Chapter 8: Conclusion

Contents

In this chapter we give an overview of the work presented in each chapter and discuss the contributions made by this thesis. Moreover, we present possible future work based on the work presented in this thesis. Lastly, we summarise the research contributions made to the field of practical network coding.

8.1 Review of the thesis and the contributions it makes

The work done by Ahlswede et al. in [**2**] led to the field of network coding, which has subsequently offered many advantages in the field of communication networks. A few of these advantages were mentioned in Chapter 1, but many more exist that were not discussed in this thesis [**3**], [**4**], [**67**]. Much of the first research done on network coding was of a theoretical nature [**10**], [**58**] with a gradual change in research focus after the introduction of random linear network coding (RLNC) by Ho et al. in [**5**] and practical network coding by Chou et al. in [**8**]. RLNC offered many practical advantages like resilience to packet loss, improvement in delay, as well as changes to network capacity and topology [**4**], [**5**], [**8**], but proved to require computationally complex coding algorithms which are not suitable for practical applications [**10**], [**31**], [**41**]. Most practical network coding applications propose the use of RLNC, but it is clear that RLNC must be designed so that the coding performance is improved for practical applications. The work presented in this thesis contributes to the field of efficient coding methods for RLNC in order to harness the advantages of random network codes in practical network environments.

Chapters 2 and 3 provide the necessary mathematical background to RLNC and network error correction. These chapters provide the algebraic framework for this thesis, which describes the network environment on which the work in this thesis is based.

Chapter 4 looks at the novel idea of exploiting the redundancy generated by an RLNC network for use in error detection. The idea was first proposed in [**50**] where possible errors were detected at receiver nodes without the addition of an outer code at the source node of the network. RLNC can potentially generate a large number of redundant coded symbols at intermediate network nodes, which can be used as additional information on the source symbols to assist in error detection.

We subsequently evaluate the method proposed in [**50**] and suggest several improvements regarding packet selection for the construction of the generator matrix at the receiver nodes for the error detection scheme. An analytical expression is developed to describe the probability of receiving packets of the required characteristic at the receiver nodes of an RLNC network for a specific network topology. Through the use of this expression and simulation, we analyse the probability of constructing valid generator matrices and determine the number of additional packets required. Moreover, we show that the reception of approximately two additional packets will allow a receiver node to detect a single error without costing the network any additional resources.

This error detection method is not optimal and it is shown that error correction using this method is more expensive than implementing an outer error correction code at the source. Accordingly, this method is not suitable for practical applications. It does, however, show that it is possible to detect single packet errors in an RLNC network without the use of an outer code.

Chapter 5 presents the implementation of fountain codes in an RLNC network environment. The chapter contributes to a research problem of recent interest where the use of belief propagation (BP) is used in RLNC networks to combat the computationally complex decoding algorithms required by RLNC. One approach to implementing fountain codes in RLNC networks was proposed by [**45**], but this was restricted for the use in content distribution networks owing to the requirement for complex encoding procedures and a centralised control system.

It is stated in [**1**] that the sparse encoding of packets to approximate fountain codes can be difficult to implement in a communication network where intermediate nodes do not require the source information. We contribute to this field of fountain coding in RLNC networks by presenting a coding scheme adapted from [**45**] that employs BP for data communication between source and multiple receivers via intermediate nodes. We propose further improvements to this Hybrid-LTNC (H-LTNC) method in terms of coding procedures and buffer flush times at intermediate nodes. We show that H-LTNC allows BP at receiver nodes that require only small encoding alterations to a fraction of intermediate nodes, leading to low complexity linear encoding at most network nodes. Further improvements to the H-LTNC method propose that the implementation of an outer FEC code leads to reduced decoding complexities at the receiver nodes.

The method presented enables the packets arriving at the receiver nodes of the RLNC network to approximate the required Robust Soliton (RS) distribution so that the packets can be decoded by BP. The disadvantage is that the method requires the implementation of a suboptimal encoding method at certain intermediate nodes.

