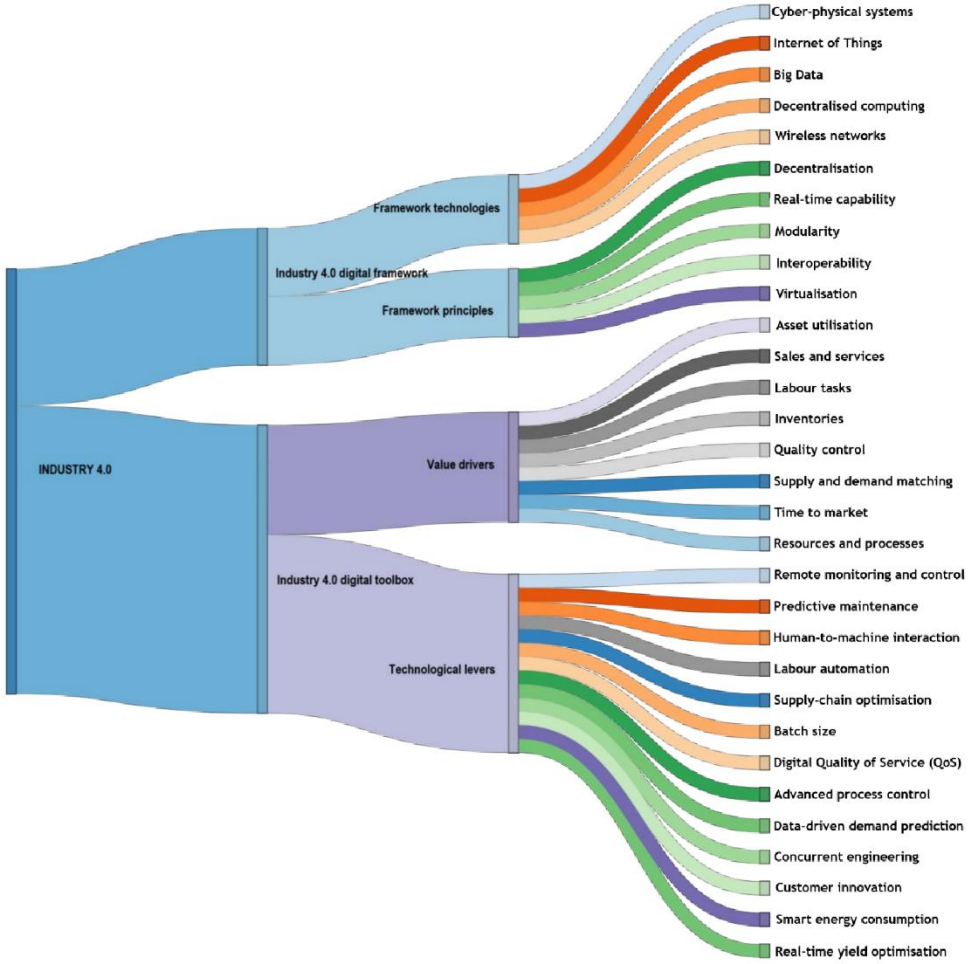


Figure 3: A detailed architectural overview of Industry 4.0 (see online version for colour)

The Industry 4.0 digital toolbox contains two main underlying components, Industry 4.0 value drivers and Industry 4.0 technological levers. Table 2 summarises the digital toolbox, and presents related publications where these technological levers are used in industry.

Several technological levers assist with labour tasks in the industrial sector. These include human-to-machine interaction, remote monitoring and control procedures, performance management structures, and labour automation. Human-to-machine interaction plays a critical role in an Industry 4.0 setup. It is believed that the primary role of human labour will be to dictate a specific production strategy and oversee the execution of that strategy [46]. Numerous challenges will be present in a fully functional Industry 4.0 environment, which implies that a human labour presence is still required to stimulate creative problem-solving in the workplace [46]. The Industry 4.0 digital

framework allows for most repetitive labour tasks to be automated across the industrial production line.

Table 2: Literature survey overview of Industry 4.0 value drivers and technological levers (adapted from [19])

Industry 4.0 digital toolbox		
Value drivers	***Technological levers***	***Publications***
Asset utilisation	Remote monitoring and control	[50], [51]
	Predictive maintenance	
Labour tasks	Human-to-machine interaction	[52]
	Labour automation	
Inventories	Supply-chain optimisation	[8]
	Batch size	
Quality control	Digital Quality of Service (QoS)	[7]
	Advanced process control	
Supply and demand matching	Data-driven demand prediction	[53]
Time-to-market	Concurrent engineering	[43]
	Customer innovation	
Sales and service	Predictive maintenance	[50], [51]
	Remote monitoring and control	
Resources and processes	Smart energy consumption	[54]
	Real-time yield optimisation	

3 INDUSTRY 4.0 ADOPTION IN THE SOUTH AFRICAN MINING SECTOR

With the clear architectural overview presented in the previous section, this section aims to use the overview to illustrate the Industry 4.0 adoption gap currently present in the South African mining sector. Current challenges in mining operations are first presented. Various existing systems are then presented from the literature that contributes to Industry 4.0 adoption practices. These existing solutions are then used to simplify Figure 3 accurately to illustrate the Industry 4.0 gap in the context of the South African mining sector. This section concludes with a short summary of the findings.

3.1 The current Industry 4.0 scope in the mining sector

The South African mining industry is involved in a continuous battle to remain profitable [55]. Factors such as government regulation and market-related pressures force the industry to investigate other methods of achieving sustainable mining operations [53]. Reducing capital expenditure has been identified as the primary method of remaining profitable. Key focus points that have a direct impact on sustainable mining operations include asset management strategies, monitoring and maintenance strategies, and energy usage profiles [52], [54], [56]. These focus points are key areas for potential Industry 4.0 solutions.

The geographical layout of deep-level mines makes it difficult to implement IoT-based solutions. A mining operation usually consists of several operational systems. These systems are divided between surface operations and underground operations [57]. Current Industry 4.0 practices emphasise wireless communication [33]. This is a major concern, since mining systems are often separated by large geographical distances, both horizontally and vertically [55]. This geographical separation limits the operation of wireless communication networks. Wireless communication infrastructure in harsh underground conditions is required to remain stable. Instability in the wireless communication infrastructure will effectively nullify the advantages Industry 4.0 has to offer. In addition to geographical constraints, limited access to existing equipment and ageing infrastructure further hamper the adoption of Industry 4.0 practices.

The challenges mentioned above limit the ability of a mine to respond and adapt to the current Industry 4.0 tide. Various IoT-related initiatives have, however, been implemented in the mining sector to assist with the key focus points discussed above. Most of these initiatives focus on the implementation of condition-based maintenance systems and remote monitoring and maintenance systems [50], [52], [58], [59]. Energy management information systems (EMIS) and automatic electricity bill analysis initiatives have also been implemented to assist heavy industry players with efficient operations [53], [54].

Condition-based maintenance systems and remote monitoring and maintenance systems form part of the technological levers present in the Industry 4.0 digital toolbox. In the context of mining operations, these systems use existing supervisory control and data acquisition (SCADA) systems to execute data collection routines. The collected data is then transmitted off-site, stored, and analysed in a central database system. The use of SCADA systems for data collection is an appropriate method, given the present infrastructural challenges in mining operations; however, the quality and extensibility of SCADA networks can hamper the quality of data collection routines [60].

Prinsloo, Mathews, du Plessis, and Vosloo [61] developed a software-based monitoring and information system to ensure wireless communication stability for effective data transmission. The analysis of the transmitted data allows various asset management strategies to be implemented. Goosen, Mathews, and Vosloo [54] proposed an electricity bill analysis system that makes use of an existing EMIS for data processing. In the scope of condition-based maintenance strategies, Van Jaarsveld, van Heerden, and van Rensburg [52] proposed an automated condition-based information system to assist with existing condition-based maintenance strategies. The main challenge present in condition monitoring systems is the analysis of large amounts of data for decision-making purposes. Van Jaarsveld *et al*. [52] simplified this process by providing a refined and simplified method to analyse the operational condition of a mining system's equipment.

3.2 Industry 4.0 adoption potential

To evaluate the potential for Industry 4.0 adoption in the South African mining industry, the availability of the framework elements required to make Industry 4.0 adoption feasible must first be investigated. After all framework elements have been identified, the various toolbox elements that are enabled through the available framework components can be identified. This will emphasise any limitations and gaps present, and will produce an Industry 4.0 adoption roadmap that can be followed.

The South African mining environment still uses the traditional industry model of centralisation [58]. Equipment is monitored and controlled from a central point, usually an industrial SCADA system, and all information is distributed via a wired telemetry system to various industrial endpoints. To allow Industry 4.0 practices to be adopted in the mining sector, a push for decentralisation and wireless interconnection must be made. The facilitation of interconnected modular systems, which allow virtualisation to take place, will effectively allow for a virtual copy of mining operations to be made. This virtual copy, referred to as a digital twin, can be considered the next step in managing mining operations. Wired telemetry still allows real-time capabilities, such as rapid responses to service delivery and production, but these capabilities are limited to local mining operations. For expert condition-based maintenance strategies to be implemented, big data and decentralised computing must be incorporated into the current operational infrastructure context.

Mining operations can be improved and optimised by incorporating intelligent systems, sensors, and other IoT-related technologies into the existing infrastructure. The next step would be to incorporate predictive maintenance strategies into existing EMIS infrastructures, to increase operational efficiency methodologies further. The expansion and incorporation of wireless sensor networks into the heavy industry realm has already been proposed, and solutions that actively focus on the improvement of mining operations and safety have been presented [62]–[64]. Figure 4 gives an overview of the key Industry 4.0 components that should be investigated and possibly incorporated into the mining sector. Key principles, drivers, and levers that have not been integrated into South African mining operations are marked in grey, while existing functionality is marked in black.

Figure 4 clearly shows that there is great potential for the adoption of Industry 4.0 practices in the mining sector. The value that Industry 4.0 adds to the mining sector is illustrated by the Industry 4.0 digital toolbox. It is, however, impossible to implement the digital toolbox fully if the digital framework does not exist. Key framework technologies and principles must, therefore, be incorporated before the digital toolbox can be applied, starting with the five framework technologies: cyber-physical systems, IoT, big data, decentralised computing, and wireless networks.

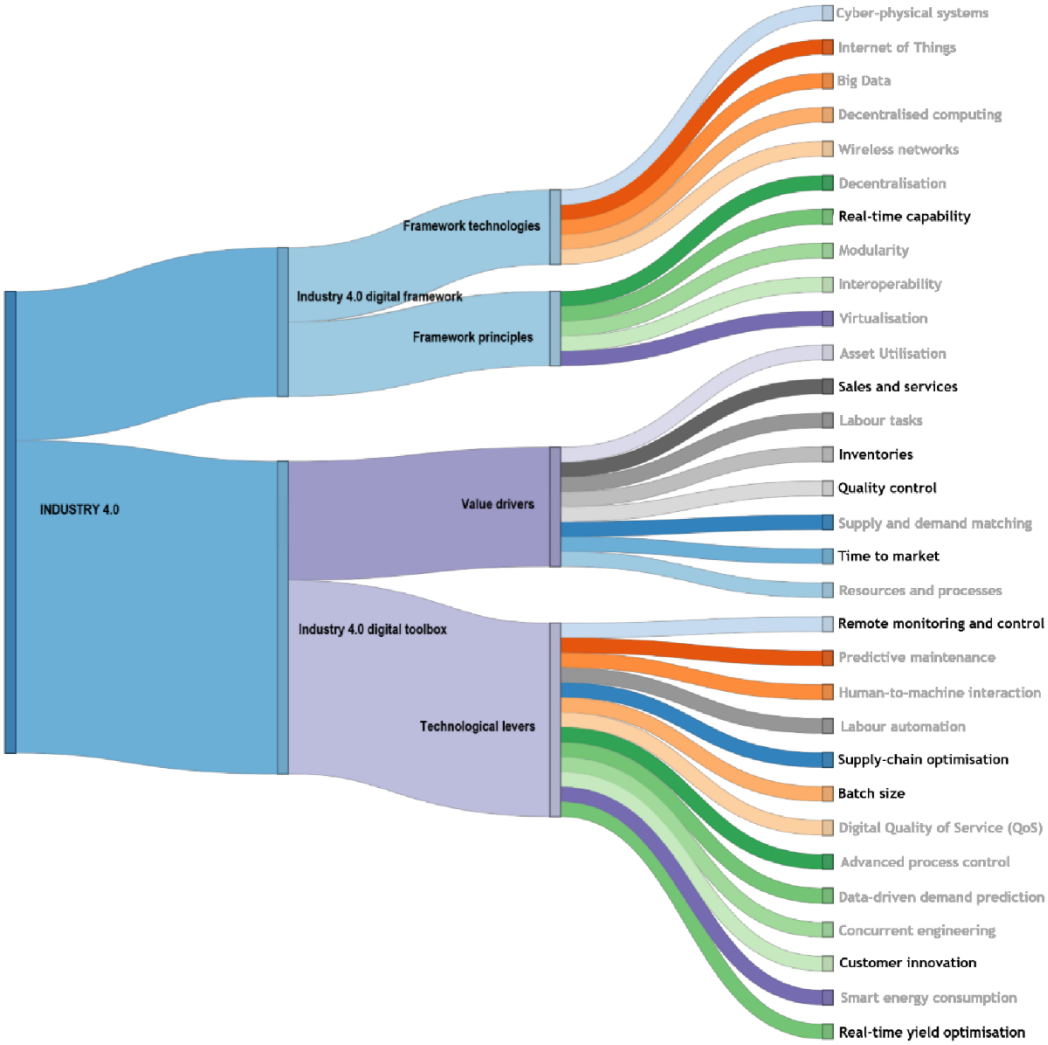


Figure 4: Key Industry 4.0 focus points for the South African mining sector (see online version for colour)

4 KEY CHALLENGES IN THE INDUSTRY 4.0 REALM

Challenges exist that can hamper the effective adoption of Industry 4.0 methods and practices in the heavy industry sector. This section presents several challenges that must be addressed, divided into two main sections. The first section presents physical challenges that directly affect the core principles of Industry 4.0. The second section presents several psychological challenges that have an indirect effect on the adoption of Industry 4.0 methods. These challenges are summarised in Table 3.

Table 3: A summary of current Industry 4.0 challenges

Industry 4.0: Summary of challenges			
Physical challenges	**Publications**	**Psychological challenges**	**Publications**
Interoperability	[65]	Impact on labour	[66]
Accessibility	[45], [67]	Technical skill-sets and education	[66]
Security and privacy	[33], [68]	Financial perspectives	[16]

4.1 Physical challenges

The decentralised nature of Industry 4.0 requires the integration of various end-point devices. These devices range from actuators and sensors to data relay nodes [47]. To ensure stable and reliable

communication between devices, communication protocols and standards need to be developed and enforced in industry [65]. The implementation of these standards can be cumbersome. To assist with this, several standardisation bodies exist that focus on drafting, establishing, and enforcing standards. These bodies include the Internet Engineering Task Force (IETF), the Institute for Electrical and Electronics Engineers (IEEE), and the European Telecommunications Standards Institute (ETSI) [65].

The communication framework and network layer of Industry 4.0-enabled systems is critical for effective operation. Wireless sensor networks, machine-to-machine communication, and wide-area wireless communications form the backbone of the Industry 4.0 network layer, and ensure interoperability between subsystems and nodes. Elghazel *et al*. [45] state that these technologies are prone to failure and can render an Industry 4.0-enabled system useless. Due to the remoteness of industrial facilities, wide-area wireless communications are employed to achieve real-time data transfer and information exchange. External interference and changes in network topology can hamper the quality of wide-area wireless communications [67]. To address these challenges in network instability, software-based information systems are required to monitor the quality and status of wide-area wireless communications. This will ensure operational stability of the network layer for industrial operations using Industry 4.0 applications.

Security and privacy are crucial factors that can hamper any digital system. Cybersecurity must be considered a top priority to protect critical industrial systems and ensure operational uptime. With the introduction of various communication standards and protocols, it is required to establish secure network policies and authentication procedures [33]. Ensuring adequate information security and privacy in a decentralised environment, such as a smart factory, can be a difficult task [68]. Xu, He, and Li [68] argue that information security and the protection of critical systems are more difficult to maintain due to an increase in the number of attack vectors that are present in an Industry 4.0 ecosystem. Aspects such as point-to-point data encryption and cloud-based security applications must be explored to enforce security and privacy effectively in the Industry 4.0 domain.

4.2 Psychological challenges

Research and development of new technologies has a direct impact on the ability, skills, and education of people [66]. With rapid advances being made in all areas of technology, traditional education principles will be required to adapt. This will ensure that the necessary skill-sets will be available to implement and maintain specialised equipment and technologies. Benešová and Tupa [66] state that communication and collaboration between industries and academic institutions must be established to ensure that academic, research, and industry applications remain aligned. This will ensure that a skilled workforce is available to implement and maintain Industry 4.0 methods and applications.

To enable the research and development of new technologies, financial support is needed. A general challenge for frontier-type technologies is the reluctance to support the development and improvement of these technologies financially. Investors generally prefer ‘tried and tested’ methods above the ‘new but unproven’ approach. Significant investment in the development of Industry 4.0 applications is required to ensure global adoption [16].

