Jonas Karlsson

Improving TCP Performance in Wireless Multi-hop Networks

Design of Efficient Forwarding and Packet Processing Techniques
Jonas Karlsson

Improving TCP Performance in Wireless Multi-hop Networks

Design of Efficient Forwarding and Packet Processing Techniques

Karlstad University Studies
2011:5
"I hear and I forget. I see and I remember. I do and I understand"

Confucius
Chinese philosopher and reformer (551 BC - 479 BC)
Abstract

Due to the high availability of cheap hardware, wireless multi-hop networks and in particular Wireless Mesh Networks (WMNs) are becoming popular in more and more contexts. For instance, IEEE 802.11 based WMNs have already started to be deployed as means to provide Internet access to rural areas in the developing world. To lower the cost and increase the coverage in such deployments, the wired network is extended with a wireless backbone of fixed mesh routers. With advances in technology and reduction in price comes also the possibility for more powerful wireless nodes, having multiple radios that allow transmitting on different channels in parallel.

To be a successful platform for providing general Internet access, wireless multi-hop networks must provide support for common Internet applications. As most of the applications in the Internet today use the Transmission Control Protocol (TCP), TCP performance is crucial. Unfortunately, the design of TCP's congestion control that made it successful in today's Internet makes it perform less than optimal in wireless multi-hop networks. This is due to, among others, TCP's inability to distinguish wireless losses from congestion losses. The current trend for operating system designers is also to focus TCP development on high-speed fixed networks, rather than on wireless multi-hop networks. To enable wireless multi-hop networks as a successful platform there is therefore a need to provide good performance using TCP variants commonly deployed in the Internet.

In this thesis, we develop novel proposals for the network layer in wireless multi-hop networks to support TCP traffic more efficiently. As an initial study, we experimentally evaluate different TCP variants, with and without mobile nodes, in a MANET context. Our results show that TCP Vegas, which does not provoke packet loss to determine available bandwidth, reduces the stress on the network while still providing the same or slightly increased performance, compared to TCP Newreno. We further propose and evaluate packet aggregation combined with aggregation aware multi-path forwarding to better utilize the available bandwidth.

IP layer packet aggregation, where small packets are combined to larger ones before sent to the link layer, has been shown to improve the performance in wireless multi-hop networks for UDP and small packet transfers. Only few studies have been made on the impact of packet aggregation on TCP traffic, despite the fact that TCP traffic constitutes the majority of the Internet traffic. We propose a novel aggregation algorithm that is specifically addressing TCP relevant issues like packet reordering, fairness and TCP timeouts. In a typical WMN scenario, the aggregation algorithm increases TCP performance by up to 70% and decreases round trip time (RTT) by up to 40%.

A detailed evaluation of packet aggregation in a multi radio setting has shown that a naive combination of multi path routing and packet aggregation can cause valuable aggregation opportunities to be lost. Therefore, we propose a novel combined packet aggregation and aggregation aware forwarding strategy that can reduce delay, packet loss and increase TCP performance by around 30%.
Keywords: TCP, transport protocols, packet aggregation, multi path routing, wireless mesh networks.
Acknowledgments

First of all I would like to thank my supervisor Prof. Andreas Kassler for giving me the opportunity to pursue my doctoral studies and for continuously providing me with inspirational ideas and guidance throughout all of my work. I would also like thank my co supervisor Prof. Anna Brunström, whose critical eye and clear logic helped me improve this work, far beyond my own capability. Without the support from both of you, neither of this would have been possible, thank you.

As a great source of inspiration and good friendship, I would also like to express my gratitude towards the colleagues and friends at Computer Science department at Karlstad University and to the members of the Distributed System and Communications Research group (DISCO), thank you all.

A huge thank you goes to my parents, Lisbeth and Bengt-Åke and my sister Marie for supporting my work and encouraging me throughout all of these long years. Special thanks also go to my grandfather, who always believed in me and encouraged me, but sadly are not here to see the product of all the hard work. Last but not least, I would finally like to send a special thanks to my wonderful girlfriend Sandra Wassberg. Thanks for tolerating my absence, quirks and long hours of work.
List of Appended Papers

This thesis is comprised of the following four papers. References to the papers are made using the Roman numbers associated with the papers such as Paper I.


Minor editorial changes have been made to the papers.

Comments on my Participation

For papers I-III, I am responsible for carrying out the experiments, and for most of the written material and ideas. For paper IV, I am responsible for the initial idea, the TCP experiments and the implementation of the packet aggregation and the written material for the same. I am also partly responsible for the ideas and implementation of the proposed forwarding schemes in the paper.
Other Papers

Apart from the papers included in the thesis, I have authored or co-authored the following papers:


<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Internet Connected MANETs and TCP Performance</td>
<td>32</td>
</tr>
<tr>
<td>2.1</td>
<td>Internet Connectivity for MANETs</td>
<td>32</td>
</tr>
<tr>
<td>2.2</td>
<td>TCP Problems in Internet Connected MANETs</td>
<td>33</td>
</tr>
<tr>
<td>2.3</td>
<td>TCP Protocols Evaluated</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>Performance Evaluations</td>
<td>37</td>
</tr>
<tr>
<td>3.1</td>
<td>Chain5 Scenario</td>
<td>37</td>
</tr>
<tr>
<td>3.2</td>
<td>Chain 5+1 Scenario</td>
<td>38</td>
</tr>
<tr>
<td>3.3</td>
<td>Random Mobility</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>Changing the Routing Protocol</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>Conclusions</td>
<td>44</td>
</tr>
<tr>
<td>Paper II: Impact of Packet Aggregation on TCP performance in Wireless Mesh Networks</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Introduction</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>Packet Aggregation in Wireless Multi-hop Networks</td>
<td>53</td>
</tr>
<tr>
<td>2.1</td>
<td>Proposed Packet Aggregation Algorithm</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>Simulation Setup</td>
<td>56</td>
</tr>
<tr>
<td>3.1</td>
<td>TCP Performance in Wireless Mesh Networks</td>
<td>56</td>
</tr>
<tr>
<td>3.2</td>
<td>Scenario Description</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>Simulation Results</td>
<td>58</td>
</tr>
<tr>
<td>4.1</td>
<td>Goodput</td>
<td>60</td>
</tr>
<tr>
<td>4.2</td>
<td>Packet Loss and Delay</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td>Conclusion</td>
<td>63</td>
</tr>
<tr>
<td>Paper III: Evaluation of Packet Aggregation with TCP traffic in Wireless Mesh Networks</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Introduction</td>
<td>69</td>
</tr>
<tr>
<td>2</td>
<td>Related Work</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>Packet Aggregation in Wireless Multi-hop Networks</td>
<td>73</td>
</tr>
<tr>
<td>3.1</td>
<td>End-to-end vs. Hop-by-hop Aggregation</td>
<td>73</td>
</tr>
<tr>
<td>3.2</td>
<td>Theoretical Gains by Aggregation</td>
<td>74</td>
</tr>
<tr>
<td>3.3</td>
<td>Proposed Packet Aggregation Algorithm</td>
<td>75</td>
</tr>
</tbody>
</table>
## CONTENTS

