NORTH-WEST UNIVERSITY

An improved error correction algorithm for multicasting over LTE networks

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Declaration

I, Johannes Mattheüs Cornelius, hereby declare that the dissertation entitled "***An improved error correction algorithm for multicasting over LTE networks***" is my own work and has not already been submitted to any other university or institution for examination.

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Signed on the 15th day of November 2013 at Potchefstroom

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I am humbled by the grace I have received.

Abstract

Multicasting in Long-Term Evolution (LTE) environments poses several challenges if it is to be reliably implemented. Neither retransmission schemes nor Forward Error Correction (FEC), the traditional error correction approaches, can be readily applied to this system of communication if bandwidth and resources are to be used efficiently. A large number of network parameters and topology variables can influence the cost of telecommunication in such a system. These need to be considered when selecting an appropriate error correction technique for a certain LTE multicast deployment. This dissertation develops a cost model to investigate the costs associated with over-the-air LTE multicasting when different error correction techniques are applied. The benefit of this simplified model is an easily implementable and fast method to evaluate the communications costs of different LTE multicast deployments with the application of error correction techniques.

Keywords: *Long-Term Evolution, MBSFN, multicasting, error correction*

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List of Abbreviations

3GPP	-	The 3rd Generation Partnership Project
4G	-	4th Generation Radio Technologies
ARQ	-	Automatic Repeat reQuest
CP	-	Control Plane
e-BM-SC	-	Evolved Broadcast Multicast Service Centre
e-MBMS	-	Evolved MBMS
e-NB	-	Evolved Node-B
e-UTRAN	-	Evolved Universal Terrestrial Radio Access Network
FEC	-	Forward error correction
GW	-	Gateway
HSDPA	-	High-Speed Downlink Packet Access
HSUPA	-	High-Speed Uplink Packet Access
IP	-	Internet Protocol
ISD	-	Inter-Site Distance
LTE	-	Long-Term Evolution
MBMS	-	Multimedia Broadcast Multicast Services
MBSFN	-	MBMS Single Frequency Network *OR* Multicast Broadcast Single Frequency Network
MCCH	-	Multicast Control Channel
MCE	-	Multicast Coordination Equipment
MIMO	-	Multiple-Input and Multiple-Output
MME	-	Mobility Management Entity
MTCH	-	Multicast Traffic Channel

OFDMA - Orthogonal Frequency-Division Multiple Access

SC-FDMA - Single-Carrier Frequency-Division Multiple Access

SFN - Single Frequency Network

SINR - Signal-to-Interference plus Noise Ratio

UE - User Equipment

UP - User Plane

VoIP - Voice over Internet Protocol

Chapter 1 – Introduction

1.1 Introduction

In this chapter we introduce the research problem and domain by providing the theoretical background leading to our hypothesis. A specific problem statement is derived from this background, providing motivation for the research done. This is summarised into a hypothesis, which is used throughout the document as a framework to evaluate the adherence of the research to its objectives. The chapter also includes a justification for the study. Research goals are stated, followed by an elaboration on the research methodology used. This chapter ends with a structural overview of the full dissertation.

1.2 Background

Long-Term Evolution (LTE) is the 3^{rd} Generation Partnership Project's (3GPP's) answer to achieving the realisation of 4^{th} Generation (4G) radio technologies. It greatly improves the speed, throughputs and capacity of mobile networks over its predecessors. Importantly for this study, multicast communication has been supported from the first release of LTE specifications in the form of a Single Frequency Network (SFN) [1]. This method of communication, when applied appropriately, significantly increases bandwidth efficiency and decreases processing overhead. Multicasting is particularly suitable for the delivery of multimedia content to a destination group of mobile receivers. The 3GPP describes a multi-cell transmission service to implement multicast technology in LTE, termed the Multimedia Broadcast Single Frequency Network (MBSFN). This is envisioned to be employed on a large scale to support multimedia distribution over cellular networks [1], [2].

One aim of multicasting is to provide reliable, error-free transmission of data. To achieve this, some form of error correction needs to be implemented. It turns out, however, that error-free multicasting poses several implementation challenges [3]. The two main traditional approaches to error correction are retransmission schemes and forward error correction (FEC). In retransmission schemes lost packets are retransmitted by the source to the group of mobile receivers. If FEC is used, the receiver relies on redundant data sent with the original transmission to decode the source message, despite possible errors in the transmission. When applied to multicast transmission, both approaches have a number of advantages and disadvantages as discussed in detail in Chapter 2. Depending on the network conditions, the selection of an error correction scheme can have a large influence on the overall cost of communication. In fact, a vast number of network parameters and topology variables need to be considered before an appropriate error correction scheme can be drawn up for a specific multicast system. It is out of this observation that our problem statement has been formulated.

1.3 Problem Statement and Motivation

The proposed research aims to develop an algorithm to improve error correction techniques in MBSFN systems. Recent research ([3], [4], [5]), published in 2011 and the first quarter of 2012, has investigated the efficiency of different retransmission and FEC techniques in MBSFN systems . Several researchers have quantified the effect of a number of network parameters on the efficiency of error correction techniques (and their associated network costs). However, no effort has yet been made to unify these studies into a systematic approach that could help with the selection of the most effective technique given certain network conditions.

Our integrated solution is to develop an algorithm that will take a broad spectrum of network parameters as input conditions. These may include network topology, number of users, density of user equipment and many others. As output, the developed algorithm would provide an idea of what error correction scheme will be most effective for the network at hand. It could, for example, help with the selection of an appropriate Raptor code for FEC under dynamic conditions. It should be noted that the goal is overall *improvement* and not mathematical *optimization* of error correction techniques – the latter requiring rigorous mathematical proofs.

Although error correction schemes have a broad range of applications across all spheres of data-communication, the research proposed here will make a definite contribution to multicasting in LTE environments. It will do so by specifically considering network conditions that apply to MBSFN systems. Considering the fact that LTE was only approved in 2008 and with deployment still in its initial stages, the actuality of the research is evident.

1.4 Hypothesis

Using a number of MBSFN network variables and the fundamental characteristics of basic error correction techniques, we can create a mathematical model to select the lowest-cost error correction scheme for the over-the-air interface of a specific MBSFN network under specific conditions.

1.5 Clarification of hypothesis

The hypothesis is clarified by explaining the specific word choices:

- ***"a number of…variables"*** - We create a mathematical cost model for an MBSFN network that considers a selection of the most important variables that influence network operation. Since we aim to create a simplified model, we do not need to represent reality in an exact manner – which would require incorporating an exhaustive list of variables. The model will be shown to model the real world closely enough to make meaningful conclusions about network costs.
- ***"the fundamental characteristics"*** - We model the fundamental operation of error correction schemes and make a number of assumptions to simplify the process. Advanced features of the different error correction techniques, such as network sensing, handshaking, etc. fall beyond the scope of the research [6], [7].
- ***"basic error correction techniques"*** - The model incorporates the two main traditional approaches to error correction, namely retransmission schemes in the form of Automatic Repeat-reQuest (ARQ) and FEC, and a combination of the two schemes.
- ***"we can create a mathematical model"*** - This is the hypothesis we set out to prove. The model is a series of mathematical computations on a collection of input variables and not merely theoretical.
- ***"to select the lowest-cost…scheme"*** - The model does not propose a new error correction scheme – it provides the necessary tools to *select* an appropriately low-cost scheme for a given scenario.
- ***"for the over-the-air interface"*** - The largest contributor towards overall communication costs in a multicast transmission over an LTE network, is the cost of transmission over the air interface (the interface between the e-NB and the

UE – see Chapter 2 Section 2.5). According to [5] it accounts for around 80% to 90% of the total cost and is therefore a suitable approximation of the total cost for the multicast transmission. We consider only this interface in our model to simplify implementation, under the assumption that results can be extrapolated to include to whole network with 80%-90% accuracy.

- ***"of a specific MBSFN network"*** - The model can simulate the telecommunications cost of a variety of MBSFN network deployments and, given a set of variables describing a specific MBSFN network, make a selection of the lowest-cost error correction scheme for that system.
- ***"under specific conditions"*** - The model also takes as input a series of variables describing the conditions apart from the specific network set-up, such as loss conditions, user mobility, etc.

1.6 Justification for study

A comprehensive literature survey revealed many opportunities for new research in this area. No documented results evaluating the costs associated with different error correction schemes over the air interface of an MBSFN network could be found. While the authors of [8] did consider the error correction costs of an MBSFN transmission over all the network interfaces, their simplified network model couldn't be mathematically duplicated and they have suggested the inclusion of more variables into a unified mathematical model as possible new research [8], [9], [10].

1.7 Research Goals

The proposed research will address the following objectives:

- Gain a thorough understanding of the LTE environment, with specific reference to multicasting and MBSFN systems.
- Study and quantify the effect of different network parameters on the reliability of multicast communication.
- Investigate different error correction schemes appropriate for MBSFN systems. Quantify the relationship between the efficiency of a selected scheme and network conditions.
- Develop a systematic approach (an algorithm) to improve the selection of error correction scheme under any given set of network conditions.
- Compare results of the algorithmic approach to existing methods and validate that it indeed led to improvement.
- Verify the algorithmic approach by showing that it is mathematically rigorous and plausible.

1.8 Research Methodology

The first step in the research process is to define the problem that the study will seek to address. This is done through an initial literature study. During this stage of the process a technical understanding of the study field is not yet required - the literature study only serves to identify a gap in current knowledge of the field and the possibility of a meaningful contribution that the research project might make.

Once a suitable problem has been defined, an in-depth literature study commences. The study must cover all aspects of LTE environments with regards to multicasting. Network parameters that might affect reliability of communication should be identified in this step. The literature study will also provide the researcher with a clear understanding of error correction schemes (as appropriate for multicast communication), their advantages, disadvantages and operation.

An additional step that will be required in this research project is a practical study (simulations) to further investigate certain concepts from the literature study. For example, the only way to truly grasp the effect of network parameters on reliability of communication is to simulate said network conditions. This step supports and augments the literature study (it does not yet test any hypotheses).

The next step is to formulate a hypothesis based on the technical and theoretical knowledge gained in the literature and practical study. It will consider network variables and the effect they have on the capabilities of error correcting schemes in an MBSFN system. The hypothesis should describe a proposed method to select error correction schemes under dynamic network conditions.

In conjunction with the hypothesis, an algorithm is now created - a quantified, systematic approach for selection of an error correction scheme (including coding methods) given the network conditions of an MBSFN system.

Next, the developed algorithm undergoes rigorous testing through simulation and experimentation. Its capabilities given any set of network conditions will be evaluated. Shortcomings or oversights in the technique are identified in this step, while changes to the algorithm are made accordingly.

The process of verification and validation occurs concurrently with the testing phase. The accuracy of the simulation is verified by comparing experimentation results to real life results. A detailed discussion of the verification and validation process appears in Section 1.9.1 below.

A detailed analysis of the final results completes the research process. Conclusions are drawn with regards to the achievement of initial research objectives, perceived shortcomings and strengths and the applicability of results in real-world scenarios.

A diagram illustrating this process appears on the next page.

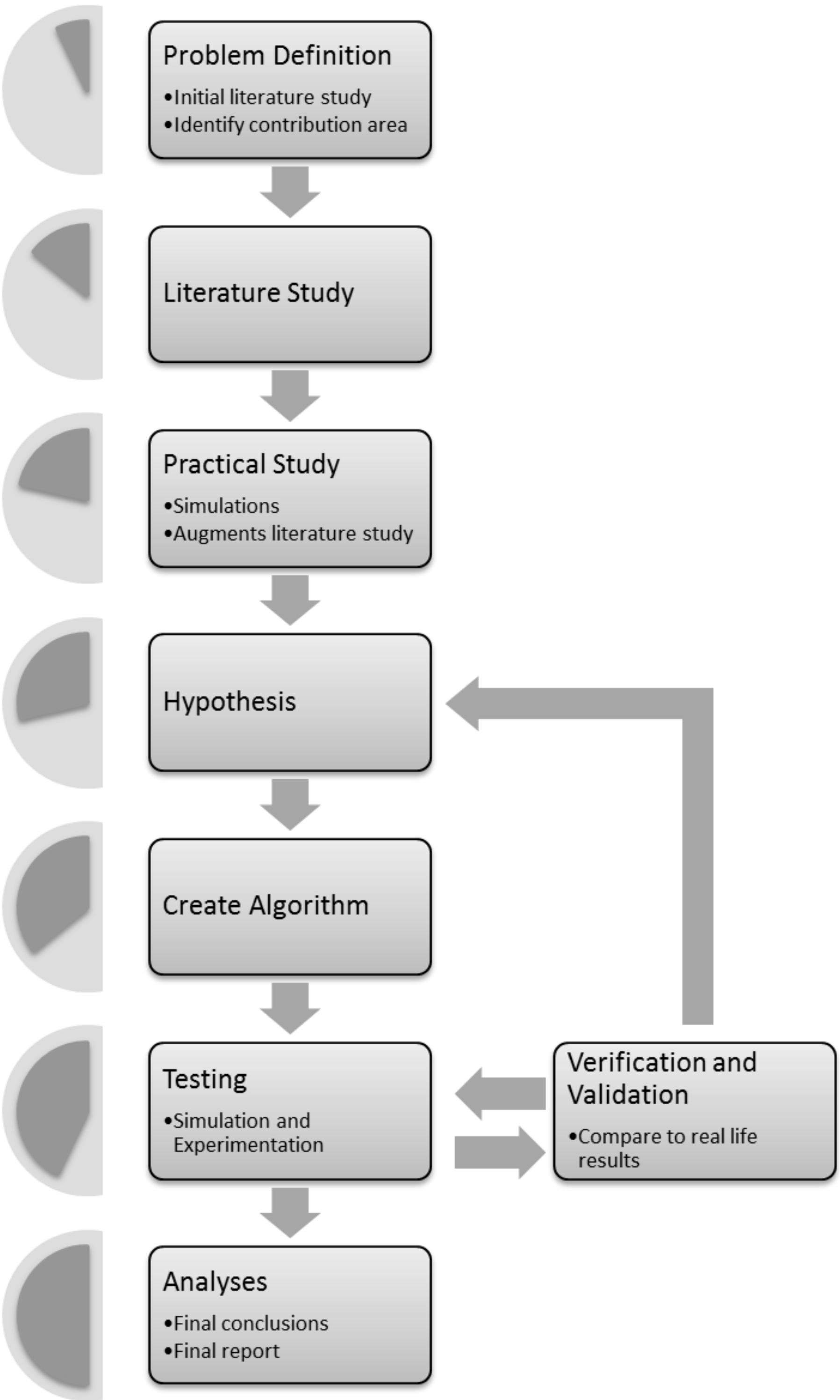

Figure 1: Research methodology

1.8.1 Verification and Validation

Once the mathematical model has been created, the results are verified by proving that they have been achieved through a mathematically rigorous process. To do this, we identify a subset of data and use it to duplicate a small simulation scenario performed by our model. This subset of data is used to generate a result set by performing step-by-step mathematical calculations by hand similar to the computer processes implemented by our mathematical model. The results are compared to those generated by a computer (the mathematical model) to prove that the programming and implementation was correct and the model is accurate.

The verification phase is followed by the validation phase by performing tests similar to those in published research documents and comparing the results. A simulation scenario is set up according to the same specifications as a published author. A correlation coefficient is computed between the result sets (own and published) to show that the underlying theories have been correctly applied to address the issues highlighted in the problem statement.

1.9 Dissertation Overview

The rest of this document is structured as follows. A detailed literature study appears in Chapter 2, providing the theoretical background for the dissertation. This is followed by an explanation of our mathematical model in Chapter 3. The model's abilities are illustrated in a series of results in Chapter 4, followed by its verification and validation in Chapter 5. We conclude this study in Chapter 6 by evaluating our adherence to stated goals and making meaningful recommendations. The document ends with a list of references. Conference contributions from this dissertation appear in the appendix.

Chapter 2 – Literature Study

2.1 Introduction

This chapter expands upon the problem and research domain by providing background on LTE environments, multicasting in LTE environments and error correction techniques appropriate for multicast environments.

2.2 Long-Term Evolution

The 3rd Generation Partnership Project (3GPP) first introduced Long-Term Evolution (LTE) in their Release 8 specification. It is designed to be a significant step towards the development of 4th generation (4G) radio technologies aiming to improve the speed, throughputs and capacity of mobile communications [1]. In fact, when first approved in 2008 LTE provided a peak downlink bitrate of 144Mbps and a peak uplink bitrate of 57Mbps. In both cases this was a factor-of-10 improvement in performance over its predecessor, the Release 6 HSDPA (High-Speed Downlink Packet Access) and HSUPA (High-Speed Uplink Packet Access) [2].

To achieve this remarkable technological enhancement, LTE proposes several novel approaches to mobile communication systems. All types of traffic in an LTE network are carried by IP (Internet Protocol) packets. This include voice traffic, for which a form of Voice over IP (VoIP) is used [1]. As explained in [11], several changes to the physical layer are also introduced. Performance and robustness are greatly improved by the introduction of multiple-antenna transmission and reception. This method is referred to as MIMO (or Multiple-Input, Multiple-Output). Furthermore, Orthogonal Frequency Division Multiple Access (OFDMA) is used as modulation scheme for downlink transmission and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink. Both these techniques require the computation of many fast Fourier transforms and the corresponding digital signal processing power to perform them. For this reason, even though the usage of these multiple access schemes has been considered before, the cost of processing power for mobile applications has only recently been sufficiently reduced to viably implement OFDMA and SC-FDMA [2]. Lastly, and most notably for purposes of this research document, multicast is supported from the very first release of LTE specifications [1]. This is the topic of the next discussion.

2.3 Multicasting in LTE environments

This section begins with a brief introduction to multicasting in general (IP multicasting), before providing background on its specific application in LTE networks.

2.3.1 IP Multicasting

When a router in an IP network receives a message from a source node, it can forward the message in one of three ways. If it forwards the message to a single destination node, it is referred to as *unicast* communication. *Broadcast* communication is when the router forwards the message to all destination nodes (or at least an indeterminate group of destinations). A very useful midway between these two scopes of communication is *IP multicasting* – the router only forwards the message to a select group of destination nodes [12].

The main advantage of IP multicasting (or, without any loss of generality, simply *multicasting*) is increased efficiency. Using only unicast communication, if a source node wants to send the same message to a group of destination nodes it would have to recreate the message as many times as there are destination nodes – each message given a different destination address. Furthermore, bandwidth is consumed by the duplicate messages that would have to be carried by the network media. This type of communication can be referred to as *multiple unicasting.* If multicasting is used instead, the source node would have to send the message only once (addressed to a destination group), after which it is duplicated by a router and forwarded to the appropriate destination nodes. This method saves bandwidth and processing effort on the part of the source node [12]. The concept of unicasting, broadcasting, multiple unicasting and multicasting is illustrated in the figures below.

In unicast communication the source addresses a message to be delivered to a single destination host. The router forwards the message accordingly.

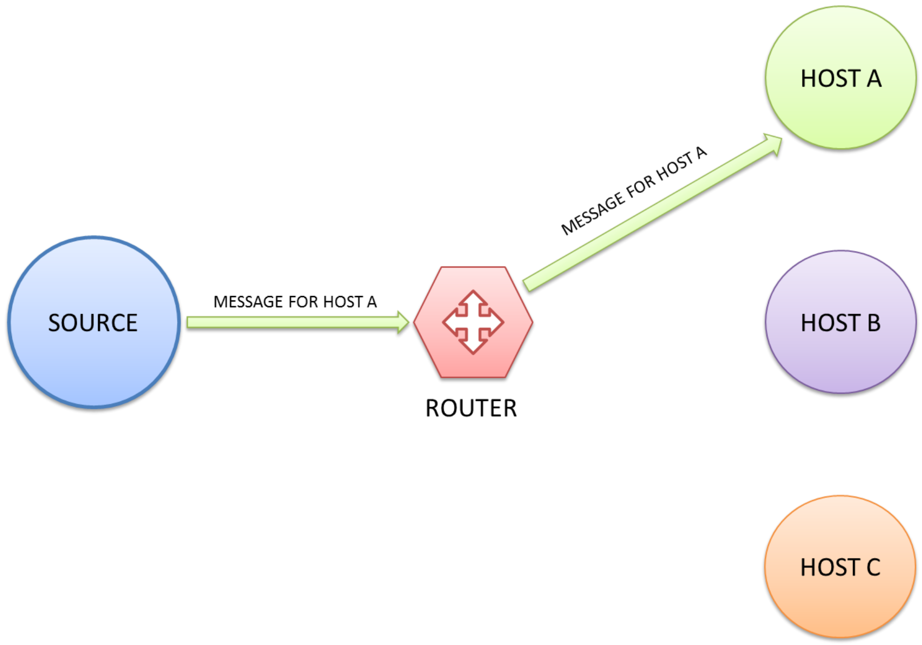

Figure 2: Unicast communication

In broadcast communication the source sends a single message to a broadcast address. The router then simply forwards the message to all destination hosts.

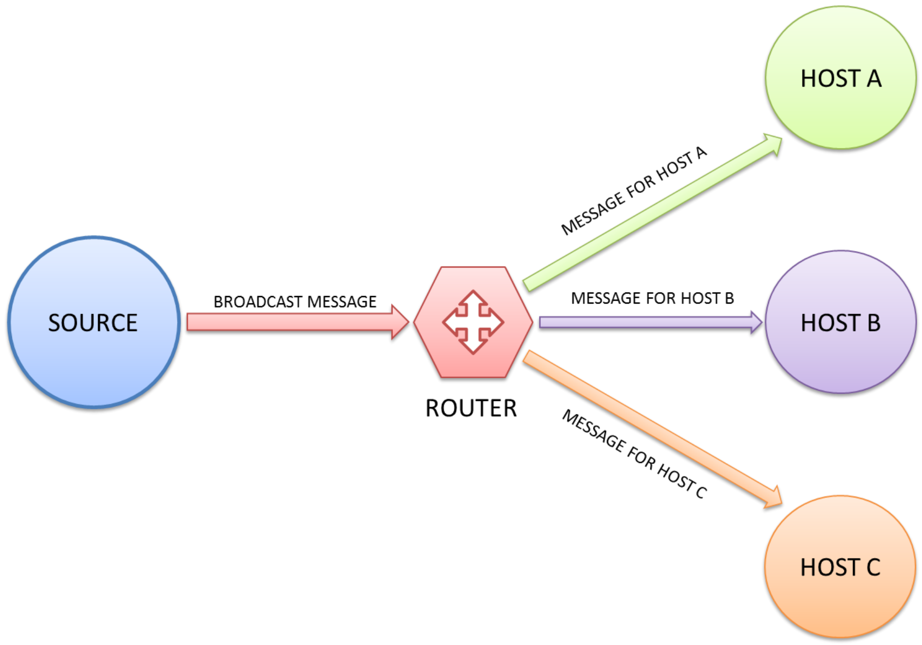

Figure 3: Broadcast communication

In a unicast system, if a source node wants to send the same message to a number of destination hosts, it would have to send an individual, appropriately addressed, copy to each.

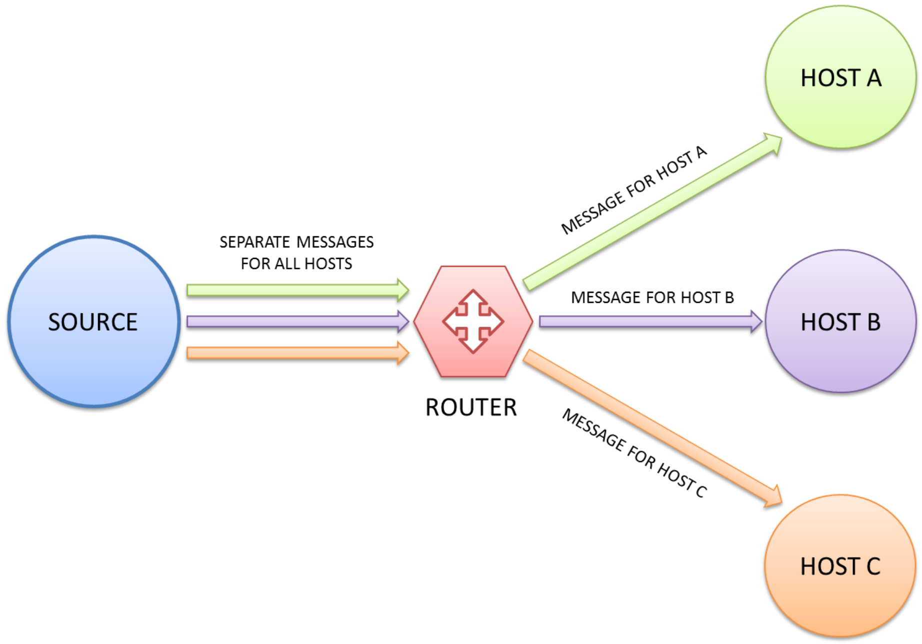

Figure 4: Multiple unicast communication

In multicasting, the source addresses a specific group of receivers in a single message. The router then forwards the message to each of the intended destination hosts.