5 INDUSTRY 4.0: THE WAY FORWARD

Although Industry 4.0 is a European initiative, the effects of this paradigm shift can already be witnessed in industrial sectors around the globe [18], [69], [70]. Incorporating Industry 4.0 methods and technologies will have a profound effect on national industrial and economic growth [38]. Industry 4.0 is, however, not without its challenges. Initiatives such as ‘Made in China 2025’, an industrial development plan spearheaded by China and published in 2015, and the gradual re-industrialisation of the manufacturing and industrial sectors of the United States, are considered to be competitors to the European Industry 4.0 vision [47]. All initiatives, however, strive toward a unified goal of digital transformation and enhancement that will ultimately lead to the Fourth Industrial Revolution.

Zhong, Xu, Klots, and Newman [34] highlight several key aspects in the field of intelligent manufacturing that should be considered as the next phase of industrial development. These aspects include the creation and provision of intelligent manufacturing models, the extension of human-machine collaboration, and the application of data-driven manufacturing models. These aspects

open the gate to a new arena of smart design, smart monitoring procedures, smart control, and smart job scheduling. Vaidya, Ambad, and Bhosle [16] state that advancement in the areas of organised supply chain management and optimised maintenance and production scheduling will continue to develop, and that a symbiotic relationship between human and machine interactions will develop.

6 CONCLUSION

This paper has presented a detailed architectural study of the Industry 4.0 paradigm. The digital framework and the digital toolbox proposed in this paper clearly highlight key areas of importance that must be addressed before Industry 4.0 adoption can take place. To illustrate the utility of the proposed architectural model, a theoretical case study was developed. In the context of the South African mining industry, a methodological shift must be made from traditional centralised operations to decentralised computing. This, together with the implementation of wireless sensor network infrastructure, will assist in the development and advancement of asset management systems, condition-based maintenance systems, and energy management systems. The incorporation of sensors and decentralised computing will enable the incorporation of predictive maintenance strategies, which in turn will improve the operational uptime of equipment.

The South African mining industry serves as an example of how the proposed framework was applied to identify Industry 4.0 adoption hurdles. The way forward is to use this framework to identify potential gaps that might hinder Industry 4.0 adoption in the heavy industry sector. After the framework has been laid down, the next step is to develop and implement the necessary tools and processes that will ensure successful Industry 4.0 adoption in the heavy industry sector.

The successful adoption of Industry 4.0 practices on a national scale — for example, in the Republic of South Africa — requires changes in current social and economic structures. For Industry 4.0 initiatives to be successful, social and economic systems must be created with the ability to respond dynamically to local and global changes. The required infrastructure to sustain Industry 4.0 methods and frameworks must be developed and integrated into society on a national scale. Finally, Industry 4.0 awareness must be created to foster a mindset of technological advancement on a social, economic, and industrial level.

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APPENDIX C: ARTICLE II

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DEVELOPMENT OF A SOFTWARE-BASED MONITORING AND INFORMATION SYSTEM FOR INDUSTRIAL TELEMETRY APPLICATIONS

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ABSTRACT

Industry stands to benefit from adopting Internet of Things (IoT) practices. However, reliability and quality of service are of the utmost importance. Challenges such as intermittent connectivity in wide-area wireless communications can hamper the adoption and efficiency of IoT principles in industry. The aim of this paper, therefore, is to propose a new system that actively monitors the status of a wide-area wireless communications network to improve quality of service and ensure reliability. The new monitoring system was implemented on a telemetry system that is used by multiple industrial facilities in the Republic of South Africa. Successful monitoring of 80 remote end-points with more than one thousand individual industrial components was achieved, with communication failures or anomalies being detected immediately. In addition to the immediate detection of communication failures, the average connection uplink time was increased by more than 25 per cent.

OPSOMMING

Die industriële sektor kan baat by die integrasie van 'Internet of Things' (IoT) toepassings. Betroubaarheid en gehalte van diens is egter belangrike faktore wat in ag geneem moet word. Huidige uitdagings soos onstabiele konnektiwiteit in koordlose netwerke kan negatiewe gevolge hê in industriële toepassings. Die doel van hierdie studie is om 'n unieke stelsel voor te stel wat in staat is om koordlose kommunikasie netwerke met 'n groot omvang te monitor, met die doel om die gehalte van diens en betroubaarheid van hierdie netwerke te verbeter. Die stelsel was prakties ontwikkel en geïntegreer met 'n bestaande netwerk wat verskeie industriële fasiliteite in die Republiek van Suid-Afrika koordloos verbind. Die stelsel was in staat om tagtig afgeleë industriële eindpunte te monitor. Meer as eenduisend individuele industriële komponente word direk geaffekteer, en konneksie probleme tussen industriële aanlegte was onmiddelik opgespoor. Algehele konnektiwiteit was verbeter met meer as 25 persent.

1 INTRODUCTION AND BACKGROUND

The rapid expansion of the Internet into more facets of everyday life paves the way for the establishment of new research and development fields. One such field is the Internet of Things (IoT) which, while relatively new, proves set to become a major component of connectivity and communication in the modern era. The term 'Internet of Things' is defined as a paradigm that focuses on the incorporation of existing technologies to achieve interconnected environments, where physical products are connected to the Internet [1]. By extending the Internet and Web into the physical realm, everyday objects can be made 'smart'. With the further interconnection of these various smart objects, new applications can be developed to provide solutions to existing challenges [2].

The IoT field is experiencing rapid growth in the industrial sector, and the term 'Industrial IoT' (IIoT) is often referred to as 'the fourth industrial revolution', or 'Industry 4.0' [3]. Industry 4.0 was coined by the World Economic Forum and presented by the German government at the Hannover Trade Fair in 2011 [4]. IoT applications are currently embraced by many industries. Heavy industries, such as mining and steel, have been slower to embrace IoT applications. While the use of smart metering and IoT has become common place in households and light industry, the power stations generating the power have been less proactive in adopting similar technologies [5].

By extending IoT applications into the industrial sector, interconnected systems and processes can be maintained and optimised; this, in turn, may add massive value in production output capabilities by improving efficient production. This is especially important due to the constraints placed on heavy industry by external factors such as government policies, economic volatility, and increased competitiveness [6]. Established heavy industries, such as mining, steel production, water distribution, and power utilities have been slow in adopting IoT practices and applications [7]. Much of this hesitance to incorporate IoT methods into existing processes is derived from legitimate concerns, such as safety, security, and costs [7].

Most of the heavy industry realm cannot yet be classified as 'smart' industries — they are still operating at a traditional 'best-effort' service level [8]. Heavy industrial facilities are also typically spread over wide geographical areas (such as water pumping schemes) and operate under adverse conditions (such as mines). However, it is still possible to bring this sector into the realm of IoT by using existing technologies. With the use of existing technologies such as radio-frequency identification (RFID), wide-area wireless communications such as the global system for mobile communication (GSM) network (including long-term evolution (LTE) networks), and the global positioning system (GPS), it is possible to convert existing industrial processes and operations into 'smart heavy industries'.

System interoperability is considered to be one of the crucial points for any industrial IoT ecosystems [9]. The quality of service (QoS) levels of wireless communication systems are considered to be paramount in sustaining the performance and effectiveness of an interoperable system [9]. The reliability and availability of wireless communication services, such as the GSM network, must therefore be ensured in order to allow industrial IoT applications to reach their full potential. Gazis [9] highlights various initiatives in the context of machine-to-machine communication that have been introduced to assist in the improvement of wireless quality of service. Most of these initiatives, such as the Internet engineering task force (IETF) and the Telecommunications Industry Association (TIA), focus on maintaining a global standard for communication protocols in order to ensure a global alignment in machine-to-machine (M2M) communication.

Studies have shown that the performance of mobile communication networks can be hampered by current resource-intensive IoT applications [10], [11]. Large-scale industrial IoT applications might also experience cellular access limitations due to extremely high levels of network traffic. Several models and methods have been proposed to prevent access limitations, such as network access overload control, network access overhead reduction, and network access deadlines [12]. Limitations in wireless networks directly affect the adoption of IoT principles in the heavy industry sector [13]. Focus must therefore be placed on guaranteed quality of service in order to allow industry to benefit from IoT applications.

By implementing IoT solutions in the heavy industry sector, operations can also be made safer and more sustainable [14]. This allows for the development of modular stand-alone systems that can be applied to a wide range of net-centric applications where standards, such as LTE and third or even fourth generation (3G and 4G) wireless communications, play a predominant role in wireless data transfer [15].

By extending the IoT field into the heavy industry sector, equipment uptime can be increased, maintenance costs can be decreased, and overall equipment and control efficiency can be optimised [16]. By integrating communication between such operations, efficiencies can be achieved by holistically viewing the entirety of operations and processes [17].

It is clear that many industrial IoT applications can be considered mission-critical systems. However, challenges currently present in the IoT field can hamper the outcomes of 'smart' systems. These

challenges typically include limited bandwidth, intermittent connectivity of wireless networks, and potential security threats [18].

These challenges have a major effect on quality of service (QoS), which is a critical component in industrial IoT applications [19]. Failure to communicate will effectively nullify the advantages of an IoT application. The consequences might thus be severe, should the connectivity of an application fail. In the context of industrial IoT applications, communication failure can result in damage to infrastructure and, in extreme cases, lead to loss of life [20]. New methods are therefore required to enhance the QoS of current industrial IoT applications and of the underlying fundamentals and building blocks of these applications. The reliability and stability of wide-area wireless communications have been identified as crucial components in the overall effectiveness of IoT applications [13].

Thus, to bring heavy industrial players into the IoT domain, it is important to address the QoS issues that currently make IoT applications unfeasible for these industries. The communication network and its underlying infrastructure are considered to be the limiting factors for industrial IoT applications. The remoteness and layout of some industrial sites require that wide-area wireless communications be used as the predominant method for data transmission.

Therefore, in this paper, a new system is proposed that actively monitors the network layer vital signs of a wide-area wireless telemetry system, and that can be deployed remotely for industrial IoT applications. It is believed that integrating this system with existing industrial IoT infrastructure will reduce the risk and effect of the current challenges.

The proposed system consists of a cloud-based software application with the ability to monitor various parameters of deployed routers, such as signal strength, data usage, and connection uplink. A design overview, as well as a detailed system design, will be given. This system allows for the connection of heavy industrial equipment to the Internet, which the proposed system then monitors.

The rest of the paper is organised as follows: Section 2 gives an overview of the current IoT architecture with a focus on limitations for industrial applications. Section 3 presents a design overview and the methodology of the proposed system. Section 4 provides system results after conducting a case study, and presents a critical analysis of the given results. The potential opportunity for future work is then discussed in Section 5, with Section 6 concluding this paper.

2 IOT: ARCHITECTURE, METHODS, AND APPLICATIONS

A clear understanding of the IoT realm (which includes current architecture models, methods, applications, and challenges) must first be obtained from the literature before a solution can be proposed. This section thus presents existing peer-reviewed articles on the architectural structure of the IoT realm. Existing mission-critical systems from peer-reviewed investigations are then presented, and key areas that highlight the contributions of this paper are identified.

2.1 The IoT architecture for industrial systems

The IoT field is broad, and various definitions and architecture models exist [21], [22]. Current architectural models allow for the development of a wide range of IoT applications, ranging from smart systems in the private sector to remote monitoring, maintenance, and data acquisition systems in industrial applications [23], [24]. For this study, a generalised architecture model was chosen and adapted to heavy industry, as can be seen in Figure 1. A similar architecture model is presented in a study by Luong *et al.* [25]; however, the focus of this model is only on the broad IoT scope.

Four distinct tasks are present in mission-critical industrial IoT applications: the acquisition of data, the transmission of data, the storage and processing of data, and the accessing of data by end-users. A top-down approach is also followed, with the physical layer being the highest tier and the application layer being the lowest tier. A detailed description of each layer is given below:

- **Physical layer:** The physical layer contains all physical devices that are responsible for data measurement, sensing, and transmission. These devices have limited resources, and are typically used for the acquisition of raw data. Apart from measurement and sensing capabilities, devices in the physical layer can also transmit measurements via the Internet to data storage

schemes [26]. An example includes pumps and compressors that are controlled by control systems that make use of temperature and flow measurements for effective control [27].

- **Network layer:** The network layer facilitates all communication within an industrial IoT application. For data to be stored and processed remotely, a communication medium is required. The rapid development of communication protocols and methods in the information and communications technology field allows for various communication methods to be used within IoT applications [13]. The mobile communication infrastructure is typically used to communicate over large distances. The remoteness of industrial sites can, however, hamper the effectiveness of mobile communications.
- **Data layer:** Raw data from the physical layer must be processed and stored. The data layer serves as a platform for real-time data processing and storage with the use of cloud-based solutions. By using 'big data' storage mechanisms, large data sets can be stored. This is required, since real-time monitoring of industrial equipment typically results in large data sets on a daily basis. The retrieval and processing of data can also be done with minimal effort [28].
- **Application layer:** The application layer gives end-users the ability to access data contained in the data layer. The application layer can include application software that resides either with the end-users or in the cloud. The application layer aims to provide users with detailed information that is constructed in a user-friendly manner [25].

Figure 1 below represents a visual map of the key IoT concepts discussed above. Key challenges or concerns that can hamper the QoS of industrial systems are identified in each layer.

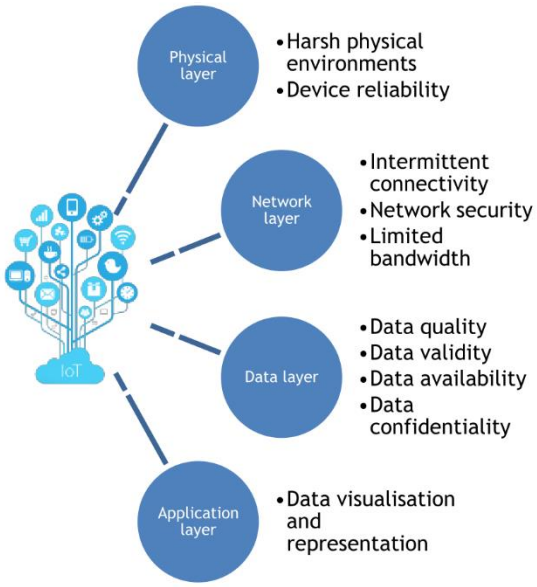


Figure 1: Existing challenges in industrial IoT applications

Key challenges within the broader IoT scope focus mainly on the areas of privacy, identity management, and security [29]. Due to the large extent of interconnected devices, standardisation and system interoperability are also flagged as major challenges. With the interconnection of devices and the integration of components on a system level, data storage and data representation become critical parts of ensuring QoS. Finally, the network layer is considered to be the most important layer for industrial IoT applications; this layer must therefore be maintained and managed to ensure optimal QoS.

2.2 Review of existing IoT applications and limitations

Advances in the IoT field pave the way for the application of its techniques to industrial IoT applications. Systems that ensure and maintain the operational status of critical facilities, such as major water resource pumping schemes or power stations, are examples of important industrial IoT applications. These systems can include real-time energy management systems for industrial equipment and remote monitoring and maintenance systems [27], [30], [31].

The low-power wireless personal area network with IPv6 (6LoWPAN) is a common communication protocol that is used by sensor networks for communication purposes [31]. This, however, limits systems so that they can only be implemented in a local environment. The communication network is the backbone of the system since, if the network fails, real-time data from the physical layer will not be available. Many IoT applications can be made inefficient if data transfer is poor due to poor network reliability or network failure. For example, failure of a Wi-Fi or cellular network used in a preventative medical care telemetry system could have consequences for patient care [32].

Several network monitoring systems have been proposed in the literature. Civerchia, Bocchino, Salvadori, Rossi, Maggiani and Petracca [33] proposed a localised industrial Internet of Things monitoring system for predictive maintenance applications. The main objective of the system is to facilitate continuous monitoring of industrial machinery. This allows for the implementation of predictive maintenance applications and strategies.

Although this system successfully achieved real-time monitoring of industrial equipment, it should be noted that emphasis was placed on the monitoring of industrial equipment, and not on the communication network that facilitates data transfer. Secondly, the system was implemented in a localised environment where sensor nodes could be easily installed and monitored. When industrial plants are separated by wide geographical distances, the quality and reliability of wide-area wireless telemetry becomes a concern, and this system does not address the challenges present in wide-area wireless communication [34].

Gisbert, Palau, Uriarte, Prieto, Palazón, Esteve, López, Correas, Lucas-Estan, Giménez, Moyano, Collantes, Gozálvez, Molina, Lázaro, and González [35] proposed a system that can monitor the performance of heterogeneous wireless networks in the context of local 'smart' factories. One key feature of the proposed system is the ability to reconfigure wireless communication nodes based on the quality of the network. The aim of the system is to help guarantee the robustness and reliability of wireless communications in the context of smart factories. The quality and reliability of wide-area wireless communication networks is, however, not addressed.

The stability of the communication network is a deciding factor for all the systems' QoS. This is specifically important for industrial IoT applications that are very sensitive to any disruption in production or reduction in safety. Wide-area wireless communications are, however, typically used as the backbone of the communication network for applications that retrieve data from remote end-points [13].