4 Simulation Setup ................................................. 78  
4.1 Simulation Description ....................................... 79  

5 Simulation Results ............................................... 80  
5.1 Basic String Scenario ......................................... 80  
5.2 Parking Lot and the 1 in 1 out Scenarios ...................... 86  
5.3 Traffic Trace Scenario ......................................... 91  

6 Conclusion ......................................................... 93  

Paper IV: An Aggregation Aware Multi-path Forwarding Paradigm for Wireless Mesh Networks ........................................ 99  

1 Introduction ....................................................... 101  

2 Architecture ...................................................... 102  
2.1 Channel Assignment and Routing ................................. 103  
2.2 Packet Aggregation ............................................. 103  
2.3 Forwarding Strategies .......................................... 104  

3 Evaluation ......................................................... 108  
3.1 Trace Analysis Single Hop ...................................... 108  
3.2 Simulations in Multi-hop Scenarios ............................. 109  

4 Related Work ...................................................... 114  

5 Conclusions and Future Works .................................. 117
Introductory Summary
1. Introduction

The success of the Internet and the rapid growth and development of last mile Internet access technologies, like DSL or fiber to the home, in the industrialized world have increased the demand for high performance networks from both users and applications. This continuing trend pushes developing countries, which lack the infrastructure, even further behind. This is commonly known as the digital divide, where the wealth of information available on the Internet is only available in industrialized countries.

A promising technology to provide Internet access in developing countries, as well as to rural areas and municipalities, are wireless multi-hop networks. In such a network, wireless nodes relay packets towards the internet gateway or the destination using wireless links without support from any pre-existing wired infrastructure network. This is beneficial in developing countries, where wire-line communication is often too costly or impossible to deploy due to political instabilities. The mass production of IEEE 802.11 radio cards and advances in technology have also lead to the possibilities of reasonably priced multi-radio nodes. Such multi-radio nodes provide a significant increase in performance as they can transmit and receive on multiple channels on different radios in parallel. This reduces network contention as less users use a common frequency band. As a result, multi-radio nodes dramatically increase performance, allowing for a reasonable alternative to provide broadband internet access. In order to access services located in the Internet, special gateway nodes need to be deployed which bridge between the fixed and the wireless multi-hop network.

The success of today’s Internet is mainly due to its simplicity and the use of the TCP/IP protocol suite. The simplicity of the TCP/IP suite has also paved the way for today’s multitude of web applications that all rely on the efficient function of TCP and the TCP/IP stack. TCP’s congestion control mechanism was designed to react in a robust way to changing network conditions that can occur in a wired network. However, the characteristics of wireless networks and especially wireless multihop networks are significantly different compared to fixed networks. Typically, mobility may lead to topology changes and route breaks. Fading and low link quality may result in high and fluctuating packet error rate and hidden node problems may lead to frequent collisions. Those effects significantly deteriorate TCP’s performance in such multi-hop networks.

In this thesis, we first evaluate TCP performance in Internet connected multi-hop networks using different mobility patterns and gateway deployment scenarios focusing on Mobile Ad-Hoc Networks. Then, we develop several novel mechanisms to improve network layer performance in order to better support TCP traffic in wireless multi-hop networks. Among those proposals, we develop a novel packet aggregation mechanisms and combine packet aggregation with multi path forwarding in a multi-channel multi-radio mesh network to better utilize the available bandwidth.

The rest of this introductory summary is structured as follows. We continue with providing a brief overview of the topics covered in this thesis. In section 2 we revisit
these topics with a more in detail analysis. Section 3 presents our research questions, followed by our research methodology detailed in section 4. Section 5 gives an overview on our main contributions. Section 6 gives a summary of the presented papers analysing also their limitations. Finally, section 7 presents our conclusions and future work.

1.1 TCP in Wireless Multi-hop Networks

In a multi-hop wireless network packets are delivered from a source to a destination using packet forwarding capabilities of intermediate (wireless) nodes. In a wireless multi-hop network that provides general Internet access, it can also be anticipated that the applications and user behavior will be similar to that of today’s Internet users. A average users send emails, get news, do shopping, search for information and watch video or listen to music. All of the above activities use the TCP protocol in some form. Current measurements have also shown that around 90 % of the Internet traffic is TCP traffic, stressing the need for good TCP performance in wireless multi-hop networks. Furthermore, TCP performance in wireless multi-hop networks depends on the characteristics of the network, e.g. if the nodes are mobile or stationary.

1.1.1 Difference between MANET and WMN

When nodes are mobile and act as both end systems and routers, the network is commonly known as a Mobile Ad Hoc Network or MANET. A MANET employs a flat hierarchy where all nodes participate in the forwarding of the traffic. The mobility of the nodes also requires the routing protocol to constantly monitor the links and when the connection is lost, e.g. a neighbor moves out of transmission range, the topology changes leading to routing updates.

With highly mobile clients, the constant route updates make it difficult in MANET topologies to use proactive routing protocols, e.g. DSDV, where all nodes know the entire network topology. Instead, highly mobile MANET deployments tend to use reactive routing protocols, like AODV, where routes are only established when needed. This reduces the routing protocol overhead because routing messages are only sent when needed. There will, however, be an initial delay of the traffic, due to the route acquisition phase. The normal assumption is also that the nodes are laptops with limited batteries using a single radio network card. As all nodes have a single radio using a common channel, collisions may occur frequently due to hidden nodes. In addition, node mobility creates route breaks and packet loss. This results in low total network performance.

