TCP over Multi-Hop Wireless Networks: The Impact of MAC Level Interactions

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Abstract. In Multi Hop Wireless Networks (MHWNs), nodes act both as end-hosts as well as intermediate routers. When communication occurs, these nodes form chains between different sources and destinations. Researchers have studied how these chains behave, discovering that MAC level interactions play a major role in determining their performance. In this paper, we extend this analysis to study how TCP connections, which involve bidirectional flows, behave over wireless chains. First, we break down and examine the types of chains that occur most frequently in TCP configurations and classify them by the nature of the MAC level interactions that arise in each. We then show that the throughput of TCP over a wireless chain is greatly affected by the type of interactions within the chain. Finally, we show the implications of the MAC level interactions on network performance: specifically, route instability and number of retransmissions.

Keywords: **Wireless Mesh Networks, MAC Interactions, TCP**

1 Introduction

Multi-Hop Wireless Networks (MHWNs) have increased in importance and usage at the edge of the Internet over the past several years. Community mesh networks can provide dynamic and extended coverage to urban and metropolitan areas. Sensor networks, another example of MHWNs, have a wide range of applications such as wild life monitoring, detection of potential forest fires, and disaster response scenarios. Mobile Ad-hoc Networks (MANETS), such as vehicular networks, provide connectivity to mobile users where infrastructure is expensive or unavailable.

Nodes in MHWNs route traffic among each other to provide connectivity between nodes that are not within direct transmission range. This sequence of nodes used to communicate between a source and destination is called a *path* or a *chain*, which represents a fundamental communication structure in MHWNs. Understanding chain behavior is critical to designing effective applications and transport layer protocols in MHWNs. Furthermore, insight into the performance of current protocols on chains is critical to predict performance of MHWNs. Amongst these protocols, TCP is especially important due to its widespread use on the Internet.

Researchers have studied the performance of uni-directional flows [1, 2] as well as bi-directional flows (TCP) [3] over MHWNs. With regards to TCP, Xu et. al. study the behavior of TCP Tahoe, Reno, Sack and Vegas over *a chain* [3]. They only analyze the performance of TCP over a chain where each hop is 200 meters. According to our findings this type of chain accounts for 8.5% of chains that occur; over 90% of the chains that occur are not studied, neither is the performance of TCP over those chains. The performance of TCP over these chains depends on the interference relations between links in the chain; these relations also differentiate between chain types.

In general, links in a chain that do not share a common node can be active simultaneously; these links exhibit different interference interactions. These interactions arise because the state of the channel at the sender, where carrier sense is attempted, is different from that at the receiver. Thus, a sender may sense the channel to be idle, and transmit to a receiver whose channel is occupied, leading to a collision (hidden terminal problem [4]). The collisions caused by these interactions significantly affect chain behavior. Therefore, understanding these interactions and their impact on chain performance is an essential first step towards predicting behavior of MHWNs and the performance of protocols running over these networks.

In this paper we extend this understanding by analyzing how TCP behaves over different types of chains in a MHWN. We first identify the spectrum of chains that occur in a MHWN - all possible types of chains that occur in a network. We then identify the most frequently occurring chains and how often each of these occurs in a random MHWN; we evaluate the performance of TCP over this subset of chains. Finally, we discuss how these chains affect network performance and categorize the chains based this effect.

This analysis leads to insights into the behavior of TCP over MHWNs. Chains that appear identical to routing protocols can behave very differently based on the link interactions they exhibit; routing protocols ought to consider link interactions when picking routes. Furthermore, TCP generates two way traffic (Data and Ack); the overall performance of TCP over a chain depends on how efficiently traffic in both directions is transmitted. Finally, we discuss how the behavior of TCP over different chains affects network performance because of route instability and excessive retransmissions. Being aware of these observations can enable design of protocols that improve network performance.

The remainder of the paper is organized as follows. In Section 2 we discuss related work. In Section 3 we discuss the different types of interactions that occur; we also define naming conventions for chains and present the measured occurrence percentages of the different types of chains. We then evaluate the performance of TCP over the types of chains that occur most frequently in Section 4. In Section 5 we study the effect of chain behavior on network performance. We finally conclude and briefly discuss our future work in Section 6.