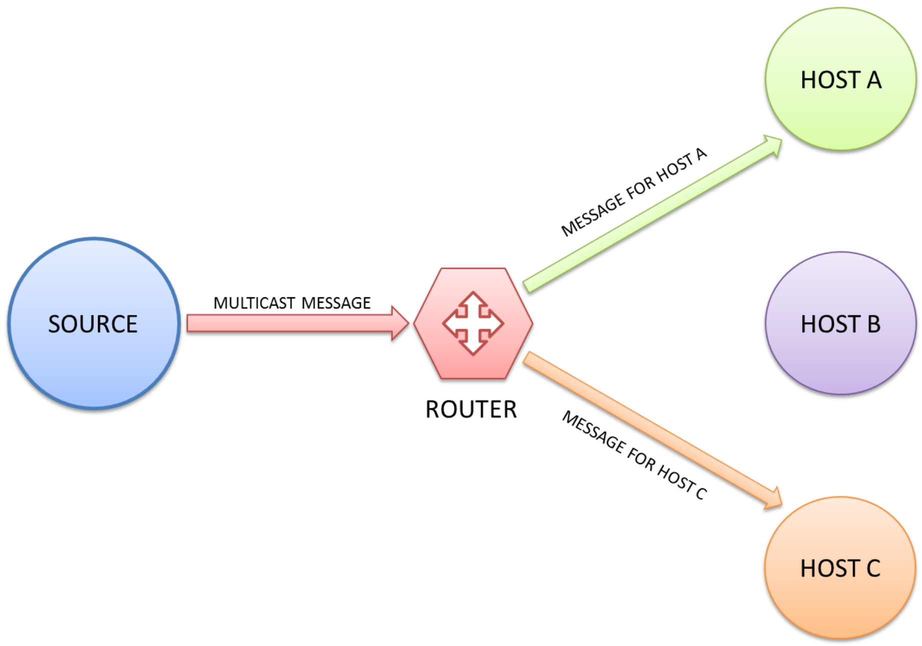

Figure 5: Multicast communication

Although multicasting provides several benefits in terms of transmission efficiency, it does impose several challenges on the network router. Quinn et al. lists six unique challenges to IP multicast applications in [13]. Among others, multicast routers are required to keep track of the destination node addresses that form part of each multicast receiver group. Since individual destination nodes can be a heterogeneous group, each with their own bandwidth and error characteristics, reliability also needs to be addressed during the management of multicast communication.

The most important application of multicast communication is the distribution of multimedia content across networks. Due to the nature of audio-visual data, it requires a large bandwidth to be transmitted reliably and at an acceptable quality level across the network (especially in real-time applications, termed *streaming*). Often groups of receivers would subscribe to receiving such content, and duplication would unnecessarily increase bandwidth usage. Saving bandwidth would lighten the demand on network resources, while increasing the quality of the transmission and shortening source-to-destination delay [12].

2.3.2 Evolved-MBMS

The 3GPP's application of multicast technology to cellular networks has been termed the MBMS, or Multimedia Broadcast/Multicast Service. For LTE systems this specification has been further enhanced to the evolved-MBMS (e-MBMS) [2]. Currently e-MBMS includes two types of multicast transmission, namely single-cell transmission and multi-cell transmission. As the terms imply, the former can only distribute multicast data within a single cell of coverage, while the latter uses a number of different, highly synchronized cells to transmit the multicast data [14].

Of the services described by e-MBMS, it is the multi-cell transmission which is envisioned to be employed in large scale to support the distribution of multimedia content (such as mobile television) [1]. In LTE environments this type of transmission is also known as MBMS Single Frequency Network (MBSFN). Its operation is based on a set of base stations transmitting the same signal at the same time and in the same frequency channel to a group of multicast user equipment (UE). From the viewpoint of the user equipment, the combined signal from the different locations will appear as if coming from a single base station, but being subject to severe multipath propagation [14]. MBSFN allows for over-the-air signal combining and other technology to change the destructive interference of multiple signals to a constructive signal resulting in a much higher Signal-to-Interference plus Noise-Ratio (SINR) compared to single-cell transmission [1]. An in-depth discussion of the physical operation of MBSFN falls beyond the scope of this document. A more complete analysis is given in [1], [2], [14], [4] and [3].

2.4 Error correction in MBSFN

From the onset it was clear that ensuring error-free multicast communication over LTE would pose some unique challenges. Efficient use of spectrum and maintaining scalability (more multicast users), are two of the most important considerations in reliable multicasting [3], [4]. However, to fully understand the case for reliable multicasting in LTE systems, a closer look needs to be taken at two vastly different approaches to transmission error correction - retransmission schemes and forward error correction (FEC).

2.4.1 Retransmission schemes

Retransmission schemes have come to be assimilated with the automatic repeat request process (ARQ). Reliable, or error-free, transmission is ensured by the sender repeatedly resending lost or damaged packets of data until both sender and receiver is satisfied that the intended message has been correctly transmitted [6]. It therefore requires a feedback channel for the receiver to indicate to the sender whether data has been successfully received (an *acknowledgement*) or whether some error has occurred (a *negative-acknowledgement)*.

In general there are two events that can trigger a retransmission of data. Firstly, if the sender has not received an acknowledgement of successful reception from the receiver in a predetermined period of time it will resend the data. This might be a result of data losses. Retransmission will also occur if the receiver determines that the data packets which it has received contain some errors. It can explicitly indicate to the sender which packets are damaged. The error is then corrected by simply retransmitting the original data (for which the sender still maintains a copy) [12]. This implies that some redundant data, which will allow for detection of errors, should be included with the transmission.

Although retransmission schemes can be implemented easily and provide high system reliability, the requirement for a feedback channel and unpredictable resending of data can create unacceptable fluctuations in data throughput. A high channel error-rate can cause a dramatic decline in throughput and quality of communication [6]. This is a particularly serious problem in multicast communication, as is discussed later in this section.

2.4.2 Forward error correction

As opposed to ARQ, no retransmission is required in an FEC system. Its mechanism for error-free transmission relies on adding redundant bits (parity data) from which the original message can be determined when a transmission error occurs [6]. Because redundant data should be sufficient to both *detect* and *correct* errors on the receiver's end, a significant amount of additional overhead is introduced in the system [3]. It is also a more involved process than for retransmission schemes, where the concern is only to ensure reliable detection of errors [12].

The redundant bits that will allow for eventual error correction are added through a process called *coding.* Coding can loosely be defined as the process of mapping a set of input bits to a set of the same amount or more output bits. A set relationship between the output data (with redundancy) and actual data then allows the receiver to detect and correct errors [12]. Several such coding schemes have been put forward, a number of which is discussed in [12] and [6]. Particularly relevant to a discussion on LTE multicasting (because it has been endorsed by the 3GPP themselves) is the class of fountain codes termed *Raptor codes*.

Fountain codes can produce a potentially infinite stream of output symbols for a finite set of input symbols. If a message containing a set of k input symbols is encoded, a decoding algorithm will be able to recover the original message from any set of n output symbols with $n \geq k$. Raptor (or *rapid tornado*) codes are the first practically realizable class of such fountain codes with linear time encoding and decoding [7].

2.4.3 Error correction challenges in MBSFN

It should be clear that ARQ on its own is not an effective method to establish error-free multicast communication. The authors of [3] name three drawbacks of ARQ in an MBSFN system, which is expanded upon below.

The most important problem with this approach is known as *feedback implosion*. Since ARQ relies on feedback from individual receivers for its operation, it is possible (even probable, under certain conditions) that a large number of retransmission requests may occur simultaneously, placing a heavy burden on network resources. Spectrum efficiency is also reduced if a large number of retransmitted messages congest the downlink network channel. Furthermore, the bursty nature of traffic in both the uplink and downlink channels has a detrimental effect on network scalability and efficiency. A fourth drawback, mentioned by the same authors in [15], is that the feedback channel in LTE (and any wireless network) consumes valuable power and is expensive to implement.

An apparent solution to the shortcomings of ARQ in an MBSFN is to make exclusive use of FEC techniques. Since all data necessary for error correction is transmitted in the downlink channel, the need for a feedback channel is greatly reduced. This eliminates the possibility of feedback implosion. Also, independent errors at different receivers have no effect on the error correction operation, allowing for network scalability [10].

Since FEC introduces a fixed amount of overhead into the system, there are, however, certain conditions under which FEC might be a less desirable approach than ARQ [15]. If a low number of users have subscribed to the multicast service, for example, ARQ could be more effective. In a reliable network, if packet loss is low, ARQ might also be the more practical option [3]. It seems therefore that a combination of the two schemes might be necessary. In fact, a vast number of network parameters and topology variables need to be considered before an appropriate error correction scheme can be drawn up for an MBSFN system.

2.5 Overview of the MBSFN architecture

A diagrammatic overview of an e-MBMS architecture is provided below in Figure 6. In the figure, the radio base stations each consist of both an antenna and a Multi-cell/multicast Coordination Entity. These stations, also known as e-NBs (evolved Node B's), are responsible for over-the-air delivery of multicast content. The logical MCE entity functions as coordinator of each MBMS session and provides the tight synchronization between cells required for MBSFN operation [9]. It also handles admission control and resource allocation within an MBSFN area [16].

The e-MBMS GW (evolved-MBMS Gateway) is located between the service centre and the e-NBs. It uses IP Multicast to distribute multicast packets to each of the e-NBs taking part in the MBSFN transmission. MBMS Session Control Signalling (such as *session starts* and *sessions stops*) is also performed by the e-MBMS GW via the MME (Mobility Management Entity). These two functions are performed by two distinct domains within the e-MBMS GW, namely the user plane (UP) for IP multicast content delivery and the control plane (CP) for MBMS Session Control Signalling. Accordingly, two separate interfaces join the Gateway and the e-UTRAN (evolved Universal Terrestrial Radio Access Network). The M1-interface is used for the user plane and the M3 interface for control signalling in the control plane [9], [16].

The e-BM-SC, or evolved Broadcast Multicast Service Centre, introduces the multicast data (such as multimedia) into the LTE network [9]. It therefore serves as an entry point of data delivery for both internal sources and external content providers through a border gateway (not shown) [17].

In a similar fashion to the M1 and M3-interfaces, the air interface (LTE-Uu) uses two downlink channels for the MBSFN operation. The Multicast Traffic Channel (MTCH) is responsible for multicast data delivery in the service area, whereas the Multicast Control Channel (MCCH) transmits MBMS control information associated with one or several MTCHs [9].

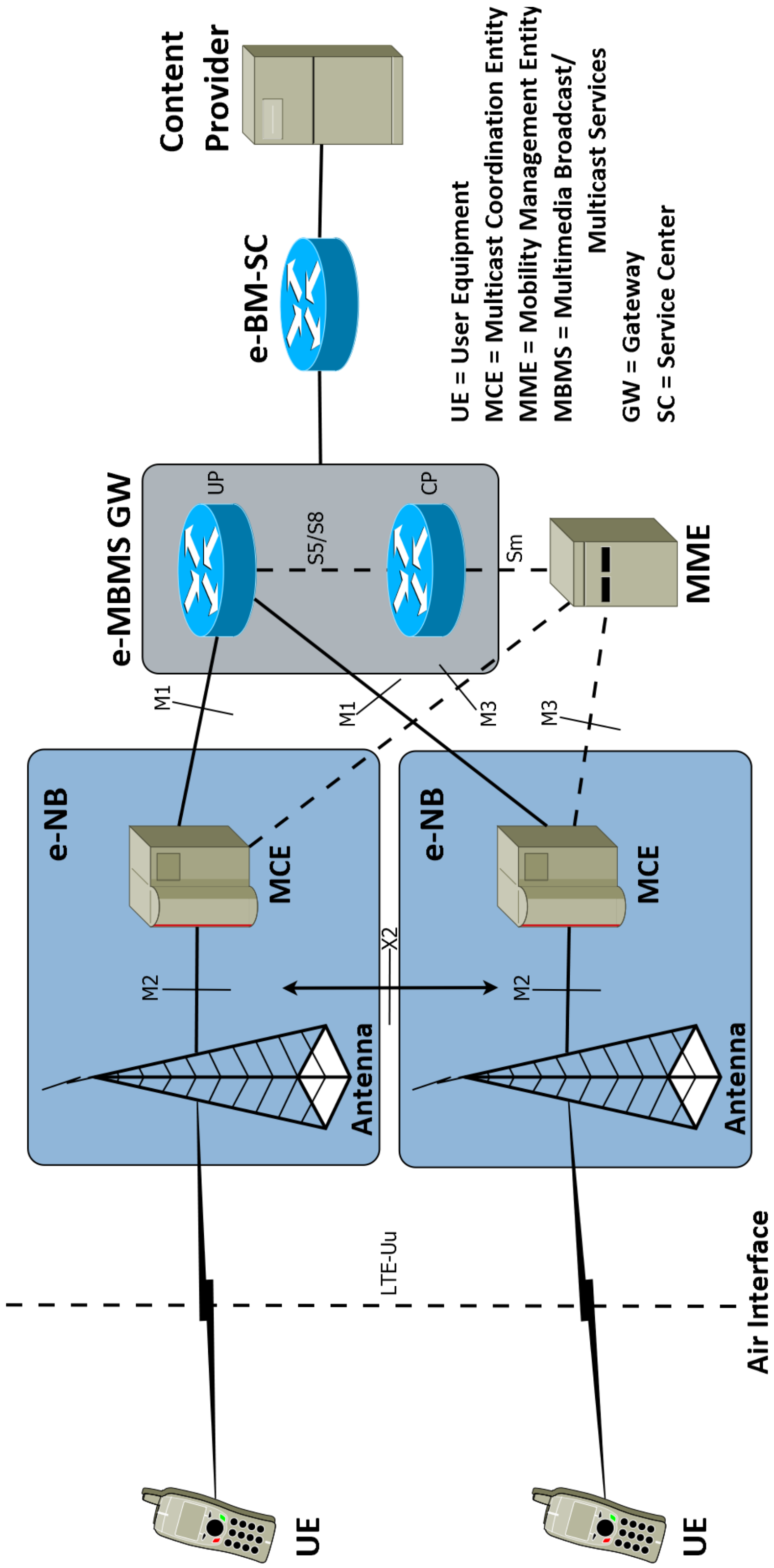

Figure 6: e-MBMS (MBSFN) architecture

2.6 Conclusion

In this chapter we provided the theoretical background on Long-Term Evolution networks and multicasting on which the rest of the research builds. A summary of the main approaches to error correction, retransmission schemes and forward error correction, is also included. In our study we specifically look at error correction when applied to multicast systems. Our application domain is a specific type of multicast network developed for LTE, namely MBSFN. We provided background on multicast systems in cellular networks in general (MBMS) and introduced the operation and architecture of the more specific MBSFN system. This theoretical discussion is continued in Chapter 3, when the topology and operation of MBSFN is described in detail and expanded into a mathematical model.

Chapter 3 – Mathematical Model

3.1 Introduction

In this chapter our simplified mathematical cost model for an MBSFN network, as implemented in MATLAB, is introduced and explained. It is expanded to include costs associated with different error correction techniques. The chapter includes details on the assumptions made during implementation and the range of variables that the model can accept as input. Throughout this chapter, the following symbols are used (adapted from [9]):

Table 1: Mathematical symbols

Symbol	Explanation
D_{Uu}	Delivery cost of a single packet over the air (Uu) interface
C_{Uu}	Total communication cost over the air interface
N_p	Total number of packets in the MBSFN session
N_{eNB}	Number of participating e-NBs in MBSFN.
RE	Resource efficiency
SE	Spectral efficiency

3.2 MBSFN Topology

Consider a hexagonal grid consisting of a number of evolved-Node B (e-NB) cells as illustrated in Figure 7.

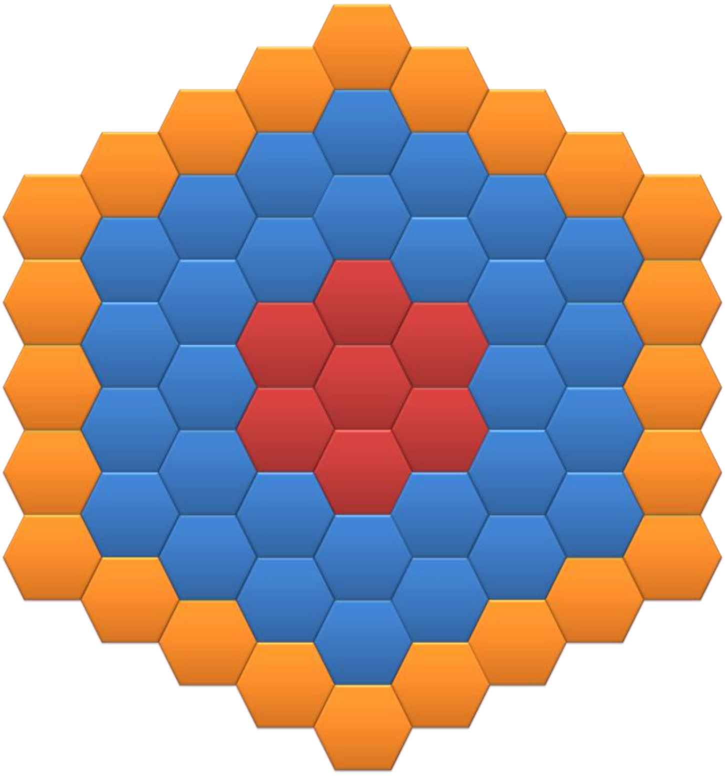

Figure 7: A hexagonal grid of cells

We'll consider a topology similar to this and will adapt a number of assumptions based on the architectural setup described in [9]. Firstly, assume the topology is scalable to include a large number of cells (approaching infinity). Secondly, assume that multicast users can be located in an ever increasing area surrounded by each ring of cells moving outward from the centre cell. That is, we can consider an infinite series of scenarios, where:

- The users are all located in the centre cell
- The users are located in the centre cell and the first ring of six cells surrounding the centre (a total of 7 cells containing UEs).

- The users are located in the centre cell, the first surrounding ring and the second surrounding ring of twelve cells (a total of 19 cells).

and so forth, until the users are located in an infinite number of cells in an infinitely large topology.

For each scenario, it is possible to enhance the spectral efficiency of the MBSFN system significantly by having the ring of cells neighbouring the “inner” area containing UEs also participate (*assist*) in the MBSFN transmission [18],[19]. Although this *assisting ring* does not contain any users subscribed to the multicast service, it will broadcast the same MBSFN data at the same frequency as the inner cells containing subscribed UEs. In fact, substantial gains in spectral efficiency can be achieved if up to three neighbouring rings of cells assist in the MBSFN transmission [18]. In the figure, the central seven cells contain UEs (red). They are surrounded by two assistive rings (blue), broadcasting the same data at the same frequency, but not containing any subscribed multicast users. The outer ring in the figure (orange) does not participate in the MBSFN session and is termed an *interference ring*. For the purposes of this research document, three different deployments are considered:

- **AII -** One ring of cells neighbouring the area containing UEs participate in the MBSFN session. The other cells act as interference rings.
- **AAI -** This is the setup illustrated in the figure. The first two neighbouring rings surrounding the area of subscribed users assist in the MBFSN system, while the outer rings act as interference.
- **AAA -** All three neighbouring cell rings assist in the multicast. Cell rings further away from the central cells than the first three neighbouring rings can be shown to have no significant effect on the MBSFN transmission [19].

A simplified MBSFN cost model is developed to accommodate scenarios where the Inter-Site Distance (ISD) between the cells are 500m and 1 732m respectively (termed macro Case 1 and macro Case 3). These are typical selections based on the Okamura-Hata propagation model [9], [18].

3.3 Cost over the air interface

Consider the following equation:

$$C_{Uu} = D_{Uu} \cdot N_p \cdot N_{eNB} \quad (1)$$

The total communication cost over the air interface is the product of the delivery cost for a single packet over the air interface with the total number of data packets in the MBSFN session. This product is then multiplied by the number of e-NBs participating in the MBSFN transmission, N_{eNB} [9]. This number is dependent on both the *user distribution* and selected *topology* of the MBSFN system. The user distribution is an indication of the number of cells containing participating UEs, while the selected topology will determine how many e-NBs from assistive cell rings (not containing any participating UEs) will participate in the MBSFN session. The sum of these two indicators is the total number of participating e-NBs.

Both N_p and N_{eNB} are invariable for each modelling scenario and will be explicitly defined for each case considered. However, the cost for a single packet over the air interface, D_{Uu}, needs to be modelled mathematically. To do so we define a resource efficiency variable. Resource efficiency is defined as the spectral efficiency for a certain topology, normalised (or multiplied) by the fraction of cells participating in MBSFN transmission that actually contains active UEs. For example, if in the hexagonal grid of cells only the centre cell contains UEs, but there are two assistive rings of cells, a total of 1 + 6*1 + 6*2 = 19 cells participate in MBSFN transmission. Even though only one cell (the centre) contains UEs interested in the MBSFN content, a total of 19 cells actually participate in the transmission. This is not a very efficient use of resources and will result in the spectral efficiency being divided by 19 (multiplied by 1/19) to compute the resource efficiency (in bps/Hz/cell) [18]. Therefore,

$$RE = SE \cdot \frac{1 + \sum_{i=0}^{k} 6 \cdot i}{1 + \sum_{l=0}^{n} 6 \cdot l} \quad (2)$$

In the above equation, RE is the resource efficiency and SE the spectral efficiency for the selected topology. The summation limits *k* and *n* are the number of cell rings (excluding the centre cell) *containing UEs* and the total number of cell rings *participating* respectively. The *k* and *n*-indices relate to each other in a different way for each considered topology.

For AII: $n = k + 1$

For AAI: $n = k + 2$

For AAA: $n = k + 3$

The spectral efficiency depends on the propagation model and specific evaluation scenario. This can be modelled using the Okamura-Hata model and considering a complex system of variables. To adhere to the scope of this document, the following tabled values are used, as provided in [18] for Case 1 and Case 3 (Inter-Site Distances of 500m and 1 732m respectively). These values were calculated at a 95% coverage level of the central cell.

Table 2: Spectral Efficiency for MBSFN deployments

SPECTRAL EFFICIENCY				
Case 1 (bps/Hz)	***Case 3 (bps/Hz)***	***Ring***		
		1	***2***	***3***
2.4	0.8	A	A	A
2.2	0.8	A	A	I
1.3	0.7	A	I	I

In order to convert the resource efficiency to an indicator of the relative cost of transmission over the air interface, a normalised version of the resource efficiency, RE_{ratio}, is defined. The resource efficiency of the current deployment is normalized to the maximum obtainable resource efficiency for each macro case, namely 2.4 bps/Hz/cell for Case 1 and 0.8 bps/Hz/cell for Case 3 [9].

$$RE_{ratio} = \frac{RE\ (current)}{Maximum\ RE} \tag{3}$$

Noting that the cost of transmission increases proportionally with a decrease in resource efficiency (and vice versa), the authors of [9] defined the cost of a single packet delivery over the air interface as:

$$D_{Uu} = \frac{1}{RE_{ratio}} \quad (4)$$

The combination of the above equations with the original cost expression in Equation 1 results in a complete mathematical model for the cost of packet delivery over the air interface in an MBSFN system.

To show how the spectral efficiency of each deployment is normalised by the factor of participating cells actually containing UEs, the resource efficiency associated with each deployment is graphed below as a function of the number of cell rings containing subscribed UEs.

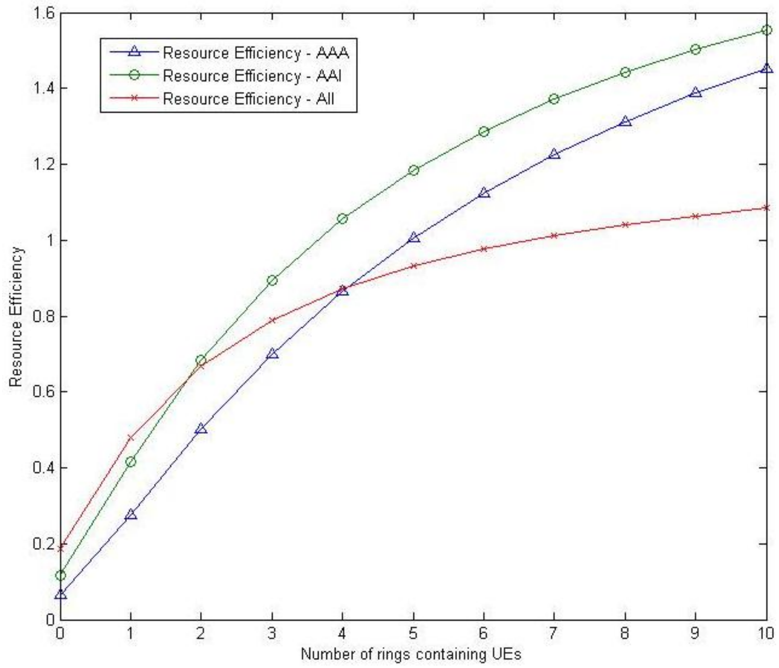

Figure 8: Resource efficiency of MBSFN deployments

It is clear that, for small topologies, AII has the highest resource efficiency. However, as the topology grows to include more cell rings, AII becomes the least efficient deployment option. This is because of the higher spectral efficiency in AAA and AAI. Since AAA has a larger spectral efficiency than AAI, it will eventually have the highest resource efficiency if the topology is sufficiently large. In fact, when the topology has grown to include an infinite number of cell rings, the resource efficiency of each deployment approaches the spectral efficiency of that deployment as presented in Table 2. To prove that, consider the following infinite analysis based on Equation 2:

Equation 2 states that

$$RE = SE \cdot \frac{1 + \sum_{i=0}^{k} 6 \cdot i}{1 + \sum_{l=0}^{n} 6 \cdot l}$$

which is mathematically equivalent to

$$\begin{aligned} RE &= SE \cdot \frac{1 + 6 \cdot \sum_{i=0}^{k} i}{1 + 6 \cdot \sum_{l=0}^{n} l} \\ &= SE \cdot \frac{1 + 6 \cdot \left(\frac{k(k-1)}{2}\right)}{1 + 6 \cdot \left(\frac{n(n-1)}{2}\right)} \\ &= SE \cdot \frac{2 + 6k^2 - 6k}{2 + 6n^2 - 6n} \end{aligned}$$

We know from Section 3.3 that,

$$k = n - C$$

where C is a constant. Therefore,

$$\begin{aligned} RE &= SE \cdot \frac{2 + 6(n-C)^2 - 6(n-C)}{2 + 6n^2 - 6n} \\ &= SE \cdot \frac{2 + 6n^2 - 12nC + 6C^2 - 6n + 6C}{2 + 6n^2 - 6n} \end{aligned}$$

Now, if the network size approaches an infinite number of cell rings,

$$\begin{aligned} RE &= SE \cdot \lim_{n \to \infty} \frac{2 + 6n^2 - 12nC + 6C^2 - 6n + 6C}{2 + 6n^2 - 6n} \\ &= SE \cdot \lim_{n \to \infty} \frac{6n^2}{6n^2} = SE \cdot 1 \\ &= SE \end{aligned}$$

Therefore, in an infinite analysis, AAA has a resource efficiency of 2.4 bps/Hz/cell, AAI has a resource efficiency of 2.2 bps/Hz/cell with AII at 1.3 bps/Hz/cell.