An interesting special kind of wireless multi-hop networks are wireless mesh networks or WMNs. A wireless mesh network is normally built as a 2-tier architecture
consisting of mobile wireless clients (laptops) as a first tier and a wireless backbone of fixed mesh routers and mesh gateways forming a second tier, see Figure 1.

Typically, the second tier consists of fixed nodes, sometimes with more than one radio. When packets can be forwarded on different channels and paths, more possibilities for route and forwarding optimizations exist, possibly reducing intra- and inter-flow interference. WMNs also have more predictable links, than a MANET due to lower link dynamicity, enabling the use of both reactive and proactive routing protocols. This allows higher performance in WMNs than in MANETs.

1.1.2 TCP in MANETs

The characteristics of MANETs, with mobile nodes and unpredictable links lead to route instabilities in the network. TCP’s congestion control algorithm performs poorly in MANETs due to e.g. its inability to distinguish between packet loss caused by congestion, MAC contention and routing layer issues, such as topology changes due to e.g. node mobility. MAC layer contention occurs when multiple adjacent nodes contend for a shared channel, which can trigger false routing errors, even with stationary nodes [39]. A contention-based packet drop is more severe as it can potentially affect multiple packets, while a congestion based drop, i.e. a queue drop, only affects a particular packet. When a packet is lost due to mobility, TCP interprets this as congestion, and unnecessarily reduces its sending rate.
1.1.3 TCP in WMNs

In Internet connected WMNs a common scenario is that many flows share the same link, e.g. towards the gateway, resulting in high contention on bottleneck links. The unfairness of the IEEE 802.11 MAC layer, where shorter packets have a lower collision risk, also poses problems even with only one flow. TCP DATA packets will have higher risk for collision than TCP ACKs that traverse in opposite direction, leading to reduced TCP performance. Unfairness between TCP flows that traverse different number of hops, can further reduce the performance of the flows that traverse more hops [47].

Network asymmetry where the forward direction of a flow, e.g. TCP DATA packets flowing towards a gateway over one path, is significantly different from the reverse direction flowing over a different path, reduces TCP performance [3]. Network asymmetry is common when flows cross a gateway, as the different flows experience a different packet loss pattern [53] or when TCP DATA and TCP ACK packets traverse different paths in the network.

Multi-path routing can reduce the stress on bottleneck links by load-balancing the traffic among the nodes in the network. To achieve optimal load-balancing it must be performed on a per packet level. The drawback of spreading the packets on different paths in the network is that the risk for packet reordering increases. As standard TCP only has limited capability to handle reordering, reordered packets can severely hamper TCP performance as it unnecessarily triggers TCP’s congestion control [28]. To minimize reordering, the load-balancing can be performed on a per flow level, thereby reducing packet reordering at the cost of less fine-granular load-balancing.

1.2 Packet Aggregation

Capacity of wireless multi-hop networks can be increased significantly by aggregating (combining) several smaller packets into larger ones as showed in [46]. This reduces header/transmission overhead and the number of medium accesses. Measurements have also shown that around 44 percent of the IP packets in the Internet are between 40-100 bytes (Figure 2). However, irrespective of the TCP DATA size, more than 1/3 of the TCP packets will be TCP ACK packets of 40 bytes, providing good possibilities for aggregation.

Frame aggregation, which operates at the MAC layer, is similar to packet aggregation that operates at the IP layer in that both save transmission time and reduce overhead [32]. The benefit of packet aggregation is, however, that it can be deployed irrespective of current hardware. Whereas frame aggregation requires hardware support or possibilities to change the firmware [20, 24]. Changing the firmware of an already deployed network is often very difficult since not all hardware architectures and vendors support such updates.
Designing an aggregation strategy for wireless multi-hop networks is challenging because in a multi-hop environment the characteristics of each link may be different. When mesh relay nodes aggregate small packets, there is an inherent trade-off regarding packet size. Aggregating more packets leads to larger packets, reduces the overall number of packets in the mesh, and thus reduces transmission overhead and medium access. However, to have enough packets to aggregate, relay nodes might additionally delay packets leading to larger end-to-end delay.

Since the overall number of MAC frames is reduced, collision risk between TCP DATA and TCP ACK are thus reduced by aggregation. TCP is more affected by packet loss than by delay [42]. This is favorable for aggregation, since it is possible to delay packets longer in order to get a higher aggregation ratio without reducing TCP performance. However, a too long delay could lead to severe TCP performance degradation, due to the increased risk for TCP timeouts. In high traffic scenarios, where aggregation is most beneficial, queues normally have enough packets to aggregate without delaying the packets. However, in scenarios with low traffic, finding a good aggregation delay is challenging.

### 1.3 Multi-path/channel Routing and Packet Aggregation

Using multiple channels and or multiple radios in wireless multi-hop networks greatly reduces the contention on highly occupied channels/links [2, 26]. Such frequency diversity not only increases throughput, but also makes multi-path routing approaches extremely interesting [52]. When next-hop neighbors are using different channels, the bandwidth available per node increases and contention and inter/intra-flow interference decreases.

There are several possibilities to accomplish frequency diversity. One common approach is to equip nodes with one radio per channel, used by that node e.g. [2, 5, 36, 55].
When using multiple radios, each radio is tuned to a given channel during a long period (typically minutes). A channel assignment algorithm, either pre-computed or on-demand, determines which channel should be assigned to which radio to ensure connectivity and minimize interference. The drawback of using one radio per channel is the increased cost and space requirements when the number of channels that a node is using becomes more than a few.

When a node uses fewer radios than channels, some of the radios need to switch among different channels \cite{27,50,52}. Using fewer radios than channels, and especially single-radio multiple channel systems reduce the cost. The drawback is increased scheduling complexity as channel switching delay with current hardware is non-trivial (5 ms) \cite{12}. Therefore, with current IEEE 802.11 hardware, in a switchable approach, when a radio has switched to a channel, it normally stays on that channel for a period of a few milliseconds to compensate for switching overhead. A non-trivial problem is to assign channels to nodes so that interference is minimized and connectivity maximized and several approaches exists for both multi- and single-radio systems, e.g. \cite{5,25,36,51,52}.

Deploying packet aggregation in multi-channel multi-path environments may result in suboptimal performance. When a multi-path routing algorithm is used, each node tries to actively spread packets to different next hop neighbors exploiting spatial and frequency diversity. At the contrary, packet aggregation tries to combine as many packets as possible to one next-hop. These two conflicting goals, resulting in that the two mechanisms work against each other, spur the need for the two mechanisms to be jointly optimized for optimal performance.