Reliable and dependable IoT solutions are considered to be of the utmost importance; network layer reliability, stability, privacy, and security are essential [36]. The system proposed in this paper serves as a solution to the challenge mentioned above. There is thus a need to develop and integrate a system to maintain QoS specifically for heavy industrial IoT applications where a lack of communication is not acceptable and the vagaries of the industry make communication more complex.

3 SYSTEM OVERVIEW AND IMPLEMENTATION

A monitoring system is proposed that can monitor the communication system to detect changes in the quality of the communication uplink between the physical layer and the data layer. The objective of the proposed solution is to detect faults in the network layer of complex industrial IoT applications.

By implementing a remote server and mobile communication router at an industrial facility, the facility can be connected to the web, which would allow for the implementation of IoT applications such as remote monitoring and maintenance. Figure 2 shows a conceptual layout of remote facilities that are connected via an existing mobile communications network.

This connection is facilitated by mobile communication routers, and it allows for critical data to be transferred wirelessly over large distances. However, the system makes use of third-party mobile communications networks over which the facility has no control.

There is thus a need to monitor the QoS of the network independently from the facilities side, to ensure optimum operation of their IoT applications. The proposed monitoring system focuses on monitoring the status of the wireless connection uplink.

In the sections that follow, a brief system overview is given, as well as a detailed design description of the proposed solution.

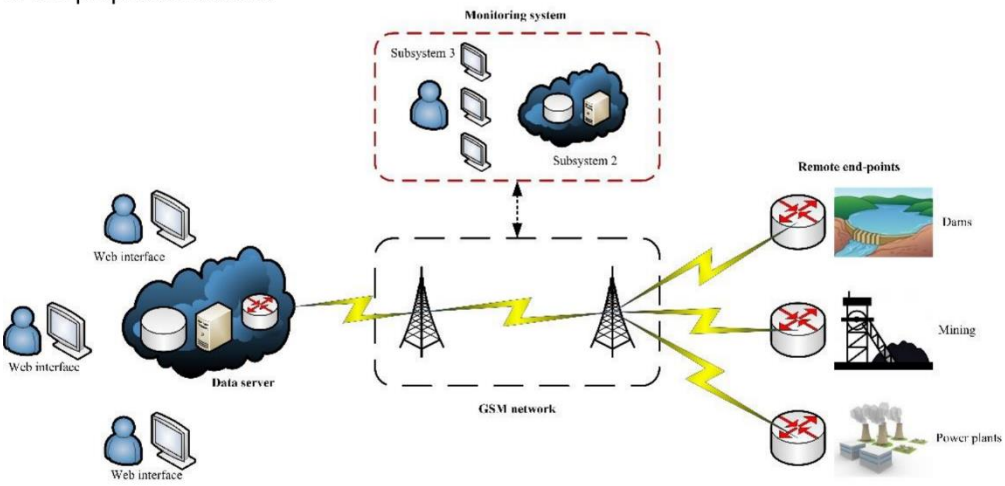


Figure 2: A conceptual diagram of a typical industrial IoT application

3.1 System overview

The proposed monitoring system can be divided into three subsystems. Figure 3 below illustrates these different subsystems, as well as the underlying structure of each subsystem.

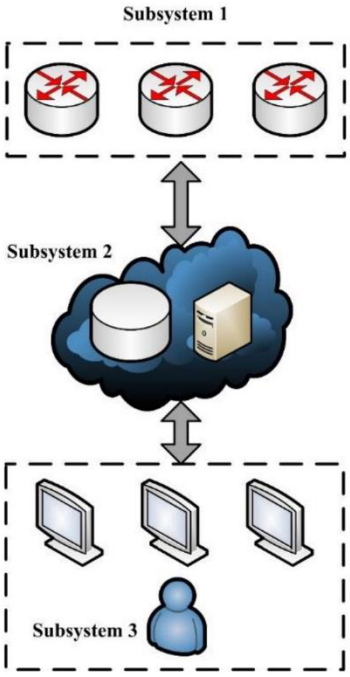


Figure 3: A basic overview of the three main subsystems

Subsystem 1 is considered to be the most important component of the system. This system consists of software routines that actively monitor the vital parameters of the network equipment, and specifically the GSM routers that are used for machine-to-machine communication. The vital parameters include the communication uplink status and the amount of mobile data currently

available. Signal strength is also considered to be a vital parameter, and is therefore included in the subsystem.

Subsystem 2 focuses on the storage of the information retrieved in subsystem 1. A relational database has been designed and implemented to facilitate the storage. The monitoring system can also retrieve information on a real-time basis, and real-time storage schemes have thus been incorporated into the design. Daily averages are, however, also calculated by subsystem 2, which implies that daily average storage schemes are also required. This has therefore been incorporated into the design.

Subsystem 3 consists of the graphical user interface (GUI), as well as event logging capabilities. For the proposed monitoring, all information is displayed in real-time. A GUI has thus been designed to relay all data to the appropriate end-user stations. From these stations, it is possible to view real-time updates on the connection uplink, the current mobile data usage profile, and the signal strength. Additional information can also be viewed, such as the IP address of the remote end-point.

Most industrial IoT applications make use of M2M protocols to facilitate data transfer between offices and remote sites. In order to establish a secure connection between the remote end-point and the receiving end-point, a private access point name (APN) or virtual private network (VPN) is used. With the use of an APN, each remote end-point is provisioned with a unique internet protocol (IP) address [37]. The only way to enable this communication effectively is by using mobile routers.

Thus the proposed system is designed to monitor the communication between a mobile communication router and an existing cloud infrastructure. The proposed system is responsible for monitoring the uplink between remote industrial sites and the receiving end-point to which data is transmitted.

3.2 Monitoring method

Two techniques were identified for monitoring a network: active and passive [38]. An active measurement approach has been followed for the proposed monitoring system. Active probing is used by transmitting internet control message protocol (ICMP) packets across the network to the remote end-point.

Generally, due to security concerns, most routers filter out ICMP packets. However, since all remote end-points are registered on a private APN, it is still possible to use ICMP packets to determine whether the remote end-point has a stable connection. The monitoring system can be configured to have one of three restriction profiles: server, administrator, or viewer. The server profile gives the system full access to executing active probing procedures. One restriction on the use of the server profile is that the system must have access to the APN.

The administrator profile allows for the addition or removal of remote end-points, but the application does not have the right to execute active probing procedures. The viewer restriction profile only allows for the viewing of the current network status. Active probing methods cannot be executed when the application is in viewing mode. The monitoring system has been designed with a modular approach in mind. It is therefore easy to add additional end-points for monitoring purposes. In order to optimise the performance of the monitoring system, multithreading techniques have been employed for all software routines.

All active probing routines, as well as database operations, are thus executed in a multithreading environment. This allows for effective monitoring of remote end-points, regardless of the number of end-points that need to be monitored. Figure 4 below illustrates the main software flow of the monitoring system. The software routine is executed periodically in a real-time fashion. Since data is transmitted from each site on a daily basis, the frequency of execution can be narrowed to hourly intervals. This interval was chosen so as not to flood the network with ICMP packages. The interval can, however, be adjusted if required.

Real-time monitoring can only be achieved if a connection to the relational database is available. A database connection check is therefore first executed. In the absence of a database connection, the monitoring routine should not be executed and no data displayed to the user. If a successful database connection is active, the status of the host machine determines whether the monitoring routine can be executed.

If the host machine is idle, all remote IP addresses are retrieved from the database and stored in a data structure. Worker threads are then created, with each worker thread responsible for checking the connection status of a single IP address. By using active probing, all active remote end-points will reply. The resulting replies are then stored in the database for processing and display purposes.

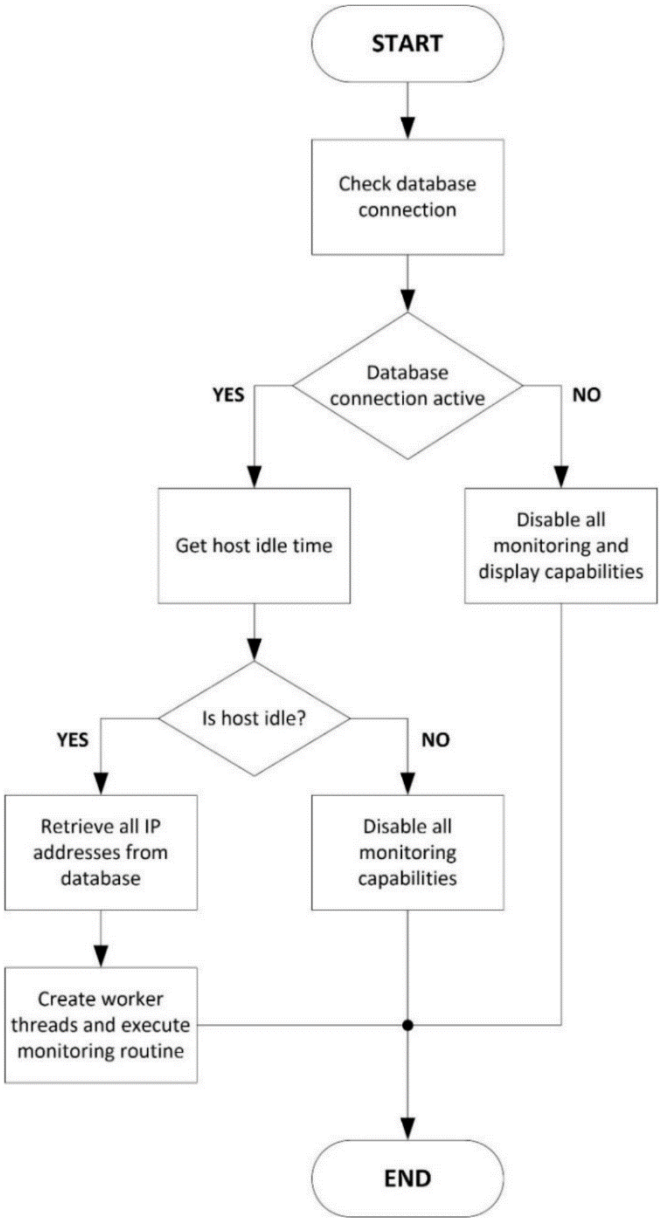


Figure 4: The main software flow of the monitoring system

3.3 Database design

A relational database schema has been designed and two tables created to facilitate real-time data storage. The first table facilitates real-time storage of all active probing results, while the second table stores a daily average value that has been calculated by the monitoring system. Figure 5 below shows the details of the two schemas.

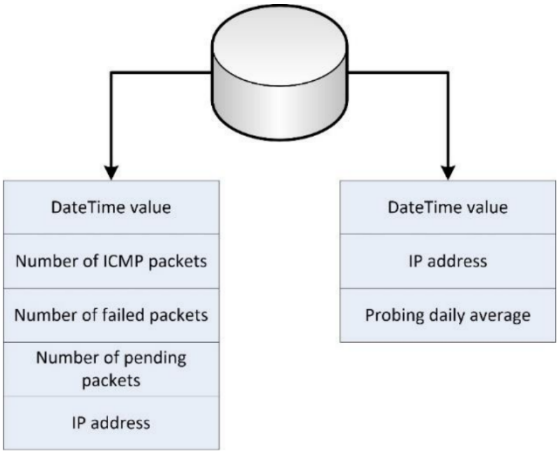


Figure 5: Relational database schemas

Since the proposed system monitors and stores results in real time, data aggregation is considered to be a key component of the database design. Data aggregation assists with reducing the size of the database as well as the query execution time, which results in an overall improvement of system performance.

3.4 Graphical user interface

To visually display real-time information, a graphical user interface is required. Since more than one network should be monitored, a grid is compiled, with each entry in the grid containing information relating to a specific end-point. In addition to the status of the network, other information — such as the device signal strength and the current data use — is also displayed.

Site-specific data is also displayed, such as the site IP address, the port number that is required for remote access, and the person responsible for the site. This site-specific information is relevant, as it is required in order to improve proactive maintenance procedures.

The current GUI has been designed to allow for the display of the system in a control room setup, but it could be modified to accommodate other monitoring configurations. A control room typically consists of multiple monitors from which personnel can perform their duties. The control room is thus the ideal place to run multiple client versions of the system, since multiple service personnel use the control room. From the control room, personnel will be able to obtain access to their specific remote sites, and will be able to monitor the real-time status of their sites at any given moment. The implementation architecture of the system can be viewed in Figure 6. Client versions of the system must be distributed on multiple workstations.

The implementation architecture of the system has therefore been designed to include one server application that runs on a dedicated server. The main objective of the server application is to facilitate real-time monitoring of the communication uplink and the storage of the data in the relational database, as discussed in the previous section. The client applications have direct access to the database, as this is required to provide a continuous live feed view of the status of each remote end-point.

Figure 7 below illustrates how the remote end-point data is represented on the graphical user interface. An administrator version of the developed system is shown. All data, as well as historical tracking of connection uplinks, is displayed in order to provide users with the means to make performance-based decisions.

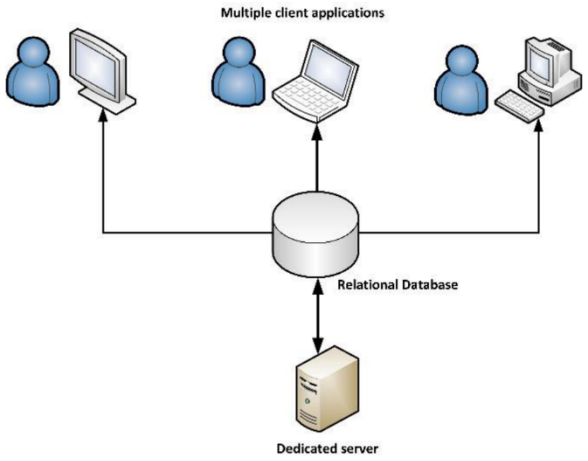


Figure 6: Implementation architecture of the system

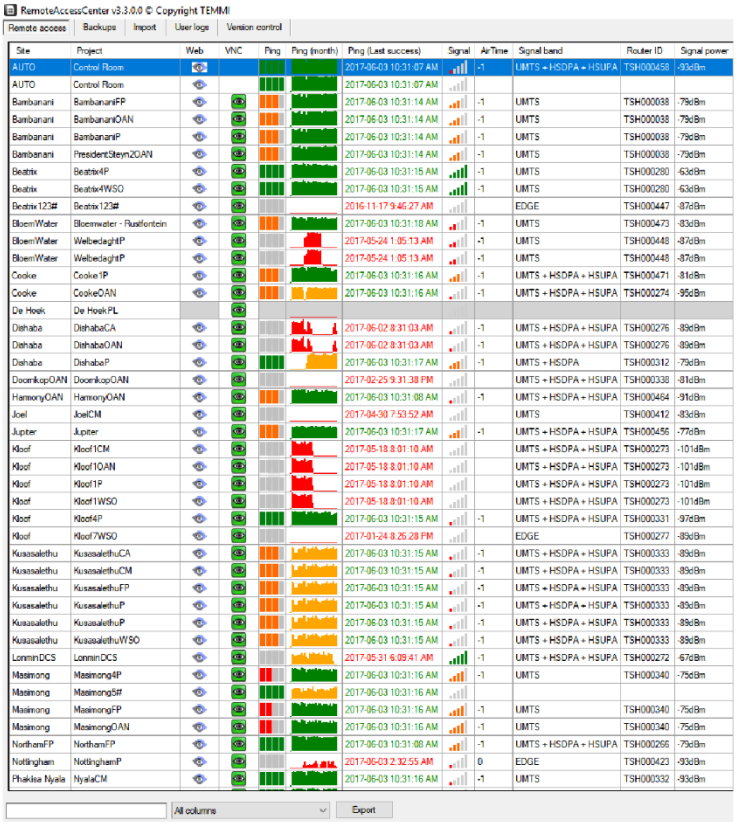


Figure 7: The graphical user interface of the developed monitoring system

4 RESULTS

4.1 Scope

The proposed system was implemented on an existing machine-to-machine telemetry network. This network was established by an energy services company (ESCo) to implement energy management systems (EMS) effectively for various industrial consumers distributed across the Republic of South Africa. Currently, the ESCo actively maintains energy projects in seven of the nine provinces in the Republic of South Africa, as shown in Figure 9. The receiving end-point for all energy data is, however, located in the Gauteng Province, marked with green in Figure 8. This creates an IoT-based EMS.

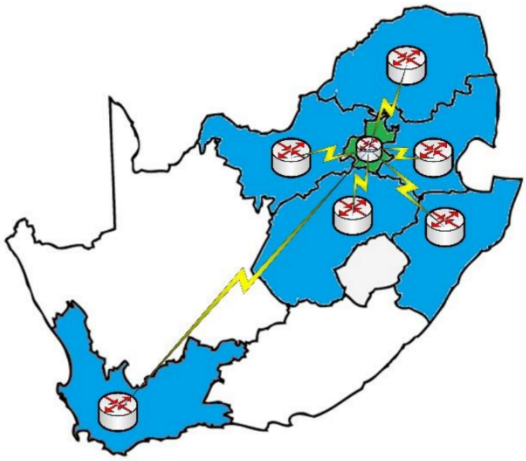


Figure 8: Map showing the geographical reach of the implemented system in the Republic of South Africa (see online version for colour)

Raw data from all remote sites connected to the telemetry network is transmitted daily to a central server. An energy management information system is then used to process the raw data and display all relevant information.