3.4 Error correction costs

3.4.1 ARQ costs

We now extend the cost model presented above to accommodate for possible errors occurring during MBSFN transmission and the application of different error correction techniques to remedy this. If the unit cost for transmitting a data packet over the air interface is given by D_{Uu} and the total number of packets in the simulation session is N_p, the total transmission cost C_{Tx} (at each participating e-NB) can be determined as follows:

$$C_{Tx} = N_p \cdot D_{Uu} \quad (5)$$

The application of error correction techniques can be modelled by computing the total number of packets lost during transmission. A distinction should be made between *global losses* and *local losses.* Global losses affect all users participating in the multicast session (e.g. in the case of outages) and are independent of the number of multicast users in the topology. Local losses occur because of individual errors at local receivers and increase in number as the number of multicast users in the topology increases. To illustrate, assume the nominal packet loss rate is 5%. If 90% of the lost packets affect all users (globally) and 10% of losses are due to individual errors at receivers, the global packet loss rate is 4.5% and the local packet loss rate 0.5%. The typical error correction remedy for both types of lost packets will be to retransmit the lost packets (to all registered multicast UEs in the topology, in the case of MBSFN). If we assume that the number of packets lost locally increases *linearly* with an increase in number of users, we can express the total number of lost packets as:

$$N_{P_{loss_{total}}} = P_{LOSS_{global}} \cdot N_p + P_{LOSS_{local}} \cdot A_{UE} \cdot N_p \quad (6)$$

where $P_{LOSS_{global}}$ and $P_{LOSS_{local}}$ are the global and local loss rates and A_{UE} is the number of UEs in the topology.

The total packet loss rate is:

$$P_{LOSS_{total}} = \frac{P_{LOSS_{global}} \cdot N_p + P_{LOSS_{local}} \cdot A_{UE} \cdot N_p}{N_p} = P_{LOSS_{global}} + P_{LOSS_{local}} \cdot A_{UE} \quad (7)$$

These equations were validated by comparing simulation results to analyses published in [3], [9] and showed good correlation. A detailed explanation appears in Chapter 5.

Now the total cost for ARQ transmission is the sum of the cost for the initial transmission and the cost of the retransmitted packets [8]. However, since the retransmissions occur under the same lossy conditions, a portion of the retransmitted packets might also be lost with some probability greater than 0. These lost packets would also need to be retransmitted in an iterative process (each iteration contributing to the total communication cost) and so forth until the maximum number of retransmissions per packet is reached. According to 3GPP specifications the maximum number of retransmissions per packet is 3, creating a ceiling of maximum transmission cost [20]. It will be shown that for ARQ transmission, as the UEs increase, the probability that each data packet needs to be retransmitted a maximum number of times becomes large very quickly.

3.4.2 ARQ-FEC Combination costs

The 3GPP recommends using Raptor Codes as forward error correction technique in MBSFN. The probability that a decoding failure may occur when a block of source code is encoded as a Raptor code, is given by

$$p_f(m,k) = \begin{cases} 1 & if\ m < k \\ 0.85 \times 0.567^{m-k} & if\ m \geq k \end{cases} \quad (8)$$

where k is the number of source symbols and m is the number of encoded symbols [21]. It is clear from the expression that, if the number of received encoded symbols is only slightly more than the number of original source symbols, the probability of incorrectly decoding the source block at each receiver decreases exponentially. If the number of encoded symbols is equal to the number of source symbols, there is still an 85% chance that a decoding failure will occur at the receiver side. The use of FEC therefore necessitates the introduction of an overhead into the system to ensure correct decoding. In this simplified model it is assumed that the FEC overhead is a constant, labelled as O_{FEC} in equations. Therefore, if the FEC overhead is 5%, $O_{FEC} = 0.05$, which is a typical simulation assumption ([3], [8]). If an MBSFN transmission using FEC experiences some packet losses, the probability of a decoding failure increases. It will then be necessary to retransmit certain packets when total packet losses grow to such an extent that the effective FEC overhead falls below an acceptable threshold, O_{MIN}. This proposed technique therefore implements a combination of FEC and retransmissions (ARQ). The total cost for this hybrid error correction technique is the sum of the cost for the initial transmission (with overhead) and the cost of retransmissions [8]. In our simplified model packets need to be retransmitted if the difference between the FEC overhead and the total loss rate exceeds O_{MIN}. The effective packet loss rate is:

$$P_{LOSS_{eff}} = \begin{cases} P_{LOSS_{total}} + O_{MIN} - O_{FEC}\,, & when\ P_{LOSS_{total}} + O_{MIN} > O_{FEC} \\ 0\,, & when\ P_{LOSS_{total}} + O_{MIN} \leq O_{FEC} \end{cases} \qquad (9)$$

3.5 Model variables

One clause in our hypothesis in Chapter 1 states that we can create a mathematical model for "*a **specific** MBSFN network under **specific** conditions*". This implies that we incorporated a number of network variables which can be used to describe a specific MBSFN setup and a different set of variables describing the conditions in which the MBSFN transmission takes place. To show that our model does address this, we summarise some of the most important variables in each category below.

Table 3: Model variables

Network Variables	
Spectral efficiency	SE
Topology	$topology$
Inter-Site Distance	$macroCase$
Number of participating cell rings	n
Number of cell rings containing UEs	k
Number of participating cells	N_{eNB}
Number of cells containing UEs	N_{UE}
Condition Variables	
User population	A_{UE}
Nominal packet loss rate	P_{LOSS}
Global packet loss rate	$P_{LOSS_{global}}$
Local packet loss rate	$P_{LOSS_{local}}$
Maximum retransmissions	M_{ReTx}
Fixed FEC Overhead percentage	O_{FEC}
Minimum FEC threshold	O_{MIN}
Number of packets in the MBSFN transmission	N_P
Packet size	P_{size}

Two of the most important variables used to describe our *network* include the *topology* and the *macro Case*. Combined, these two variables describe the implementation of the MBSFN system in terms of the physical deployment of the cells (AAA, AAI, AII) and the Inter-Site Distances between these cells. We also need to express the size of the network in terms of the number of participating (n) and UE-containing cell rings (k). Depending on the type of deployment, these values can be translated to the actual number of participating cells (N_{eNB}) and the number of cells containing subscribed UEs (N_{UE}). This group of variables can be combined to mathematically represent our simplified MBSFN system as described in Section 3.2. Depending on the values chosen for each variable, each simulated MBSFN system is characterised by its specific *spectral efficiency*, which is used in cost calculations.

Once the network has been adequately modelled, we want to express the conditions under which it operates for each simulation scenario. In an investigation into error correction techniques, it is important to vary the *packet loss rates* experienced by the subscribed *user population*. To model the behaviour of different error correction techniques, we have to consider retransmissions for an ARQ-approach (specifically the *maximum number of retransmissions* allowed per packet) and the overhead introduced if forward error correction is used. Lastly, each simulation *session* will consist of a certain *number of data packets* of a certain *size.* A combination of these variables is sufficient to create the many simulation scenarios in our result set, which is the subject of the next chapter.

3.6 Conclusion

In this chapter, our model was explained at the hand of a series of equations and accompanying discussions. Some assumptions with regards to the simulation parameters and topology were clarified, followed by the mathematical definition of the transmission *cost* over the air interface. This concept of "cost" was expanded to incorporate the cost of different error correction techniques. We rounded off this chapter with a discussion of each of the variables used to model both the *network* and the *conditions* under which it operates. In summary, this chapter introduced the set of mathematical tools that was developed to perform the tests in the next chapter.

Chapter 4 – Results

4.1 Introduction

In this chapter we present the results of four tests, each differently designed to demonstrate the functionality and versatility of our model. The first test considers the effect of a growing user population on the cost of communication. This is followed by a test where the packet loss rate is varied, providing results where the lowest-cost error correction scheme can be selected given the loss conditions under which the simulation occurs. The third test can be used to select the number of FEC redundant symbols that will result in the lowest communication cost under given loss conditions, by expressing the cost as a function of the fixed FEC overhead. The last test considers user distribution as an indication of the size of the MBSFN topology and comments on the effect this variable has on the cost of communication. Since this last variable, the *user distribution*, plays an important role in our algorithm, it is added as a third dimension in all tests. We also publish results for both macro Cases – Case 1 with an ISD of 500m and Case 3 with an ISD of 1 732m.

4.2 Test 1: User Population vs. MBSFN Cost

4.2.1 Test scope and purpose

This test investigates and quantifies the effect of a growing user population on a multicast LTE environment. It only considers the cost associated with over-the-air transmission in an MBSFN system and will study three different MBSFN deployments (AAA, AAI, AII). Three different error correction paradigms will be applied to each deployment – ARQ, combination ARQ-FEC (labelled HARQ) and FEC only. A third dimension, the size of the selected topology (the number of participating e-NB cells), significantly affects the test results and is discussed and measured as well. The model will provide a first-order answer to selecting the lowest-cost combination of deployment and error correction scheme given a certain number of subscribed multicast users.

4.2.2 Simulation setup

Two different test scenarios are set up. The first for an ISD of 500m (Case 1) and the second for an ISD of 1 732m (Case 3). For both tests a total of 10 000 data packets are transmitted in the simulation. Propagation characteristics are according to the Okamura-Hata model [18]. We also assume that the UEs have low mobility (average UE speed of only 3km/h). The e-NB cells are arranged in a hexagonal grid, as discussed. To show the effect of the third dimension (network size), the results of this test are presented for a small network and a large network for each macro Case. The smaller network contains UEs in the centre cell and the first two cell rings surrounding the centre (i.e. $K = 2$). This amounts to a total of 19 UE drop locations. For the larger network, a total of 19 cell rings (plus the centre cell) contains subscribed UEs – i.e. 1 141 cells. For this simulation the user population increases in intervals of 25 from 1 subscribed user to a total of 400 multicast UEs.

The simulation occurs in a lossy environment, with a nominal packet loss rate of 5%. The local loss rate is 10% of the nominal and the global loss rate is 90% of the nominal. Three different error correction techniques are applied. The first is a simple application of ARQ. Secondly, a combination of ARQ and FEC techniques are applied. Lastly, a theoretical application of pure FEC is simulated. Overhead due to FEC is fixed at 5%. This is a typical simulation assumption discussed in [3], [8] and [22].

4.2.3 Test results

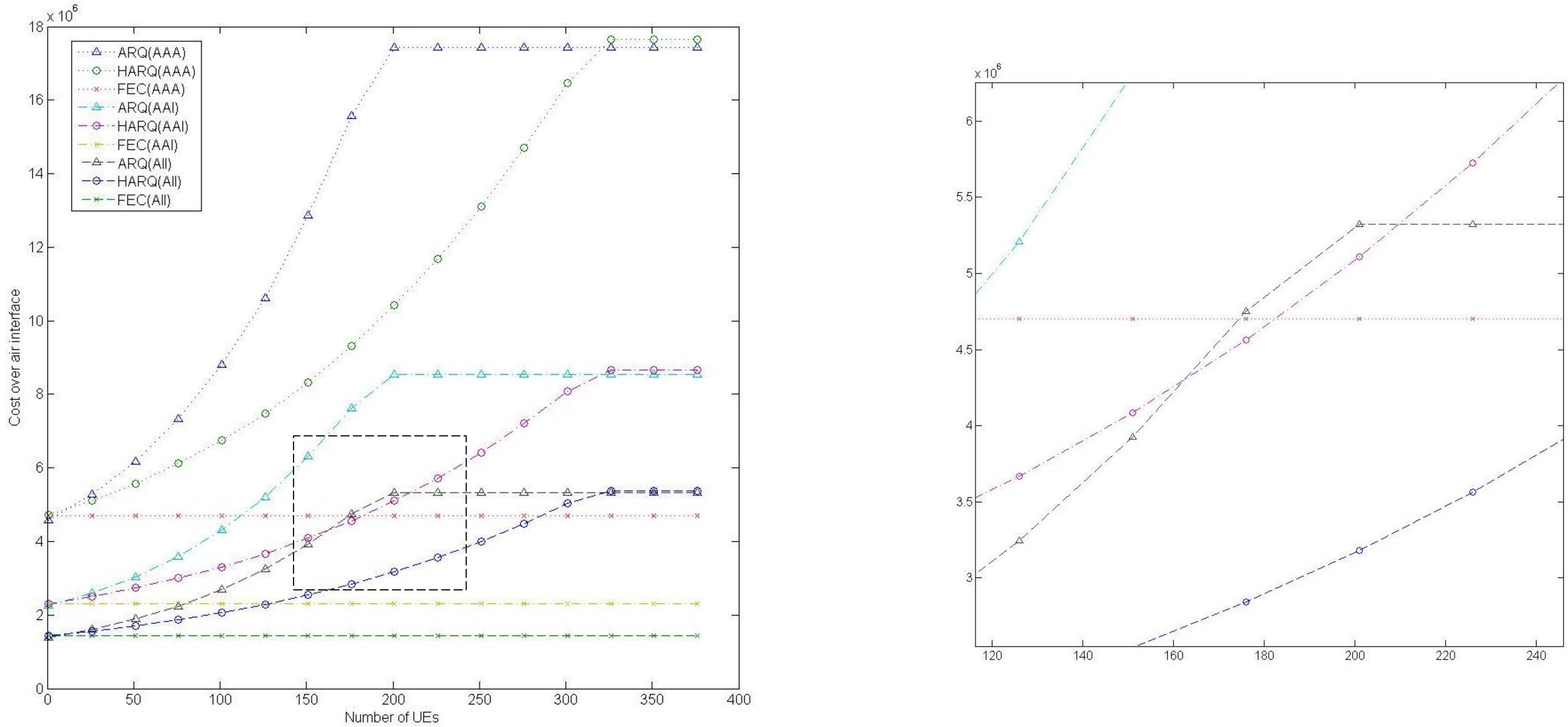

Figure 9: User Population vs. MBSFN Cost - Case 1, k = 2. The bordered section is enlarged on the right to show more detail.

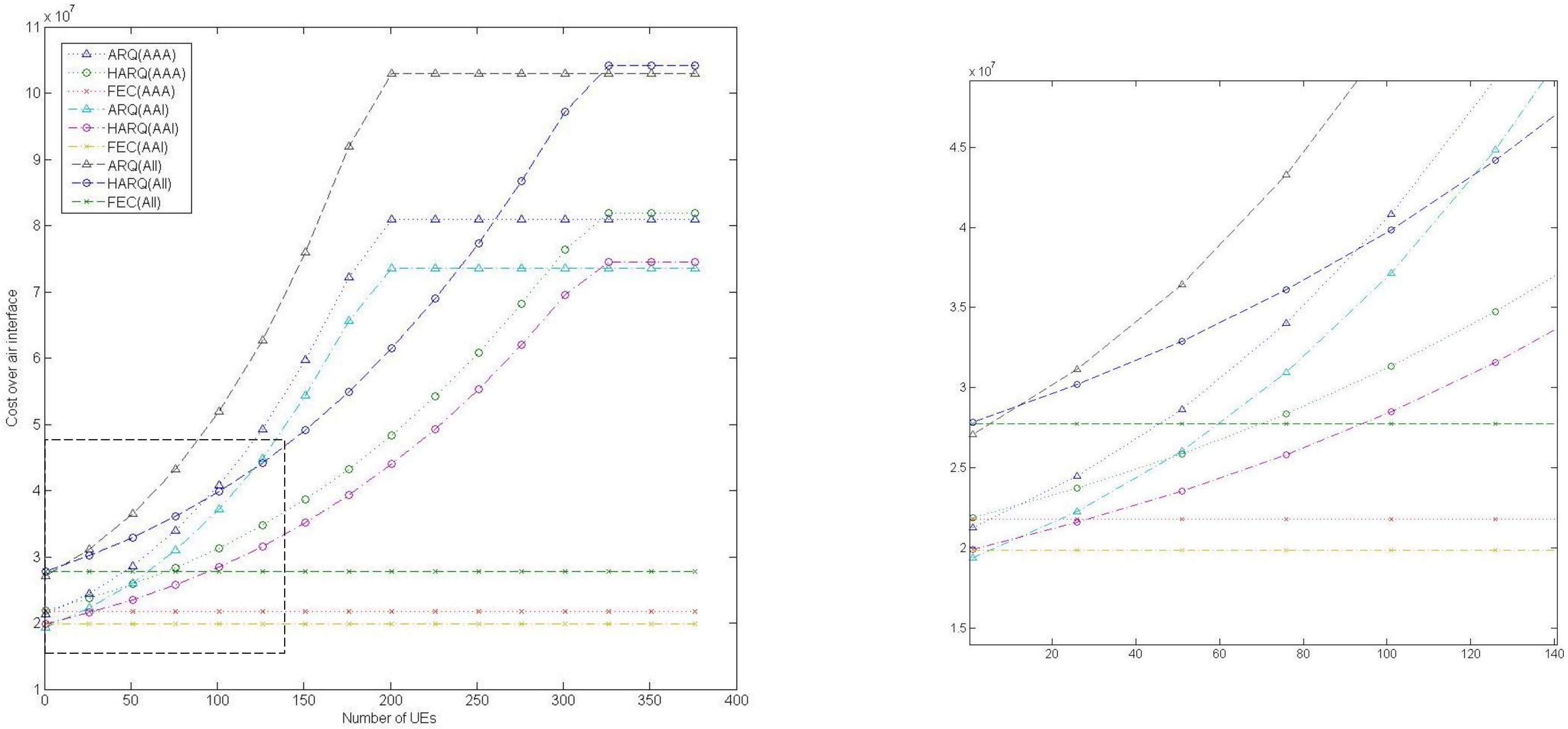

Figure 10: User Population vs. MBSFN Cost - Case 1, k = 19. The bordered section is enlarged on the right to show more detail.

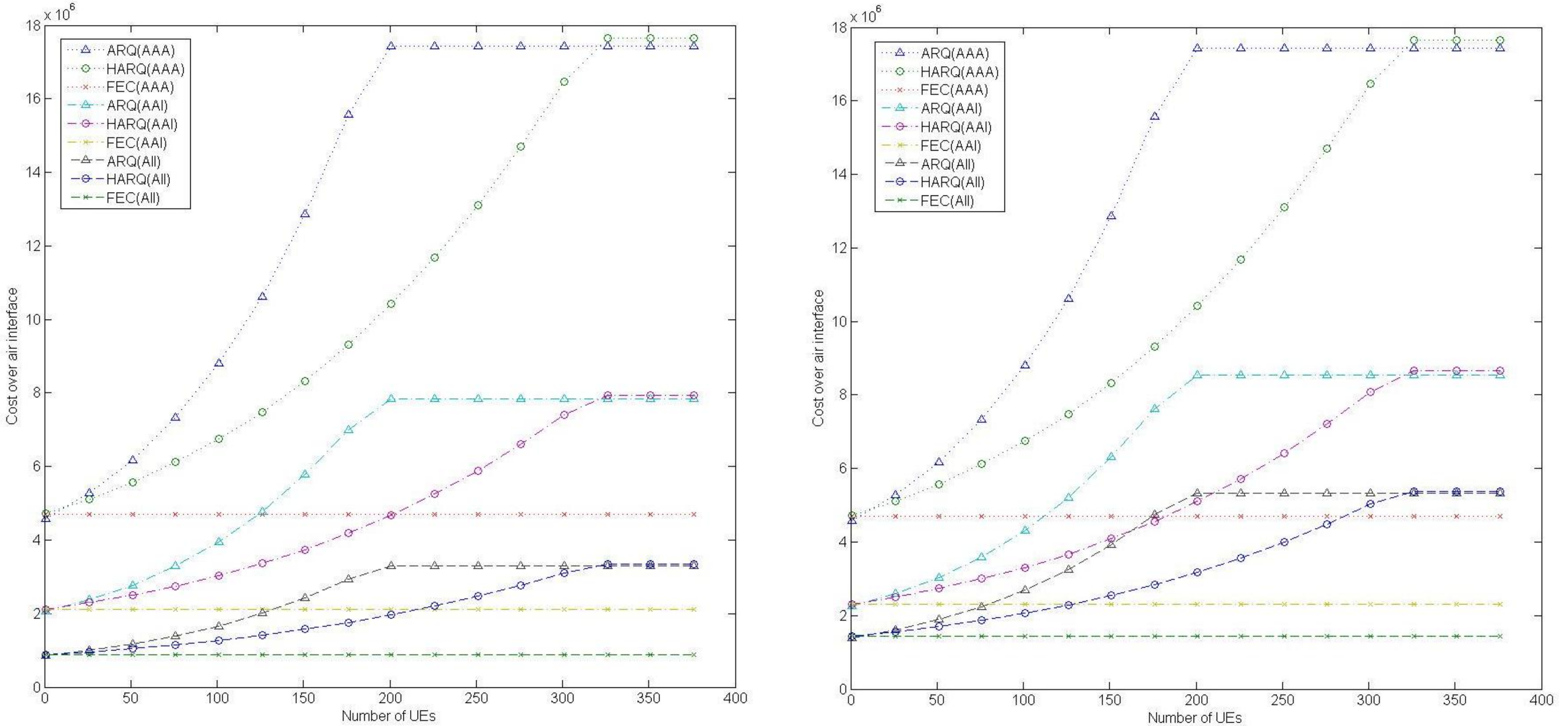

Figure 11: User Population vs. MBSFN Cost – Case 3, k = 2. Figure 9 (Case 1, k = 2) is repeated on the right to aid visual comparison.

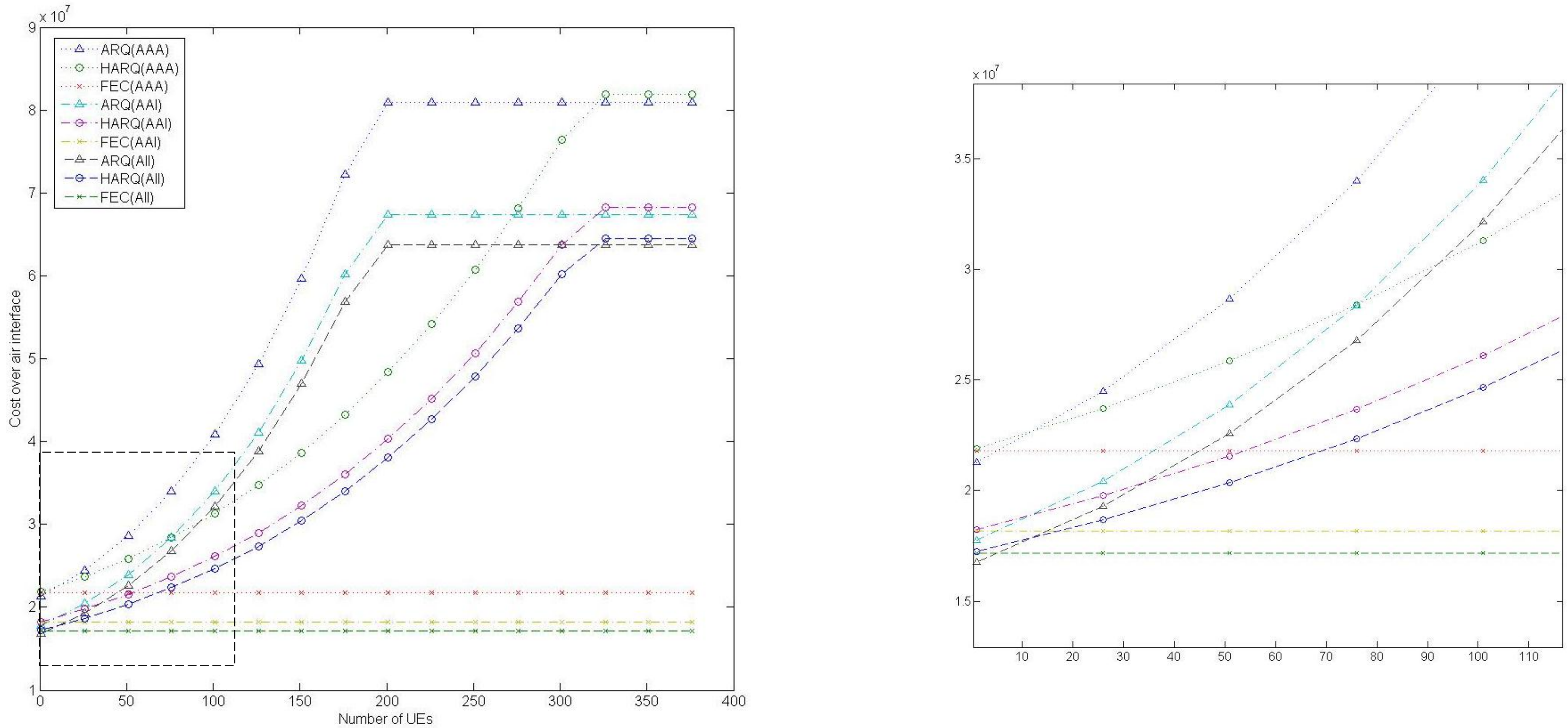

Figure 12: User Population vs. MBSFN Cost - Case 3, k = 19. The bordered section is enlarged on the right to show more detail.

4.2.4 Discussion

Consider the cost diagram for Case 1 (Figure 9). For each deployment considered, the cost associated with ARQ transmissions quickly grows to a maximum with an increase in user population. A larger number of users results in a higher probability of transmission failure, increasing the number of required retransmissions. 3GPP specifications dictate that ARQ cost is at a maximum if each data packet in the session is retransmitted three times, creating the cost ceiling evident in the figure [20]. A hybrid combination of ARQ and FEC techniques (labelled HARQ in the figure) will provide a better cost characteristic. A constant FEC overhead of 5% is assumed. Even though FEC transmission introduces a high overhead into the system, it is less affected by packet losses since each receiver can tolerate a number of lost packets and still be able to decode all source packets correctly. This results in a lower overall cost than ARQ for user populations less than 300 [22]. When the population rises to above 300, the probability that each packet needs to be retransmitted a maximum number of three times increases to near unity, resulting in a cost ceiling. For HARQ, the maximum cost is slightly higher than for ARQ as it includes a small FEC overhead for each data packet. The third approach is a purely theoretical approach and was proposed by [8]. It utilizes only forward error correction. Since FEC is completely unaffected by individual errors at isolated receivers, this approach can scale to any number of users without a rise in total cost. It can be shown, however, that the required overhead might become unacceptably high for a high number of users. This approach will also require a significant amount of feedback from each subscribed user to ensure that each source block has been correctly decoded [22].