2 Background and Related Work

In this section we will revisit the topics covered in section 1 providing more in detail information to the work presented in this thesis.

2.1 TCP in Wireless Multi-hop Networks

In single channel wireless multi-hop networks, where all nodes operate on a common channel, the transmission of earlier received packets can disturb the reception of later packets in the same flow. This phenomenon is called intra flow interference, which is especially problematic when the traffic comes in bursts and under high traffic load. This problem also occurs when the traffic is flowing in opposite directions, which are problematic for TCP, since TCP ACKs and TCP DATA packets may traverse the same route in opposite directions. As a result, ACKs compete with TCP DATA packets for medium access leading to increased contention \cite{49}.

TCP’s congestion control cannot distinguish between packet loss caused by congestion, interference or routing layer issues \cite{49}. In MANETs, the mobility poses an addi-
2. Background and Related Work

2.1.1 TCP in MANETs

In MANETs, a significant portion of packet losses are caused by link failures either due to high bit error rates or mobility of nodes resulting in topology changes, route errors or network partitions. When a node moves closer to the destination and or a new shorter route is found, it is crucial to quickly determine the available bandwidth so that the higher bandwidth can be utilized, as indicated in \[19\]. In such circumstances, a too slow increase of the congestion window and probing of available bandwidth is not beneficial \[33\]. A too aggressive approach is also not beneficial as it might create MAC layer contention as further discussed in section 2.1.2.

The choice of the routing protocol is also important. Different routing protocols may react differently on packet loss, caused by e.g. MAC layer contention. This follows our findings from Paper I, where TCP Vegas [10] less aggressive approach, performs slightly better than TCP Newreno’s [16] more aggressive approach when using a reactive routing protocol (AODV). The simulations in Paper I also show that using a proactive routing protocol (DSDV), and with node mobility, TCP Newreno performed slightly better than TCP Vegas. Due to TCP Newreno’s ability to more quickly utilize the full bandwidth of the path.

Several solutions for TCP’s congestion control algorithms as well as new transport layer protocols have been proposed for standalone MANETs that try to avoid the problems of TCP, a good overview can be found in e.g. [4]. However, in an Internet connected MANET, to use a specialized MANET protocol requires a split connection approach [54]. When wireless nodes access wired nodes/servers in the Internet, which run a standard TCP/IP stack, the gateway needs to translate between the specialized protocol and standard TCP used in Internet hosts. This introduces overhead due to protocol conversion within the gateways. Furthermore, if the gateway is changed during an ongoing session, then a state transfer is necessary between the gateways, complicating gateway design and the interaction among them [29].

2.1.2 TCP in WMNs

In a WMN, the nodes are stationary and route breaks caused by e.g. movement of the node or node failures, should seldom happen. However, the complex cross-layer interaction between the MAC, routing and transport layer can provoke route breaks. When TCP aggressively probes for bandwidth during the slow start phase, there is a high probability for MAC layer contention induced packet loss, which may cause the routing proto-
col to trigger route error messages [39]. When TCP starts to react, the routing protocol might already use a different route, which causes unnecessary route changes, even with no mobility. Furthermore, when updating the route, route repair messages contribute to the contention and during this time all traffic is halted, which might lead to a TCP timeout [39]. This in combination with TCP (New)Reno’s overshooting the available bandwidth in wireless multi-hop networks and therefore operate with a too large congestion window, leads to increased contention [17].

TCP versions that focus on wireless multi-hop networks, while maintaining TCP interoperable with any valid TCP implementation, have been proposed, such as TCP-AP (Adaptive Pacing) [14]. TCP-AP implements adaptive pacing at the sender side while retaining TCP end-to-end semantics. However, the approach requires the senders to be located in the multi-hop network. This is normally not the case as most servers are still connected to wired links for performance reasons. Due to this, the authors of TCP-AP proposed TCP-GAP, which use a pacing buffer at the gateway to pace the TCP flows that originates in the wired Internet [15]. This removes the need for changes to existing Internet hosts at the cost of a more complex gateway design. However, TCP-GAP still requires changes to the wireless clients as they are still required to run TCP-AP.

The unfairness of the IEEE 802.11 MAC layer, where one flow can capture a channel, combined with TCP's congestion control mechanism, can lead to starvation of other flows. Even within a single TCP flow, the capturing effect can cause starvation between the TCP DATA and TCP ACK packets flowing in the opposite direction [49].

2.2 Packet Aggregation

The overhead for transmitting small packets, such as TCP ACKs, is large in IEEE 802.11-based wireless multi-hop networks. One way of reducing the problem of small packet transfers is to perform frame or packet aggregation. Packet aggregation, which operates at the IP layer, does not require a change of the current hardware and can therefore easily be deployed and integrated in existing wireless networks.

In end-to-end packet aggregation, only the end-nodes (de-)aggregate. Alternatively, it is possibly to only aggregate within the wireless network and let the gateway (de-)aggregate before forwarding the packets. End-to-end aggregation can almost double the throughput for constant bit rate (UDP) traffic and improve throughput by 20% for HTTP traffic compared to an unaggregated case [46]. The drawback of end-to-end approaches are the lost aggregation opportunities at intermediate nodes and the need for support at both end nodes, of which one might possibly be an Internet host.

In hop-by-hop aggregation, every wireless node is capable of (de-) aggregation. A common technique, in both end-to-end and hop-by-hop aggregation, is to add a forced delay before sending a packet. This allows the queues to build up which increases the aggregation possibilities [21]. In hop-by-hop approaches the aggregation possibilities are
potentially higher than in end-to-end approaches. There is, however, a risk that the path delay might be considerably longer due to the added delay on each hop. Therefore, in a hop-by-hop approach, a suitable value of the aggregation delay parameter is dependent on more parameters than in end-to-end approaches, including (wireless) path length and contention at intermediate nodes.

A third variant is the accretion aggregation algorithm, which only adds forced delay at the ingress nodes [23]. The intermediate nodes therefore only aggregate when the media access delay makes the queues build up naturally. This reduces the possibilities for unpredictable path delay. However, since intermediate nodes do not delay the packets, with an unfortunate packet arrival pattern, valuable aggregation opportunities might be lost.