In the industrial sector, EMSs are deployed to reduce the energy consumption profiles of consumers. EMSs also facilitate electricity cost savings for the consumer, and reduce the load on the electricity supplier during peak consumption periods [39]. An EMS can automatically control industrial equipment from predefined control philosophies [27], [40]. In addition to control operations, these systems can also perform data and event logging. Dynamic changes in production profiles also imply that continuous maintenance needs to be performed on the EMS [30].

In order to assist with EMS maintenance, Du Plessis, Pelzer and Vosloo [41] introduced a reactive maintenance approach to sustain, and possibly improve, the performance of existing EMSs. The development of a remote diagnostics and maintenance system allows for a remote EMS to be connected to a maintenance control centre through a secure communication channel [30].

The challenge present in the proposed system is that an unreliable communication link to the remote EMS can result in data loss and poorly maintained energy savings initiatives. This hampers the effectiveness of remote diagnostic and maintenance systems, and causes energy management systems to underperform. Energy management systems are considered to be critical industrial systems because they perform real-time dynamic control on industrial equipment.

Thus the consequences might be severe if control fails on a site and the communication to that site is unstable. Unfortunate consequences not only include the underperformance of EMS systems, but also safety issues and unwanted interruptions in service delivery or production schedules.

Some of the components monitored by the EMS include water pumping schemes in water-scarce regions, and sophisticated control systems on production-sensitive machine components in mines and processing plants. This system can therefore be improved by including a network layer monitoring system, as proposed in this paper, that actively monitors the status of the network to ensure optimum service delivery of the IoT-based EMS system.

4.2 Uplink monitoring

Figure 9 and Figure 10 are representative of the connection uplink for two independent critical facilities situated at remote locations. Table 1 lists the overall impact of the system. For this study, a total of 80 remote sites were monitored by the system. The remote sites include platinum mines, gold mines, processing plants, coal power plants, and major pumping schemes. The underlying

industrial equipment used on these sites includes compressors, pumps, fridge plants, fans, actuators, bulk air coolers, and measurement devices.

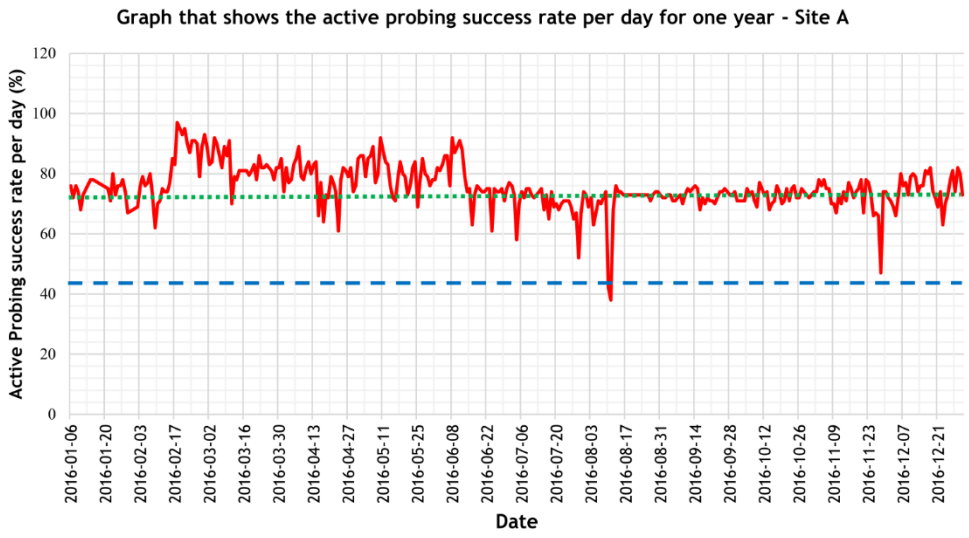


Figure 9: An example of a remote end-point that has a stable connection uplink

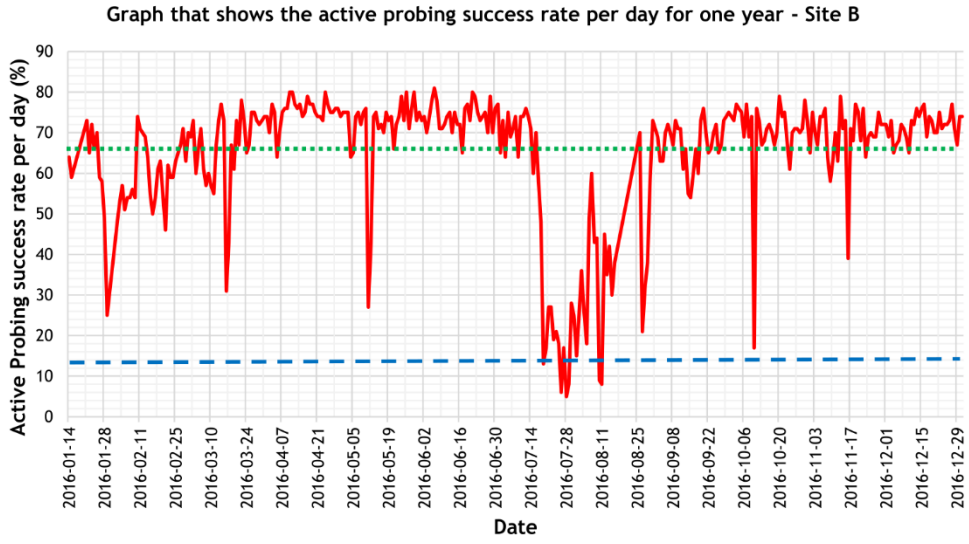


Figure 10: An example of a critical facility that experienced connection issues at some point

Table 1: Monitoring system overview

Description	Value	Percentage (%)
Number of sites monitored	80	n/a
Number of healthy sites	57	71.25
Number of unhealthy sites	11	13.75
Number of dormant sites	12	15

With the monitoring of 80 sites, the total amount of heavy industry equipment being monitored is well over a thousand individual components. Monitoring results for the 80 sites were obtained on an hourly basis to ensure that connection issues were identified as fast as possible before the daily transmission of raw data. It was found that active probing on an hourly basis gave an accurate

account of the uplink status, while keeping the load on the mobile communications router within an acceptable range.

A 24-hour sample size was also found to be large enough to identify all sites that experienced connection issues. Dormant connections were also identified and marked for investigation. Before the implementation of the system, the number of sites with unhealthy connections and of dormant sites were unknown. Personnel were thus tasked to investigate continuously the cause for data loss at the receiving end-point.

Before the implementation of the system, no connection monitoring was done. After system implementation, the first three months were used as the baseline to evaluate the operation of the system. The baselines for all monitored sites have been determined by calculating the average active probing success rate per day for a period of three months. The baselines are indicated by the blue dashed line in Figures 9 and 10.

A clear improvement in network communication can be seen in both sites after three months of operation. The improved baseline after three months of operation is indicated by the green dotted line in Figures 9 and 10. The active probing success rate for site A increased from 42 per cent to about 70 per cent. For site B, the active probing success rate increased from 12 per cent to about 65 per cent.

Figure 9 shows the result of a stable communication uplink, with an active probing success rate per day of between 60 and 100 per cent. Figure 10 above shows the result of a critical facility that experienced connection issues in the month of July 2016. The monitoring system allowed for the immediate detection of the state of the network. This prompted investigations to be conducted on the site in order to determine the cause of the unstable connection.

The primary objective of the proposed system was actively to monitor the vital signs of a GSM-based telemetry system. The system thus monitored and displayed the status of a mission-critical telemetry system on a real-time basis. The results of two independent remote end-points using this system found that unstable connections were identified within one hour of operation. This clearly illustrates the benefits of implementing such a system on existing industrial IoT applications to ensure optimum service delivery.

Greater benefit from the IoT-based EMS in the case study of this paper was achieved due to an increase in the stability of the network layer. This system can also be expanded to incorporate other mission-critical industrial applications, as described in Section 2.

5 FUTURE WORK

As with all ongoing research and development, there is room for the improvement and expansion of the current monitoring system. The current version of the system requires a server for effective operation. Two expansion opportunities are thus presented that would extend the operational functionality of the system.

The first expansion opportunity is to incorporate methods that would allow for the automatic generation of reports. Automatic report generation can be included within the system, or the system can be integrated with dedicated report generation systems, such as the system designed by Liebenberg [42]. By generating reports from the data, detailed analyses can be done on the state of the network infrastructure. It is believed that automatic reports could have a positive impact on telemetry QoS.

The second expansion opportunity is to incorporate the system into a web-based information and data consolidation system, such as the system designed by Goosen [43], since a desktop application is considered to have a limited impact. Expanding the monitoring system into a web-based system will thus improve the system’s sphere of influence. Security is, however, a concern, and this will need to be addressed by implementing appropriate security measures.
The proposed system can also be implemented in the corporate world for the monitoring of company handheld devices, such as cell phones, tablets, and rugged smart devices. This is regarded as potential future work for the expansion of the system.

6 CONCLUSION

The impact of an unstable communication network in the field of industrial IoT applications can be severe. Extensive study of existing mission-critical systems showed that network layer monitoring is seldom incorporated into the designs of industrial IoT systems. Therefore, as described in this paper, a novel monitoring system that monitors the communication uplink status of remote wide-area wireless communication end-points was developed. The objective of this study was to develop and integrate this system into existing industrial IoT infrastructure in order to improve the robustness of existing infrastructure.

The proposed system has been designed and implemented on existing energy management projects of an established energy services company. A total of 80 remote end-points, encompassing over a thousand individual components, were incorporated into the system for monitoring purposes. Unstable connections were successfully flagged and earmarked for investigation. Necessary steps were then taken to rectify the issues.

The results achieved demonstrate that real-time monitoring of mission-critical end-points was successfully achieved. The integration of this system further improved the robustness of industrial IoT infrastructure. It is believed that the incorporation of the proposed system will serve as motivation to incorporate IoT solutions and applications in the heavy industry realm.

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APPENDIX D: ARTICLE III

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THE VALUE OF A TELEMETRY MONITORING SYSTEM IN SUSTAINING THE OPERATIONAL PERFORMANCE OF INDUSTRIAL INFORMATION SYSTEMS

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ABSTRACT

Revolutionary advances in the information and communication technology field pave the way for automation and data exchange in the heavy industry sector. Currently, Industry 4.0 solutions are more readily accepted in factories and in more advanced economies, where good infrastructure is in place to facilitate these solutions. In the context of these heavy industries, wide-area wireless telemetry networks play an important role in facilitating accessibility and allowing for real-time monitoring and data transmission over wide geographical distances. This paper emphasises the value of a new wireless telemetry monitoring and diagnostic system that allows for the development of a detailed troubleshooting methodology when communication disruptions occur. The system was implemented on an existing telemetry system that is used by an energy services company to maintain the operational status of various remote information systems. The network is also used to facilitate various demand-side management projects throughout the Republic of South Africa. The results obtained show that the proposed system can enhance the robustness of existing Industrial Internet of Things infrastructure, and this promotes the adoption of Industry 4.0 concepts in the heavy industry sector.

OPSOMMING

Revolusionêre vooruitgang in die inligting- en kommunikasietegnologie-veld baan die weg vir outomatisering en data-uitruil in die swaar nywerheidsektor. Tans word oplossings van Industrie 4.0 makliker in fabrieke en in meer gevorderde ekonomieë aanvaar waar goeie infrastruktuur in plek is om hierdie oplossings te fasiliteer. In die konteks van hierdie swaar nywerhede speel wye draadlose telemetrie netwerke 'n belangrike rol om toeganklikheid te vergemaklik en vir intydse monitering en data-oordrag oor wye geografiese afstande voorsiening te maak. Hierdie manuskrip beklemtoon die waarde van 'n nuwe draadlose telemetrie monitering en diagnostiese stelsel om toe te laat dat 'n gedetailleerde probleemoplossingsmetodologie ontwikkel word wanneer kommunikasie-versteurings plaasvind. Die stelsel is geïmplementeer op 'n bestaande telemetrie stelsel wat gebruik word om die operasionele status van verskeie afgeleë inligtingstelsels te handhaaf. Die resultate het getoon dat die voorgestelde stelsel die robuustheid van bestaande 'Industrial Internet of Things'-infrastruktuur kan verbeter, en dit bevorder die aanvaarding van Industrie 4.0 konsepte in die swaar nywerheidsektor.

1 INTRODUCTION

Revolutionary advances in the information and communication technology field pave the way for automation and data exchange in the heavy industry sector [1]. The application of these Industry 4.0 technologies and methods can lead to the creation of 'smart' industries, which can improve production efficiencies, reduce production costs, and maintain reliable service delivery initiatives. Industry 4.0 solutions are currently more readily accepted in factories and in more advanced economies, where good infrastructure is in place to facilitate these solutions [2]. However, the adoption of these same techniques

and solutions is slow in the heavy industries of developing economies, where infrastructure is poor and there are wide geographical distances between operating plants [3–6].

The backbone of Industry 4.0 techniques and solutions relies on machine-to-machine communication and wireless networks [7, 8], and therefore the quality and stability of the network layer forms a crucial part of an optimal Industry 4.0 ecosystem. Disruptions in accessibility and connectivity can thus effectively nullify the advantages of an Industry 4.0 ecosystem [2, 9–11].

In the context of these heavy industries, wide-area wireless telemetry networks play an important role in facilitating accessibility and allowing for real-time monitoring and data transmission over wide geographical distances [12–14]. It is infeasible to make use of traditional wired methods of communication due to the large geographical separation between industrial facilities. To achieve data transfer between remote locations, existing infrastructure, such as third party mobile cellular networks, is used [15–18].

The use of existing third party infrastructure implies that no control can be exercised over the network. The end user of the network must, therefore, cater for potential communication disruptions over which they have no control. Disruptions in communication can result in data loss, which can have a negative impact on the performance of industrial processes and systems. Several industrial information systems investigated in the literature rely heavily on a stable communication network [14, 19–21]. Should the existing cellular communication network experience disruptions in communications, these systems would become unreliable and have no benefit for industrial clients.

With industry currently using existing infrastructure such as cellular communication networks to carry out real-time communication and data transmission, there is a need for a telemetry monitoring system that actively monitors the status of the third party communication network. Since no control can be exercised over the network, quality-of-service issues cannot be directly addressed, and so a solution is required to enable corrective action to be taken.

2 STATE OF THE ART

From the start of the Internet of Things (IoT) revolution, cellular communication technologies and infrastructure played a dominant role in facilitating real-time communication [22]. To use this infrastructure for real-time data transmission, minimal hardware needs to be installed. For most applications, a single industrial router is required, after which access can be obtained to the entire cellular network. In addition to the installation of a router, mobile subscriber identification modules (SIMs) must be incorporated to allow for wireless communication [17].

Mobile communication networks have been a key enabler of various IoT applications [23–26]. These networks consist of technical characteristics that allow effective communication to take place. The critical parameters listed below have been identified from the literature as key components that can cause communication disruptions if not managed and monitored properly [27]:

- Overall network quality, measured by packet transmissions [28];
- mobile network bandwidth; and
- mobile network signal strength and attenuation.

It is possible to access these characteristics via the industrial router, since integrated hardware allows these characteristics to be measured. With network characteristic data available, a system can be developed that extracts the parameter values of the different characteristics from the industrial router.

Several network monitoring systems have been proposed in the literature. A system that can monitor the performance of wireless networks of a heterogeneous nature in the context of local smart factories is proposed by Gisbert *et al*. [29]. The ability to reconfigure wireless communication nodes based on the quality of the network is one of the key features of this system. The objective of the proposed system is to help guarantee the robustness and reliability of wireless communications in the context of local dynamic smart factories. This system does not, however, address the limitations present in wide-area wireless communications, and no troubleshooting methodology has been presented to troubleshoot network problems.

Civerchia *et al*. [30] proposed a localised Industrial Internet of Things monitoring system for predictive maintenance applications. The main objective of the system is to facilitate pervasive monitoring of

industrial machinery. This allows for predictive maintenance applications and strategies to be implemented. Although this system successfully achieved real-time monitoring of industrial equipment, it should be noted that emphasis was placed on the monitoring of industrial equipment, and not on the communication network that facilitates data transfer. Second, the system was implemented in a localised environment where sensor nodes could be easily installed and monitored. When industrial plants are separated by wide geographical distances, the quality and reliability of wide-area wireless telemetry becomes a concern; and this system does not address the challenges present in wide-area wireless communication [31].

Prinsloo, Mathews, du Plessis and Vosloo [32] developed a monitoring and information system to assist with real-time communication anomalies in industrial telemetry applications. This system focuses primarily on wide-area wireless telemetry systems that make use of the cellular network to achieve real-time data transmission. The objective is to monitor the connection uplink of Global System for Mobile Communication-based telemetry systems with the aim of improving service delivery in the South African heavy industry sector. Although this system succeeded in detecting communication anomalies, various critical network parameters have been neglected in the system design. The system only focuses on the communication uplink, and does not consider network parameters such as cellular network bandwith and signal strength. Both of these parameters can have a direct impact on the quality and reliability of wide-area wireless telemetry networks. This paper therefore aims to expand this system by introducing the monitoring of these parameters.