The results also illustrate the relationship between the different deployments considered (AAA, AAI, AII). Figure 9 is a small network, with the number of cell rings containing subscribed users (K) equal to two. For this smaller network the AAA-deployment has proportionally the highest average cost for all three error correction paradigms, followed by AAI and with AII the lowest-cost option. This is because of the inefficient use of resources when a large number of cells assist in the MBSFN transmission, with only a small subset actually containing subscribed users [9]. There are, however, multiple points of intersection between the individual error correction curves for each deployment. For example, from the enlarged section in the figure it is clear that for a simulation scenario of between 160 and 205 users, an ARQ-FEC combination in an AAI deployment would be a lower-cost solution than an AII-deployment using ARQ as error correction. In the same way, pure FEC in an

AAA-deployment will be lower-cost than ARQ and HARQ in the proportionally lower-cost AAI and AII deployments for user populations larger than 300.

Figure 10 presents a much more complex picture. The network size has grown to a total of 19 cell rings containing subscribed users (k = *19*) with the costs associated with each deployment having converged. AII-deployments are now proportionally the highest-cost solutions, followed by AAA and AAI. However, for a population between 50 and 280 UEs, an AAA-deployment with HARQ will be a lower-cost solution than AAI with ARQ. AII with HARQ will provide a lower overall telecommunications cost than both AAA and AAI with ARQ, for a population between 125 and 235. Several other points of intersection can be identified from the figure, with all curves converging for small populations. To show the complex interrelationship between the deployments for small populations, a section of the figure is enlarged showing several points of intersection.

Now consider the same test done on a Case 3 network (Figures 11 & 12). Though the results are similar to those for a Case 1 network, the different deployments compare differently to each other, with AAA still most expensive for smaller networks. For a large network (k = 19), the curves associated with each deployment has converged in a similar manner to those for Case 1 networks. However, AAA remains the most expensive deployment for this setup, followed by AAI and AII (in that order). For more on the effect of network size on the total telecommunications cost for each deployment, see Section 4.5.

4.2.5 Validation

The results of this test are used to validate the simplified model for over-the-air MBSFN transmission, by comparing it to a similar model. The mathematical model was validated by comparing simulation results to analyses published in [3], [9] and showed good correlation. Even though this new model uses some approximations and assumptions for a simpler, faster model, it correlates well with published results. For a detailed discussion and the computation of a correlation coefficient with literature, see Chapter 5 Section 5.3. All other tests published in this document are new tests – either unpublished or significantly different from published sources as far as our literature survey could determine.

4.3 Test 2: Packet Loss Rate vs. MBSFN Cost

4.3.1 Test Scope and Purpose

We next investigate the effect of a varying packet loss rate on the performance of the three defined error correction paradigms. Once again this test is conducted using a simplified MBSFN cost model for data transmission over the air interface of the LTE system. We seek to quantify the relationship between the costs of these error correction approaches when each is applied to three different MBSFN deployments (AAA, AAI, AII), if they are plotted against an ever increasing nominal packet loss rate. A third dimension, the size of the selected topology, will affect the results of the test significantly and is discussed and measured as well. The model will provide a first order answer to selecting the lowest-cost combination of deployment and error correction scheme given the packet loss rate of the air interface.

4.3.2 Simulation Setup

The test is conducted for both of the macro Cases that our model was designed for. Macro Case 1 corresponds to an ISD of 500m and Case 3 to an ISD of 1 732m. Note that, although the macro Cases are presented in different result sets for the sake of simplicity, the model is able to compare costs between deployments of each of the cases and will eventually be able to suggest a lowest-cost case for a specific scenario, considering all parameters. Propagation characteristics are similar to those used for Test 1. The simulation session consists of 10 000 data packets in a hexagonal grid of e-NB cells with a fixed population of 100 subscribed users. To show the effect of the third dimension (network size), the results of this test are presented for a small network and a large network for each macro Case. The smaller network contains UEs in the centre cell and the first two cell rings surrounding the centre. This amounts to a total of 19 UE drop locations. For the larger network, a total of 19 cell rings (plus the centre cell) contains subscribed UEs – i.e. 1 141 cells. We increase the nominal packet loss rate in intervals of 1% to around 30% for each test. The local loss rate is still 10% of the nominal loss rate, while the global loss rate is at 90% of the nominal. The FEC overhead is variable to show its effect on costs – results are published for a 5% and a 15% FEC overhead for each Case and network size.

4.3.3 Test Results

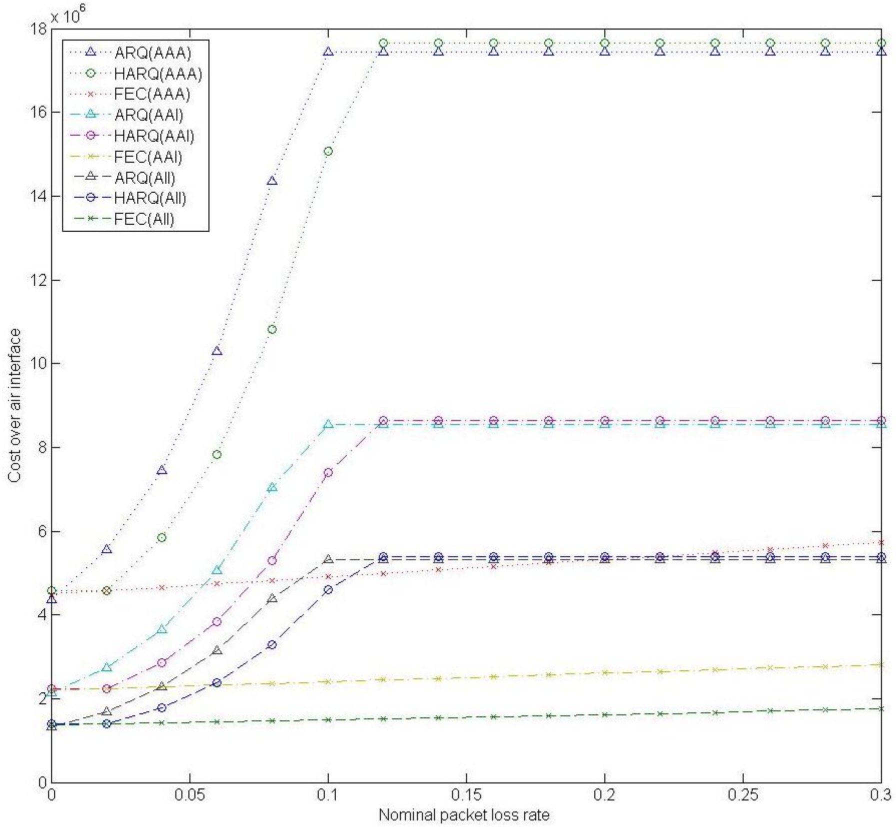

Figure 13: Packet Loss Rate vs. MBSFN Cost – Case 1, k = 2, FEC = 5%

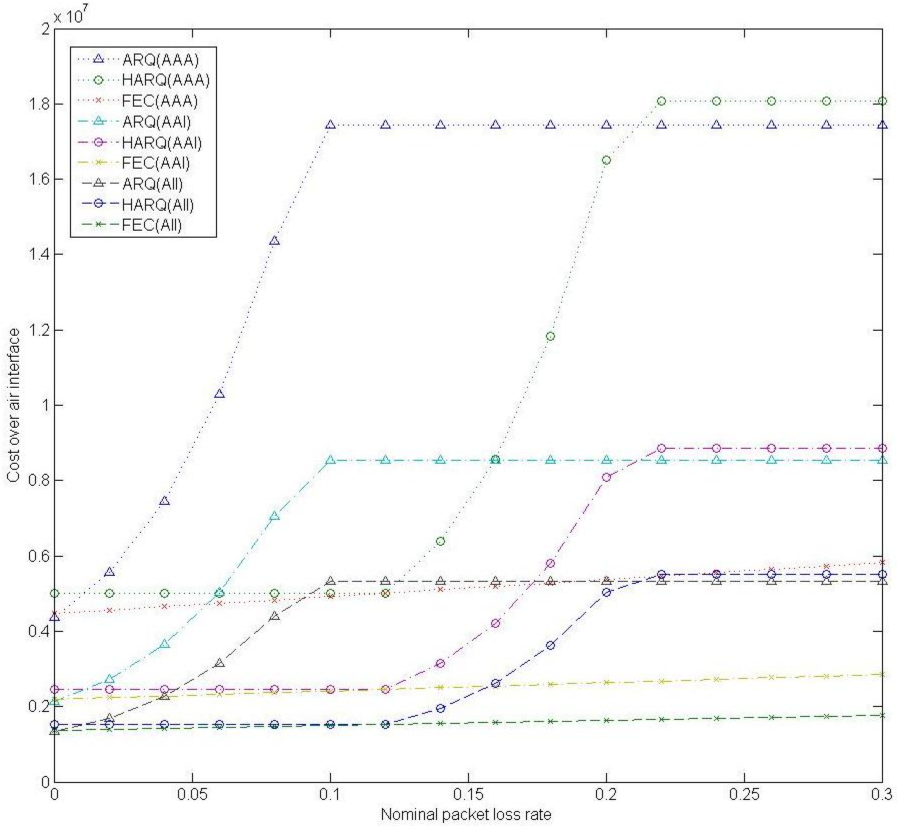

Figure 14: Packet Loss Rate vs. MBSFN Cost – Case 1, k = 2, FEC = 15%

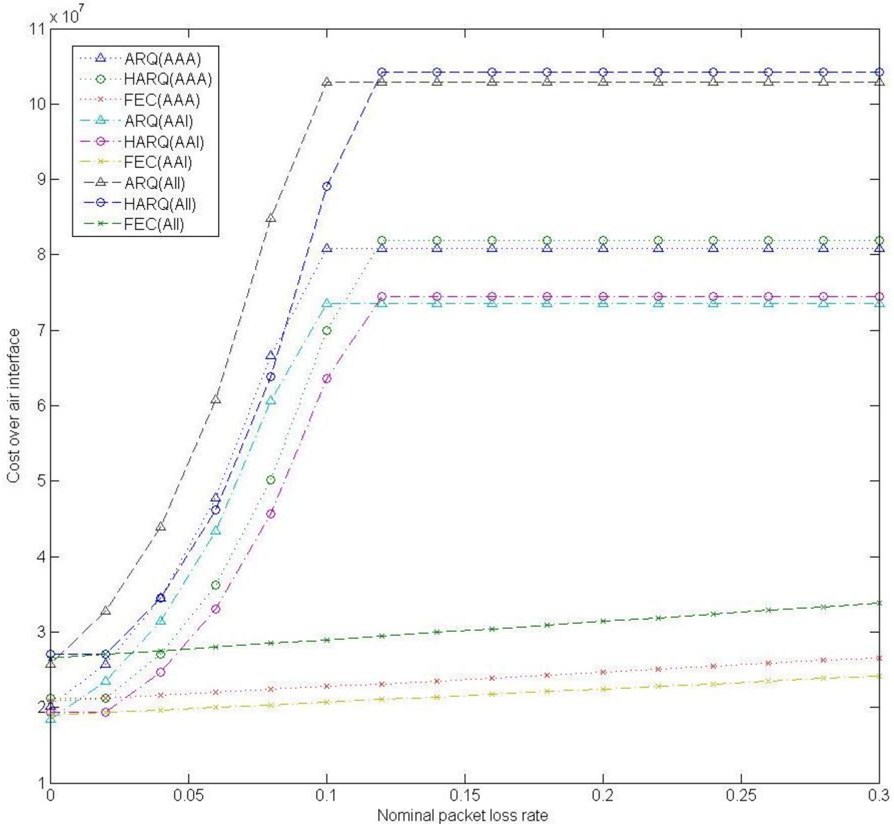

Figure 15: Packet Loss Rate vs. MBSFN Cost – Case 1, k = 19, FEC = 5%

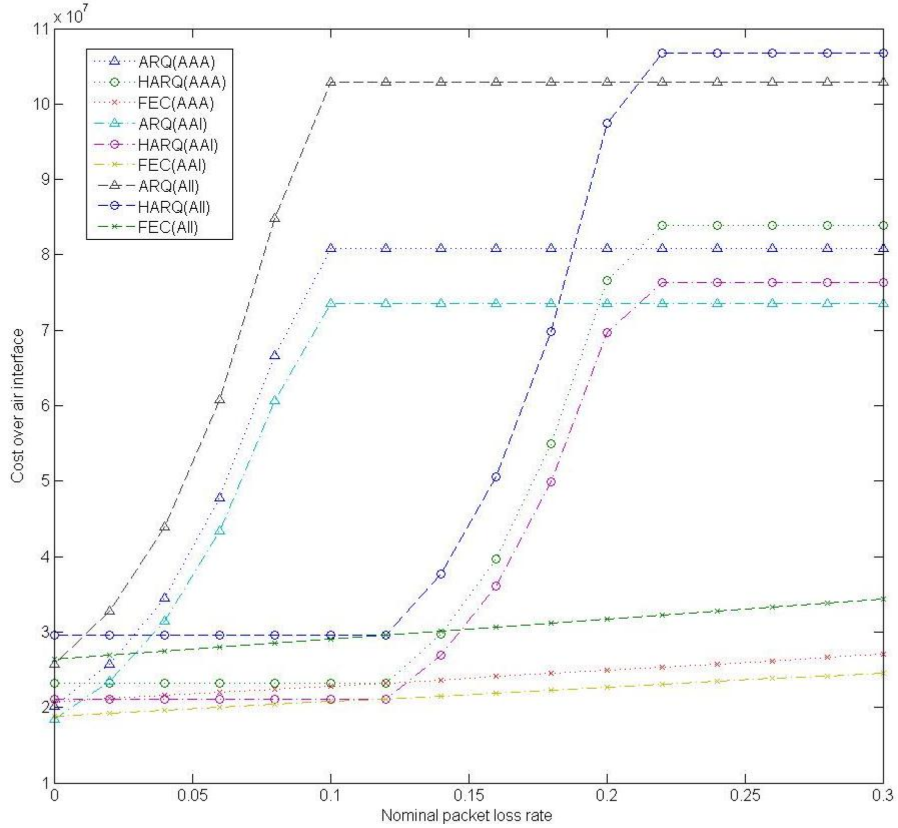

Figure 16: Packet Loss Rate vs. MBSFN Cost – Case 1, k = 19, FEC = 15%

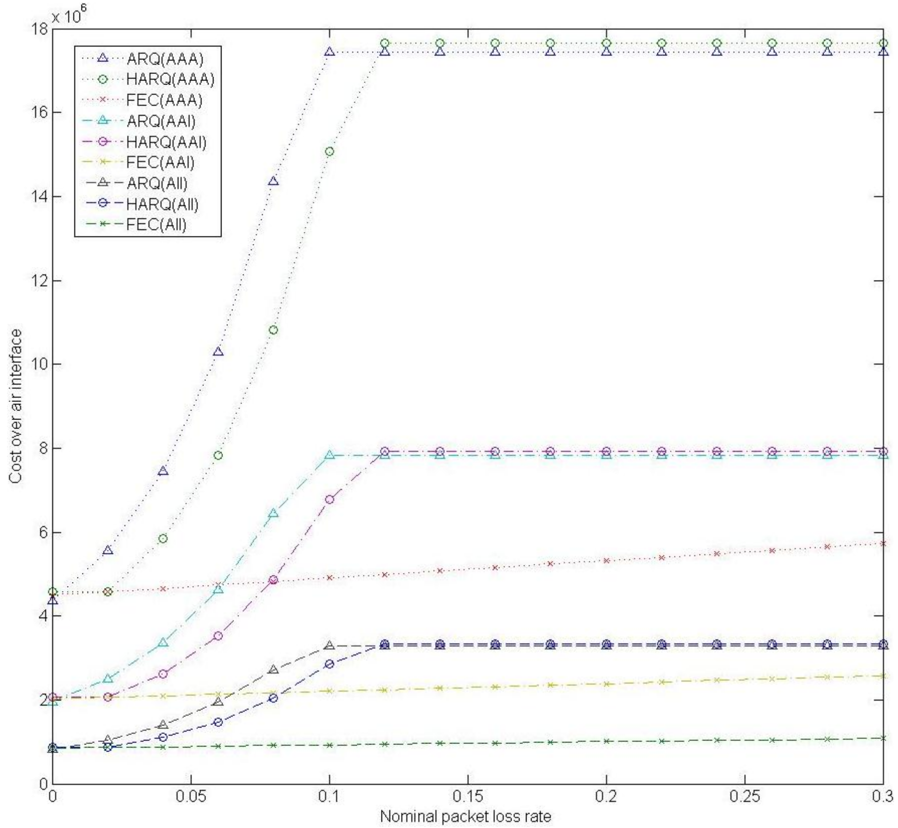

Figure 17: Packet Loss Rate vs. MBSFN Cost – Case 3, k = 2, FEC = 5%

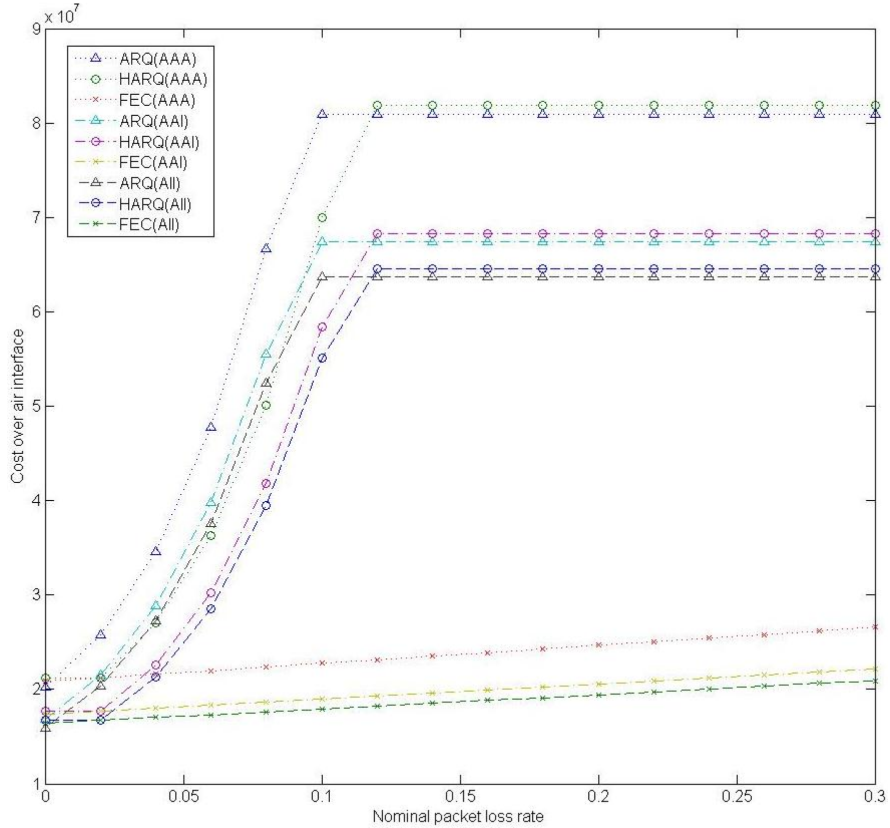

Figure 18: Packet Loss Rate vs. MBSFN Cost – Case 3, k = 19, FEC = 5%

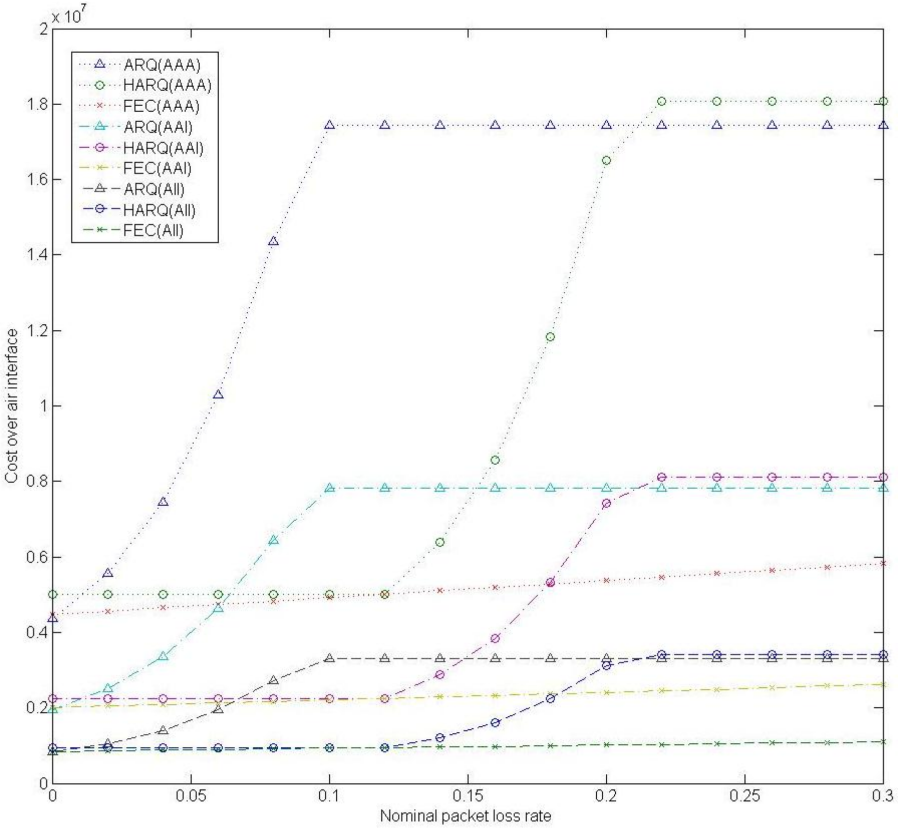

Figure 19: Packet Loss Rate vs. MBSFN Cost – Case 3, k = 2, FEC = 15%

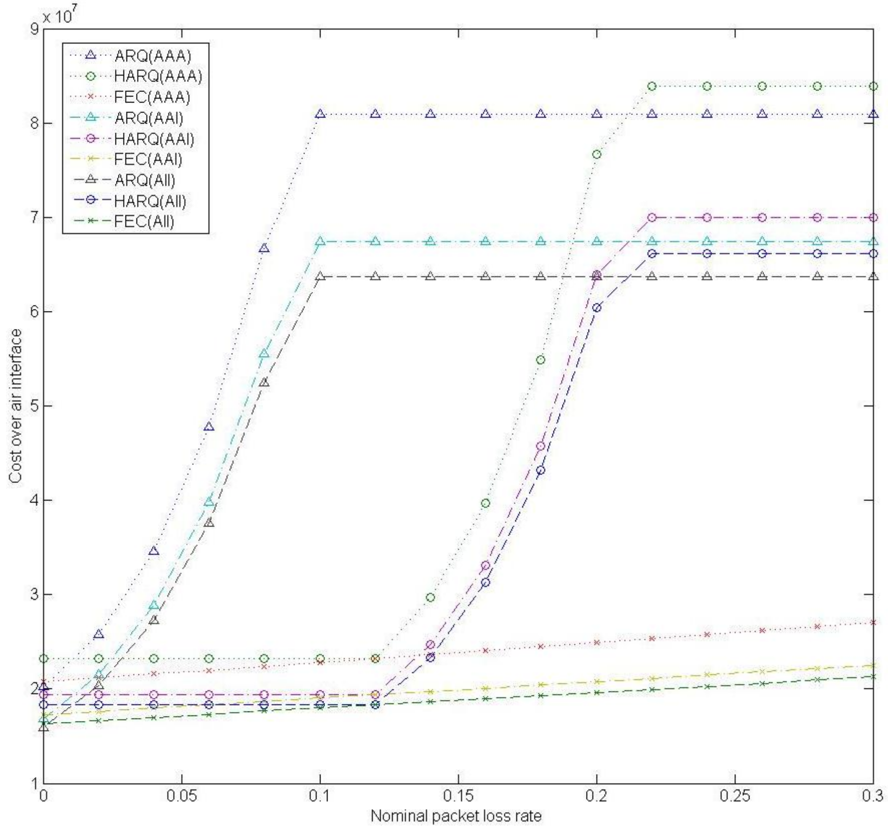

Figure 20: Packet Loss Rate vs. MBSFN Cost – Case 3, k = 19, FEC = 15%

4.3.4 Discussion

From Figure 13 it is clear that ARQ costs increase quickly with an increase in the packet loss rate – a higher number of transmission errors necessitates a higher number of retransmissions. Note that FEC overhead is fixed at 5% in this figure. This results in the HARQ costs for all three deployments remaining constant, or closely following the ideal curve for pure FEC, for nominal packet loss rates of under 3%. This is because the fixed amount of FEC overhead included in the data provides enough redundancy to decode the source message, even with some losses in the transmission. As soon as the packet loss rate increases to above 3%, the HARQ costs for each deployment increases at the same rate of change as that of the ARQ costs for the same deployment (the parallel lines in the figure). Both ARQ and HARQ (for each deployment) reach a maximum cost at a nominal packet loss rate of around 10%. The maximum value conditions are the same as those for the previous test (Section 4.2) with a maximum number of allowed retransmissions of three [16]. The pure FEC approach increases incrementally with a rise in packet loss rate, since more packet errors would require a greater amount of FEC overhead to decode the MBSFN transmission with an acceptably low failure probability (see Luby's probability for decoding failure of Raptor codes in Section 3.4.2 and [7], [23]).

Comparing Figure 14 with Figure 13, the effect of FEC overhead becomes clear. Figure 14 presents the same macro Case and network size than that of Figure 13, but with a fixed FEC overhead of 15% as opposed to 5%. The HARQ costs remain constant for longer for each deployment, as the large amount of FEC overhead is enough to decode the source message even with a considerable amount of transmission errors. Also, the larger overhead added to each retransmitted packet results in a larger maximum cost for HARQ costs at the maximum allowed three retransmissions per packet.