Frame aggregation, which operates at the MAC layer, is similar to hop-by-hop packet aggregation but cannot easily be deployed without changing currently deployed hardware and/or firmware [24]. Various incompatible proprietary frame aggregation techniques are implemented in commercial WLAN products [32]. The proposed IEEE 802.11n standard [20], features packet aggregation at the link layer, overcoming the incompatibility issues with existing techniques. The standard however, specifies two different strategies for frame aggregation, one where the aggregation is done when the packets enter the MAC layer (A-MSDU) and one when the packets leave the MAC layer (A-MPDU). The aggregation strategy most similar to our packet aggregation algorithm is the A-MPDU. The standard does not define, however, an aggregation algorithm; it only enables the use of such mechanism within its framework. Our aggregation algorithm proposed in paper II and used in papers II-IV is implemented as a hop by hop IP layer packet aggregation scheme, but could, applying minor changes, be implemented as a frame aggregation scheme.

2.3 Multi-path/channel Routing and Packet Aggregation

Interference can be alleviated by using multiple channels and multiple radios in a network. The IEEE 802.11b/g and IEEE 802.11a standards define three and twelve non-overlapping frequency channels, respectively. In this section, we will describe the issues and challenges with using multiple channels/radios and combining this with multi-path routing and packet aggregation.

2.3.1 Multi-radio-/channel Wireless Multi-hop Networks

Using multiple channels in multi-radio wireless multi-hop networks greatly improves the network capacity by reducing interference on highly occupied channels/links, by spreading the traffic load on different orthogonal channels. However, with several radios in one node, the risk of mutual interference by conduction as well as radiation inside the node increases [2, 48, 56]. In addition, antenna separation is increasingly difficult as the
number of radios increase.

When using fewer radios in a node than the number of channels used to communicate to the node’s neighbors, the radios must switch between the channels. With current off-the-shelf hardware, this imposes a non-trivial switching delay \([12, 51]\).

When using multiple channels there is also the need to address the problem of which channel to use for a particular transmission/link. In dynamic channel assignment schemes, with either one or multiple radios, the channels are changed frequently, e.g. based on traffic load or the current state of the medium such as external interference. Dynamic channel assignment requires fast channel switching often not possible with current IEEE 802.11 based hardware as a typical packet transmission only takes a few microseconds \([51]\).

Static or quasi-static assignment schemes only change channels when there are significant changes to traffic load, network topology or due to external interference. These approaches require that the channel changes are infrequent enough so that the channel switching delay becomes negligible and that multiple radios are attached at each node \([51]\).

When a radio is tuned to a particular channel, it cannot hear communication taking place on a different channel. Due to this, nodes may suffer from multi-channel hidden terminal problems \([13, 50]\). Therefore, unless the nodes are clock synchronized, when a radio is switched to a new channel, the node must stay mute for a period of time until it has sensed the channel \([50, 52]\). This complicates packet scheduling and reduces performance, even if new hardware could reduce the channel switching delay. In addition, with a non-trivial channel switching delay, MAC layer broadcasts are costly as a node needs to switch between all used channels to reach its neighbors \([13]\). With channel switching, the network might also experience temporal disconnection called the deafness problem \([13]\). The deafness problem is caused by the fact that, when a node communicates with a neighbor it is deaf to all other communication attempts by neighbors on other channels. This might lead to the false assumption, by its neighbor, that the node is permanently unreachable \([13]\).

When one channel per radio is used, the deafness and multi channel hidden terminal problems are avoided. However, extra concerns must be taken when (re)assigning channels so that the network is fully connected. This is called “the channel dependency” problem and requires channel changes to be propagated to avoid network partitions \([13]\). When only one channel is used per radio, changing the channel may also alter the topology as new links may be created or disappear \([6, 13]\). Furthermore, since all links that share the same channel, within interference range, also have to share the common channel capacity, channel assignment determines the available bandwidth on each link. This affects the routing and indicates that routing and channel assignment should be jointly optimized \([5]\).

A jointly optimized routing and channel assignment is NP-complete. Therefore,
approximative methods to solve the problem must be used, e.g. [5, 6]. One possible solution we use in paper IV is to solve the two problems separately, as first presented in [6]. First, for each node a relative set of pre-calculated flow-rates are assigned to each link/interface. The calculations only aim to maximize the network capacity, and are thus not dependent on any particular traffic profile. Secondly, a static channel assignment is performed on the nodes to satisfy the given flow-rates while preserving the network connectivity. A flow-rate is defined in the form of a relative value, e.g. send 50% of the packets on link A. The algorithm assumes that the routing layer enforces the flow-rates on each link. The benefit of this approach is that it requires no channel switching and there is no need to measure or adapt to the current traffic pattern.

Hybrid approaches, where one radio is fixed or semi fixed to one channel and the other radio is switchable, avoid the deafness and network partition problems. However, the path delay might be significantly increased compared to using fixed channels. When multiple channel switches are required along a path, the switching cost of multiple channel switches and the cost to cope with the multi-channel hidden node problems could be large [13].

2.3.2 Multi-path Routing in Wireless Multi-hop Networks

When using multi-path routing, nodes actively try to load balance the traffic on the nodes in the network so to avoid bottleneck nodes/links. This is done by splitting packets along two or more link disjoint paths leading towards the destination. This increases performance and improves fault tolerance [3]. Multi-path routing has proven beneficial in single-channel networks and several routing protocols have been developed such as AOMDV [35]. However, when using multi-path routing for load-balancing with single-channel systems, there is always a potential interference problem when the paths are not link disjoint. Such links are for example the last hop before the destination or when two different nodes are within interference range.

The frequency diversity achieved with multiple channels, not only increases throughput in general but also makes multi-path routing approaches extremely interesting. Since more links will be disjoint, the increased channel diversity combined with multi-path routing further reduces the risk for intra and inter-flow interference. Therefore, the biggest advantage of multi-path routing is when it is used in multi-channel networks [52]. In Internet connected WMNs where it can be anticipated that most of the traffic will be to or from a gateway, further optimizations can be done to load-balance the traffic, either over single- or multi-radio systems [40].

2.3.3 Combining Multi-channel/path Routing and Packet Aggregation

Deploying packet aggregation in a multi-channel/path environment may result in sub-optimal performance. When a multi-path routing algorithm is used, each node tries to
actively spread packets to different next-hop neighbors exploiting spatial and frequency diversity. At the contrary, aggregation tries to combine as many packets as possible to one next-hop. When using multi-path routing, packet reordering is a well-known problem for TCP that can cause severe degradation \cite{8, 30, 31}.