2 Related Work

Several researchers have been studying the behavior of chains in MHWNs. Li et al. examine the performance of chains as the number of hops are increased and study the effect of cross-interference between chains [5]. They analyze the effect of MAC 802.11 behavior on the performance of multi-hop chains but do not categorize interference patterns that govern network performance in terms of throughput and bandwidth utilization. Ping et al. present a hop by hop analysis of a multi-hop chain, study the impact of hidden terminals on the throughput chains, and present a quantitative approach towards estimating this throughput [6]. They show that hidden terminals cause packet drops affecting chain throughput and causing route stability.

Razak et al. have studied the effect of MAC interactions on single chains under saturated UDP traffic [1]. They develop a systematic methodology for determining the types of interaction that are possible in chains of 3 and 4 hops and the study the effect of these interactions on chain performance. They further extend their work to analyze chains of n hops. These studies do not consider the effect of TCP traffic on chain performance. TCP introduces several factors like bi-directional traffic, congestion control, round trip time estimations for timeout prediction etc. that are affected by interference interactions within a chain. As we will show in this paper, the types of interactions within chain have a substantial effect on the performance of a network under TCP traffic.

Xu and Saadawi evaluate the performance of TCP over wireless chains. They demonstrate that TCP traffic in a chain has instability problems that degrade chain throughput [3]. They study the effect of various TCP flavors and report a degradation of throughput from 11% in 3-hop chains to 21% in 7-hop chains. In this paper, we show that even within 3 and 4 hop chains, there is throughput degradation of around 25% based on the type of interactions between links of the chain. We also show that the chains Xu and Saadawi consider, represent a small fraction in the spectrum of chains that can occur in bi-directional flows.

3 Chains in a MHWN

In this section we observe all possible interactions under bi-directional flows in a chain. We start by analyzing 3-hop chains, which are the smallest chains with two links that can be simultaneously active. We then analyze chains with four hops. Under normal ratios of carrier sense and communication ranges (carrier sense range more than twice communication range), a four-hop chain is the smallest unit that allows us to analyze links within a chain with hidden terminal interactions. The analysis of three and four hop chains is the basic building block for generalizing this study for arbitrary long chains. This generalization is part of our future work. We first present some general terminology used throughout the paper. Afterwards, we describe the prominent types of link interactions possible in a chain in the presence of bi-directional TCP flows (data and ack). Finally, we determine the types of chains that are possible in a network and calculate occurrence probabilities for each of these chains.

3.1 Terminology

Wireless networks use Carrier Sense Multiple Access (CSMA) protocols to share the wireless medium. IEEE 802.11, which is based on Carrier Sense Multiple

Access (CSMA), is the most commonly used channel access protocol in wireless networks. CSMA based protocols avoid simultaneous access to the medium from multiple transmitters by requiring each sender to sense the channel and transmit only after the channel has been idle for a specific amount of time. This method allows only one node to transmit within a Carrier Sense range of a transmitter. The channel is sensed around the sender and not the receiver, it is possible for the state of the channel to be different at the sender and the receiver. Hence packets transmitted by a node that senses the channel to be idle maybe dropped if the medium around the receiver is busy - the *hidden terminal* problem, which causes collisions that are detrimental to the performance of a wireless network.

Signal strength in wireless transmissions attenuates with distance and other environmental factors. A node can successfully receive a packet if the Signal to Interference and Noise Ratio (SINR) of a packet is above a certain threshold. This ability of a receiver to capture packets in the presence of interference from other transmitters is called the *capture effect*.

A chain is a sequence of nodes that forward messages to enable communication between a source and destination that are not within transmission range. Two consecutive nodes in the chain can communicate with each other and can exchange packets with eachother on both directions. We refer to this communication between two nodes as a *flow* and the communication channel is referred to as the *link*. Links that do not share a node can be active simultaneously and can affect each other at the MAC level. The location of the interacting links and the direction of flow on each link defines the interaction. The kind of effect these links have on each other is termed the interaction type.

3.2 Link Interactions

In multi-hop wireless networks, two interfering links can interact in several different ways. Given two source-destination pairs $S1-D1$ and $S2-D2$, there exist four secondary links: $S1-S2$, $S1-D2$, $S2-D1$, and $D1-D2$ that can interfer with each other. Although there can be a large number of combinations for these interactions [7, 8], we discover that a limited number of these interactions are possible between links of chain. We summarize these interactions in Figure 1, and briefly describe each one.

1. Senders Connected (SC): In SC interactions, the sources of the two links are within carrier sense range. Thus, CSMA prevents senders from concurrent transmissions; and no collisions other than those arising when the two senders start transmission at the same time will occur. These collisions are low in probability and we refer to them as synchronized collisions. SC interaction allow equal share of the channel between the senders.