Several quantitative conclusions can also be drawn from the side-by-side comparison of Figures 13 and 14. Since packet retransmissions quickly increase the cost of communication (the sections of the ARQ and HARQ curves with the steepest slope), it should be avoided. The minimum inflection point of each of the HARQ-curves in Figure 13 indicates that, with a fixed FEC overhead of 5%, packet losses of up to 3% can be tolerated before retransmissions are required. However, the same inflection points in Figure 14 occur only at a much higher packet loss rate of 12%. This reveals that the higher FEC overhead of 15% will allow for the maximum allowable packet loss rate to be pushed up to at least 12% before retransmissions are required. Another important deduction can be made from the maximum inflection points of each of the curves. Once the maximum allowable number of retransmissions is reached, extra retransmission requests for the same data packet from subscribers will be ignored and they might be unable to fully decode the source message. Therefore the maximum inflection points indicate the maximum packet loss rate at which that error correction technique can reliably be used, while still allowing for all subscribers to correct all transmission errors. Figures 13 and 14 indicate that ARQ can only be used as error correction technique in MBSFN systems where the packet loss rate is less than 10%. Our model predicts that for a packet loss rate higher than this, transmission errors could be unavoidable. HARQ can be reliably used as error correction technique under conditions where the loss rate is up to 12% (assuming a FEC overhead of 5%) and up to 22% if the amount of fixed FEC overhead is 15%.

In Figure 15 the network is larger ($k = 19$), changing the relationship between different deployments. Specifically, AII is now proportionally the most expensive deployment, with AAI the least expensive solution. This is because of the much higher spectral efficiency of AAA and AAI when compared to AII, as discussed in Section 3.3 [18]. The relationship between individual curves are however more complex than that, with many points of intersection evident in the figure. Figure 16 presents the same scenario as Figure 15, but with a much larger fixed FEC overhead. The comparison of Figure 16 with Figure 15 is analogous to the discussion above comparing Figures 13 and 14.

Figures 17 to 20 repeat the tests in Figures 13 to 16, but for macro Case 3 (ISD of 1 732m). The results are much the same as those already discussed, but note that the three deployments considered overlap less for smaller networks. The side-by-side comparison of Figures 17 and 18 illustrates the effect of network size on the communication cost. Note that for the smaller network ($k = 2$) in Figure 17, the total cost for each deployment option is considerably lower (in the order of 10^6) than that for the larger network in Figure 18 (with costs in the order of 10^7). It is clear that for a larger network, there are many more points of intersection between the individual error correction cost curves of each deployment, indicating that the decision for a lowest-cost error correction scheme becomes more complex as the network grows in size. This is because the subscribed users are more distributed in a larger network. The effect of network size on communication costs is thoroughly examined in Section 4.5.

4.4 Test 3: FEC Overhead vs. MBSFN Cost

4.4.1 Test Scope and Purpose

We now vary the amount of fixed FEC overhead in our second error correction approach – using a combination of ARQ and FEC – in order to demonstrate our model's ability to determine the optimal FEC overhead for a specific MBSFN setup. Costs are compared between three MBSFN deployments (AAA, AAI, AII) and each error correction paradigm. Two more dimensions are considered and their effects demonstrated: the packet loss rate will influence the point of optimal FEC overhead; the size of the selected topology greatly influences the relationship between the three different MBSFN deployments.

4.4.2 Simulation Setup

For this test we assume a macro Case 1 network with an ISD of 500m. For all tests a total of 10 000 data packets are transmitted in the simulation. We also assume a fixed population of 100 subscribed users. Propagation characteristics are similar to the previous tests (Sections 4.2 – 4.3). We illustrate the effect of network size on the total communications cost by publishing results for a small network (*k = 2*) and for a large network (*k = 19*). Another important dimension for this test is the effect of the nominal packet loss rate on the optimal point of FEC overhead for a combination ARQ-FEC setup. The packet loss rate was investigated in detail in a previous test (Section 4.3), so for this test we only publish results for loss rates of 5% and 10% for each simulation setup. The fixed FEC overhead in the combination ARQ-FEC error correction approach (labelled "*HARQ*" in all figures) are increased from 1% to 15% in intervals of 1%. The local loss rate is still 10% of the nominal loss rate, while the global loss rate is at 90% of the nominal. As per 3GPP specifications , the maximum number of retransmissions in the ARQ and HARQ schemes is three [16].

4.4.3 Test Results

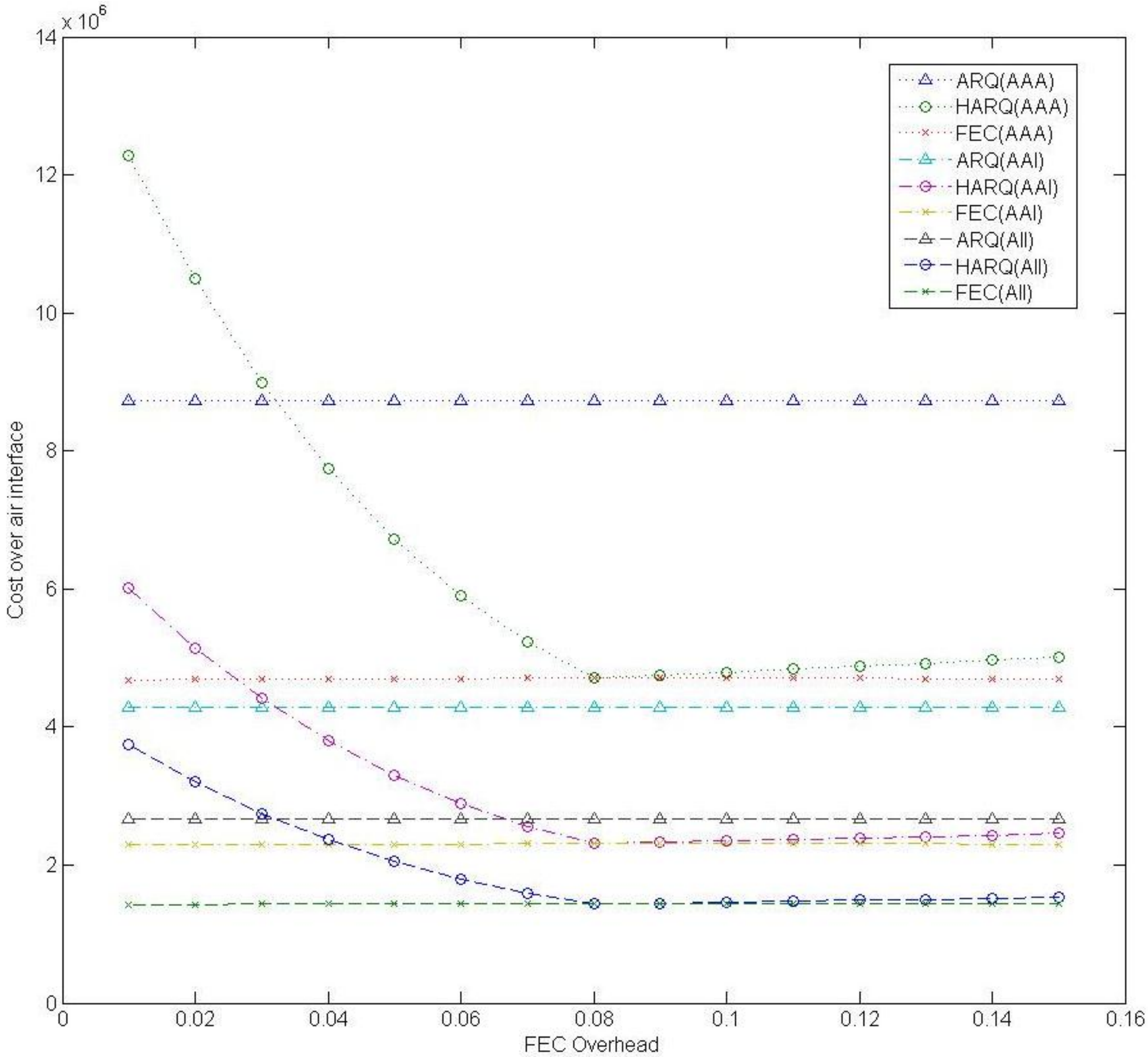

Figure 21: FEC Overhead vs. MBSFN Cost – Case 1, k = 2, Packet loss rate = 5%

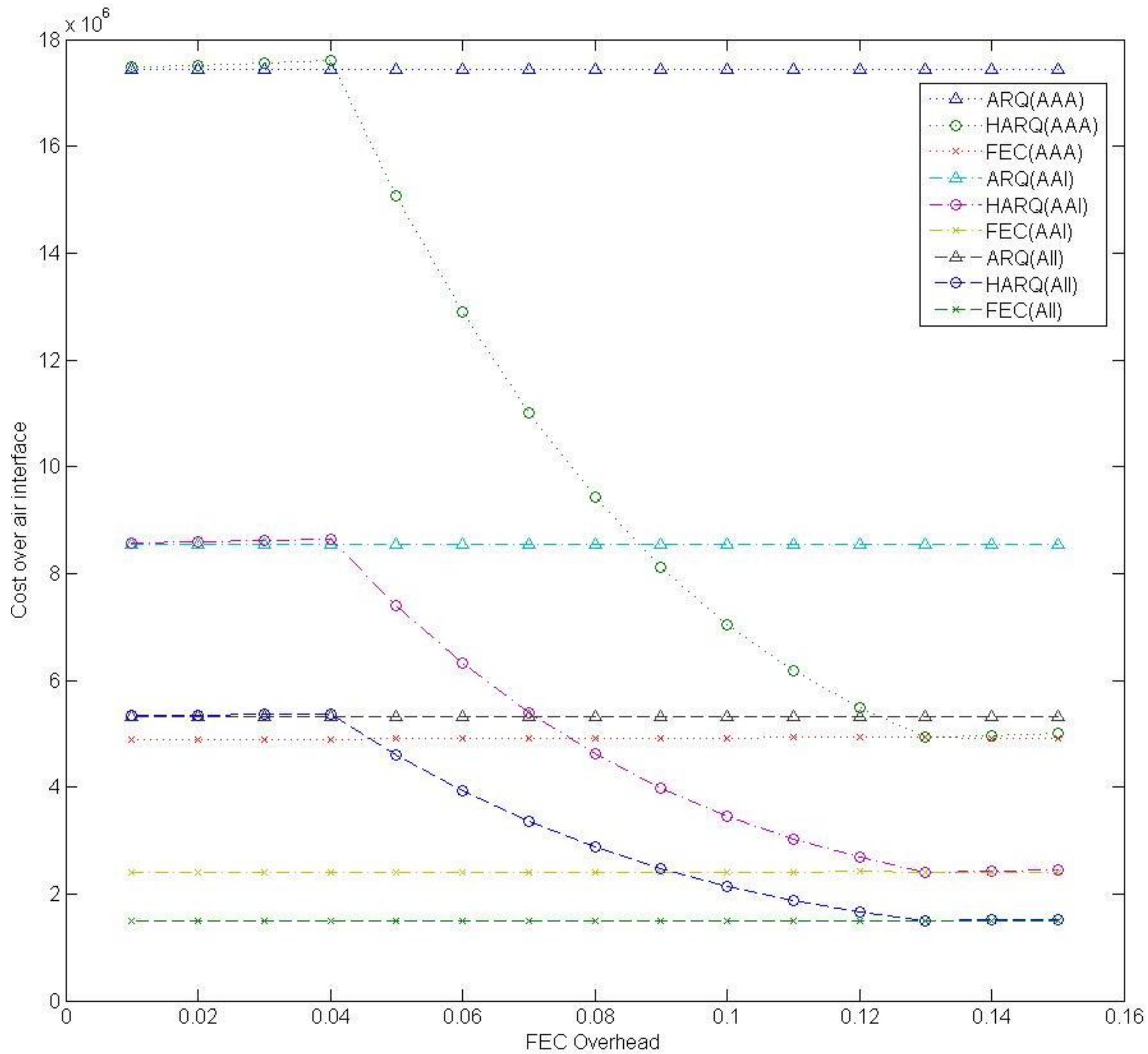

Figure 22: FEC Overhead vs. MBSFN Cost – Case 1, k = 2, Packet loss rate = 10%

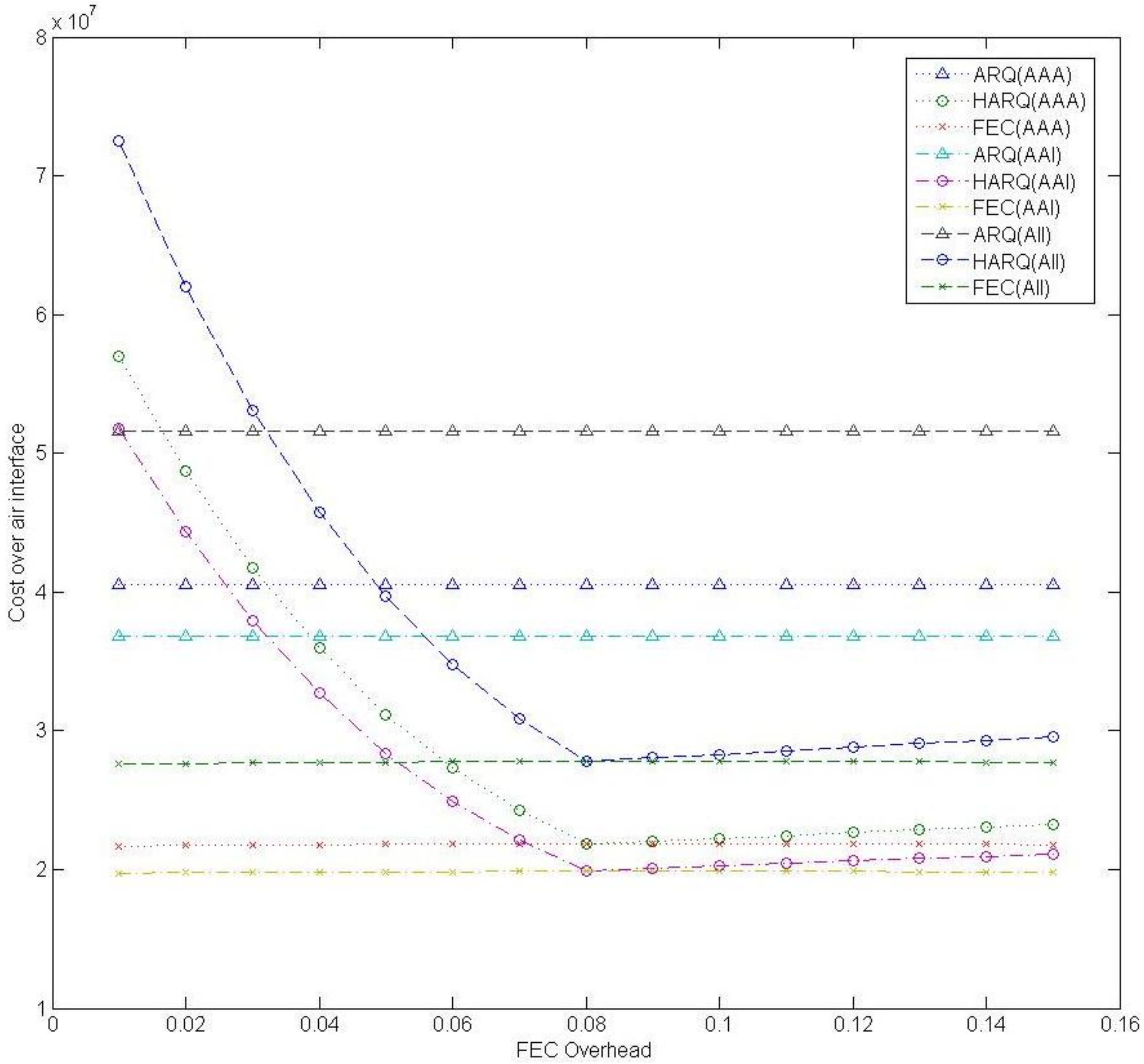

Figure 23: FEC Overhead vs. MBSFN Cost – Case 1, k = 19, Packet loss rate = 5%

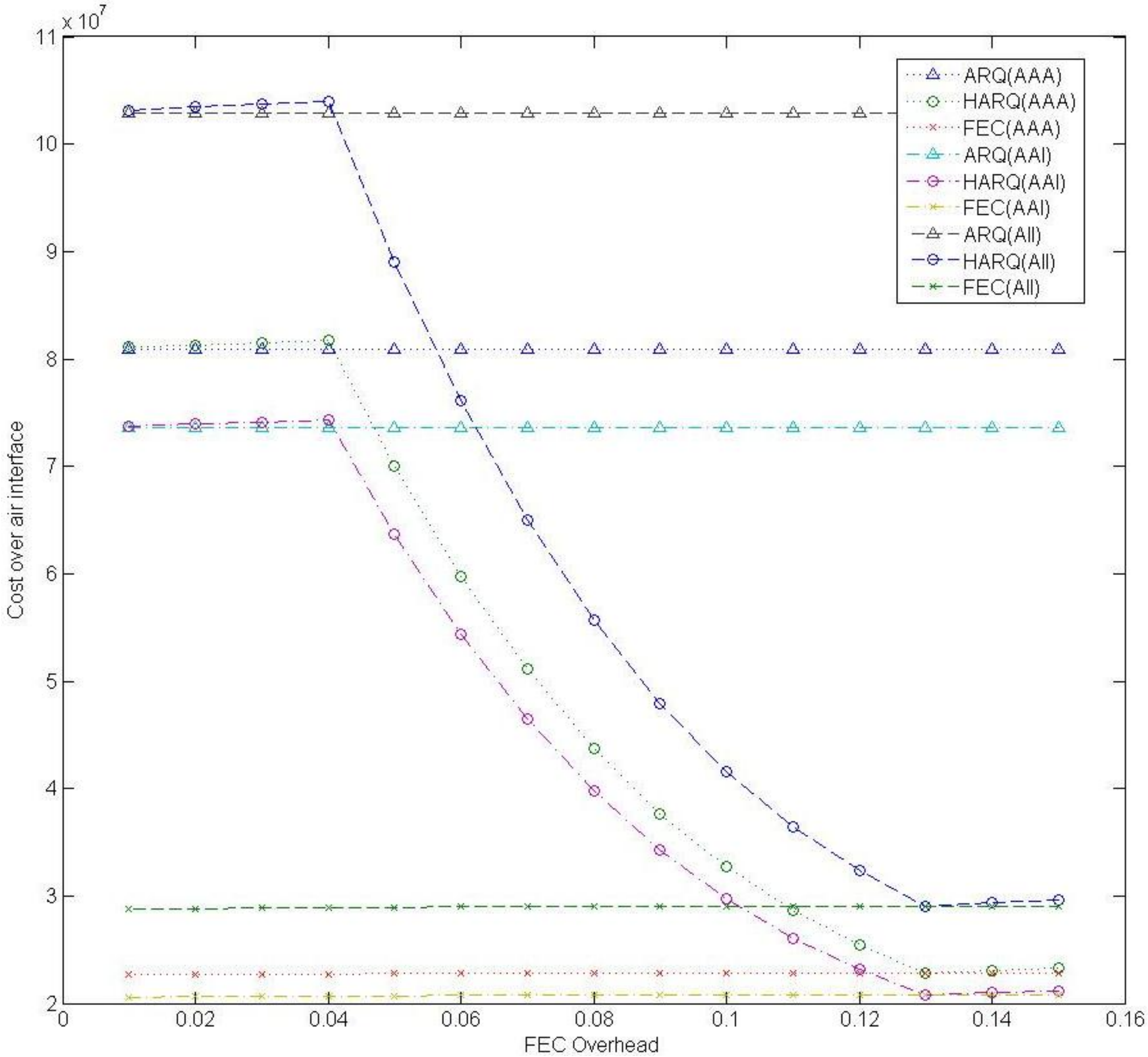

Figure 24: FEC Overhead vs. MBSFN Cost – Case 1, k = 19, Packet loss rate = 10%

4.4.4 Discussion

Figures 21 to 24 present the total telecommunications cost as a function of the fixed FEC overhead in HARQ in a number of different scenarios. Since the ARQ and pure FEC approaches do not contain any fixed FEC overhead they are independent of this variable and their respective cost values remain constant. Both values are included in this figure, however, to show the points of intersection between the curves. The amount of fixed overhead does impact the telecommunications cost of the combination ARQ-FEC approach significantly. For each deployment the lowest cost point on the HARQ curve, intersecting with the constant pure FEC cost value, is the optimal fixed FEC overhead point for that system. In Figure 21, with a packet loss rate of 5%, that optimal point is shown to be a fixed FEC overhead of 8% for all three deployments considered. For lower FEC overhead conditions (1% to 7%) the cost is high because of the large number of retransmissions required to successfully recover the source message from a lossy transmission. In these cases the prefixed FEC overhead does not provide enough redundancy to counter the packet losses and there is a high probability that the source message will not be successfully decoded (see Equation 8 in Chapter 3). For FEC overhead values larger than 8%, the total cost increases without having any effect on the system’s performance [8]. This is because the fixed FEC overhead will already provide enough redundancy to successfully decode the source message at 8% and any extra overhead is unnecessary. Note that the HARQ and pure FEC curves intersect at the 8% point, indicating that at this point the fixed FEC overhead is exactly enough to decode the source message successfully for this packet loss rate without requesting any retransmissions from the source. Determining this point can be difficult in the real world though, since it requires accurate knowledge of the loss characteristics of the utilized communication channel. Nevertheless, it provides a sufficiently low communication cost, close to the ideal, to be a main point of investigation in this study. Amongst other things, it will indicate to operators the type and number of Raptor Code symbols to be used in the transmission.

In Figure 22 the loss rate has increased to 10%. Since more packets are lost during transmission, a higher FEC overhead is required to successfully decode the source message. In this case the optimal fixed FEC overhead is around 13%. For this high packet loss rate, there is a slight increase in the HARQ costs for FEC overhead values of 1% to 4%. This is because the added FEC overhead is not enough to avert any retransmissions, but does require the transmission of redundant data. We can conclude from this that, under conditions where the packet loss rate is up to 10%, it is inefficient to add FEC overhead of less than 4%. At 4% the HARQ curves for each deployment forms a local maximum inflection point and rapidly falls to the minimum inflection point as the number of required retransmissions decreases. Figures 23 and 24 repeats these two tests, but for a large network ($k = 19$). Results are similar to Figures 21 and 22 for each individual deployment, but the relationship between different deployments has changed, with AII now the most expensive solution and AAI the least expensive. For a detailed discussion on the effect of network size on costs, see Section 4.5.

4.5 Test 4: User Distribution vs. MBSFN Cost

4.5.1 Test scope and purpose

With this test we illustrate the effect and complex nature of the all-important "third dimension" in previous tests, namely the network size. The total telecommunications cost in the MBSFN system is depicted as a function of the number of hexagonal cell rings actually containing UEs subscribed to the multicast transmission. Since the number of UEs is a constant for each scenario, a larger network implies a wider distribution of UEs, whereas a smaller network, containing the same amount of UEs, implies a dense user distribution. For this reason, the test can be regarded as a *user distribution test*. We compare the costs of the three MBSFN deployments (AAA, AAI, AII) with the error correction paradigms applied to each. The telecommunications cost and the relationship between the MBSFN deployments are further dependent on the amount of fixed FEC overhead in the HARQ-approach and the packet loss rate. We consider both variables in our test. This test provides a first order answer to selecting the lowest-cost MBSFN deployment combined with an error correction scheme, given a user distribution.

4.5.2 Simulation Setup

The test is completed for two macro Cases – macro Case 1 with an ISD of 500m and macro Case 3 with an ISD of 1 732m. Similar to previous tests, a total of 10 000 data packets are transmitted in the simulation, with a fixed user population of a 100 subscribed users. Propagation characteristics are the same as in previous tests (Sections 4.2 – 4.4). The main independent variable in this test is the network size. The size is expressed as the number of hexagonal cell rings containing UEs subscribed to the MBSFN transmission (the variable k in previous tests). The size is increased from 0 cell rings (UEs are all contained in the centre cell) to a large network of 20 cell rings. We publish results for a packet loss rate of 5% and 25%. The fixed FEC overhead in the combination ARQ-FEC error correction approach (labelled "*HARQ*" in all figures) are increased from 5% to 15% in two separate scenarios. The local loss rate is still 10% of the nominal loss rate, while the global loss rate is at 90% of the nominal.