There exist well known solutions to minimize reordering problems for TCP \cite{30, 45}. However, in a general-purpose wireless multi-hop network it can be anticipated that most clients will run standard TCP variants that do not have mechanisms to handle reordering. Therefore, lower layer solutions that work with standard TCP, using buffers to reorder packets within the last node in the wireless multi-hop network \cite{45}, but this is out of scope for this thesis.

3 Research Questions

The objective of this thesis is to improve TCP performance in wireless multi-hop networks by adapting and improving the network layer.

To fulfill this objective we will focus on the following research questions.

Question 1: *How is TCP performance influenced by (bad) cross layer interactions?*

The main idea about congestion control in TCP is to estimate and adapt to the available bandwidth. A common technique to estimate the available bandwidth is to increase the network load until a packet drop occurs. A too aggressive or too slow measure of the available bandwidth can both be contra productive in wireless multi-hop networks, as discussed in section 2.1.1. In Paper I we present simulations with different TCP variants, showing TCP’s problem of determining the correct available bandwidth in Internet connected wireless multi-hop networks both with and without mobile nodes. Consistent with research on stand alone wireless ad hoc networks \cite{39}, we could see that an aggressive approach, such as to provoke packet loss, to determine the available bandwidth was contra-productive. The packet loss caused by the probing of available bandwidth forced the routing layer to issue route repair messages, increasing the contention and creating route instabilities.

Question 2: *What can be done on a local node level to better support TCP in wireless multi-hop networks?*

Internet connected wireless multi-hop networks and WMNs are often seen as a mean to provide increased Internet coverage. The majority of the traffic sources will therefore be located in the wired Internet, running standard TCP variants not specially adopted for wireless multi-hop networks. One can argue that the TCP standard is not static and is always evolving, which could lead to a more wireless multi-hop network friendly TCP version being deployed in the wired Internet someday. This is, however, not the current trend. On the contrary, most TCP
proposals that are deployed in popular operating systems, focus on a good utilization of high bandwidth links [18, 34] which have, if not opposite, thus very different characteristics from the wireless multi-hop links we study. Therefore it is important in Internet connected multi-hop networks to be able to provide good support for TCP on a local basis and not rely on or negatively impact end-to-end mechanisms deployed in the wired Internet. In Paper II we design and evaluate the possibility to use a non-intrusive and easily deployable packet aggregation scheme to improve local link capacity in small WMNs. The evaluation is continued in Paper III to also hold for larger WMNs with more diverse traffic patterns. The conclusion from the evaluations is that packet aggregation can give a substantial performance increase for TCP traffic.

Question 3: How can we improve network services for TCP in a wireless multi-hop network with the emergence of powerful multi-radio nodes?

Two interesting techniques to improve performance in wireless multi-hop networks are multi-channel/multi-path routing/forwarding and packet aggregation. Multi-path forwarding actively tries to load balance the traffic on several next hops to reduce the possibility for bottleneck nodes. However, for packet aggregation to be beneficial there must be enough packets destined towards a single next hop to achieve a good aggregation ratio. A naive combination of the two approaches might, therefore, lead to suboptimal results due to the conflicting goals of the two approaches, see Section 2.3.3. In Paper IV we propose two novel aggregation aware forwarding algorithms. The algorithms work on a local basis and require no extra transfer of information between nodes. The simulation results show that both packet loss and delay are decreased. However, as the forwarding is not flow aware, the improvements in packet loss and delay come at the cost of heavy packet reordering.

4 Research Methodology

Two research methodologies are commonly used in computer science to test theories: analytical and experimental.

In analytical methods, theories and problems are modeled as mathematical formulas and results are obtained by solving these formulas by using mathematical methods. Analytical methods often provide deep insights into how various parameters affect the end results and hard upper and lower bounds can often be determined. However, in many cases, extensive simplifications must be made to the model to be able to find a solution.

Experimental methods are normally used when the problem is too complex or requires too many simplifications when solved analytically. In experimental methods, problems and theories are modeled by simulation, by real measurements or by emulation.

Simulation use an abstract model of the system defined in a simulation tool called a
simulator. The simulator makes representation of a problem more straightforward than in analytical models but at the cost of high computational complexity. Simulation also allows for a higher degree of separation between different effects due to a more controlled environment, than when using a real system.

When using real measurements, an operational system is studied. A major advantage of real measurements is that there is no difference between the “model” and the real environment. The drawback of real measurements is that, due to the unpredictability and uncertainty of the environment, it is often hard to produce controlled and reproducible experiments.

Emulation combines simulation and real measurements, where parts of the system are abstracted and parts run on a real system. The advantage is the combination of repeatability and controlled environment from simulation with the use of a real system from real measurements.

For this thesis we mainly used simulation as the research method. We used the network simulator ns2 [38] extended and modified with our own proposals as described in each paper. By using simulation we were able to evaluate larger topologies/more complex traffic scenarios with higher repeatability and control than otherwise possible.

5 Main Contributions

The main contributions of this thesis are summarized below.

- We evaluate TCP performance in wireless multi-hop networks and suggest some improvements, to lower layers, to better support TCP type traffic. In particular, we
  - Present an extensive evaluation of different TCP variants in Internet connected wireless multi-hop networks with and without mobile nodes. With mobile nodes, TCP will suffer from packet drops and changing path characteristics due to route breaks occurring when the nodes move. When the nodes are stationary, e.g. as is the case of a Wireless Mesh Network, route changes and packet drops are caused by the inflicted load on the network by TCP, following results presented in earlier work [39]. This contribution is presented in Paper I.
  - Evaluate and implement a packet aggregation scheme tailored to suit TCP type traffic. The aggregation algorithm uses a conservative aggregation policy to avoid packet reordering, possible flow starvation and queue overflows that would hamper TCP performance. With typical TCP applications, like FTP or web browsing, IP packet size will be bipolar with large TCP DATA packets and small TCP ACK packets. This in combination with the different traffic
characteristics of TCP, where TCP tries to grab the entire bandwidth of the path, makes the conditions for packet aggregation very different from the normally considered VoIP/UDP scenario. This contribution is presented in Paper II and Paper III.