2. Hidden Terminal (HT): In this interaction, the source for one link is a hidden terminal for the destination of the second link but not vice versa. Both senders are disconnected and can transmit simultaneously. One destination drops its packets because of interference from the opposite sender. The other destination can successfully receive its packets because it does not experience any interference. In this interaction, one link will always be successful at obtaining

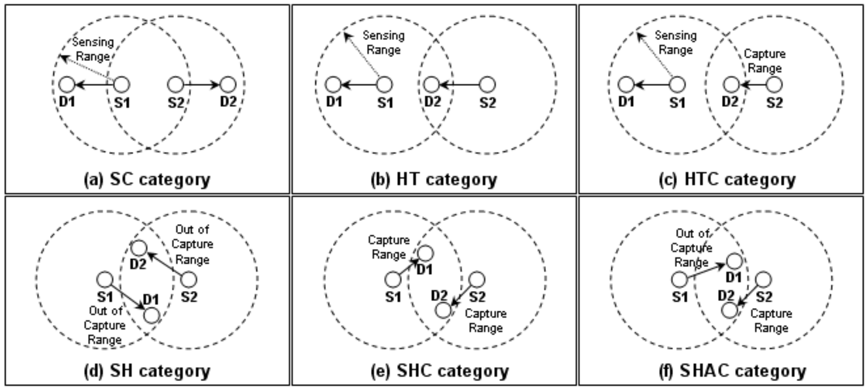


Fig. 1. The dominant types of link interactions observed in a MHWN.

maximum throughput, while the second link will experience frequent collisions that will detriment its performance.

3. Hidden Terminal with Capture (HTC): This interaction is similar to HT interaction but the destination that experiences interference is able to capture its packets. Hence whenever the source for this destinations starts transmission first, the link will experience successful packet reception and throughput on this link will not be as severely affected as in HT interaction [9].

4. Symmetric Hidden Terminal (SH): In this interaction, both links experience hidden terminals as both sources interfere with opposite destinations. Both links will experience collisions as the senders transmit concurrently causing throughput to be severely affected.

5. Symmetric Hidden Terminal with Capture (SHC): This interaction is similar to SH interaction except both links are able to capture their packets under interference from opposite sender. In this interaction, every simultaneous transmissions will be successful at one link (the link whose sender starts first) and will fail on the other link. This interaction will suffer from short term unfairness. Overall throughput for both links would be similar to SC interactions except at a cost of much higher number of transmissions.

6. Symmetric Hidden Terminal with Asymmetric Capture (SHAC): This interaction has hidden terminal between both links but only one destination is able to capture its packets. Symmetric interactions occur between links carrying Data traffic in forward direction and links carrying ACK packets back to the source. Because of the geometric restrictions of chains, there are no symmetric interaction between links with uni-directional flows.

3.3 Chain Interactions

We now identify and develop a naming convention for different types of chains, and present their occurrence probabilities in random networks. Figure 2 illustrates the link interactions that we study in three and four hop chains. Each row has an interaction number along with the links in that interaction. The arrows

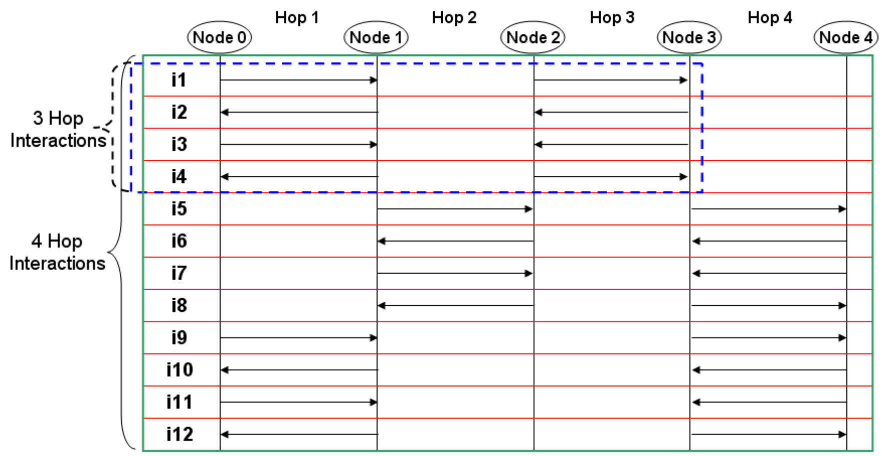


Fig. 2. All the interactions in a three and four hop chain. Each row shows the interaction between two specific links in specific directions.

in each row mark which links are considered in that interaction; the arrow direction depicts the flow direction considered. For the TCP flow running on a chain, node 0 is the source and node 3 and node 4 are the destinations for three and four hop chains respectively. Therefore, in the figure, all flows towards the right carry TCP Data packets and all flows towards the left carry TCP Ack packets.