4.5.3 Test Results

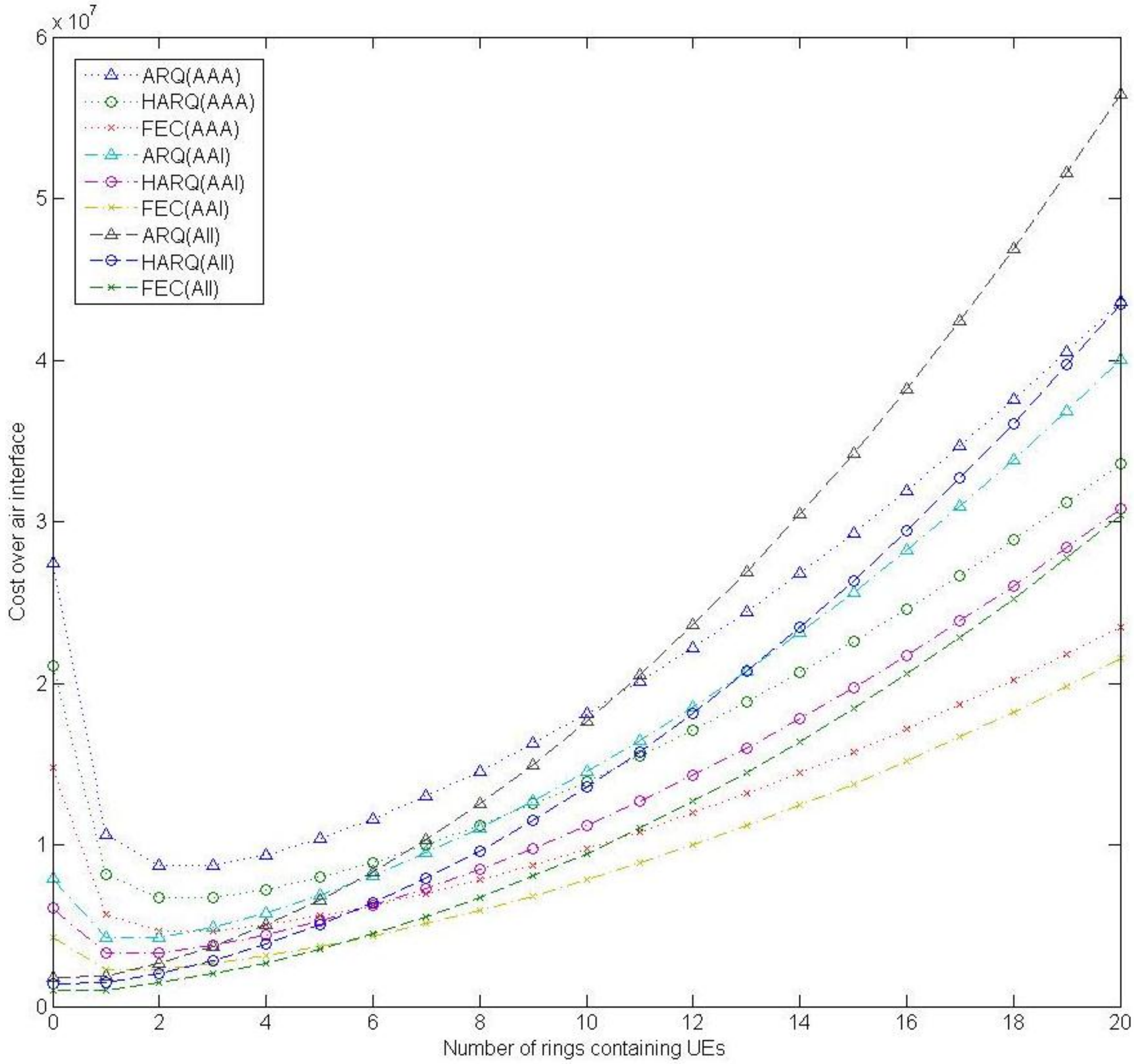

Figure 25: User Distribution vs. MBSFN Cost – Case 1, Packet loss rate = 5%, FEC Overhead = 5%

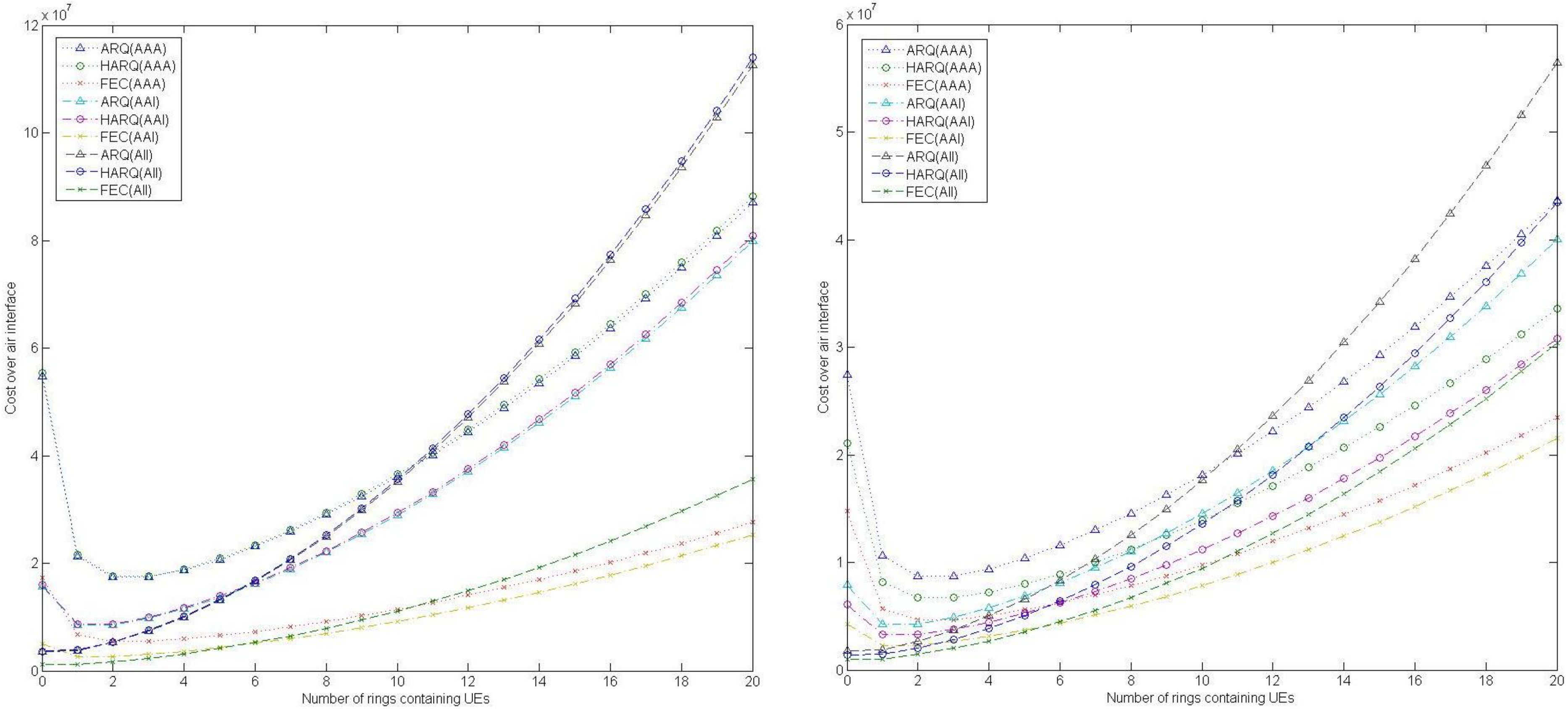

Figure 26: User Distribution vs. MBSFN Cost – Case 1, Packet loss rate = 25%, FEC Overhead = 5%. Figure 25 (Packet loss rate = 5%, FEC Overhead = 5%) is repeated on the right to aid visual comparison.

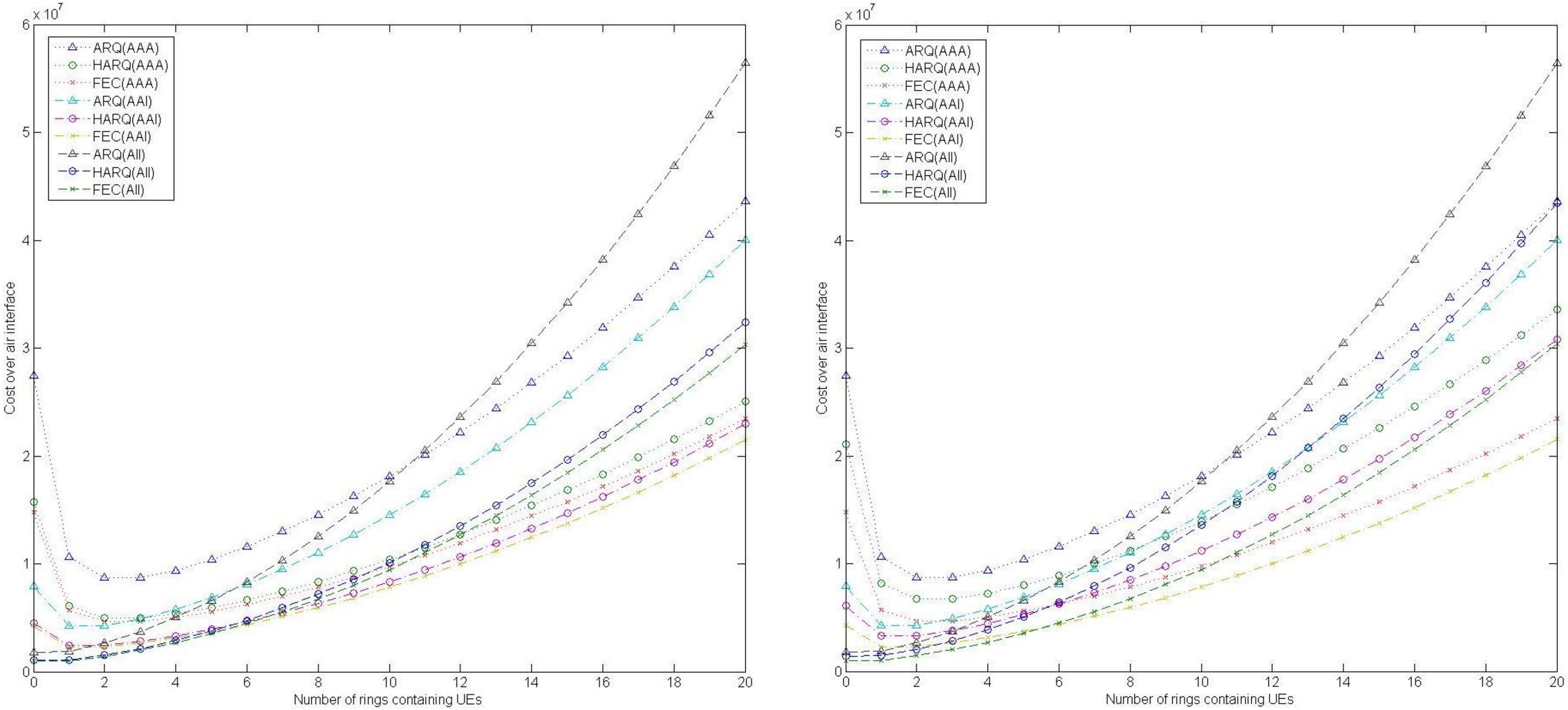

Figure 27: User Distribution vs. MBSFN Cost – Case 1, Packet loss rate = 5%, FEC Overhead = 15%. Figure 25 (Packet loss rate = 5%, FEC Overhead = 5%) is repeated on the right to aid visual comparison.

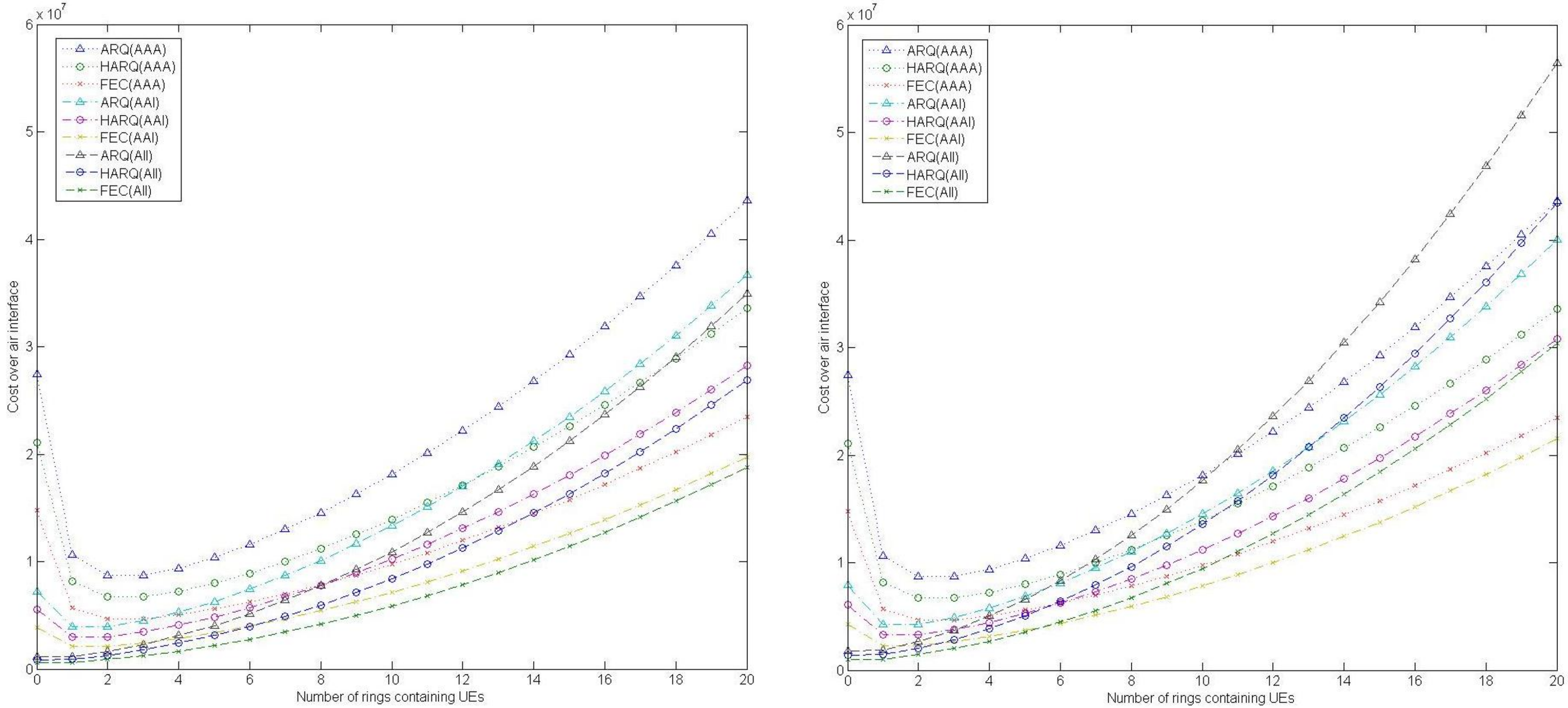

Figure 28: User Distribution vs. MBSFN Cost – Case 3, Packet loss rate = 5%, FEC Overhead = 5%. Figure 25 (Case 1) is repeated on the right to aid visual comparison.

4.5.4 Discussion

Consider Figure 25 with a nominal packet loss rate of 5% and a fixed FEC overhead of 5%. The complex comparison between MBSFN deployments of different sizes is evident in this figure. It is clear that for small topologies, the AII deployment provides the lowest overall cost. At this loss rate and overhead percentage (5% each) we can conclude from our previous results that for each deployment (AAA, AAI, AII) the ARQ-curve will always be the most expensive option for *that* deployment at all network sizes, followed by HARQ and then the pure FEC approach. Therefore, the ARQ(AII)-curve is always above the HARQ(AII) curve in Figure 25, followed by the FEC(AII)-curve tracing the theoretical minimum for an AII-deployment against a growing network size. The same is also true of AAA and AAI-deployments. However, as was shown in previous tests, the network size does determine which of the three deployment options provides the lowest overall cost (average of all three error correction approaches for *that* deployment), so we can expect some points of intersection between the individual cost curves if the network size is varied. In fact, when the number of cell rings containing UEs is 0 (i.e. all users are located in the centre cell), the cost for all three error correction approaches in an AII-deployment is significantly lower than those for AAA and AAI. The high initial costs for the AAA and AAI deployments are a result of the low resource efficiency when the number of cell rings containing UEs is low. The AII-deployment has, however, a lower spectral efficiency than AAA and AAI, resulting in the total cost quickly rising as the topology grows to include more cell rings. At a network size of just *two* rings, the ARQ(AII)-curve already intersects the FEC(AAI)-curve, becoming a more expensive option for networks larger than two rings. It is quickly followed by the HARQ(AII)-curve, crossing the FEC(AAI) curve at a network size of three. The cost curves for AII continue to cross the AAA and AAI-curves, gradually becoming the more expensive option at each point of intersection. For large topologies (number of participating cell rings more than 12), AII is the most expensive deployment option (average cost for the three error correction paradigms), followed by AAA and AAI. From our infinity analysis in Section 3.3 we can conclude that AAA will eventually become the cheapest deployment option if the network continues to grow.

In Figure 26 the packet loss rate is increased to an artificially high 25%, to illustrate the effect that this variable has in the third dimension. The packet loss rate has already been investigated in Test 2 (Section 4.3) and this figure serves to clarify the role that network size plays in determining the communication cost if the packet loss rate is varied. A side-by-side comparison with Figure 25, allows for the higher packet loss rate (25%) to be compared to the lower loss rate of 5%. Note that the cost scale in Figure 26 is double that of Figure 25. A higher loss rate implies a larger number of retransmissions, increasing the total telecommunications cost for the ARQ and HARQ error correction schemes considerably. Since both of these error correction paradigms approach the maximum number of retransmissions at this high loss rate, the individual ARQ and HARQ curves converge for each MBSFN deployment, as can be seen from the side-by-side comparison with Figure 25

Comparing Figure 27 with Figure 25, shows the effect of the fixed FEC overhead on the telecommunications cost. Refer back to Test 3 (Section 4.4) for a detailed look at the amount of FEC overhead added if a combination of ARQ and FEC is used as error correction technique. Since the ARQ approach contains no FEC overhead and the pure FEC approach utilises a variable FEC overhead, it is only the HARQ costs that are affected by this variable. More specifically, a higher amount of fixed FEC overhead results in a lower overall HARQ cost as the network grows. This is because the fixed amount of FEC overhead is enough to decode the source message at all network terminals without requiring extra packet retransmissions when losses occur. The side-by-side comparison reveals that the order of the curves changes at large network sizes. At a size of 20 cell rings, the HARQ(AII)-curve is more expensive than the ARQ(AAI)-curve and almost just as expensive as the ARQ(AAA)-option if the FEC-overhead is 5% (Figure 25). In Figure 27 the FEC-overhead is increased to 15% and HARQ(AII) is now less expensive than both ARQ(AAA) and ARQ(AAI), since no retransmissions are required.

Finally, Figure 28 illustrates the difference between Case 1 and Case 3 networks. The same simulation parameters is used in both figures, but the Inter-Site Distance is increased from 500m to 1 732m. Since the difference in spectral efficiency between different Case 3 deployments is much lower than that for Case 1 networks (see Table 2 in Section 3.3), there is much less overlap between individual curves in Figure 28 (on the left) than Figure 25 (on the right) when the network grows. For the same reason, the cost increases at a lower rate of change in Figure 28 as the network grows, resulting in lower overall transmission costs at a large network size of 20 rings when compared to Figure 25.

Chapter 5 – Verification and Validation

5.1 Introduction

In this chapter we will *verify* and *validate* our mathematical model and results. In the *verification* phase, we aim to prove that our model is mathematically accurate and performs correctly. This is done by setting up a small simulation scenario and computing two result sets – one by using our computerised model and the other by hand. We then compare the results to show that results obtained using the computerised model are plausible, as the same can also be obtained using step-by-step computations by hand.

The model is *validated* by setting up a simulation scenario according to the same specifications as a published author and comparing the results. Since we have developed a new improved model it would be impossible to copy a published simulation scenario in an exact manner, so we simply compare our model to a similar model in literature. Several similar aspects of both models are highlighted, confirming the validity of our model. We prove that there is indeed a strong correlation between our model and credible, real world results by computing the Pearson correlation coefficient between our result set and the published results.

5.2 Verification

In this section the model is verified by comparing computer-generated results with results calculated by hand.

5.2.1 Simulation scenario

In this scenario we compute the *total* cost of communication for an AAI deployment when applying three different error correction paradigms, namely simple ARQ, a combination of ARQ and FEC (labelled HARQ) and pure FEC. We consider a macro Case 1 network (see Chapter 3 Section 3.2) in accordance with [8] when the packet loss rate is 5%. The fixed FEC overhead in the combination ARQ and FEC approach is 6%. The user population is fixed at 100 UEs contained in the first 4 rings of cells neighbouring the centre cell. We configure the simulation to compute the total cost for an MBSFN transmission consisting of 12 000 data packets.

5.2.2 Modelled results

Our mathematical model provides the following result set for the scenario described above:

Table 4: Modelled results

Variable	Description	Value
N_{eNB}	Number of participating e-NBs in MBSFN	127
k	Number of cell rings containing UEs	4
n	Number of participating cell rings	6
RE	Resource efficiency	1.0567
RE_{max}	Maximum resource efficiency	2.4000
RE_{ratio}	Resource efficiency ratio	0.4403
D_{Uu}	Delivery cost of a single packet over the air (U_u) interface	2.2712
C_{Uu}	Total communication cost over the air interface	$3.4614\text{x}10^{6}$

Variable	Description	Value
C_{ARQ}	Communication cost with ARQ applied	$6.9362\text{x}10^6$
C_{HARQ}	Communication cost with a combination of ARQ and FEC applied	$4.6813\text{x}10^6$
C_{FEC}	Communication cost with pure FEC applied	$3.7351\text{x}10^6$

5.2.3 Calculated results

See Chapter 3 for a definition of the symbols used in this chapter and the theoretical background to our calculations.

Since the number of cell rings containing subscribed UEs (*k*) is 4, we know from the discussion in Chapter 3 that,

$$n = k + 2 = 4 + 2$$
$$= 6\, rings$$

The total number of cells participating in the transmission, N_{eNB}, is:

$$N_{eNB} = 1 + \sum_{l=0}^{n} 6 * l = 127\, cells$$

Consider the spectral efficiency values below:

Table 5: Spectral Efficiency for MBSFN deployments

SPECTRAL EFFICIENCY				
Case 1 (bps/Hz)	*Case 3 (bps/Hz)*	*Ring*		
		1	*2*	*3*
2.4	0.8	A	A	A
2.2	0.8	A	A	I
1.3	0.7	A	I	I

For a Case 1 network and an AAI deployment, the spectral efficiency is 2.2 bps/Hz. From Equation 2 in Chapter 3, we can compute the resource efficiency as:

$$\begin{aligned} RE &= SE \cdot \frac{1 + \sum_{i=0}^{k} 6 * i}{1 + \sum_{l=0}^{n} 6 * l} \\ &= 2.2 \cdot \frac{1 + \sum_{i=1}^{4} 6 * i}{1 + \sum_{l=1}^{6} 6 * l} \\ &= 2.2 \cdot \frac{61}{127} \\ &= 1.0567\ bps/Hz/cell \end{aligned}$$

The theoretical maximum resource efficiency for a Case 1 network is 2.4 bps/Hz/cell. This indicates that:

$$\begin{aligned} RE_{ratio} &= \frac{RE\ (current)}{Maximum\ RE} \\ &= \frac{1.0567}{2.4} \\ &= 0.4403 \end{aligned}$$

We use the inverse of the resource efficiency to define a cost value for the transmission (as discussed in Chapter 3).

$$\begin{aligned} D_{Uu} &= \frac{1}{RE_{ratio}} \\ &= \frac{1}{0.4403} \\ &= 2.2712 \end{aligned}$$

Using this value, and noting that the total number of packets in the transmissions, N_P, is 12 000, we can compute the total transmission cost (before error correction), as:

$$C_{Uu} = D_{Uu} \cdot N_P \cdot N_{eNB} = 2.2712 \cdot 12000 \cdot 127 = 3.4613 \times 10^6$$

Since $P_{LOSS} = 0.05$ we know that

$$P_{LOSS_{global}} = 0.9 \cdot 0.05 = 0.045$$

$$P_{LOSS_{local}} = 0.1 \cdot 0.05 = 0.005$$

From Equation 7,

$$P_{LOSS_{total}} = P_{LOSS_{global}} + P_{LOSS_{local}} \cdot A_{UE}$$
$$= 0.045 + 0.005 \cdot 100$$
$$= 0.545$$

5.2.3.1 ARQ cost

If the initial number of retransmissions required is N_{ReTx},

$$N_{ReTx(1)} = P_{LOSS_{total}} \cdot N_P$$
$$= 0.545 \cdot 12000$$
$$= 6540\ retransmissions$$

The cost associated with these retransmissions, $C_{ReTx(1)}$, is

$$C_{ReTx(1)} = N_{ReTx(1)} \cdot D_{Uu}$$
$$= 6540 \cdot 2.2712$$
$$= 14853.648\ per\ cell$$

We can assume that, under the same lossy conditions, the retransmitted packets would also experience an equivalent amount of losses. We will then require a total of

$$N_{ReTx(2)} = P_{LOSS_{total}} \cdot N_{ReTx(1)}$$
$$= 0.545 \cdot 6540$$
$$= 3564.3\ retransmissions$$

Corresponding to a cost of

$$C_{ReTx(2)} = N_{ReTx(2)} \cdot D_{Uu}$$
$$= 3564.3 \cdot 2.2712$$
$$= 8095.2382$$

Keeping in mind that the maximum allowable number of retransmissions is 3 (according to 3GPP specifications [20], we can compute, in a similar manner, that

$$N_{ReTx(3)} = 1942.5435$$

$$C_{ReTx(3)} = 4411.9048$$

The total cost of the communication, including retransmission costs, is:

$$\begin{aligned} C_{ARQ} &= C_{Uu} + N_{eNB} \cdot (C_{ReTx(1)} + C_{ReTx(2)} + C_{ReTx(3)}) \\ &= 3.4613 \times 10^6 + 127 \cdot (14853.648 + 8095.2382 + 4411.9048) \\ &= 6.9361 \times 10^6 \end{aligned}$$

5.2.3.2 HARQ cost

The cost for an approach using a combination of FEC and ARQ can be computed in a similar manner. We assume that the fixed amount of FEC overhead is $O_{FEC} = 0.06$. According to the discussion in Chapter 3, the probability that a decoding failure could occur increases as the number of packet losses increases. That is, the added overhead might not provide enough redundancy to *detect* and *correct* possible errors in the transmission and some retransmissions will be required. The total cost of this error correction approach is the sum of the FEC overhead cost and the cost of possible retransmissions.

From Chapter 3 we get that:

$$P_{LOSS_{eff}} = \begin{cases} P_{LOSS} + O_{MIN} - O_{FEC}\ , & when\ P_{LOSS} + O_{MIN} > O_{FEC} \\ 0\ , & when\ P_{LOSS} + O_{MIN} \leq O_{FEC} \end{cases} \quad (10)$$

To simplify this scenario, we'll assume that O_{MIN} is constant at 3%. (This value is based on results published in [8] and our own similar conclusion in Chapter 4, Section 4.3).