- Develop and evaluate two novel routing and forwarding schemes, that combine the benefit of multi-channel/path routing and packet aggregation. To achieve a high aggregation ratio, there is a need for packets to travel to the same next hop. For high efficiency of multi-path routing, packets should be load balanced between the next hops. These two conflicting goals make a naïve combination of packet aggregation and multi-path routing less than optimal. In Paper IV, we propose two aggregation aware multi path forwarding schemes. In the long term, the first scheme both satisfies the flow-rate requirement of each link, as mandated by the channel assignment and routing strategy [6], and provides good packet aggregation possibilities. The second scheme jointly optimizes aggregation delay and aggregated packet size, without fulfilling the flow-rate criteria. The schemes only require the packet aggregation to expose queue size, timer values and available packet space.

• Implementation of the ns 2 modifications and additions used in papers II - IV.

- During the work of the thesis we have continuously improved and modified the packet aggregation algorithm used in papers II - IV.

- For paper IV we implemented three multi-path routing and forwarding schemes in the ns 2 miracle platform [7]. We first implemented a round robin scheme used as a comparison baseline. The scheme use a simple load-balancing algorithm to disperse the packets among the next-hop neighbors. Secondly we implemented two novel aggregation aware schemes that optimize delay and network throughput as described above. To be able to report information needed for the last two schemes, we also added cross-layer functionality to the packet aggregation layer.

- We identified and modified ns 2 TCP implementation and default values, to better reflect current status of standard TCP.

6 Summary of Papers

This section contains summaries of the papers included in this thesis.
6.1 Paper I - TCP Performance in Mobile Ad Hoc Networks Connected to the Internet

Throughout time, TCP has been modified and revitalized with new mechanisms to better suit changing network and end user requirements.

In this journal article we investigate the performance of three different TCP variants in a wireless multi-hop network connected to the Internet. We consider small to medium sized topologies with both mobile and static single radio nodes. In the evaluation we use two single path routing algorithms, AODV-UU [41] and DSDV, four traffic patterns and three TCP variants, TCP Vegas, TCP Newreno and TCP AP [14]. In total we perform 96 different simulations over three different topologies.

We show that TCP Vegas reduces the amount of packets in flight and the number of false route errors while providing the same or better performance as compared to TCP Newreno and TCP AP. With AODV-UU, TCP Vegas’ more accurate bandwidth estimation gives it a slight advantage over TCP Newreno’s more aggressive but less accurate estimation. We also highlight that TCP Newreno, due to its aggressive probing for bandwidth, can create excessive route flapping. We also show that although the overall performance was slightly lower with DSDV than with AODV-UU (with mobile nodes), the advantage gained by using TCP Vegas is reduced with DSDV as routing protocol. This is because TCP Newreno could more quickly utilize the temporary shorter routes when the node moved closer to the gateway.

The main limitations of this article are the synthetic traffic models and topologies used. In the paper we used a FTP type of traffic pattern that highlights the problem areas addressed but only to a limited extent is comparable to the more diverse traffic patterns found in a real system. From the topologies in the paper only the random one can be said to represent a real MANET. The other topologies where due to there size (the string and the string plus one moving node) and topology (the grid) rather chosen to highlight different interesting areas.

6.2 Paper II - Impact of Packet Aggregation on TCP Performance in Wireless Mesh Networks

In Internet connected multi hop networks and in particular WMNs, the majority of the sources are located in the wired Internet and the receivers are typically normal laptop users. Although several approaches that split the connection exist, e.g. MTCP [54], they are not always applicable due to high overhead and difficulties with handling handover between gateways [29]. This emphasizes the importance for good application performance with standard TCP, e.g. TCP Newreno.

In this paper we examine the possibilities of using packet aggregation to better support standard TCP traffic in small Internet connected single radio WMNs with no hid-
den nodes. We also introduce our novel packet aggregation algorithm. The algorithm captures the key parameters for aggregating TCP traffic and favors packet order and fairness over aggregation possibilities. We evaluate the algorithm in an arrow topology and use standard TCP Newreno (with Selective [37] and Delayed ACKs [9]), both with and without deploying packet aggregation. We simulate large file transfer(s) with an FTP like application using two different maximum segment sizes (MSS), 1460 and 536 bytes.

The simulation results show that adding a small artificial delay when aggregating both increases TCP goodput up to 70 % and reduces round trip time (RTT) up to 40 %. This is because of the improved MAC layer performance with fewer but larger packets.

The main limitations of this paper are the size of the WMN topology, the consideration of only good links, where all wireless bit errors could be recovered by MAC layer retransmissions and the synthetic traffic models used. We further increased the number of allowed “hello”-messages lost in order to achieve stable routing, as our simulations should not be influenced by instability of the routing layer. We also did extensive monitoring and design of the topology to ensure that all wireless losses could be recovered by MAC layer retransmissions.

6.3 Paper III - Evaluation of Packet Aggregation with TCP Traffic in Wireless Mesh Networks

In this article we give a detailed description of and evaluate the proposed packet aggregation scheme in single radio WMN topologies with hidden nodes. We examine the packet aggregation algorithm with a diverse set of topologies and traffic patterns, including patterns based on wireless traces and patterns well-known for causing TCP performance problems. The user scenarios are both an FTP like file transfer, using 1460 and 536 bytes as TCP MSS, and a trace-based approach using a TCP MSS of 1460 bytes.

We show that, with FTP like traffic, packet aggregation increased TCP performance up to 60 % and reduced the impact of the TCP packet size on goodput. We further showed that aggregation can decrease TCP round trip time in loaded networks by up to 30 %. In some scenarios we could also see a slight improvement of fairness by using aggregation with forced delaying of packets. In the trace based simulation in which many TCP flows do not enter steady state, the TCP performance improvement is, as expected, less than in the FTP like scenarios. The simulation does, however, highlight the importance of the traffic pattern where the highest gains by aggregation can be seen when there are many simultaneous TCP flows in the network. We further show that the total amount of packet loss was similar with and without packet aggregation, but that the burstier packet losses experienced with aggregation gives an increase of TCP performance as compared to not using packet aggregation. This is because for a given packet loss rate, random losses are more negative for TCP performance than correlated losses. We also showed that aggregation does not change the ratio between TCP packets resent due to fast retransmit and time out.
The main limitations of this article are to only include good links and neglect the influence of routing. We used topologies and techniques similar as in Paper II to achieve good links and stable and fixed routes. This isolates the effects we study, but in a real system instabilities and efficiency of the routing protocol and links must be considered. In this paper we did not consider the use of multiple radios/channels.

