Chapter 5 – Conclusion

The goal of studying network coding in the different OSI layers is to determine where in the OSI stack it would be most favourable to implement network coding. Since it is a large research task, the work in this thesis concentrated on characterising network coding implemented in the MAC layer only. It therefore, paves the way for further research in the field of network coding, with specific regard to the implementation of network coding in different layers of the OSI stack. In chapter 1 we give a background to concepts which are relevant to this study. In chapter 2 we explain how network coding can be implemented in each of the layers of the OSI stack, as well as other methods for the implementation of network coding, such as a cross layered approach or adding a network coding layer to the OSI stack. In chapter 3 we present the benchmark network used to characterise network coding in the MAC. The node model, network topology and applications used in the benchmark network are also presented and discussed in this chapter. We present the results from our experiments in chapter 4. The results enable us to characterise the behaviour of network coding in the MAC whilst using different network parameters, topologies and protocols. The knowledge obtained is the starting point for the full characterisation of network coding in all the layers of the OSI stack. Even though we implemented network coding in only one layer, the results give new insight into the subject of network coding. The future work (section 5.3) includes suggestions for making network coding in the MAC more efficient, as well as suggestions about the implementation of network coding in other layers.

5.1 Conclusion from the results

A standard network was created which was used to find the influence of the data speed, the network topology, the amount of data sent through the network, the physical wireless technology used, the transport layer protocol, and delay on network coding in the data link layer. Each comparison yielded its own results, but all the results agreed on a common theme: the key to better network coding performance is receiving frames from different origins interchangeably, rather than long streams of frames from the same origin. Synchronisation between source nodes could prove difficult to implement, especially in larger networks, but if the network could ensure interchanging sending slots rather than relying on opportunistic coding opportunities to arise, it would greatly increase network coding performance in a network.

The results from our proof of concept differ greatly from our standard testing network. The percentage of frames network coded with our standard network was normally around 3%, with a maximum of 42.5%. The proof of concept provided almost 100% of frames being network coded. The proof of concept provided a perfect network coding environment, but it is not based on a practical model like our standard testing node model is. This great difference in performance is a reminder that the gap between theory and practice is not something to be neglected.

5.2 Conclusion on the theme of this thesis

From the literature study and the results it can be seen that there is probably no "best layer" for the implementation of network coding. Each layer has its own benefits and drawbacks. Depending on the needs of the network, and the function of the network coding, one could probably select a layer in which some kind of network coding could be done most effectively. But it would not be possible to find a single layer in which all types of network coding could always be implemented most effectively.

5.3 Future work

Even though [**21**] discusses the pros and cons of the implementation network coding in different layers of the TCP/IP stack, there is no formal comparison based on data from simulations or physical experiment between the layers. The authors in [**63**] offers a good comparison between the physical and MAC layers based on a physical implementation, but unfortunately the results are only valid for a very specific type of network. The work in [**64**] gives a more thorough comparison between logical and analogue network coding based on theoretical principles, but is still far from providing general rules for a practical network and the different functions of network coding.

The results from chapter 4 indicated that the more the source nodes sent data interchangeably, the more network coding took place. A fully deterministic approach with synchronisation between all nodes would yield much greater network coding performance. The simulations that were done for this thesis used a very simple network topology, and static routing. The extended node model with network coding capability which we used could be altered to support more than two sending and receiving pairs. This would enable larger topologies which could create more network coding opportunities. Similar simulations to those presented in chapter 4 can then be done to find out how great an influence the number of network coding opportunities has on network performance. If the node model were changed to have its own adaptive network coding routing mechanism, this would enable the simulation of any network topology, and possibly even moving topologies (MANETs). All these changes would add to having a broader understanding of different aspects of network coding in the MAC layer.

A basis for the implementation of network coding in the IP layer has already been created in our extended node model. One can simply build on this model for further experimentation with network coding in the IP layer. The ideal would be to develop our extended node model to support network coding in as many layers of the OSI stack as possible. This way it would be simple to compare

network coding in different layers as the same network and other parameters could be used whilst only changing the layer in which network coding must be done.

The purpose of implementing network coding in the data link layer in this thesis was to exploit routing benefits that network coding presents. If network coding were implemented with the purpose of exploiting its robustness or security benefits, for instance, it could be implemented in the data link layer and analyzed. Likewise it could then also be implemented in other layers and the results compared with each other.

It would also be interesting to find out whether network coding can be applied in more than one layer simultaneously, and what influence the different instances network coding would have on each other.

5.4 A final thought

A platform for further research has been created by the work in this thesis. This study is part of a bigger whole, and more similar studies must be done on other layers, on cross-layered architectures, and on adding in whole new layers before a definite answer can be given on which is the most favourable position for the implementation of network coding. Besides only looking at which layer does network coding the most efficiently or fastest, other factors can also play a large role, like which method is most compatible with other existing protocols and systems, or in which would the development be the easiest. Also, the purpose of the network coding would also play a large role, for instance the most ideal layer to implement network coding could be one for the fastest throughput, and another for security purposes. Therefore, the final result cannot indicate in which layer or position network coding is best implemented, but rather which layer or position is the most favourable for each purpose of the implementation of network coding.

When considering all pros and cons of implementing network coding in the different layers of the OSI stack (as described in section 2.2), the pros of creating a new network coding layer stand out above the rest. A dedicated network coding layer does not have to take all the other functions performed by the other layers into account, or change the way the layers function. It is difficult to add a concrete value to an advantage or disadvantage or to say that one advantage is greater than another. The personal experience gained from the work done for this thesis taught me that the integration was most difficult to perform. The greatest difficulty with developing the node model capable of performing network coding, was to integrate the functionality of network coding into the layer, without affecting any of the layer's other functions. For this reason creating a dedicated network coding layer appears to be the best option.