Since,

$$\begin{aligned} P_{LOSS} + O_{MIN} &= 0.05 + 0.03 \\ &= 0.08 \\ &> O_{FEC} \end{aligned}$$

we know that

$$\begin{aligned} P_{LOSS_{eff}} &= P_{LOSS} + O_{MIN} - O_{FEC} \\ &= 0.05 + 0.03 - 0.06 \\ &= 0.02 \end{aligned}$$

and from our previous discussion

$$P_{LOSS_{eff}}{}_{global} = 0.9 \cdot P_{LOSS_{eff}} = 0.018$$

$$P_{LOSS_{eff}}{}_{local} = 0.1 \cdot P_{LOSS_{eff}} = 0.002$$

which results in

$$\begin{aligned} P_{LOSS_{eff}}{}_{total} &= P_{LOSS_{eff}}{}_{global} + P_{LOSS_{eff}}{}_{local} \cdot A_{UE} \\ &= 0.018 + 0.002 \cdot 100 \\ &= 0.218 \end{aligned}$$

Using the same process as for ARQ cost, we get that

$$N_{ReTx(1)} = 2616$$

$$C_{ReTx(1)} = 5941.4592$$

$$N_{ReTx(2)} = 570.288$$

$$C_{ReTx(2)} = 1295.2381$$

$$N_{ReTx(3)} = 124.3228$$

$$C_{ReTx(3)} = 282.3619$$

The total cost of the communication, including overhead and retransmission costs, is:

$$\begin{aligned} C_{HARQ} &= C_{Uu} + O_{FEC} \cdot C_{Uu} + N_{eNB} \cdot (C_{ReTx(1)} + C_{ReTx(2)} + C_{ReTx(3)}) \\ &= (1 + 0.06) \cdot 3.4613 \times 10^6 + 127 \cdot (5941.4592 + 1295.2381 + 282.3619) \\ &= 3.669 \times 10^6 + 954920.5184 \\ &= 4.6239 \times 10^6 \end{aligned}$$

5.2.3.3 FEC Cost

This theoretical approach assumes that the operation of FEC is completely unaffected by individual losses at isolated receivers (i.e. the *local* loss rate). We will not discuss its operation in detail, but to show that results are credible, consider this approximated approach:

If we assume that the amount of FEC needed to correctly decode all data in the transmission is dependent only on the global loss rate, we know that:

$$O_{FEC_{eff}} \cong P_{LOSS_{global}} + O_{MIN} \cong 0.075$$

which results in an approximate total cost of

$$\begin{aligned} C_{FEC} &\cong C_{Uu} + O_{FEC_{eff}} \cdot C_{Uu} \\ &\cong (1 + 0.075) \cdot 3.4613 \times 10^6 \\ &\cong 3.7209 \times 10^6 \end{aligned}$$

5.2.4 Conclusion

Consider the modelled results compared to those calculated by hand:

Table 6: Modelled results compared to calculated results

Cost	Simulated result	Calculated result
$\boldsymbol{C_{ARQ}}$	6.9362×10^6	6.9361×10^6
$\boldsymbol{C_{HARQ}}$	4.6813×10^6	4.6239×10^6
$\boldsymbol{C_{FEC}}$	3.7351×10^6	3.7209×10^6

The calculated cost for the ARQ approach shows a difference of 0.001%, those for HARQ differs by 1.23% while the pure FEC approach has a discrepancy of 0.4% between the modelled and calculated results. These differences can be attributed to rounding errors. Some approximations were also made to calculate the cost of the pure FEC approach. We can conclude that our model is mathematically accurate and performs correctly.

5.3 Validation

In this section our new model is validated by comparing important aspects of it to a similar published model in an analogous scenario. The Pearson correlation coefficient is computed to confirm the similarities mathematically.

5.3.1 Simulation scenario

In this scenario we compute the *normalized* cost of communication for an All deployment when applying three different error correction paradigms, namely simple ARQ, a combination of ARQ and FEC (labelled HARQ) and pure FEC. In accordance with [8], we consider a macro Case 1 network when the packet loss rate is 5%. The fixed FEC overhead in the combination ARQ and FEC approach is 5%. We express the cost for each of these curves as a function of a growing user population. Equivalent to [8], we increase the user population in intervals of 25 from 0 to a maximum of 500.

5.3.2 Result sets

We generate a set of results using our model and sampling equivalent points from published results in [8]. Both sets of results are shown below for each of the three cost curves.

Table 7: Own results (modelled) compared to published results

UEs	ARQ (model)	ARQ (published)	HARQ (model)	HARQ (published)	FEC (model)	FEC (published)
0	0.2632	0.26	0.2673	0.26	0.27	0.27
25	0.3027	0.65	0.2896	0.38	0.27	0.27
50	0.3543	0.88	0.3158	0.54	0.27	0.27
75	0.4206	0.95	0.3465	0.65	0.27	0.27
100	0.5047	0.98	0.3824	0.72	0.27	0.27
125	0.6095	0.99	0.424	0.8	0.27	0.27
150	0.738	1	0.4721	0.83	0.27	0.27
175	0.893	1	0.5273	0.87	0.27	0.27
200	1	1	0.5903	0.9	0.27	0.27
225	1	1	0.6617	0.92	0.27	0.27

UEs	ARQ (model)	ARQ (published)	HARQ (model)	HARQ (published)	FEC (model)	FEC (published)
250	1	1	0.7422	0.93	0.27	0.27
275	1	1	0.8325	0.94	0.27	0.27
300	1	1	0.9331	0.98	0.27	0.27
325	1	1	1	0.99	0.27	0.27
350	1	1	1	1	0.27	0.27
375	1	1	1	1	0.27	0.27
400	1	1	1	1	0.27	0.27
425	1	1	1	1	0.27	0.27
450	1	1	1	1	0.27	0.27
475	1	1	1	1	0.27	0.27
500	1	1	1	1	0.27	0.27

All six curves are shown as a function of the user population below:

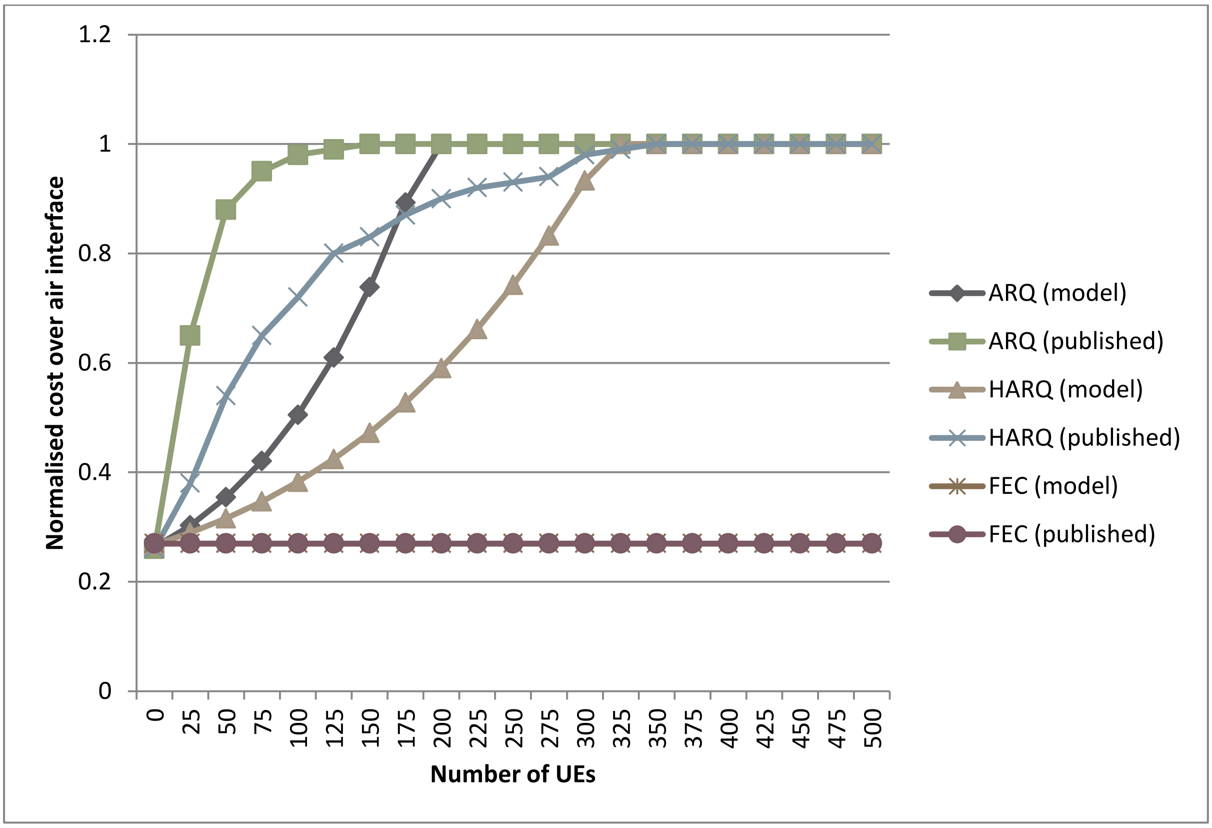

Figure 29: Own results (modelled) compared to published results in [8]

5.3.3 Qualitative comparison

Consider Figure 29 showing the error correction cost curves for both our mathematical model and similar results published in [8]. Since we have developed a new model we do not aim to copy the published results, but simply compare certain aspects of it to a similar model. It will in any case be impossible to copy the simulation scenario in an exact manner, since the implementation details described in [8] are incomplete (such as loss conditions, error distribution, maximum value conditions etc.). The scenario applied to our new mathematical model was built from first principles in specification documents [16]. The vague application of environmental and network variables in [8] explains most of the visible discrepancies between results. Though specified maximum value conditions result in similar cost ceilings for the modelled and published result sets, the published results generally show higher costs for small user populations. The published results are the sum of transmission costs over the air interface *and* the core network, which have a compounding effect if the number of attached UEs is low, explaining this difference. Our new model only considers the air interface, as explained in Section 1.5. For example, the ARQ (model) curve shows lower costs then the ARQ (published) curve for a user population lower than 200. The HARQ (model) curve follows the HARQ (published) curve more closely, but shows divergence for a user population between 0 and 300.

It is clear, however, that the overall *trend* between the modelled and published results is the same. A rise in cost in the published results generally corresponds to a similar cost rise in the modelled results. It is also important to note that the *comparative relationship* between the individual cost curves is the same for both the modelled and published results. For a user population between 0 and 325, the modelled results show that HARQ is a lower-cost option than ARQ, while the published results come to *exactly* the same conclusion. For large user populations, our model also computes the same maximum cost ceiling for the ARQ and HARQ curves as that in the published result set. For our purpose, selecting the lowest-cost error correction scheme in this scenario, it seems that our new model provides similar answers. To show mathematically that our model is fit to be applied for this purpose, we compute the correlation coefficient between the individual curves (published and modelled) as well as the overall correlation.

5.3.4 Correlation coefficient

5.3.4.1 The Pearson correlation coefficient

If X is a series consisting of points sampled using our own simplified model, and Y is a series of corresponding points obtained from literature (visually sampled from a graph), the Pearson correlation coefficient can be expressed as:

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{s_X}\right)\left(\frac{Y_i - \bar{Y}}{s_Y}\right)$$

with n the number of samples in each array X and Y. $\bar{X}$ and $\bar{Y}$ are the mean of X and the mean of Y respectively. s_X and s_Y are the standard deviations of array X and array Y.

Since it is known that,

$$s_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

and s_Y is computed with an analogous equation, we can simplify the formula for r as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

It is also known that,

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n}X_i$$

with n the number of samples until both the modelled and published curve have reached a maximum (from Table 7).

5.3.4.2 ARQ curve

According to our definitions above, for the ARQ curve:

X = {0.2632, 0.3027, 0.3543, 0.4206, 0.5047, 0.6095, 0.738, 0.893, 1}

Y = {0.26, 0.65, 0.88, 0.95, 0.98, 0.99, 1, 1, 1}

We can compute that

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$
$$= \frac{1}{9}(5.086)$$
$$= 0.5651$$

and equivalently

$$\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$$
$$= \frac{1}{9}(7.71)$$
$$= 0.85667$$

Therefore,

$$r = \frac{0.3485}{(0.7466)(0.7089)}$$
$$= 0.6585$$

a correlation close to 66% between the modelled and published ARQ curves.

5.3.4.3 HARQ curve

For the HARQ curve,

X = {0.2673, 0.2896, 0.3158, 0.3465, 0.3824, 0.424, 0.4721, 0.5273, 0.5903, 0.6617, 0.7422, 0.8325, 0.933, 1, 1}

Y = {0.26, 0.38, 0.54, 0.65, 0.72, 0.8, 0.83, 0.87, 0.9, 0.92, 0.93, 0.94, 0.98, 0.99, 1}

The means can be computed as:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$
$$= \frac{1}{15}(8.7848)$$
$$= 0.5857$$

$$\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$$
$$= \frac{1}{15}(11.71)$$
$$= 0.7807$$

Therefore,

$$r = \frac{0.6997}{(0.9788)(0.8567)}$$
$$= 0.8344$$

a correlation of around 83%.

5.3.4.4 FEC curve

To compare the modelled FEC curve with the published results, we note that

X = Y = {0.27}

at all sample points.

Since both series are exactly the same:

$$\bar{X} = \bar{Y} = \frac{1}{n}\sum_{i=1}^{n} X_i$$
$$= \frac{1}{21}(5.67)$$
$$= 0.27$$

Therefore,

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

$$= \frac{\sum_{i=1}^{n}(X_i - \bar{X})(X_i - \bar{X})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}}$$

$$= \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

$$= 1$$

a correlation of 100% (both curves are exactly the same).

5.3.4.5 Total correlation

We now compare the modelled results with the published results by using all sample points from all three curves in the simulation:

If we compare all sample points from all three curves:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$
$$= \frac{1}{45}(19.5408)$$
$$= 0.0.4342$$

$$\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$$
$$= \frac{1}{45}(25.09)$$
$$= 0.5576$$

Therefore,

$$r = \frac{2.8991}{(1.6062)(2.1272)}$$
$$= 0.8485$$

a total correlation of almost 85%.

5.3.5 Conclusion

We validated our new model by comparing it to a similar, published model. Similarities in terms of trends, the comparative relationship between curves and maximum values were pointed out. We have shown that there is indeed a mathematical resemblance between our modelled results and the published results, by computing a correlation coefficient. This indicates that our model provides new and believable results while expanding upon published knowledge.

Chapter 6 – Conclusion

6.1 Introduction

In this chapter we conclude and critically evaluate the research done and presented in this dissertation. We refer back to the hypothesis and research objectives stated in Chapter 1 to assess if, and to what level, our aims were achieved. We briefly review the content of each chapter and conclude with a number of recommendations and possible future work on this topic.

6.2 Research hypothesis

In Chapter 1, a hypothesis was defined for our research:

> *"Using a number of MBSFN network variables and the fundamental characteristics of basic error correction techniques, we can create a mathematical model to select the*

lowest-cost error correction scheme for the over-the-air interface of a specific MBSFN network under specific conditions."

We now use this formulation as a guideline by which we evaluate the outcomes of our research as presented in this dissertation:

- ***"a number of…variables"*** – We created a mathematical cost model for an MBSFN network that considered a selection of the most important variables influencing the operation of the network. A list of all the variables considered appears in Chapter 3, Section 3.5 and includes a description of the MBSFN topology. We implemented three different topology options in our model, based on the number of assisting and interfering cell rings, namely *AII, AAI* and *AAA*. The selection of a topology greatly influences the *spectral efficiency* of the system. We proved that this selection of incorporated variables allows our model to represent real world scenarios adequately, by validating our results against published results in Chapter 5 and highlighting important similarities.
- ***"the fundamental characteristics"*** – Details on the way error correction schemes were implemented in our model and an explanation of the assumptions made, appear in Chapter 3.
- ***"basic error correction techniques"*** – Our model successfully incorporated the two main traditional approaches to error correction in the form of Automatic Repeat-reQuest (ARQ) and forward error correction (FEC). We also implemented a combination of the two schemes and applied all three approaches to each of our test setups. Results appear in Chapter 4.
- ***"we can create a mathematical model"*** – This was the hypothesis that we set out to prove. Implementation details of our model appear in Chapter 3, with a set of results in Chapter 4. We proved this hypothesis by validating our model and verifying the results. A detailed explanation of this process is presented in Chapter 5.
- ***"to select the lowest-cost…scheme"*** – Our model provided us with the tools to compare the communication cost associated with different error correction approaches and make a selection of the lowest-cost scheme for a given scenario. This is shown in our set of results in Chapter 4. Our definition of "communication cost" is explained and mathematically developed in Chapter 3.
- ***"for the over-the-air interface"*** – Our model computed the cost over the air interface by manipulating the spectral efficiency of different MBSFN deployments. This is detailed in Chapter 3.

- ***"of a specific MBSFN network"*** – Our model could make a selection of the lowest-cost error correction scheme for a system described by a given set of variables. The network variables incorporated into our model is listed in Chapter 3.
- ***"under specific conditions"*** – Our model also takes as input a series of variables describing the conditions under which the MBSFN transmission takes place, such as packet loss rates, user mobility, etc. An exhaustive list appears in Chapter 3.

From the discussion above, it can be concluded that we adequately adhered to the requirements as set out in our hypothesis.

6.3 Chapter Review and Research Objectives

In this section we will review the content of the chapters in this document against the framework of our stated research goals in Chapter 1.

- ***Gain a thorough understanding of the LTE environment, with specific reference to multicasting and MBSFN systems.***
  This goal was addressed in Chapter 2 in a thorough literature study on these and other theoretical subjects of interest.

- ***Study and quantify the effect of different network parameters on the reliability of multicast communication.***
  A set of network parameters affecting the reliability of multicast communication was studied and summarised into a mathematical in Chapter 3 with numerical results appearing in Chapter 4.

- ***Investigate different error correction schemes appropriate for MBSFN systems. Quantify the relationship between the efficiency of a selected scheme and network conditions.***
  The costs associated with different error correction schemes, as appropriate for MBSFN, are modelled in Chapter 3 as a function of network condition variables. The numerical results for a number of scenarios are presented in Chapter 4.

- ***Develop a systematic approach (an algorithm) to improve the selection of error correction scheme under any given set of network conditions.***
  This goal is addressed in the development of a mathematical cost model comparing error correction schemes in Chapter 3.

- ***Verify the algorithmic approach by showing that it is mathematically rigorous and plausible.***
  A full verification of results appears in Chapter 5.2.

- ***Compare results of the algorithmic approach to existing methods and validate that it indeed led to improvement.***
  The model is validated against published results of a similar model in Chapter 5.3.

6.4 Conclusions

In Chapter 1 we detailed a problem statement which we have shown was fully addressed in the course of this research project. We set out to create an algorithm to improve the selection of an appropriate error correction technique in MBSFN systems. It was indicated in our results section (Chapter 4), that our model works well under different scenarios. To illustrate its performance, some of the more significant results from this chapter are summarized below. This model can be used by telecommunications companies rolling out LTE-networks to improve reliability of their multicast delivery mechanisms in a more efficient manner. It provides insight into the main traditional approaches to error correction, namely retransmission schemes and forward error correction, and will allow such companies and operators to select the most appropriate, lowest-cost method of error correction based on their specific implementation needs. Two peer-reviewed conference articles have been published during the course of this research. They are presented in Appendix A.

6.5 Significant Results

In Test 1 (Section 4.2) we have shown that, if a telecommunications company is rolling out an MBSFN system for a group of UEs and the users are densely distributed over a small geographic space ($k = 2$), an All-deployment using a combination of ARQ and FEC (HARQ) as error correction technique will be the most cost-efficient implementation (Figure 9). However, if the users are more widely distributed in a large network (*k = 19*), an AAI-deployment with HARQ error correction will be cheaper for all user populations. Although it is shown that a HARQ-approach to error correction is generally less expensive in MBSFN systems than simply using ARQ and companies may assume as much based on the suggestion by the 3GPP to use HARQ in MBSFN rollouts ([16]), our results show that this is not always the case. In fact, when AII with HARQ is used in a large network (*k = 19*) it will only be less expensive than both AAA with ARQ and AAI with ARQ for populations of between 120 to 250 users (Figure 10). These conclusions are based on the assumption that the Inter-Site Distances between individual cells are 500m, though our model also allows for operators to model their macro Case 3 networks with ISDs of 1 732m (Figures 11 & 12).

Our second test (Section 4.3) further aids selection of an appropriate error correction method by showing at which packet loss rates the HARQ-approach will perform best. If the amount of fixed FEC overhead is at 5% (Figure 13), HARQ will closely follow the ideal lowest-cost FEC-curve at packet loss rates of below 3%. At a FEC overhead of 15% (Figure 14), HARQ will perform best for loss rates of below 12%. Figure 13 also shows that HARQ with a FEC overhead of 5% will not perform reliably at loss rates of more than 12%, due to the restriction of a maximum of three retransmissions imposed by the 3GPP [20]. If the amount of fixed FEC overhead is pushed up to 15%, this maximum tolerable loss rate is increased to 22% (from Figure 14).

It is clear then that one important aspect for operators planning to roll out a HARQ-based MBSFN system, is the decision of how many redundant symbols to add as FEC overhead, based on their particular implementation scenario. Our model addresses this concern in Test 3 (Section 4.4), by showing the point of FEC overhead that will result in the lowest overall cost based on the current loss conditions in the network. It was shown (in Figure 21) that 8% FEC overhead will provide the lowest-cost HARQ-implementation if the packet loss rate in the network is at 5%. In fact, this will allow the HARQ costs to achieve the theoretical minimum cost of error correction indicated by the lowest-cost pure FEC-curve. In the same way the point of optimal FEC overhead for networks with a packet loss rate of 10% is at around 13% redundancy (Figure 22).

Our last test, Test 4, makes numerous suggestions to operators based on the size of the network being rolled out. It was shown, for example, that an AAI-deployment with HARQ as error correction technique performs best at a network size of larger than six participating cell rings (Figure 25). AII-deployments perform best at network sizes of less than five rings. On the other hand, at a network size consisting of more than 13 cell rings, an AII-deployment with HARQ performs even worse than AAI with ARQ, even though the latter requires multiple retransmissions. Nevertheless, if a macro Case 3 network is deployed and the Inter-Site Distances between cells are 1 732m, nothing performs better than AII with HARQ, even in large networks of up to 20 cell rings (Figure 28).

6.6 Future work and recommendations

Future work in this area of research can incorporate the following recommendations:

- Our model assumes a random distribution of packet losses and a constant loss rate in each scenario. The model can be expanded to include different error distributions and varying loss conditions during a series of MBSFN transmissions.
- The application of pure FEC as an error correction technique for MBSFN could be simulated more realistically by adding the uplink costs of feedback messages required to ensure that all subscribed nodes have received enough Raptor coded symbols to decode the source message successfully. The current implementation of pure FEC, as discussed in Chapter 4, assumes full knowledge of loss conditions in the network, making it a purely theoretical approach for now.
- Our model only considers the cost of communication over the air interface of an MBSFN system. It can be expanded in a similar manner, from first principles in specification documents, by adding the transmission costs over other MBSFN interfaces.
- The concept of “communication cost” is defined in this document only as a function of the cost of packet *transmissions.* This concept can be broadened by adding metrics describing the *processing costs* associated with the MBSFN operation.

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Appendix A – Conference Contributions from this Dissertation

A.1 Work in Progress: An Improved Error Correction Algorithm for Multicasting over LTE Networks

Presented at:

Southern African Telecommunication Networks and Applications Conference (SATNAC)

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An Improved Error Correction Algorithm for Multicasting over LTE Networks

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Abstract – Multicasting in LTE environments poses several challenges if it is to be reliably implemented. Neither retransmission schemes nor Forward Error Correction (FEC), the traditional error-correction approaches, can be readily applied to this system of communication if bandwidth and resources are to be used efficiently. This paper details current work in progress aiming to develop an algorithm to select the best error-correction scheme for such a multicast network.

Index Terms—Long-Term Evolution, MBSFN, multicasting, error correction

I. INTRODUCTION

The most likely candidate to achieve the realisation of 4th generation (4G) radio technologies is the 3rd Generation Partnership Project's (3GPP) Long-Term Evolution (LTE) system. With LTE's improvements in speed and capacity over its predecessors, multicast communication has been supported from the first release of its specifications in the form of a Single Frequency Network (SFN) [1]. This method of communication can greatly increase bandwidth efficiency and is particularly suitable for the delivery of multimedia content to a group of mobile receivers. It turns out, however, that error-free multicasting poses several implementation challenges [2]. It is this area that this research in progress seeks to address.

The remainder of this paper includes a background and elaboration on the aforementioned technologies in Section II. The proposed research is presented in Section III, followed by a summarized methodology (Section IV). Section V concludes this document.

II. BACKGROUND

A. Multicasting in LTE Environments

The 3GPP's application of multicast technology to cellular networks has been termed the MBMS, or Multimedia Broadcast/Multicast Service. For LTE systems this specification has been further enhanced to the evolved-MBMS (e-MBMS) [3]. Currently e-MBMS includes two types of multicast transmission, namely single-cell transmission and multi-cell transmission. As the terms imply, the former can only distribute multicast data within a single cell of coverage, while the latter uses a number of different, highly synchronized cells to transmit the multicast data [4].

Of the services described by e-MBMS, it is the multi-cell transmission which is envisioned to be employed on large scale to support the distribution of multimedia content (such as mobile television) [1]. In LTE environments this type of transmission is also known as MBMS Single Frequency Network (MBSFN). Its operation is based on a set of base stations transmitting the same signal at the same time and in the same frequency channel to a group of multicast user equipment (UE). From the viewpoint of the user equipment, the combined signal from the different locations will appear as if coming from a single base station, but being subject to severe multipath propagation [4]. MBSFN allows for over-the-air signal combining and other technology to change the destructive interference of multiple signals to a constructive signal resulting in a much higher Signal-to-Interference plus Noise-Ratio (SINR) compared to single-cell transmission [1]. An in-depth discussion of the physical operation of MBSFN falls beyond the scope of this document. A more complete analysis is given in [1], [2], [3], [4], and [5].

B. Error Correction in MBSFN

Two traditional approaches to error-correction in communication systems are retransmission schemes and forward error-correction (FEC). Retransmission schemes, specifically the automatic repeat request (ARQ) process, rely on feedback from the receiver to the source to ensure error-free communication. Lost or corrupt packages are simply retransmitted by the source. In FEC, redundant data, sent from source to receiver, allows the receiver to both *detect* and/or *correct* possible errors in communication.