Various methods and techniques for monitoring communication networks have been proposed. One method of monitoring the status and quality of a communication network is to make use of active probing routines. For active probing, the user injects packets into the network from a host, and observes the response from the network to the injected packets. Active probing is the primary method for monitoring the status of a network [28]. Communication protocols, such as transmission control protocol (TCP) and internet control message protocol (ICMP), are regarded as the predominant protocols to implement active probing on a network [33–35].

Intermittent connectivity in mobile communication networks can have the effect of hampering the quality of service (QoS), and thus the effectiveness of information systems in the heavy industry sector [36–38]. Industrial information systems will fall short of their objectives if no input data is received from industrial sites. The existing network infrastructure used for real-time data transmission is therefore considered to be a critical component in the overall information system architecture, as well as in other IoT-related systems [39-40].

An external monitoring system is therefore required that provides insight into the status of third party networks. By gaining insight into the status of the cellular network, a detailed troubleshooting methodology can be developed and used in the event of communication disruptions. The aim of this paper is thus to illustrate the value of such a system in the context of industrial communication.

3 METHODOLOGY

The effectiveness of information systems and other Industry 4.0-related applications can be severely limited if no stable communication network is present. This paper emphasises the value of a new wireless telemetry monitoring and diagnostic system that allows for the development of a detailed troubleshooting methodology when communication disruptions occur. The system was implemented on an existing telemetry system that is used to maintain the operational status of various remote information systems.

3.1 System architecture

The telemetry monitoring system consists of three main design components, which are presented and discussed below.

1. *Component 1* — The physical layer: The first component of the system focuses on the acquisition of data. To determine the state of the communication network, data needs to be retrieved. This is done by using an active probing procedure to determine whether the communication network is online. For the proposed system, the physical layer will be the execution of active probing software routines to determine the state of the various network parameters listed in Table 1 below.
2. *Component 2* — The data layer: The results obtained from the active probing routine then need to be processed and stored in a database. This component is categorised as the data layer of the system. Active probing procedures are invoked routinely during the day, and the data is processed to obtain

daily and hourly averages. The data layer also acts as a historian that can be used as an additional tool to evaluate the performance of energy management systems. For the proposed system, the data layer will be in the form of an SQL database.

3. *Component 3* – The application layer: The final component of the system allows the processed data to be relayed to visual dashboards for analysis and decision-making purposes. The application layer allows trained personnel to start a troubleshooting and diagnostic process to rectify issues that might arise without the need to travel to the actual industrial site to start troubleshooting. For the proposed system, the application layer will be in the form of a graphical user interface (GUI).

A modular design approach has been followed to allow for rapid expansion if additional industrial sites need to be included for telemetry monitoring purposes. Visual dashboards are presented to personnel, and serve as a graphical user interface on which telemetry status signals can be viewed.

3.2 Physical layer

Industrial plants and compounds are distributed across large geographical distances. To enable data transmission, the mobile cellular communication network is used as the communication infrastructure. This requires industrial mobile cellular communication routers to be installed on-site to facilitate data transmission via the cellular network. For mobile cellular communication routers to transmit data successfully, SIMs must be present in every router.

In several cases, industrial facilities serve as a hub for wireless data transmission. Data is transmitted from other facilities to one central location, from which control systems can acquire access to the data via an open platform communication interface. Mobile cellular communication routers are also used for this purpose. Internet protocol (IP) addresses are assigned to all remote end-points, which are also interconnected via a virtual private network (VPN). Figure 1 below shows the scope of wide-area wireless communication, as well as the strategic importance of the proposed system.

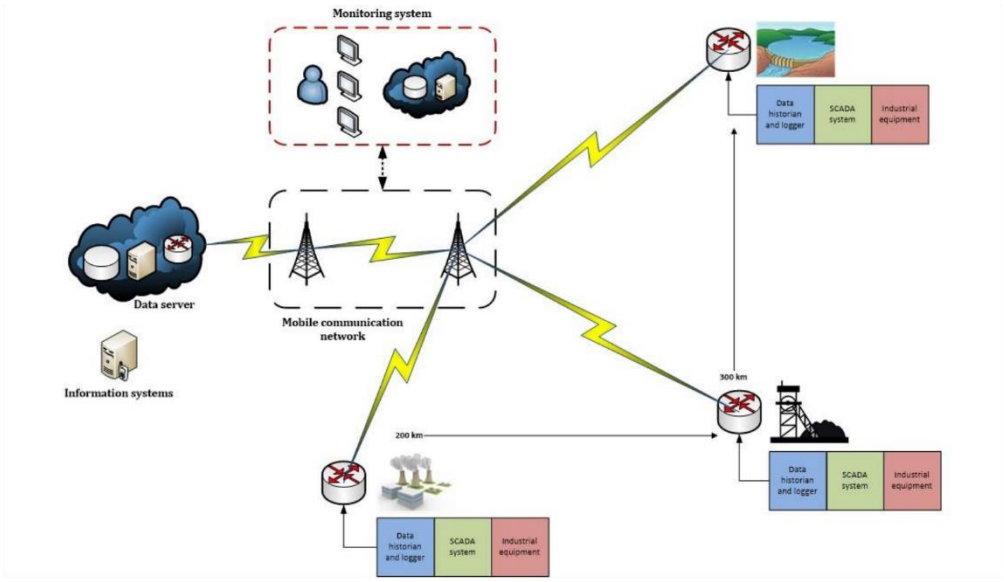


Figure 1: The scope of the proposed telemetry monitoring system in an existing IIoT energy management ecosystem

3.3 Data layer

Three key perspectives that are crucial to the overall quality and stability of a wireless communication network were identified from the literature. The first perspective is the global operational status of the wireless communication network. This perspective can be labelled the 'line-of-site' perspective, even though wide-area wireless communications are not considered to be directional.

Active probing methods are regarded as the best approach to determine the state of a network [28]. Software subroutines were implemented to determine the operational status of the line-of-site perspective. This entails the transmission of data packets across the network link to the receiving endpoint located at an industrial facility. An operational end-point with a stable link will reply with an echo data packet in

response to the active probing transmission. The responses can then be recorded, and a history can be compiled for troubleshooting purposes.

The second perspective focuses on the use of mobile data to facilitate all network communication. Mobile data is an expensive resource, and so it should be constantly monitored. A depletion in the mobile data bundle will also result in network downtime, which is unacceptable in the context of Industry 4.0 applications.

The third and final perspective focuses on the quality of the network link. This can be determined by looking at the signal strength of the network, as signal strength provides valuable insight into the current state of the network, and can highlight potential issues such as coverage gaps in remote areas, as well as interference that might disrupt wireless communication over long distances. Figure 2 below illustrates the operation of the system.

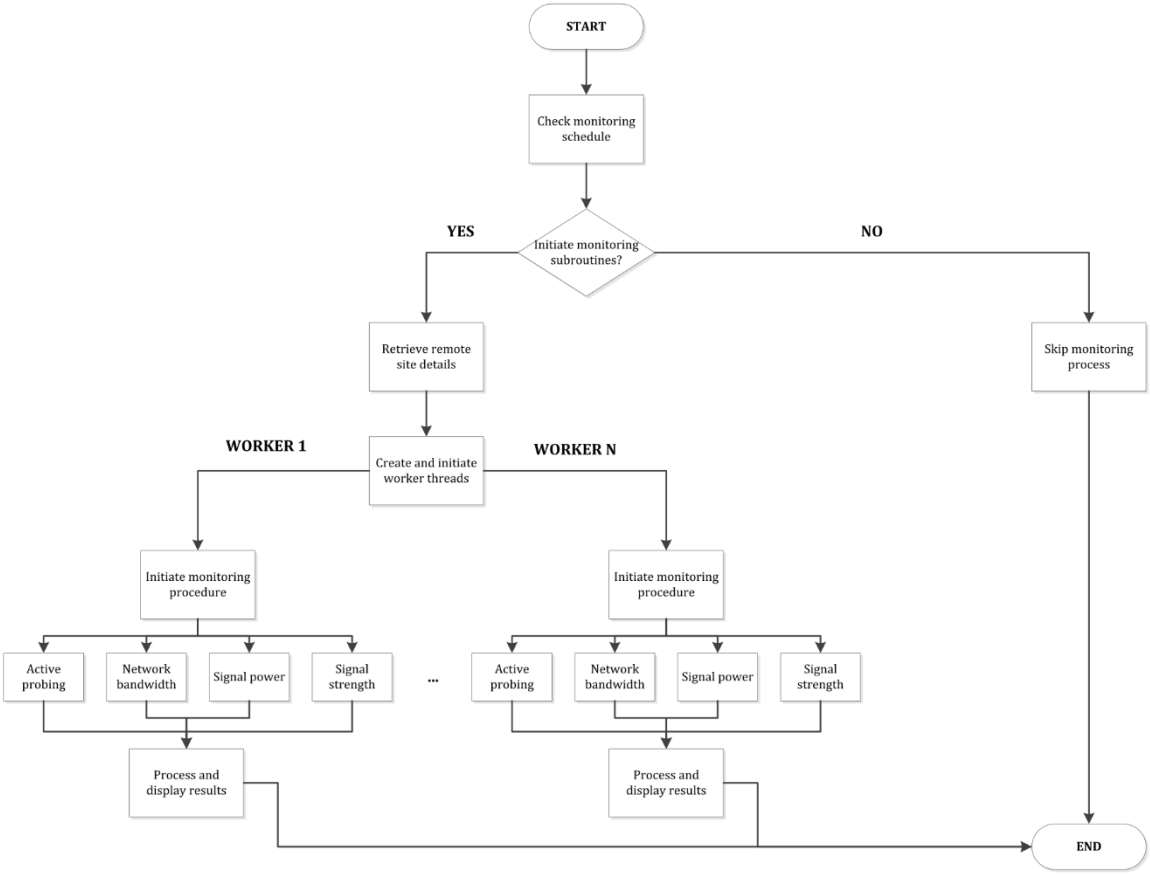


Figure 2: A detailed software architectural flow of the telemetry monitoring system

The two main techniques for network monitoring are active probing and passive probing. During system implementation, it was decided to make use of active probing procedures. These involve the transmission of internet control message protocol (ICMP) packets across the network to the remote industrial end-point. The resulting response from the remote end-point is then used to determine the state of the remote end-point. All remote IP addresses are retrieved from the database and stored in a data structure. Worker threads are then created, with each worker thread responsible for checking the connection status of a single IP address. By using active probing, all active remote end-points will reply. The resulting replies are then stored in the database for processing and display purposes.

To optimise the performance of the monitoring system, multithreading techniques have been employed for all software routines. All active probing routines, as well as database operations, are thus executed in a multithreading environment. This allows for effective monitoring of remote end-points, regardless of the number of end-points that need to be monitored. The active probing software routine is executed

periodically in real time. The use of a multithreading environment allows for any number of sites to be monitored, which implies that the system is easily expandable if required.

The proposed system allows for the monitoring of several key mobile cellular communication network parameters. The monitoring of key network parameters also introduces several capabilities that assist maintenance personnel in troubleshooting. These network parameters, as well as the capabilities, are listed and discussed in Table 1 below.

Table 1: Monitoring system objectives and capabilities

Network parameter	Monitoring objective	Maintenance capabilities
Active probing success rate	The objective of active probing success rate monitoring is to determine the overall quality of the telemetry uplink. ICMP packets are transmitted across the network, and replies from remote end-points are logged. An average success rate based on the number of successful replies is calculated and stored as a percentage value. Section 4.1 provides results from two case studies.	The active probing success rate serves as the primary indicator of the status of the network uplink for a remote end-point. Maintenance personnel can use this parameter to determine the overall quality of the communication network.
Network bandwidth	The objective of network bandwidth monitoring is to determine the available bandwidth for each individual end-point. In most cases, wireless data transmission will cease if bandwidth levels drop to zero. For national key points, data transmission will continue, but the cost of communication will increase significantly due to 'out of bundle' data rates. Section 4.2 provides results from two case studies.	Monitoring of network bandwidth allows maintenance personnel to determine the transmission load of individual end-points. Industrial sites that continuously transmit large amounts of data will deplete their bandwidth levels at a much faster rate. This parameter allows maintenance personnel to check wireless data transmission from a site proactively.
Signal power	The objective of signal power monitoring is to determine the signal power level for each individual end-point. The signal power level is measured in decibel-milliwatts (dBm). The signal power level provides an accurate representation of the absolute power levels of the network end-point. The signal power can also be defined as a received signal strength indicator (RSSI).	See 'Network signal' below.
Network signal	The signal power level is used to provide maintenance personnel with a colourised representation of the router signal strength. The network signal parameter is converted to a percentage value from the RSSI indicator. Section 4.3 provides results from a case study.	The colourised representation of the RSSI value discussed above gives maintenance personnel a visual representation of the current network signal strength. Poor network signal strength should encourage maintenance personnel to investigate external factors, such as radio frequency interference.

3.4 Application layer

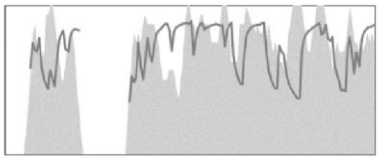
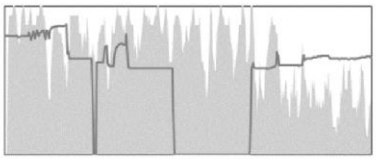
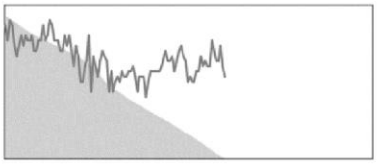
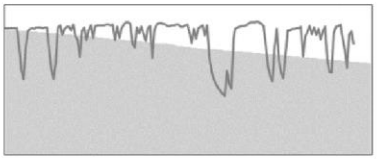
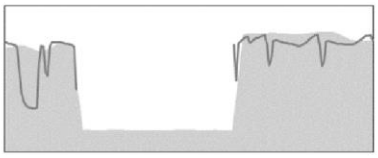
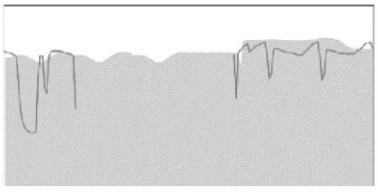
By gaining insight into the status of the cellular network, a detailed troubleshooting methodology can be developed and used in the event of communication disruptions. Holistically, three overarching challenges are present that disrupt wide-area wireless communications: network challenges, network billing issues, and equipment challenges.

In all three challenges, data transmission from sites will fail. This implies that information gaps will be present on industrial information systems that rely on wide-area wireless communication for data transmission for each of the three disruption cases mentioned above. A detailed troubleshooting methodology is therefore needed to determine the exact cause of any information gap in industrial information systems. The system described in this paper addresses this need, and allows for effective troubleshooting to take place in the context of wide-area wireless communications for industrial players.

Table 2 below gives a summary of the different communication disruption scenarios that can be present, and graphically illustrates how the system will represent the disruption. The scenario is then mapped to a potential root cause of the disruption. A troubleshooting procedure is then presented, which must be followed to resolve the communication disruption. Several case studies, which serve to emphasise the importance of gaining insight into the status of the cellular network for industrial data transmission purposes, are presented in Section 4. Each illustration contains an area chart and a line chart. The area

chart represents a specific network measurement, while the line chart represents an equipment measurement. Implementing the proposed system allows for a detailed mapping of any communication anomaly to determine the root cause of communication disruptions.

Table 2: Communication disruption diagnosis and troubleshooting

Characteristic	Illustration	Diagnosis	Troubleshoot
Network quality		Faulty network. Network downtime results in data loss. Without an active network connection, data transmission is impossible. This is illustrated by the gap in the area chart.	Network assets and infrastructure must be checked to determine whether faulty equipment results in network downtime.
		Stable network, but faulty equipment measurements. Data loss on a stable network implies that equipment measurement challenges are present on-site. An operational network can be seen in the area chart.	No troubleshooting needs to be done on the communication network if network bandwidth and signal strength are positive (see below). Investigations are required on-site to determine the cause of data loss.
Network bandwidth		Network bandwidth usage depleted. Depletion of network bandwidth results in network downtime. The area chart shows the data depletion.	Additional data bundles must be activated on the required wireless node. Data transmission routines must also be investigated on-site to determine why excessive data usage is present.
		Network bandwidth usage stable. Enough bandwidth is available to realise data transmission. This implies that equipment measurement challenges are present on-site.	No troubleshooting needs to be done on the communication network if network uplink and signal strength parameters are positive. Investigations are required on-site to determine the cause of data loss.
Equipment resilience		Network signal strength degradation. Weak signal strength results in unstable data transmission. The area chart shows the degradation in signal strength.	The geographical location of network infrastructure must be investigated and rectified to improve wireless signal reception. Faulty hardware must also be investigated.
		Network signal strength healthy. Stable network signal strength implies that equipment measurement challenges are present on-site.	No troubleshooting needs to be done on the communication network if network uplink and bandwidth parameters are positive. Investigations are required on-site to determine the cause of data loss.