Razak et al. have determined that, between any two links, there can be 10 different interference interaction possible [8]. For a three-hop chain only interactions i1 - i4 apply. With 4 interactions and 10 interaction types for each interaction we can have 10^4 types of chains. In a four-hop chain, the possibilities are even more overwhelming. Four hop chains have 12 interactions, each with 10 possible interaction types; we can have 10^{12} different chains. Fortunately due to geometric limitations, in reality there are only 3 chain types that most commonly occur in three-hop chains and 8 chain types that commonly occur in four-hop chains.

Occurrence Percentage	**Chain Type** Forw/Back/Cross	**Dominant Interaction** Forward	Backward	Cross
7.3	HT/SC/SHAC	i9	-	i3
3.6	HTC/HTC/SHAC	i9	i10	i7
8.4	HTC/HTC/SHC	i9	i10	i3
32.1	HTC/SC/HTC	i9	-	i11
2.3	SC/HT/HTC	-	i10	i11
1.8	SC/HTC/HTC	-	i10	i11
1.6	SC/SC/SC	-	-	-
37.8	SC/SC/SHC	-	-	i11

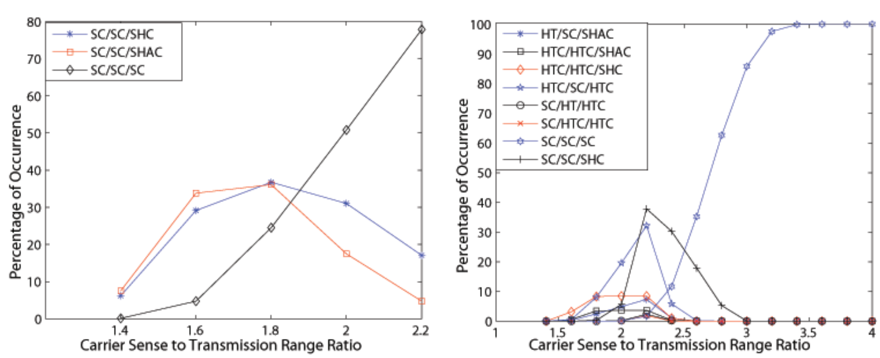
Table 1. The types of four-hop chains that occur most frequently in a MHWN. The last three columns depict the interaction number of the dominant interaction (refer to Figure 2) in the forward, backward and cross flows, respectively. A dash (-) means that no interaction dominates in that direction. Note that current routing protocols can not differentiate between these chains even though they are significantly different.

We use the following notation to name these chains: Each chain is represented as F/B/C. F is the prominent interaction between links carrying the forward traffic (data). B is the prominent interaction between links carrying backward traffic (ack), C is the prominent interaction between cross links, i.e. between links carrying forward traffic (data) and backward traffic (ack). A prominent interaction, as used in the above naming, is defined as the interaction number (from Figure 2) that has the most effect on the performance of a chain in a particular direction, forward, backward or cross. Table 1 illustrates the four-hop chains that occur most frequently and states the interaction number of the prominent interaction in the forward, backward and cross flow. The table showing the same information for three hop chains is omitted due to space constraints.

In order to determine commonly occurring interactions and calculate their occurrence probability, we consider a 1500m x 1500m network with 500 nodes, randomly placed with uniform distribution. For routing, we use our implementation of NADV [10], which uses a greedy protocol to pick best next hop at each node. The metric for selecting the hop is the product of link quality and distance traveled towards the destination.

We use this routing protocol to generate all possible three and four hop chains in random networks. We classify the chains according to their type, using the F/B/C convention described above, and study the most frequently occurring chains. Figure 3 shows occurrence probabilities of chain types for three and four hop chains as the carrier sense is varied.

To avoid clutter, we only study a subset of the chains that occur. This subset consists of all chains that have an occurrence probability of over 1.5% in a random network for a realistic carrier sense to transmission range ratio. Most commercial radios set carrier sense range to slightly over twice the transmission range, and this is what we define realistic carrier sense to transmission range ratio to be. As the carrier sense range is increased more pairs of nodes in the network become sender connected until (as depicted in Figure 3(b)) the carrier sense range is high enough to make all nodes in the network sender connected and the only chain type remaining is SC/SC/SC.