It should be clear that ARQ on its own is not an effective method to establish error-free multicast communication. The authors of [2] name three drawbacks of ARQ in an MBSFN system. The most important problem with this approach is known as *feedback implosion*. Since ARQ relies on feedback from individual receivers for its operation, it is possible (even probable, with multiple receivers) that a large number of retransmission requests may occur simultaneously, placing a heavy burden on network resources. Spectrum efficiency is also reduced if a large number of retransmitted messages congest the downlink network channel. Furthermore, the bursty nature of traffic in both the uplink and downlink channels has a detrimental effect on network scalability and efficiency. A fourth drawback, mentioned by the same authors in [6], is that the feedback channel in LTE (and any wireless network) consumes valuable power and is expensive to implement.

An apparent solution to the shortcomings of ARQ in an MBSFN is to make exclusive use of FEC techniques. Since all data necessary for error correction is transmitted in the downlink channel, the need for a feedback channel is greatly reduced. This eliminates the possibility of feedback implosion. Also, independent errors at different receivers have no effect on the error correction operation, allowing for network scalability [7].

Since FEC introduces a fixed amount of overhead into the system, there are, however, certain conditions under which FEC might be a less desirable approach than ARQ [6]. If a low number of users have subscribed to the multicast service, for example, ARQ could be more effective. In a reliable network, if packet loss is low, ARQ might also be the more practical option [2]. It seems therefore that a combination of the two schemes might be necessary. In fact, a vast number of network parameters and topology variables need to be considered before an appropriate error correction scheme can be drawn up for an MBSFN system. It is out of this observation that our problem statement has been formulated.

III. Proposed Research

The proposed research aims to develop an algorithm to improve error correction techniques in MBSFN systems. Recent research ([2], [5], [8]), published in 2011 and the first quarter of 2012, has investigated the efficiency of different ARQ and FEC techniques in MBSFN systems . Several researchers have quantified the effect of a number of network parameters on the efficiency of error correction techniques (and their associated network costs). However, no effort has yet been made to unify these studies into a systematic approach that could help with the selection of the most effective technique given certain network conditions.

The algorithm will take a broad spectrum of network parameters as input conditions. These may include network topology, number of users, density of user equipment and many others. As output, the developed algorithm would provide an idea of what error correction scheme will be most effective for the network at hand. It could, for example, help with the selection of an appropriate Raptor code for FEC under dynamic conditions. It should be noted that the goal is overall *improvement* and not mathematical *optimization* of error correction techniques – the latter requiring rigorous mathematical proofs.

IV. Methodology

An *initial literature study* on LTE, MBSFN and error-correction techniques was done to identify a gap in current knowledge and define the area of contribution for this research project.

An *in-depth literature study* will follow, covering all aspects of LTE environments with regards to multicasting. Network parameters that might affect reliability of communication and error correction schemes will be identified in this step.

A *simulated LTE environment*, using a software packet such as OMNet++, will be created. This will be used to *develop and analyse* an error-correction algorithm for MBSFN systems. It will serve as a model of interaction from which the algorithm can be evaluated.

Finally, the results will be *validated and verified* by comparing experimentation results to real life results. For this research project, a special step of validation will investigate and propose new areas to practically implement error-free multicasting in LTE environments.

V. Conclusion

This paper introduced the problem of creating an algorithm to select the most efficient error-correction scheme given a set of network conditions for multicast systems in LTE environments. Background on the aforementioned was given. Future work entails the development and analysis of such an algorithm in the context of a simulated LTE network. The expected output is a *systematic, quantified approach* to select the best error-correction scheme given a specific LTE multicast application.

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A.2 A Simplified Cost Model to Evaluate Error Handling Techniques for Multicasting over LTE

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A Simplified Cost Model to Evaluate Error Handling Techniques for Multicasting over LTE

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Abstract-Several challenges need to be addressed to reliably implement multicasting in LTE environments. A large number of network parameters and topology variables can influence the cost of telecommunication in such a system. These need to be considered when selecting an appropriate error correction technique for a certain LTE multicast deployment. This paper develops a simplified cost model to investigate the costs associated with over-the-air LTE multicasting when different error correction techniques are applied. The benefit of this simplified model is an easily implementable and fast method to evaluate the communications costs of different LTE multicast deployments with the application of error correction techniques.

Index Terms— Long-Term Evolution, MBSFN, multicasting, error correction

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) has introduced Long-Term Evolution (LTE) as their answer to achieve the realisation of 4th generation (4G) radio technologies. LTE implements significant improvements in speed and capacity over its predecessors. Multicast communication has been supported from the first release of LTE's specifications in the form of a Single Frequency Network (SFN) [1]. Multicast technology in cellular networks, as applied by the 3GPP, has been termed the Multimedia Broadcast/Multicast Service (MBMS). In LTE systems this specification has been further enhanced to evolved-MBMS (e-MBMS) [2].

e-MBMS describes a multi-cell transmission service which is envisioned to be employed on a large scale for the distribution of multimedia content, such as mobile television and radio streaming [1]. This type of transmission is known as an MBMS Single Frequency Network (MBSFN) in LTE environments. Its basic functionality relies on a group of base stations transmitting the same signal at the same time and in the same frequency channel to a group of multicast User Equipment (UEs). These signals are recombined at the user equipment and will appear as if coming from a single base station, but being subject to severe multipath propagation [3].

The application of an MBSFN system can greatly increase bandwidth efficiency if the same content is to be delivered to a group of receivers. However, ensuring that this delivery method is error free poses several implementation challenges. Traditionally, two approaches to error correction in communication systems have been used. The first, retransmission schemes (specifically the automatic repeat request, or ARQ, process), relies on feedback from the receiver to the source to ensure error free communication. If a data packet is lost or corrupted, it is simply retransmitted by the source, after a notification has been sent by the intended receiver. The second approach is forward error correction (FEC). In FEC redundant data is sent from source to receiver. This data is generated in such a way that it will allow the receiver to both *detect* and/or *correct* possible errors in communications.

The authors of [4] explain some of the drawbacks of ARQ in an MBSFN system. Since this approach relies on feedback from individual receivers for its operation, it is probable that a large number of simultaneous retransmission requests might occur from time to time. This occurrence, also known as *feedback implosion*, can place a heavy burden on network resources and often lead to network overload. The downlink network channel might also become congested by a large number of retransmitted messages, reducing spectral efficiency.

The most apparent solution to the shortcomings of ARQ in an MBSFN is to make exclusive use of FEC as error correction technique. All data necessary for error detection and correction is transmitted in the downlink channel. This greatly reduces the need of a feedback channel and eliminates the possibility of a feedback implosion. Furthermore, the error correction operation is not affected by independent errors at individual receivers, allowing for network scalability [5].

However, FEC still introduces an amount of overhead into the system (required to transmit the redundant data), and might be a less desirable approach than ARQ under certain network conditions [6]. If, for example, a low number of users have subscribed to the multicast service, ARQ could be more effective than FEC. Also, when packet losses are low, ARQ might be the desirable option [4]. It seems therefore that a combination of the two schemes might be desirable. In fact, many variables and parameters related to the network and selected topology need to be considered in order to draw up the most appropriate error correction scheme for an MBSFN system. This document presents research on this observation by developing a simplified cost model for over-the-air MBSFN transmission with the application of different error correction techniques.

II. BACKGROUND

In this section a simplified cost model for over-the-air MBSFN transmission is developed and expanded to include costs associated with error correction techniques. The following symbols are used throughout this paper (adapted from [7]):

Table 1: Mathematical symbols

Symbol	Explanation
D_{Uu}	Delivery cost of a single packet over air (Uu) interface
C_{Uu}	Total communication cost over air interface
N_p	Total number of packets in the MBSFN session
N_{eNB}	Number of participating e-NBs in MBSFN.
RE	Resource efficiency
SE	Spectral efficiency

A. *Forward Error Correction in MBSFN*

As already mentioned, FEC relies on redundancy for its operation. The redundant bits that will allow for eventual error correction are added through a process called *coding.* Coding can loosely be defined as the process of mapping a set of input bits to a set of the same amount or more output bits. A set relationship between the output data (with redundancy) and actual data then allows the receiver to detect and correct errors [8]. Several such coding schemes have been put forward, a number of which is discussed in [8] and [9]. Particularly relevant to a discussion on LTE multicasting (because it has been endorsed by the 3GPP themselves) is the class of fountain codes termed *Raptor codes*.

Fountain codes can produce a potentially infinite stream of output symbols for a finite set of input symbols. If a message containing a set of k input symbols is encoded, a decoding algorithm will be able to recover the original message from any set of n output symbols with $n \geq k$. Raptor (or *rapid tornado*) codes are the first practically realizable class of such fountain codes with linear time encoding and decoding [10].

B. *MBSFN Topology*

Consider a hexagonal grid consisting of a number of evolved-Node B (e-NB) cells as illustrated in Figure 1. We'll consider a topology similar to this and will adapt a number of assumptions based on the architectural setup described in [7]. Firstly, assume the topology is scalable to include a large number of cells (approaching infinity). Secondly, assume that multicast users can be located in an ever increasing area surrounded by each ring of cells moving outward from the centre cell. That is, we can consider an infinite series of scenarios, where:

- The users are all located in the centre cell
- The users are located in the centre cell and the first ring of six cells surrounding the centre (a total of 7 cells containing UEs).
- The users are located in the centre cell, the first surrounding ring and the second surrounding ring of twelve cells (a total of 19 cells).

and so forth, until the users are located in an infinite number of cells in an infinitely large topology.

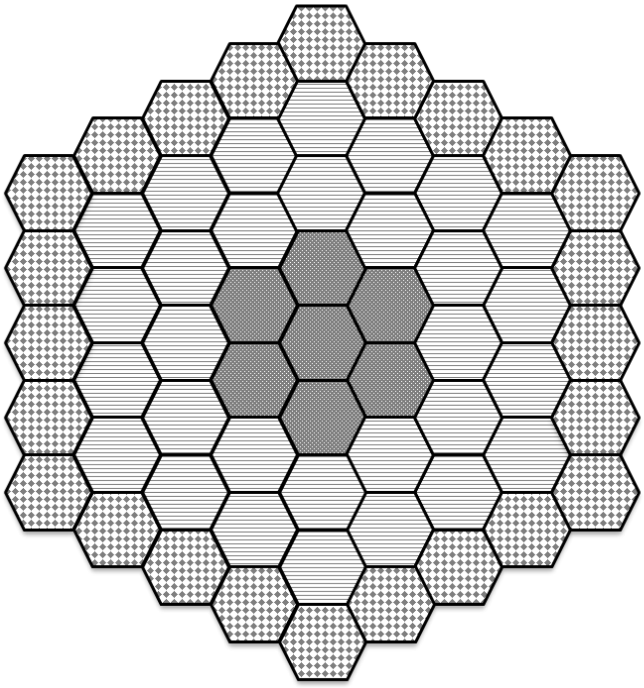

Figure 1: A hexagonal grid of cells (*Source:* Own construction)

For each scenario, it is possible to enhance the spectral efficiency of the MBSFN system significantly by having the ring of cells neighbouring the "inner" area containing UEs also participate (*assist*) in the MBSFN transmission [11],[12]. Although this *assisting ring* does not contain any users subscribed to the multicast service, it will broadcast the same MBSFN data at the same frequency as the inner cells containing subscribed UEs. In fact, substantial gains in spectral efficiency can be achieved if up to three neighbouring rings of cells assist in the MBSFN transmission [11]. In figure 1, the central seven cells contain UEs (shaded). They are surrounded by two assistive rings (striped), broadcasting the same data at the same frequency, but not containing any subscribed multicast users. The outer ring in the figure (blocks) does not participate in the MBSFN session and is termed an *interference ring*. For the purposes of this research document, three different deployments are considered:

- **AII -** One ring of cells neighbouring the area containing UEs participate in the MBSFN session. The other cells act as interference rings.
- **AAI -** This is the setup illustrated in the figure. The first two neighbouring rings surrounding the area of subscribed users assist in the MBFSN system, while the outer rings act as interference.
- **AAA -** All three neighbouring cell rings assist in the multicast. Cell rings further away from the central cells than the first three neighbouring rings can be shown to have no significant effect on the MBSFN transmission [12].

A simplified MBSFN cost model is developed to accommodate scenarios where the Inter Site Distance (ISD) between the cells are 500m and 1732m respectively (termed macro Case 1 and macro Case 2). These are typical selections based on the Okamura-Hata propagation model [7], [11].

C. Transmission cost over the air interface

Consider the following equation:

$$C_{Uu} = D_{Uu} \cdot N_p \cdot N_{eNB} \quad (1)$$

The total communication cost over the air interface is the product of the delivery cost for a single packet over the air interface with the total number of data packets in the MBSFN session. This product is then multiplied by the number of e-NBs participating in the MBSFN transmission, N_{eNB} [7]. This number is dependent on both the *user distribution* and selected *topology* of the MBSFN system. The user distribution is an indication of the number of cells containing participating UEs, while the selected topology will determine how many e-NBs from assistive cell rings (not containing any participating UEs) will participate in the MBSFN session. The sum of these two indicators is the total number of participating e-NBs.

Both N_p and N_{eNB} are invariable for each modelling scenario and will be explicitly defined for each case considered. However, the cost for a single packet over the air interface, D_{Uu}, needs to be modelled mathematically. To do so we define a resource efficiency variable, RE. Resource efficiency is defined as the spectral efficiency for a certain topology, normalized (or multiplied) by the fraction of cells participating in MBSFN transmission that actually contains active UEs. For example, if in the hexagonal grid of cells only the centre cell contains UEs, but there are two assistive rings of cells, a total of 1 + 6*1 + 6*2 = 19 cells participate in MBSFN transmission. Even though only one cell (the centre) contains UEs interested in the MBSFN content, a total of 19 cells actually participate in the transmission. This is not a very efficient use of resources and will result in the spectral efficiency being divided by 19 (multiplied by 1/19) to compute the resource efficiency (in bps/Hz/cell) [11]. Therefore,

$$RE = SE \cdot \frac{1 + \sum_{i=0}^{k} 6 \cdot i}{1 + \sum_{l=0}^{n} 6 \cdot l} \quad (2)$$

In the above equation, RE is the resource efficiency and SE the spectral efficiency for the selected topology. The summation limits *k* and *n* are respectively the number of cell rings (excluding the centre cell) *containing UEs* and the total number of cell rings *participating*. The *k* and *n*-indices relate to each other in a different way for each considered topology.

For AII: $n = k + 1$

For AAI: $n = k + 2$

For AAA: $n = k + 3$

The spectral efficiency depends on the propagation model and specific evaluation scenario. This can be modelled using the Okamura-Hata model and considering a complex system of variables. To adhere to the scope of this document, the values in Table 2 are used, as provided in [11] for Case 1 and Case 3 (Inter Site Distances of 500m and 1732m respectively). These values were calculated at a 95% coverage level of the central cell.

Table 2: Spectral Efficiency for MBSFN deployments

SPECTRAL EFFICIENCY				
Case 1 (bps/Hz)	***Case 3 (bps/Hz)***	***Ring***		
		1	***2***	***3***
2.4	0.8	A	A	A
2.2	0.8	A	A	I
1.3	0.7	A	I	I

In order to convert the resource efficiency to an indicator of the relative cost of transmission over the air interface, a normalized version of the resource efficiency, RE_{ratio}, is defined. The resource efficiency of the current deployment is normalized to the maximum obtainable resource efficiency for each macro case, namely 2.4 bps/Hz/cell for Case 1 and 0.8 bps/Hz/cell for Case 3 [7].

$$RE_{ratio} = \frac{RE\ (current)}{Maximum\ RE} \quad (3)$$

Noting that the cost of transmission increases proportionally with a decrease in resource efficiency (and vice versa), the authors of [7] defined the cost of a single packet delivery over the air interface as:

$$D_{Uu} = \frac{1}{RE_{ratio}} \quad (4)$$

The combination of the above equations with the original cost expression in Equation 1 results in a complete mathematical model for the cost of packet delivery over the air interface in an MBSFN system.

D. Error correction costs

1) ARQ Costs

We now extend the cost model presented above to accommodate for possible errors occurring during MBSFN transmission and the application of different error correction techniques to remedy this. If the unit cost for transmitting a data packet over the air interface is given by D_{Uu} and the total number of packets in the simulation session is N_p, the total transmission cost C_{Tx} (at each participating e-NB) can be determined as follows:

$$C_{Tx} = N_p \cdot D_{Uu} \quad (5)$$

The application of error correction techniques can be modelled by computing the total number of packets lost during transmission. A distinction should be made between *global losses* and *local losses*. Global losses affect all users participating in the multicast session (e.g. in the case of outages) and are independent of the number of multicast users in the topology. Local losses occur because of individual errors at local receivers and increase in number as the number of multicast users in the topology increases. To illustrate, assume the nominal packet loss rate is 5%. If 90% of the lost packets affect all users (globally) and 10% of losses are due to individual errors at receivers, the global packet loss rate is 4.5% and the local packet loss rate 0.5%. The typical error correction remedy for both types of lost packets will be to retransmit the lost packets (to all registered multicast UEs in the topology, in the case of

MBSFN). If we assume that the number of packets lost locally increases *linearly* with an increase in number of users, we can express the total number of lost packets as:

$$N_{P_{loss_{total}}} = P_{LOSS_{global}} \cdot N_p + P_{LOSS_{local}} \cdot A_{UE} \cdot N_p \quad (6)$$

where $P_{LOSS_{global}}$ and $P_{LOSS_{local}}$ are the global and local loss rates and A_{UE} is the number of UEs in the topology. The total packet loss rate is:

$$P_{LOSS_{total}} = P_{LOSS_{global}} + P_{LOSS_{local}} \cdot A_{UE} \quad (7)$$

These equations were validated by comparing simulation results to analyses published in [4], [7] and showed good correlation.

Now the total cost for ARQ transmission is the sum of the cost for the initial transmission and the cost of the retransmitted packets [13]. However, since the retransmissions occur under the same lossy conditions, a portion of the retransmitted packets might also be lost with some probability greater than 0. These lost packets would also need to be retransmitted in an iterative process (each iteration contributing to the total communication cost) and so forth until the maximum number of retransmissions per packet is reached. According to 3GPP specifications, the maximum number of retransmissions per packet is 3, creating a ceiling of maximum transmission cost [14]. It will be shown that for ARQ transmission, as the number of UEs increase, the probability that each data packet needs to be retransmitted a maximum number of times becomes large very quickly.

2) *ARQ-FEC Combination Costs*

The 3GPP recommends using Raptor Codes as Forward Error Correction technique in MBSFN. The probability that a decoding failure may occur when a block of source code is encoded as a Raptor code, is given by

$$p_f(m,k) = \begin{cases} 1 & if\ m < k \\ 0.85 \times 0.567^{m-k} & if\ m \geq k \end{cases} \quad (8)$$

where k is the number of source symbols and m is the number of encoded symbols [15]. It is clear from the expression that, if the number of received encoded symbols is only slightly more than the number of original source symbols, the probability of incorrectly decoding the source block at each receiver decreases exponentially. If the number of encoded symbols is equal to the number of source symbols, there is still an 85% chance that a decoding failure will occur at the receiver side. The use of FEC therefore necessitates the introduction of an overhead into the system to ensure correct decoding. In this simplified model it is assumed that the FEC overhead is a constant, labelled as O_{FEC} in equations. Therefore, if the FEC overhead is 5%, O_{FEC} is 0.05. This FEC value is a typical simulation assumption ([4], [13]). If an MBSFN trans-mission using FEC experiences some packet losses, the probability of a decoding failure increases. It will then be necessary to retransmit certain packets when total packet losses grow to such an extent that the effective FEC overhead falls below an acceptable threshold, O_{MIN}. This technique therefore implements a combination of FEC and retransmissions (ARQ). The total cost for this hybrid error correction technique is the sum of the cost for the initial transmission (with FEC overhead) and the cost of retransmissions (also with FEC overhead). In our simplified model, packets need to be retransmitted if the difference between the FEC overhead and the total loss rate exceeds O_{MIN}. The effective packet loss rate is:

$$P_{LOSS_{eff}} = \begin{cases} P_{LOSS_{total}} + O_{MIN} - O_{FEC} & when\ P_{LOSS_{total}} + O_{MIN} > O_{FEC} \\ 0 & when\ P_{LOSS_{total}} + O_{MIN} \leq O_{FEC} \end{cases} \quad (9)$$

III. Purpose of Research

The presented research aims to make use of the simplified MBSFN model above to develop an algorithm to improve error correction techniques in MBSFN systems. In 2011 and the first quarter of 2012, many research documents ([4], [16], [17]) were published investigating the efficiency of different ARQ and FEC techniques in an MBSFN system. However, no effort has yet been made to unify these studies into a systematic approach that could help with the selection of the most effective technique given certain network conditions. This study then implements a simplified cost model for different topologies in an MBSFN and investigates the efficiency of a variety of error correction techniques under different network conditions. It can take a broad spectrum of network parameters as input conditions, including network topology, number of users and density of user equipment.

IV. Simulation Results

In this section, the results of two tests performed using the presented, simplified cost model are given.

1) *Total cost over air interface*

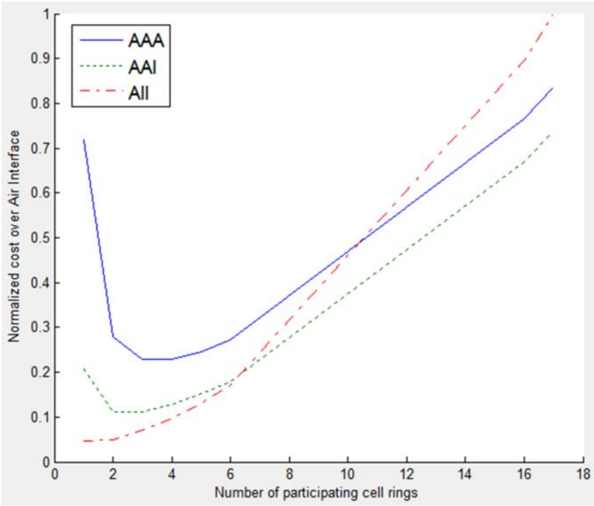

Figure 2: Total communications cost for different MBSFN deployments

Figure 2 shows the normalized communications cost over the air interface for an MBSFN system against the total number of participating cell rings in the hexagonal grid. Costs are compared between the three topologies discussed earlier (AAA, AAI, AII) in an ideal scenario (a packet loss rate of 0). No error correction techniques or FEC overhead were considered for this evaluation. The macro case considered is Case 1 – an Inter Site Distance of 500m. The simulation session consisted of 10 000 data packets to an assumed user population of 100.

From the graph it is clear that for small topologies (number of participating cell rings less than six), the AII deployment provides the lowest overall cost over the air interface. However, since an AII-deployment has a much lower spectral efficiency than that of deployments with more assistive cell rings, the total cost quickly rises as the topology grows to include more cell rings. If more than ten cell rings participate in the MBSFN session, the graph shows that AAI-deployment is the least expensive and AII-deployment the most expensive. The high initial costs for the three topologies considered are a result of the low resource efficiency when the number of participating cell rings is low.

2) Error correction costs

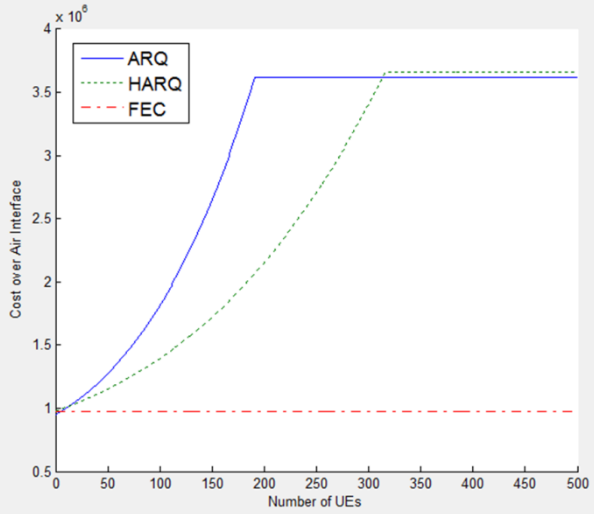

Figure 3: Total communications cost for an AII-deployment under lossy conditions

A more realistic cost simulation is presented in Figure 3. The simulation session still consists of 10 000 data packets, but now a packet loss rate of 5% is applied to the system. The total costs associated with three different approaches to error correction is generated and graphed. Each technique's cost is plotted against a rising number of User Equipment subscribed to the multicast session. As the user population grows, the probability of individual errors occurring during transmission of each data packet increases. This necessitates a higher number of retransmissions. It is assumed that all UEs reside in the centre cell. From the previous simulation (Figure 2) it is clear that for such a deployment, the AII-topology has the lowest total cost. We therefore only consider the error correction costs associated with AII in this simulation (one assistive cell ring). Once again macro Case 1 is applied.

The costs associated with ARQ transmissions quickly grow to a maximum as the number of required retransmissions increases with the user population. ARQ cost is at a maximum if each data packet needs to be retransmitted three times, according to 3GPP specifications. A better approach uses a hybrid combination of ARQ and FEC techniques (labelled HARQ in the figure). A constant FEC overhead of 5% is assumed. Even though FEC transmission introduces a high overhead into the system, it is less affected by packet losses since each receiver can tolerate a number of lost packets and still be able to decode all source packets correctly. This results in a lower overall cost than ARQ for user populations less than 300. The maximum cost associated with HARQ is slightly higher than for ARQ as it includes a small FEC overhead for each data packet. A third, and purely theoretical approach, was proposed by [13] and utilizes only Forward Error Correction. Since FEC is completely unaffected by individual errors at isolated receivers, this approach can scale to any number of users without a rise in total cost. It can be shown, however, that the required overhead might become unacceptably high for a high number of users. This approach will also require a significant amount of feedback from each subscribed user to ensure that each source block has been correctly decoded.

V. Conclusion

In this paper, a simplified cost model for MBSFN transmission over the air interface was developed and presented. This model can effectively compare the communications costs associated with different deployments in order to select the most cost effective MBSFN configuration for a given set of network parameters. It was found that for small topologies, an AII deployment provides the lowest overall cost. If UEs are located in more than ten cell rings, AAI deployment is best suited.

This model was expanded to include the extra costs associated with error correction techniques in a more realistic lossy environment. A cost-effective combination of ARQ and FEC techniques was proposed. This was tested against an ever increasing number of subscribed users and showed favourable results.

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