3.5 System application and verification

The developed system was implemented on an existing telemetry network that is used by an energy services company to facilitate various demand-side management projects throughout the Republic of South Africa. About 80 remote industrial sites are currently within the scope of the telemetry monitoring system, which implies that the system has a direct impact on the performance of thousands of individual items of industrial

equipment. The energy services company uses multiple mobile cellular communication networks to facilitate real-time data transmission across remote industrial locations. The system that is being monitored consists of a collection of industrial cellular routers designed by Truteq.

The energy services company currently maintains demand-side management projects that are distributed in seven of the nine national provinces. Wide-area wireless communications are used to facilitate real-time data transfer and remote troubleshooting. In addition to the active demand-side management projects, the energy services company also maintains condition-based maintenance agreements with multiple industrial energy consumers.

Results from the developed system are detailed and discussed in Section 4 below. The results from the telemetry monitoring system are represented by area graphs with the scale on the right y-axis, while the results from the industrial information system are displayed by line graphs with the scale on the left y-axis. All results are time-based, so the x-axis is broken down into a time component.

4 RESULTS

This section presents various case studies to validate the impact of this system and to emphasise the value of the system in industry, which includes mining industries and various national key points such as water pumping schemes and power stations.

Three major real-world troubleshooting scenarios are presented to illustrate the troubleshooting procedure for root cause challenges. The first scenario focuses on the importance of constantly monitoring the status of line-of-sight communication to remote sites to determine the overall quality of the mobile network. The second scenario focuses on the monitoring of mobile network bandwidth, and the third scenario focuses on the monitoring of mobile network signal strength. The importance of these three parameters has been highlighted in the previous section.

All three mobile network characteristics are monitored by the proposed system, and are presented on the secondary vertical axis of each graph. A critical equipment measurement is represented on the primary vertical axis of each graph. Finally, all results are provided for a certain period, defined on the horizontal axis of each graph. It should be mentioned that the critical equipment measurement present in each graph represents a specific equipment characteristic, and can be viewed as correct for the purpose of this study.

4.1 Perspective 1: Troubleshooting network uplink challenges

Perspective 1 presents two case studies. These case studies aim to illustrate the value of the monitoring system on critical industrial systems that need constant monitoring. The first case study illustrates the effect of telemetry link downtime. The second case study illustrates how the telemetry monitoring system assisted maintenance personnel to conduct effective maintenance.

4.1.1 Case study A: Network communication failure

One key observation that needs to be made is the data loss that is present in Figure 3. Data loss occurred in two separate periods during which no accurate assessment could be made on the temperature levels of the pump unit. Scenarios like these require energy services companies (ESCos) to send out maintenance teams to investigate, troubleshoot, and restore system operation. This is a time-consuming task when the exact cause for data loss is not determined prior to arriving on site.

The status of the telemetry system between the ESCo and the industrial site on which the pump asset is situated is illustrated by the area chart in Figure 3. The graph shows the average active probing success rate of the telemetry uplink to the remote industrial site for the month during which data-loss was experienced. A clear drop in the communication uplink can be seen at two separate places. This resulted in a failure to relay real-time data to the information system. However, the communication link to the remote site was restored, which allowed for the successful transmission and reception of real-time pump temperature levels.

The telemetry system was successful in determining the cause of data loss. This aided the maintenance team greatly, since the number of factors that could lead to data loss was reduced to the communication network alone. After the rectification of the communication network downtime, real-time data transfer resumed.

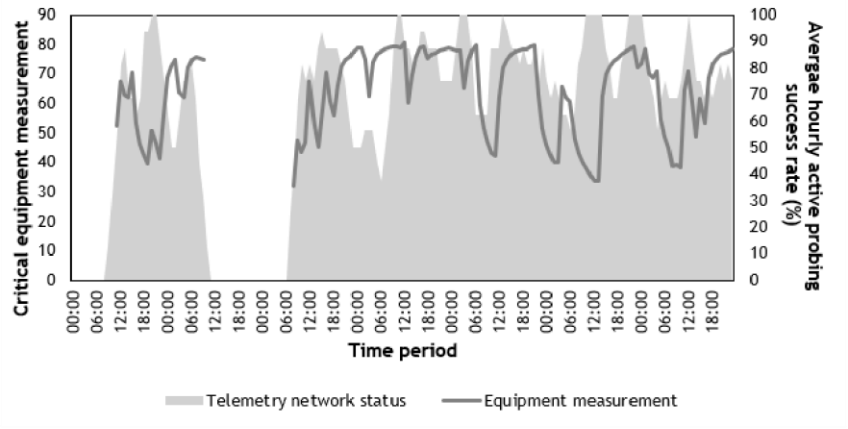


Figure 3: Chart that shows a critical equipment measurement, as well as the status of the telemetry system

4.1.2 Case study B: Stable communication network

Figure 4 shows a period when all temperature levels dropped to zero. This prompted an investigation to determine whether real-time data transmission from the site was operational or not. The monitoring data from the telemetry monitoring system indicated that real-time data transmission from the site was indeed active and operational. The status of the telemetry uplink between the ESCo and the remote industrial site is again illustrated by the area chart in Figure 4.

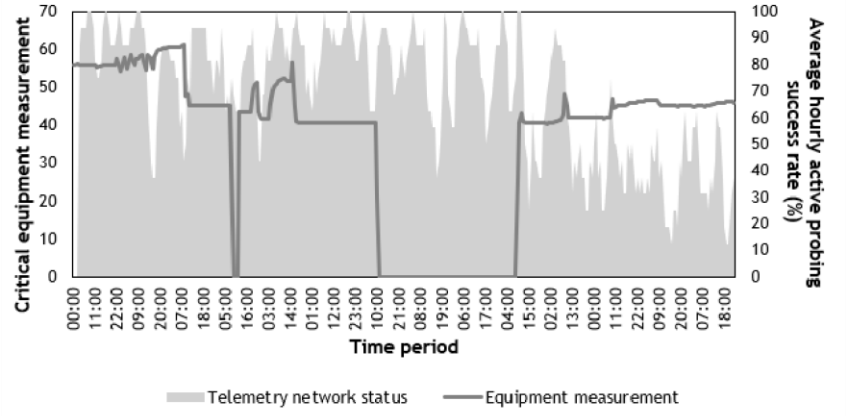


Figure 4: Chart that shows a critical equipment measurement

Since a stable communication uplink was present between the ESCo and the remote industrial site (represented by the area chart), it was possible to connect remotely to the energy management server on site. On connecting, it was established that the open platform communication (OPC) server was offline. The OPC server allows for direct communication between the on-site energy management system and the industrial supervisory control and data acquisition (SCADA) platform of the energy consumer. After the issue had been rectified, real-time temperature levels returned to normal operating levels.

One final observation is the decline in the quality of the telemetry network uplink in the final section of the graph. The network is stable enough to allow for remote maintenance to be conducted, as well as to facilitate successful transmission of efficiency parameters. However, the decline in the quality does signal that network downtime can be expected, and proactive measures should, therefore, be implemented to prevent any network downtime. The results illustrated in Figure 4, therefore, illustrate the proactive maintenance component that the system introduces into an existing IIoT ecosystem.

4.2 Perspective 2: Troubleshooting network bandwidth usage

Excessive data usage was reported on multiple systems that formed part of the maintenance agreements. The data usage is due to the volume of data transferred from the site to the information system. The telemetry monitoring system uses minimal data for network probing purposes. Two case studies are presented. The first case study illustrates a loss in component data, but with stable data usage. The second case study illustrates the effect of excessive data usage that resulted in a data limit being reached. Once the limit was reached, all communication to the site was lost and no data could be received. In the event of a data limit being reached, the mobile service provider requires the client to purchase additional data bundles to re-enable communication. This results in additional network costs and the operational downtime of industrial information systems.

4.2.1 Case study C: Stable bandwidth usage

Figure 5 below shows a clear discontinuity in the temperature data for the pump component. The hourly mobile data information obtained by the telemetry monitoring system showed that sufficient data was present to allow for real-time data transmission (represented by the area chart). This prompted an investigation into the cause of data loss, which was found to be system downtime. Unresponsive software was restarted, and a server reboot was required to resolve the issue. The telemetry monitoring system parameters, specifically the data level, indicated that the issue was located on-site.

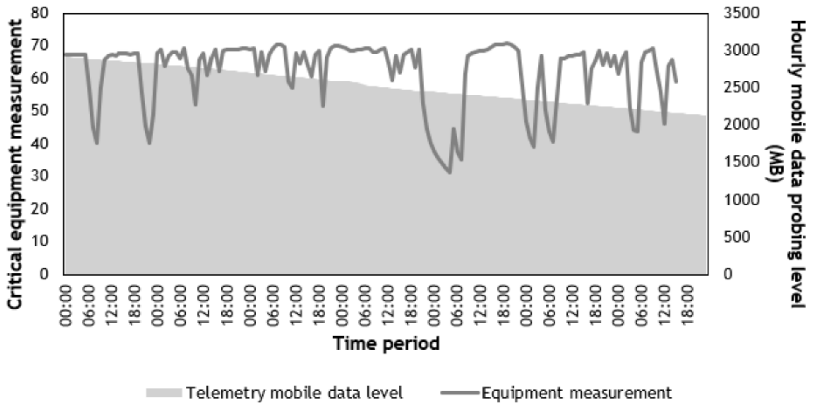


Figure 5: Chart that shows a critical equipment measurement, as well as the status of the mobile data level

After rectifying the issue, data transmission resumed. By monitoring the data level, additional insight was obtained into the status of the communication network. This, in turn, assisted with effective diagnostics and troubleshooting. Depletion of a data bundle results in communication downtime, as can be seen in the next case study.

4.2.2 Case study D: Bandwidth depletion

Data loss is once again present in Figure 6 (represented by the line chart). One key observation is that the actual data level of the communication network was depleted at a significant rate (represented by the area chart). Real-time data transmission and remote monitoring and maintenance procedures are impossible once a data bundle has been depleted. To rectify the issue, an additional data bundle must be manually loaded. Loading a data bundle can take several hours to reflect on the system, which results in a temporary dead time, during which no data transmission is possible. The telemetry monitoring system can proactively prevent dead times by constantly monitoring the data usage of a remote end-point.

Excessive data consumption has various causes. The first and most common cause for excessive consumption is negligence on the part of maintenance personnel. The communication uplink to sites is also used to allow for remote desktop sessions so that maintenance personnel can perform routine maintenance and inspections remotely. Remote desktop sessions are resource-intensive, and should only be executed on a fixed schedule or when the need arises. Failure to close a remote session is common; and this increases the load on the telemetry data bundle pool. Furthermore, several industrial sites serve as national key points, which means that connections are not allowed to be blocked. If bandwidth is depleted for a national key point, communication must be allowed to continue at out-of-bundle data rates, since a blocked connection would result in communication downtime.

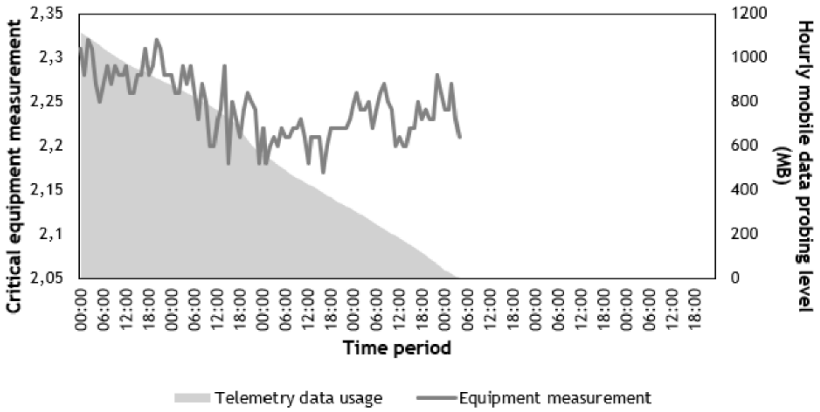


Figure 6: Chart that shows a critical equipment measurement, as well as the status of the mobile data level

A second cause of excessive data consumption is the continuous retransmission of raw data from the site, as well as the excessive manual transfer of raw data files. The manual transmission of raw data files must be kept to a minimum, as they are large. An email client is used to transmit raw data from site to the storage and processing facility. The continuous retransmission of data, or transmission looping, occurs when a dataset is retransmitted over the network, even when the previous transmission was successful. Retransmission should occur only when the previous data transmission has failed. Transmission looping usually occurs when the email client fails to delete on-site data from the transmission directory. Additional software abnormalities, such as irregular data logging on the data server itself, can also result in data retransmission.

The causes of excessive data consumption form part of the troubleshooting and diagnostics process of the dedicated maintenance teams. The telemetry monitoring system assists the maintenance team by providing a reference point from which troubleshooting can be done.

4.3 Perspective 3: Troubleshooting network signal strength degradation

Signal strength levels play a vital role in sustaining maintenance agreement effectiveness. One case study is presented below. It illustrates the effect of weak signal strength on the real-time monitoring capabilities for maintenance agreement purposes.

4.3.1 Case study E: Network equipment failure

Figure 7 shows a clear drop in the quality of the network signal strength (represented by the area chart). This drop results in data loss (represented by the line chart). A variety of factors, such as electromagnetic interference and limited network coverage, can influence the signal strength of wide-area wireless communications. To compensate for the gaps in network coverage, a detailed coverage investigation must first be done to determine the state of the network coverage. This information must then be used to determine a suitable location for the installation of an energy management system and the supporting infrastructure.

The decline in the signal strength shown in Figure 7 was a result of infrastructure being moved to a different on-site location. The new location experienced periodic dead times in network coverage, which resulted in occasional dead times during which no data transmission was possible. The telemetry monitoring system assisted with diagnostics and troubleshooting, and the issue was rectified by moving the installed infrastructure to a new position.

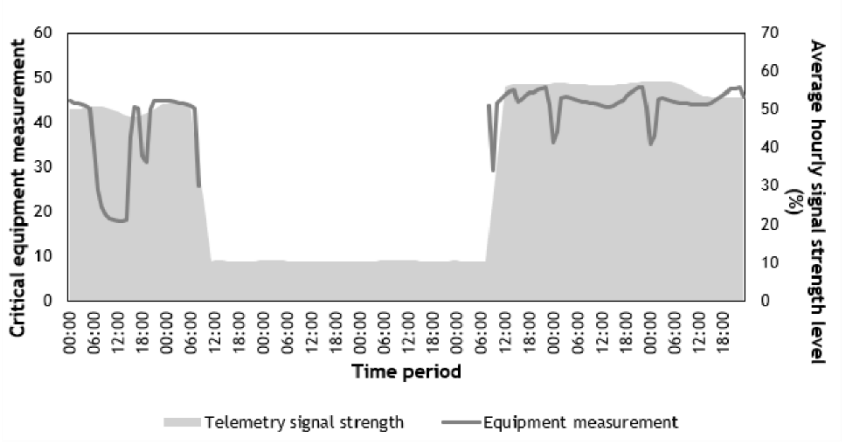


Figure 7: Chart that shows a critical equipment measurement, as well as the status of the telemetry signal strength

5 DISCUSSION

With industry still using the existing infrastructure to achieve real-time communication and data transmission via the cellular network, there was a need to develop a telemetry monitoring system that actively monitored the status of the communication network. Since the network could not be controlled, quality of service issues could not be directly addressed. An external monitoring system was therefore required that provided insight into the status of the cellular network. By doing so, a detailed troubleshooting methodology could be developed and used in the event of communication disruptions.

The telemetry monitoring system succeeded in providing accurate insight into the status of the mobile communication networks used by remote industrial sites, by monitoring overall network quality, network bandwidth, and network signal strength. However, there is scope for future work and improvements. The telemetry monitoring system is currently isolated from the existing energy management ecosystem. Although actual results are combined to give a more causal representation of information system data loss, the system is physically separated from other information systems. There is a need to combine the telemetry monitoring system with existing information systems, such as energy management information systems and condition-based maintenance systems.

The inclusion of telemetry status parameters in reports that can then be sent to industrial consumers is also considered to be an appropriate expansion to the current solution. By including the results of the telemetry monitoring system in the automatic report generation structure, detailed insight can be obtained into the overall health of the energy management ecosystem. This will also promote information awareness and increase the ability to perform proactive maintenance.

Several existing systems in the literature have been presented and discussed in Section 1 of this paper [13-15, 19, 21]. The review of existing industrial information system applications in Section 2 showed that industrial information systems do not include monitoring routines for the status and quality of wide-area wireless telemetry networks. It is believed that the telemetry monitoring system proposed in this paper would greatly strengthen these systems.

The implementation of a telemetry monitoring system ensures that the full potential of industrial information systems can be achieved. By monitoring the status of the telemetry between an energy services company and remote industrial sites, the overall quality of service can be improved and sustained. The proposed system also implements a novel approach of combining telemetry monitoring data with industrial information system data. By doing so, accurate and effective troubleshooting can be done to determine the cause of potential data loss in industrial information systems.