### 6.4 Paper IV - An Aggregation Aware Multi-path Forwarding Paradigm for Wireless Mesh Networks

In the previous papers, we considered single path routing with all nodes tuned to the same channel. The current trend is towards more powerful nodes equipped with fast processors and multiple radio interfaces for increased performance. The appealing property of multi-path routing is the ability to spread the load in the network and thereby reduce stress on bottleneck nodes. Deploying packet aggregation in multi-channel multi-path environment may result in suboptimal performance. When a multi-path routing algorithm is used, each node tries to actively spread packets to different next-hop neighbors exploiting spatial and frequency diversity. At the contrary, aggregation tries to combine as many packets as possible to one next-hop. For this reason, it is important to make the multi-path routing algorithm aware of the packet aggregation, to effectively combine multi-path routing and packet aggregation.

In this paper we extend the previous work to cover multi-path routing over multi-channel/radio nodes. We propose two new aggregation aware forwarding paradigms for multipath routing. The proposed paradigms try to maximize throughput or minimize aggregation delay. We evaluate the proposed forwarding paradigms by simulating the forwarding process both on a wireless packet trace and in the ns2 simulator, simulating two random topologies. We evaluate both TCP and UDP traffic, where UDP throughput is increased by around 90% and TCP traffic around 30%. Although the throughput increase with UDP is promising, TCP performance cannot fully benefit from the increased network capacity. This is due to a massive amount of reordering, of up to 30% of the packets. This shows that the forwarding paradigms significantly increase network throughput, however, at the cost of a higher packet reordering.

The main limitation of this paper is the lack of in detail evaluation of the difference between UDP and TCP throughput. Left for future work is also to evaluate if the reordering, caused by the new forwarding paradigms, could be minimized while maintaining a similar network throughput as before.

### 7 Conclusions and Future Work

TCP performance is one of the key barriers to enable wireless multi-hop networks to be as popular and successful as single-hop networks such as (WLANs) are today. Wireless
multi-hop networks allow for rapid and flexible deployment, making them attractive for numerous applications ranging from broadband Internet access to surveillance systems. Wireless multi-hop networks also offer the major advantage of WLANs that they can be deployed in places where wired communication is too costly or otherwise impossible, e.g. historical buildings.

In this thesis we investigate how we can improve performance of TCP traffic in typical IEEE 802.11 wireless multi-hop networks to enable wireless multi-hop networks as a competitive platform for broadband Internet access. In the first part of the thesis we investigate the performance of different TCP versions and how they interact with lower layers. We show that TCP’s congestion control can negatively interact with lower layers, following already presented results [39]. We continue to argue that it is important to provide good performance with standard TCP versions for Internet connected wireless multi-hop networks. Especially, since the current trend among OS developers is to focus on high speed (wired) links.

We propose packet aggregation and aggregation aware multi-path forwarding as two complementary methods of improving network layer services for good TCP performance. Our packet aggregation algorithm can be deployed with current hardware as an IP layer solution, or with slight modifications be implemented as a MAC layer solution. The novel aggregation aware forwarding is an independent solution that, with the support from packet aggregation, can improve the performance in multi-radio environments and only requires minimal exchange of cross layer information.

In future work we will also address some major limitations of this thesis, such as that the current approaches only consider locally available information. Although this is advantageous as it reduce overhead and complexity, it can create globally suboptimal solutions. We will therefore focus on path optimizations, in contrast to the more local link focus of current proposals. We also plan to extensively evaluate different queuing strategies, focusing on the impact of aggregation delay on packet loss and total path delay. To overcome a major shortcoming of this thesis we plan to extend our traffic patterns to cover a broader usage scenario than the now dominant FTP scenario. To fulfill this goal, we will use real packet traces or other means of providing diverse usage scenarios. In the short term we are also planning to extend the work begun with the aggregation aware forwarding trying to minimize the reordering of packets that today negatively influence TCP performance.

References


throughput optimization in multi-radio wireless mesh networks. In Proceedings of
the 11th annual international conference on Mobile computing and networking, pages

and a layer-2.5 forwarding paradigm for multi-radio wireless mesh networks. Net-

[7] Nicola Baldo, Federico Maguolo, Marco Miozzo, Michele Rossi, and Michele
Zorzi. ns2-miracle: a modular framework for multi-technology and cross-layer
support in network simulator 2. In Proceedings of the 2nd international conference
on Performance evaluation methodologies and tools, ValueTools ’07, pages 16:1–16:8,
ICST, Brussels, Belgium, Belgium, 2007. ICST (Institute for Computer Sciences,
Social-Informatics and Telecommunications Engineering).


[9] R. Braden. RFC 1122 - Requirements for Internet Hosts–Communication Layers,
1989.

[10] L.S. Brakmo and L.L. Peterson. TCP Vegas: end to end congestion avoidance on
a global Internet. Selected Areas in Communications, IEEE Journal on, 13(8):1465
–1480, October 1995.


channel multi-interface network. In Proceedings of the 2nd international workshop


Improving TCP Performance in Wireless Multi-hop Networks

Due to the high availability of cheap hardware, wireless multi-hop networks and in particular Wireless Mesh Networks (WMNs) are becoming popular in more and more contexts. For instance, IEEE 802.11 based WMNs have already started to be deployed as means to provide Internet access to rural areas in the developing world. To lower the cost and increase the coverage in such deployments, the wired network is extended with a wireless backbone of fixed mesh routers. With advances in technology and reduction in price comes also the possibility for more powerful wireless nodes, having multiple radios that allow transmitting on different channels in parallel.

To be a successful platform for providing general Internet access, wireless multi-hop networks must provide support for common Internet applications. As most of the applications in the Internet today use the Transmission Control Protocol (TCP), TCP performance is crucial. Unfortunately, the design of TCP’s congestion control that made it successful in today’s Internet makes it perform less than optimal in wireless multi-hop networks.

In this thesis, we develop novel proposals for the network layer in wireless multi-hop networks to support TCP traffic more efficiently. As an initial study, we experimentally evaluate different TCP variants, with and without mobile nodes, in a MANET context. We further propose and evaluate packet aggregation combined with aggregation aware multi-path forwarding to better utilize the available bandwidth.