In Chapters 6 and 7 we contribute to the field of practical RLNC decoding methods by modifying the earliest decoding (ED) method presented in [**8**]. In an RLNC network, where the coding vectors of the received packets resemble a lower triangular structure, ED is able to decode the transmitted source symbols with small computational delay and complexity. As this decoding method is dependent on the lower triangular structure of the generation matrix, erased packets influence the decoding efficiency.

A practical network configuration is presented in Chapter 6 that allows the receivers of the RLNC network to obtain the required lower triangular structure for ED. This lower triangular structure is evaluated and a mathematical model constructed to help evaluate the decoding possibilities. A new decoding algorithm, modified earliest decoding (MED), is designed for the implementation in this network environment. MED proves to have a lower decoding delay than ED and requires less arithmetical operations for decoding. We also prove through both analysis and simulation that MED is more resilient to packet erasures than ED.

The MED method has been proven to be advantageous, as source symbols can be decoded at receiver nodes with low complexity and delay. The MED method offers low decoding delay and complexity and can be used in networks where the receiver nodes obtain packets of a lower triangular structure, constructed according to the network configuration presented in Chapter 6.

8.2 Future work

The first potential area for further research concerns the practical implementation of MED proposed in this thesis. It would be of interest to determine the size of the source data that can be effectively decoded in RLNC networks by MED before the computational complexity of RLNC becomes a performance bottleneck. In this thesis only the decoding complexity and decoding delay were examined; therefore it is the natural next step to evaluate this decoding method in a practical network scenario.

In this thesis MED was introduced and evaluated for the binary field alone. As this decoding method shows practical potential, it would be of interest to expand the work done on MED to larger finite fields. As practical implementations of RLNC are largely focused on coding over fields of size 2^8 or 2^{16} [**8**], this work can improve greatly on the practicality of MED.

As the research field regarding the implementation of fountain codes in RLNC networks is very new, limited work has been done so far. As with the H-LTNC presented in this thesis, there are encoding methods and approaches that could possibly be used to enable the sparse encoding of packets to approximate fountain codes. It can be seen from the literature presented in this thesis that this topic is of current interest and could have a large impact on the field of practical RLNC networks [**1**], [**31**].

As discussed in Chapter 5, the EH-LTNC presented in this thesis, can be extended to include an outer erasure correction code. The erasure correcting capability of the EH-LTNC method can be further improved by using the same technique as Raptor codes, where the source packets are precoded using a traditional erasure code. With the implementation of an outer erasure correction code, a receiver node only requires the decoding of a constant fraction of the transmitted packets, where the erasure code enables the receiver to recover the original source information in the presence of possible packet erasure. This implementation can further reduce the encoding and decoding complexities in the RLNC network. Future work could include the implementation of an outer erasure correction code with EH-LTNC for further improvement.

8.3 Summary

In this thesis the current body of knowledge and technology in practical RLNC was extended through the contribution of effective decoding techniques in network coding networks. As RLNC is widely proposed for practical network coding applications, the computationally complex coding algorithms associated with RLNC must be overcome. Existing research offers many practical solutions to the problem of decoding complexity. In this thesis we contribute to this research field by building on the current solutions available through the utilisation of familiar coding schemes combined with methods from other research areas, as well as developing innovative coding methods.

We show that by transmitting source symbols in specific patterns from the source node, the causality of the RLNC network can be used to create structure at the receiver nodes. This structure enables us to introduce an innovative decoding scheme of low decoding complexity and delay. This decoding method has also been proven to be resilient to the effects of packet loss. It therefore seems possible to implement this decoding scheme in multimedia communication, as this decoding method shows minimum decoding delay as well as resilience to packet erasures.

We show that fountain codes can be implemented in RLNC networks without changing the complete coding structure of such networks. By implementing an adapted encoding algorithm at strategic intermediate nodes in the network, the receiver nodes can obtain encoded packets that approximate the degree distribution of the encoded packets required for successful BP.

In addition we showed that the redundant packets generated by RLNC networks can be used for error detection at the receiver nodes. This error detection method can be implemented without implementing an outer code; thus, it does not require any additional network resources.

This research contributes to the field of practical RLNC by presenting new, low-complexity coding algorithms with low decoding delay.