Real-time data transmission, processingm and display are crucial factors in condition-based maintenance systems and energy management information systems. The proposed system ensures that these factors are maintained to ensure smooth operation. Effective maintenance strategies and the need-to-know are also

considered to be crucial factors in energy savings initiatives. The proposed system could assist in this to maintain energy management system stability.

6 CONCLUSION

The performance of integrated demand-side management projects and other maintenance strategies can be greatly affected by an unstable telemetry uplink between an energy services company and a remote industrial site. An investigation into the state of the art of Industry 4.0 applications showed that Industrial IoT applications rely on a stable telemetry uplink, but do not monitor the uplink itself. This implies that current IIoT systems can be unreliable if the quality of the communication network degrades.

This paper emphasised the value of a stand-alone telemetry monitoring system that can independently monitor the status and quality of a mobile communication network. The proposed system was developed and implemented on the existing telemetry network of a South African energy services company. Around 80 sites, each with a fully functional energy management system on-site, were incorporated into the scope of the monitoring system. This allowed for more than a thousand individual industrial assets to be monitored and maintained.

The results demonstrate the value of this system. Positive impacts were made on equipment monitoring in the heavy industry sector. The system is generic and can, therefore, be applied to any IIoT ecosystem where mobile communication networks are used for real-time data transmission. The results show that the proposed system can enhance the robustness of existing IIoT infrastructure; and this promotes the adoption of Industry 4.0 concepts in the heavy industry sector.

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APPENDIX E: CONFERENCE PAPER



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AN INFORMATION SYSTEMS APPROACH TO THE PROACTIVE MANAGEMENT OF SUBSCRIBER IDENTIFICATION MODULES IN INDUSTRY

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ABSTRACT

The Industry 4.0 paradigm focuses heavily on decentralisation, modularity and interoperability. These principles form the foundation for an effective Industry 4.0 ecosystem. The South African heavy industry still relies heavily on the traditional approach to centralised monitoring and control. Various Industry 4.0 initiatives have however been proposed and implemented in the heavy industry sector. For these initiatives to operate effectively, a stable network layer is required to facilitate reliable data transfer. To achieve data transfer over large geographical distances, most industrial information systems make use of mobile cellular networks, which implies the use of subscriber identification modules (SIMs) and supporting hardware such as network routers. The mismanagement of SIM cards can however result in excessive communication costs, which can in turn hamper the effectiveness of wireless data transmission. This paper presents a comprehensive information and asset management system to assist with overall SIM card management. The system allows for the accurate analysis of communication costs and ensures transparency both in the financial domain and in the physical domain. Results in this paper illustrate the effectiveness of this system in isolating communication anomalies that result in excessive data costs. The results show that the system can improve the quality and reliability of wide-area wireless telemetry and maintain indirect expenses that are associated with industrial information system communications. The proposed system assisted in reducing overall wide-area wireless communication cost with approximately 62%.

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1. INTRODUCTION

The term Industry 4.0 is a relatively new concept that is still considered to be in its infancy. Industry 4.0, initiated by the German government and presented at the Hannover Trade Fair in 2011, aims to address growth challenges in the European manufacturing sector [1]. The primary objective of the Industry 4.0 paradigm is to promote digitisation and integrate technological collaboration between various industrial systems [2]. For Industry 4.0 initiatives to be successful, various principles such as decentralisation, real-time production, modularity and interoperability need to be integrated into traditional methods of production [3].

The South African heavy industry, such as the mining and steel industry, still makes use of traditional centralised approaches to monitoring and control of production and assets [4]. This makes a full shift to decentralised and autonomous monitoring and control infeasible since the infrastructure to support Industry 4.0 initiatives must still be incorporated into the current industrial architecture. Various Industry 4.0-related initiatives and methodologies have however been proposed and implemented in the South African heavy industry. These initiatives mostly focus on indirect support and service delivery and includes condition-based maintenance systems, energy management information systems, automated bill analysis systems and remote monitoring and maintenance systems [5–8].

A fundamental component required to facilitate Industry 4.0 is the “Internet of Things” (IoT) to achieve its main goals [9]. The interconnection of individual devices allows for the transmission and reception of data. Data gathered by individual devices can then be used for intelligent decision-making purposes. This layer of intelligence, realised by IoT, allows devices to operate collectively in order to achieve predefined goals [10].

The fundamental component to the systems mentioned above is the communication network used to relay raw data from industrial sites to decentralised storage and computing infrastructure. To achieve data transmission, these systems make use of wide-area wireless telemetry networks, such as mobile cellular networks [11]. To utilise mobile cellular networks for data transmission and reception, subscriber identification modules (SIMs), as well as related hardware systems such as network routers, must be implemented at each remote industrial endpoint [12]. Mismanagement of these modules can result in additional expenditures and network instability, which in turn can effectively hamper the quality and reliability of Industrial IoT (IIoT) information systems discussed above.

Based on the context and challenges discussed above, the objective of this paper is to present and emphasise the value of an information and asset management system for SIM cards used by existing IIoT applications. To achieve this objective, the following sections will:

- present an architectural overview of industrial information systems in the context of the Industry 4.0 domain;
- discuss key challenges that can hamper the network layer quality and stability of industrial information systems;
- introduce a comprehensive information and asset management system to address SIM management; and
- analyse results of the information and asset management system to emphasise its value in industry.

2. AN OVERVIEW OF INDUSTRIAL INFORMATION SYSTEMS

This section aims to introduce an architectural overview of industrial information systems. A generic description of industrial information systems is first presented, after which two information system examples are provided to highlight critical points in the overall operation of these systems.

Industrial information systems typically follow an input-output service delivery model. For these systems to provide valuable feedback for decision-making purposes, data must first be provided from various sources. Raw data is then stored and processed in a decentralised storage and computing environment, after which information is relayed to visual dashboards for user notification purposes. Figure 1 gives an overview of the operation of an industrial information system.

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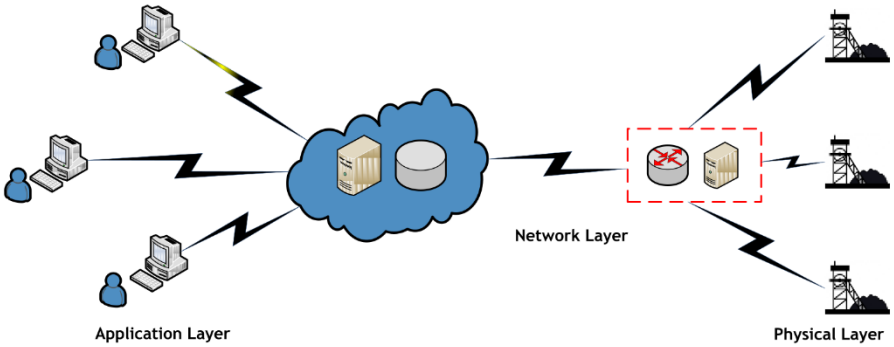


Figure 1: An overview of an industrial information system.

An industrial information system can be divided into three main parts namely, the physical layer, the network layer and the application layer. The collection of raw data takes place in the physical layer. Various sensors and actuators can be used to perform this task, but it is also possible to make use of an existing industrial supervisory control and data acquisition (SCADA) system to collect data.

The data obtained from industrial endpoints must then be transmitted to a decentralised storage scheme for data processing and storage. Cloud-based systems are used to allow for decentralised accessibility. Wide-area wireless communications, such as the Global System for Mobile communication (GSM), is used to transmit data to the cloud-based facility. This requires industrial GSM routers to be installed at industrial endpoints. Each router must also be fitted with a SIM card for connection to a mobile service provider network. Various works in literature emphasise the importance of wide-area wireless communications in IoT applications [11, 13–16]. Without a stable network layer, industrial information systems will be rendered inoperable.

Processed data can be relayed to users at the application layer. From here, system statuses can be viewed and informed decisions can be made. The decentralised nature of the storage and processing subsystem allows users to gain access without being restricted to certain geographical locations. All users are provided with system credentials for security purposes. Figure 1 illustrates a basic overview of a typical industrial information system. Two examples of existing systems in industry are provided below. An architectural overview of each system is given. Limitations and benefits of each system are also presented.

2.1 Example A: An Energy Management Information System (EMIS)

Goosen et al. [7] proposed a comprehensive energy management information system with the objective of providing industry with the ability to comply with various energy management standards, legislation and incentive structures. The system facilitates data collection and storage processes, as well as data analysis methods to provide users with accurate energy reports. Input data is provided to the system from external metering parties, the state-owned electricity utility Eskom, as well as direct input from industrial SCADA systems. Accurate energy reports are then provided as output. The energy reports can be viewed in document format, or the data can be viewed on real-time electronic dashboards. Figure 2 below gives an operational overview of the EMIS.

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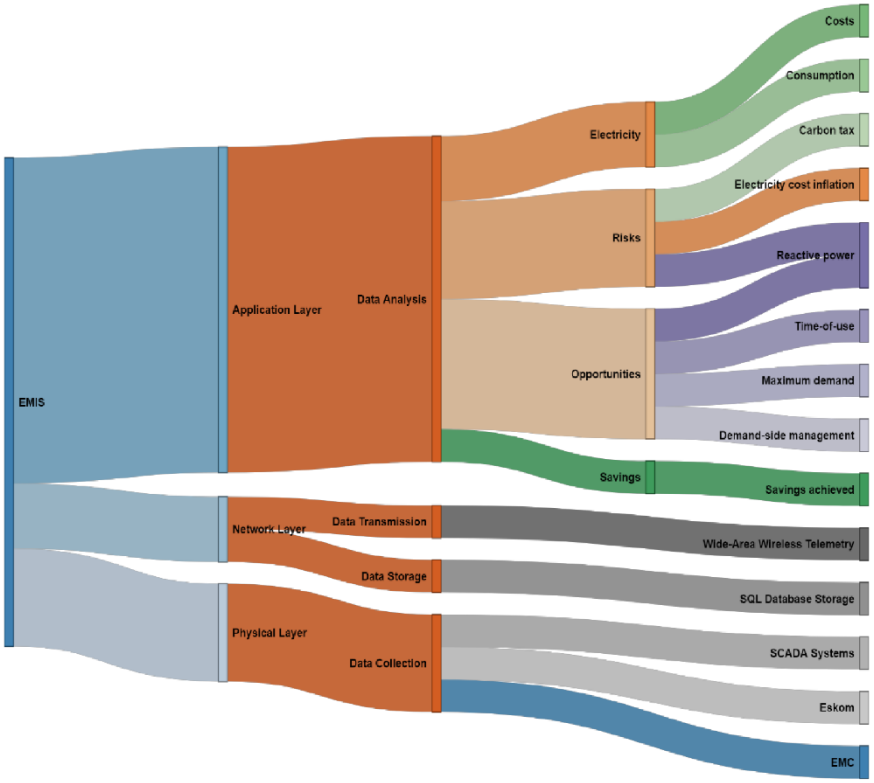


Figure 2: An operational overview of an EMIS (adapted from [7]).

The system proposed by Goosen et al. [7] provides an efficient and time effective way of allowing energy consumers to track their energy consumption and compare it to historic profiles. This system promotes decentralisation and is easily expandable. Goosen further expanded this system by incorporating an automated process where electricity bills are analysed [6]. This further improved the robustness of the EMIS and provided energy consumers with valuable information. The EMIS relies heavily on the GSM network for data transfer. Should intermittent connectivity issues present themselves, the EMIS will effectively be offline. The quality and stability of wide-area wireless communications is therefore considered to be a critical component to the effective operation of this system.

2.2 Example B: A condition-based maintenance system

Van Jaarsveld et al. [8] proposed a condition-based maintenance system with the objective of providing industry with the ability to accurately determine in real-time fashion the status of vital assets, such as pumps, compressors and fridge plant units. This system follows a similar approach to that of the EMIS proposed by Goosen et al. Only one source of input is used, which is the industrial SCADA system. Various status and efficiency parameters are monitored, such as vibration characteristics, temperature levels and trip counters. Data is transmitted in real-time fashion to a decentralised processing and storage unit, after which the processed data is relayed to visual dashboards. The transmitted data is processed for exception reporting, as well as “Safe, Caution, Risk, Failure” (SCRF) assessments. Figure 3 below provides an operational overview of the condition-based maintenance system.

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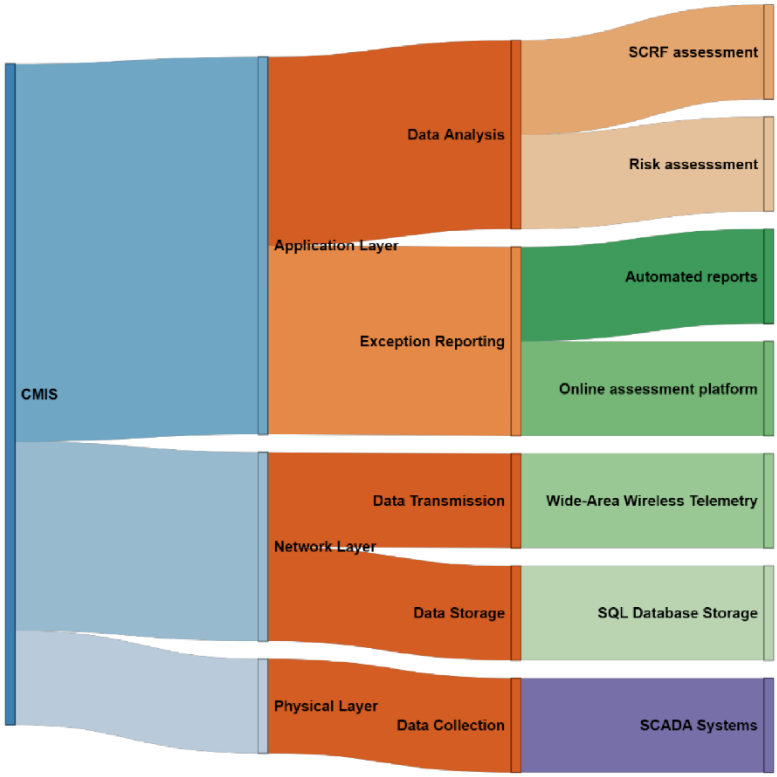


Figure 3: An operational overview of a condition-based maintenance system (adapted from [8]).

The system proposed by van Jaarsveld et al. [8] provides a unique and effective way of allowing industry players to know the operational status of critical assets. This improves maintenance processes and prevents unnecessary capital expenditures. As with the EMIS discussed above, this condition-based maintenance system also relies heavily on the GSM network for data transfer. Intermittent connectivity will hamper the effectiveness and reliability of this system. Emphasis must therefore be placed on the quality and reliability of the network layer.

2.3 Summary

This section aimed to provide an overview of industrial information systems. An industrial information system consists of three layers: the application layer, the network layer and the physical layer. The use of the GSM network and Internet Protocol technologies for Machine-to-Machine (M2M) communication and industrial wireless telemetry is a broadly accepted method for achieving connectivity and can therefore be considered as a key enabler for Industry 4.0 applications [10, 17-19]. Two examples of industrial information systems were presented. Both systems utilise the GSM network for wide-area wireless telemetry. The network layer is the backbone of an industrial information system. The quality and reliability of the network layer is therefore crucial for industrial information system stability. Based on the information discussed above, there is a need for a comprehensive information and asset management system that ensures transparency in the management of SIM units and other related network layer equipment. This system must ensure the stability in network layer communication and keep communication costs at a minimum.

3. CHALLENGES THAT DISRUPT DATA TRANSMISSION

Several challenges exist that inhibits the ability of industrial information systems to relay critical data in a real-time fashion. Mismanagement of SIM cards, the mismanagement of GSM routers on site and general hardware failures are among the few challenges that can result in intermittent connectivity. These challenges are discussed below and examples are provided.

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3.1 Hardware failure

The most common challenge present in the network layer of industrial information systems is hardware failures. Industrial GSM routers are required to facilitate data transmission from site to cloud infrastructure. No transmission is possible if hardware failure occurs. Examples of router hardware failure include on board electronic failures, as well as power supply failures. In both cases, the router must be retrieved from the industrial site and a new router must be requisitioned to replace the defective unit. Replacing a router results in communication downtime, which is unacceptable in the context of mission-critical information systems. Hardware failure occurrences is however inevitable and proactive measures must be implemented to prevent interruptions in data transmission. A solution would be to incorporate network layer redundancy where more than one router is utilised for data transmission purposes. This however has cost implications, both on the hardware side as well as on the bandwidth side.

3.2 SIM card mismanagement

The mismanagement of SIM cards is also a key concern that can hamper network layer stability. For industrial GSM routers to relay data, they must be connected to the backbone network of a mobile service provider. As discussed in Section 2, SIM cards are used to facilitate this uplink. The mismanagement of these modules can result in additional expenses, either in the form of new mobile broadband contracts that need to be acquired, or purchasing of additional data bundles for existing mobile broadband contracts. Mismanagement can also lead to potential theft of both routers and SIM cards. It is therefore required to accurately monitor monthly data contract bills on a consistent basis. Monthly expenses must be analysed to determine the current state of individual modules. The bills must then be compared to the operational status of router units to determine whether these modules are crucial to information system operations or an unnecessary expense.

3.3 Router mismanagement

Router mismanagement often occurs with the repositioning of equipment. One of the prominent parameters that can directly be affected by router repositioning is network signal strength. A low signal strength results in intermittent connectivity. Remote industrial locations often have weak spots in the wireless network. It is therefore crucial to first perform an investigation to determine the optimal positions where GSM routers will have maximum signal strength. Interference on site can also hamper the signal strength of a GSM network router. This should be considered when determining the best location for network equipment. To ensure that no defective router is provided to an industrial site, accurate asset management procedures must be implemented that provide details of the status of all equipment. Router theft is also a key concern that can disable the network layer of an industrial information system. GSM routers must always be installed in locations with restricted access and these locations should be recorded for future reference.

3.4 Summary

This section presented several challenges that can disrupt the transmission of data in an industrial information system. Table 1 below summarises the main causes and provides examples that are related to the listed challenges.

Table 1: A summary of the challenges that can disrupt data transmission in an industrial information system.

Challenges that disrupt data transmission	
Challenges	***Examples from industry***
Hardware failure	• Power supply failure • On board electronic failure • Antenna failure
SIM card mismanagement	• Theft • Failure to analyse costs and budgets
Router mismanagement	• Repositioning of routers • Issuing of defective routers • Theft

4. A COMPREHENSIVE INFORMATION AND ASSET MANAGEMENT SYSTEM

Based on the sections above, a comprehensive information and asset management system is required that facilitates the effective management of SIM cards in industry. The information and asset management system can be divided into two main functional blocks. The general management block serves to link various SIM cards to industrial sites or personnel. The module management block identifies individual SIM units and serves to

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provide cost and administrator details of individual SIM cards. This allows for a cost and budget analysis to be conducted. The following sections describe each functional block in detail.

4.1 Module management

The module management subsystem focuses primarily on providing accurate cost analysis functionalities based on the provided input data. Figure 4 gives an overview of the module subsystem.

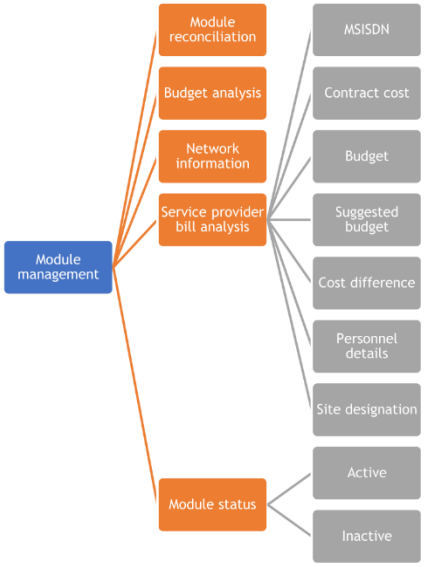


Figure 4: An overview of the module management subsystem.

For the subsystem to provide accurate cost analysis results, data contract invoices, as well as mobile service provider summary sheets must be provided as input on a monthly basis. In addition to cost analysis functionalities, the module management subsystem includes a module reconciliation section that reconciliates individual SIM cards with the corresponding module IP address. The system uses the mobile service provider summary sheet to update all MSISDN numbers with the corresponding IP address. The module reconciliation section will relay all mismatches to the user. The module management subsystem also displays network information for all SIM cards. This information includes the mobile service provider name, the contract type, and the network IP address that is linked to the module.

The cost analysis functionality relies on a separate service provider bill analysis section. The service provider bill analysis section uses the data contract invoices as input and extracts the module MSISDN number and the monthly expense for that module. This data is then compared to a suggested budget. From this comparison, a cost difference can be calculated to determine the usage condition of the module. If the module cost exceeds the suggested budget, the module is flagged as a negative expense and further investigation must be done to determine the nature and possible reason for exceeding the budget. In most cases, the sending of short message system (SMS) messages is the reason for exceeding stipulated budget values. Industrial information systems usually issue alarms via SMS to relevant personnel. Since data contracts do not cover SMS costs, an additional value is levied on the monthly contract amount.

4.2 General management

The main objective of the general management subsystem is to link a SIM card to a user. Figure 5 gives an overview of the module subsystem.

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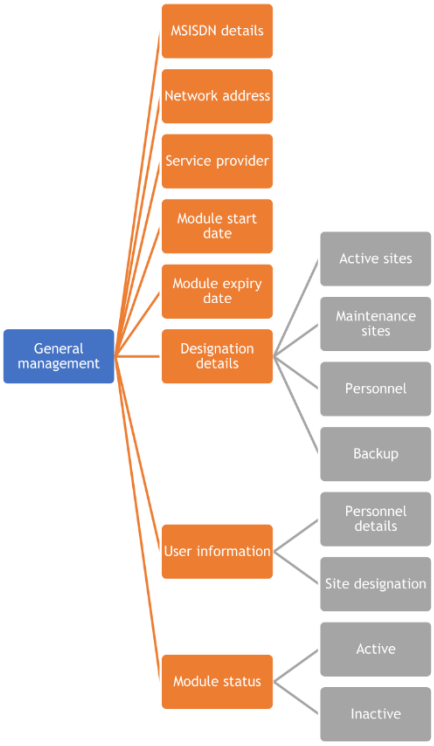


Figure 5: An overview of the general management subsystem.

The user can either be personnel or an industrial site. Personnel often require SIM cards for remote monitoring and maintenance of site equipment and systems. A SIM card with a designated IP address allows a project engineer to securely access on-site servers from a remote location. Modules that are allocated to industrial sites are utilised for data transmission purposes and forms an integral part of the network layer of industrial information systems. The general management subsystem lists module details such as the MSISDN number, the network address, the mobile service provider and the module activation and expiry date.

In addition to the information listed above, the general management subsystem also links group information to SIM cards. The purpose of the group information is to accurately indicate where the module is in use. The options that are available include active sites (sites where industrial information systems are currently active), maintenance sites, personnel and backup. Maintenance sites usually require modules to assist with remote monitoring and maintenance purposes. The general management subsystem also contains user information. If a module is labelled as a personnel module, the user information section will contain the personal details of the user, usually the name and surname, of the user. If the module is labelled as a site module, either an active site or a maintenance site, the site designation is provided. The site designation includes the industrial client group name, as well as the area of operations. Finally, the module is labelled as active or inactive. All modules issued either to personnel or to industrial sites must be in an active state.

The information and asset management system presented in this section allows for the effective management of SIM cards. The primary benefit of this system is the automated cost analysis functionality. Results of this functionality is presented below.

5. RESULTS

The information and asset management system presented in Section 4 above has been implemented on an existing telemetry network that sustains the network layer of multiple industrial information systems. These information systems are actively used by industrial client groups in the Republic of South Africa. The results presented below in Figures 6 to 9 are cost analysis results based on monthly data contract costs. An Energy

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Services Company (ESCo) is responsible for maintaining the communication uplink to the different industrial client groups.

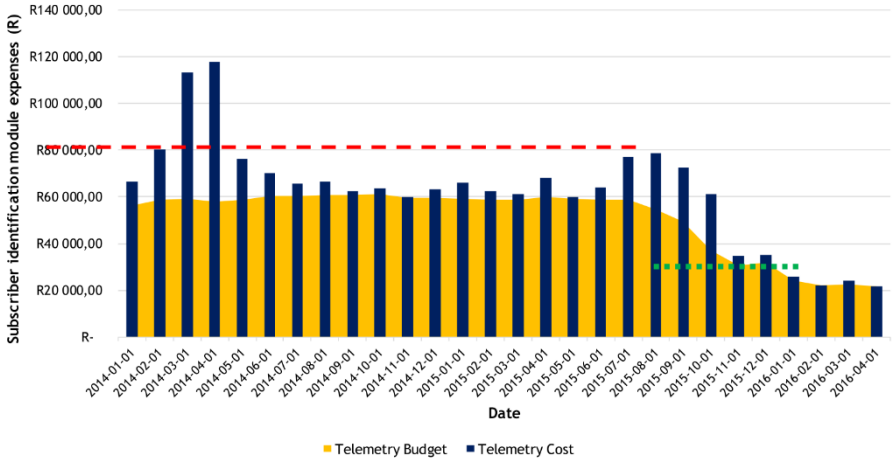


Figure 6: A cost analysis of existing SIM cards in circulation for information system operations.

Figure 6 represents a global cost analysis in South African Rand of sustaining telemetry uplinks to multiple industrial client groups. The actual cost per month is shown by the bar chart and the budgeted value is shown by the area chart. Multiple crossover points can be seen, where the total cost for the month exceeded the budgeted amount. This is because multiple SIM cards exceeded their monthly data limit. This resulted in out-of-bundle data rates coming into effect, which further increased the communication costs for the applicable months. The information and asset management system also assisted in the identification of SIM units on industrial sites that do not require any monitoring and maintenance. These SIM units were marked for decommissioning, which led to the decrease in the overall telemetry cost illustrated in Figure 6. The dashed line represents the average communication costs which equates to an amount of R71,698.93. After decommissioning unused and unnecessary cards, the average communication cost dropped to an average amount of R27,287.48, which is illustrated by the dotted line. This signifies a decrease in overall communication cost of approximately 62%.

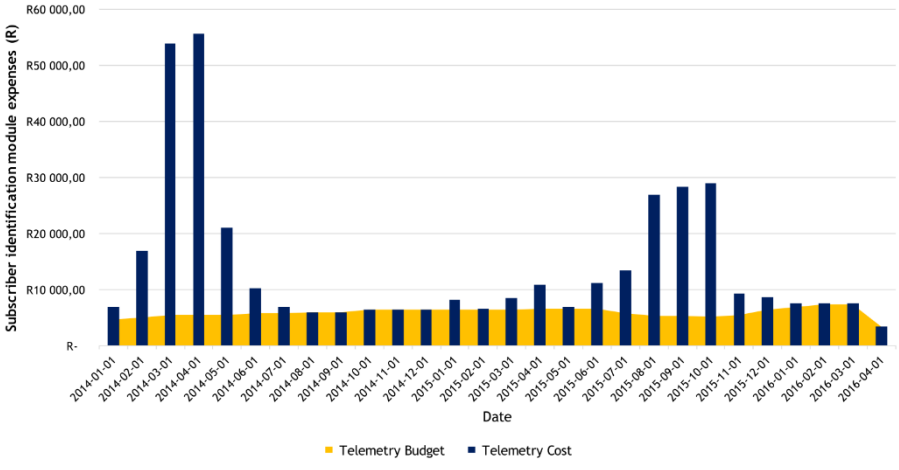


Figure 7: A cost analysis of SIM cards in circulation for a specific pumping scheme.

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Figure 7 shows a specific cost analysis that was applied to a single industrial client group that was responsible for the operation of a water pumping scheme. The SIM cards utilised for sustaining the telemetry of the pumping scheme project exceeded the budgeted amount. The information and asset management system effectively allowed the ESCo to isolate the cause for excessive data bundle expenses seen in Figure 6. An individual cost analysis of the water pumping scheme telemetry network isolated the water pumping scheme network as the main cause for going over-budget. An investigation was launched by the ESCo to determine the exact cause for excessive data usage in both instances and the issues were rectified.

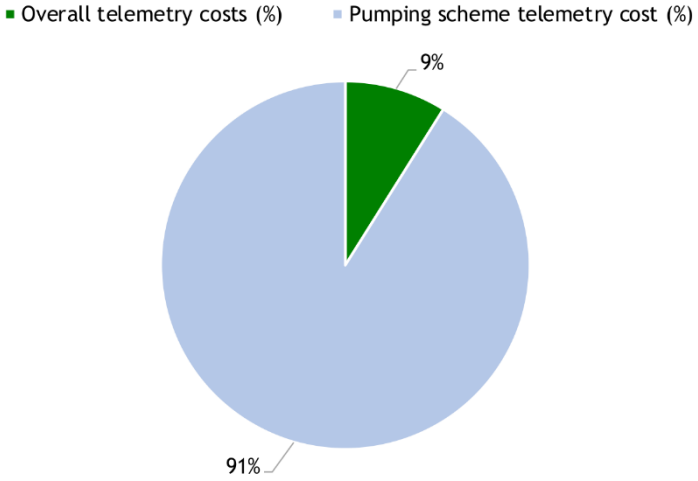


Figure 8: A cost comparison between overall telemetry costs and the telemetry cost of a pumping scheme network with exceptional data usage.

The proposed information and asset management system also allows for weight analyses to be done on different industrial client groups. Figure 8 illustrates the total weight of the water pumping scheme during the excessive data usage periods. The cost of maintaining the water pumping scheme telemetry network clearly outweighs the combined cost of other industrial client groups. This analysis can be used as a risk metric to determine the status of the telemetry network of a specific industrial client group. By doing a weighted analysis, excessive data usage can be highlighted and pinpointed to an industrial client. Investigations can then be initiated to determine the cause of excessive usage.

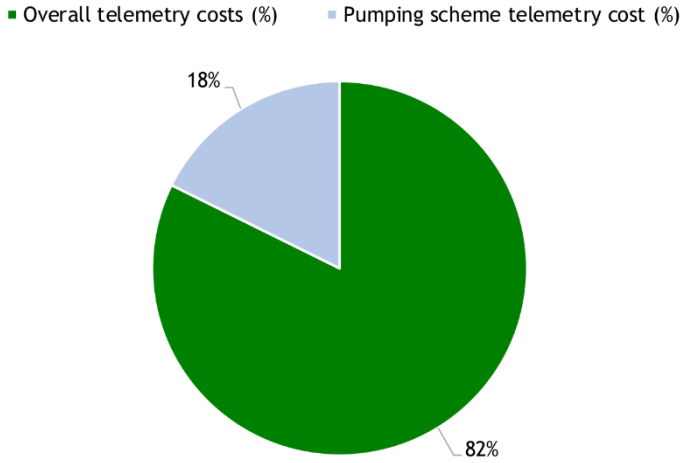


Figure 9: A cost comparison between overall telemetry costs and the telemetry cost of a pumping scheme network with normal data usage.

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Figure 9 illustrates the same detailed cost analysis represented by Figure 8 however, this cost analysis was executed in a period where normal data usage was present. The total cost to maintain the telemetry network for the water pumping scheme is a mere 18% compared to the combined telemetry costs of all industrial client groups. This confirms that the telemetry uplink for a specific client is operating within acceptable budget parameters.

6. DISCUSSION OF RESULTS

A review of existing systems from literature and industry shows that there is a need for a comprehensive information and asset management system to address the management of SIM cards in industry. This system forms an integral part of the network layer of any Industry 4.0 information system that utilises the GSM network for real-time wireless data transfer. The information and asset management system proposed in this paper allowed for accurate cost analyses to be executed on SIM contracts. The system automatically generates these profiles based on billing invoices provided as input. The results presented in the previous section clearly shows the value of the system. The automated cost analyses can provide valuable insight into the health of the network layer and it can identify communication anomalies that has a direct effect on the cost of maintaining a wide-area wireless telemetry uplink.

The system proposed in this paper will ensure that industrial information systems, such as remote monitoring and maintenance systems proposed by Yang et al. [20] and condition-based maintenance systems as proposed by Van Jaarsveld et al. [8] will always be able to maintain real-time communication, whilst keeping communication costs at a minimum. In addition to the pumping scheme case study presented in the previous section, the system also identified SIM cards that were subject to theft. Module theft is usually flagged by excessive data costs. One investigation showed that a module linked to a router that was not operational still showed excessive data costs. An on-site investigation revealed that an unauthorised SIM swap was done with the replacement SIM being defective. The system proposed in this paper approaches network layer maintenance and stability from a cost and budget point of view. Not only does this improve the quality and reliability of wide-area wireless telemetry, but it also maintains indirect expenses that are associated with industrial information system communications.

The system is currently implemented as a standalone desktop system. This implies that the system can only be used locally. To increase operational and management efficiency, this system must be incorporated into existing information systems. An example would be to incorporate this system into the EMIS proposed by Goosen et al. [7]. This would not only allow industrial client groups to view telemetry cost analyses online, but it will also allow for the incorporation of these cost analyses into generated reports. This integration will expand the reach of the system and will allow clients to take responsibility of the communication costs.

7. CONCLUSION

The network layer is the backbone of any industrial information system. In the context of Industry 4.0, most information systems rely on wide-area wireless telemetry to achieve data transmission and decentralised storage and processing of data. The GSM network is currently an acceptable method to achieve this. Challenges are however present that can hamper the effectiveness of industrial information systems. These challenges include the mismanagement of hardware devices, mismanagement of SIM cards and hardware failures.

This paper presented an information systems approach to the management of SIM cards utilised in industry. The system consists of two main foundational blocks which allows for automated cost analyses to be calculated. Cost analyses contain actual expenses as well as budgeted values, which allows for budget comparisons to be made. Weighted analyses are also possible which assists in determining exceptions where communication anomalies are present.

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APPENDIX F: JOURNAL GUIDELINES



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INSTRUCTIONS TO AUTHORS

- Scope and policy
- Form and preparation of manuscripts
- Manuscripts submission

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justification, should be used on B5 paper size. Header and footer layout 15 mm.
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9. References in the text should be by author with the reference number in square brackets e.g. Li[1]. The required reference format is illustrated below.
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11. Photographs must be supplied in TIFF or JPEG format at least 300 dpi for good quality reproduction.

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