(a) (b)

Fig. 3. Occurrences of Different Types of Chains. (a) shows the occurrence probability of 3-hop chains.(b) shows the occurrence probability of 4-hop chains.

4 TCP Evaluation over Chains

In this section we evaluate, via simulation, the behavior of a TCP flow on different chains that occur in a MHWN. We start with three hop chains; the smallest chains that have the interactions we consider. These chains show how TCP behaves when the sources are sender-connected. In general, chains in MHWNs are not limited to three hops; we study four hop chains as well. These give us insight into how TCP behaves over chains in which not all links are sender-connected. This analysis of TCP over three and four hop chains is an important step towards understanding TCP performance over general n-hop chains.

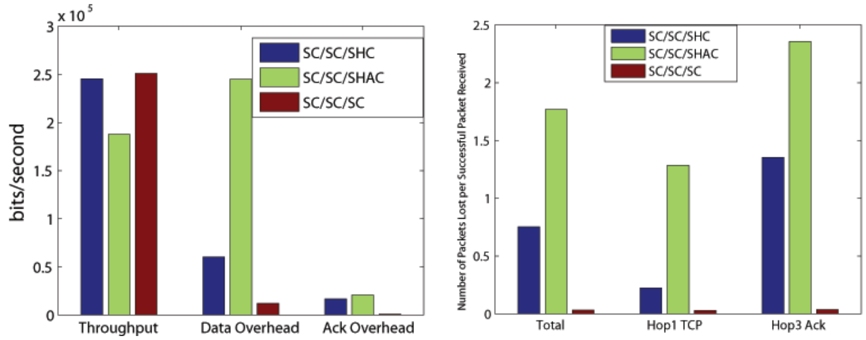
We use network simulator (ns-2 release 2.33) to analyze TCP performance over the most frequently occurring chains identified in section 3. We use FTP at the application layer with TCP Tahoe as the transport layer protocol; all simulation parameters have default values. The simulations use static routes and last 75 seconds each Using static routes ensures that efects of TCP over MHWN are isolated from routing layer effects.

4.1 TCP on Three Hop Chains

This section discusses the performance of TCP over three hop chains. Figure 4(a) illustrates that the SC/SC/SHAC chain has approximately 25% lower throughput compared to the SC/SC/SC and SC/SC/SHC chain. In the SC/SC/SHAC chain links carrying backward flow, i.e. ack traffic, have an SHAC interaction with links carrying forward flow, i.e. data traffic. This interaction causes unfairness towards the forward flow on Hop1. All such cases, where a link carrying backward flow asymmetrically causes drops at a link carrying forward flow, behave similar to each other.

We explain this behavior by a detailed discussion of how the SHAC interaction acts in an SC/SC/SHAC chain. Refer to Figure 2 for the numbers and locations of the nodes and hops used in the following explanation. In the SC/SC/SHAC chain, Hop1 and Hop3 behave as follows. Nodes 0 and 3 can transmit concurrently since they are not sender-connected. When both these nodes transmit concurrently there is a collision at node 1 since it is in capture range with both nodes. However, when node 3 starts transmitting before node 0, node 2 is able to capture the packet [9]; a collision at node 2 occurs only when node 0 starts transmission before node 3. In this interaction, the link between node 0 and node 1 is the *weak* link, i.e. it faces unfairness in terms of collisions. Figure 4(b) shows that this unfairness causes the collision drops for TCP traffic at Hop1 for the SC/SC/SHAC chain to be significantly higher than the other two types of chains. This translates to a high retransmission overhead as depicted in Figure 4(a).

At the TCP layer this effect causes the forward going link to drop packets anytime hops Hop1 and Hop3 are active simultaneously. The repeated TCP drops cause timeouts at the sender and the congestion window is reduced to one. In the mean time, the ack traffic acquires enough channel access to empty the chain of acks, eventually reducing the traffic in the chain. This reduction



(a) (b)

Fig. 4. Performance of Three-Hop Chains. (a) Throughput achieved by each chain and the retransmission overhead of data and ack packets. (b) MAC collisions in each chain and how many of these are data packet drops at Hop1 and ack packet drops at Hop3.

allows the sender to successfully obtain access to the medium and finally resume transmitting successfully. This phenomenon keeps repeating, causing inefficient use of the medium. This pattern results in the 25 percent lower throughput for the SC/SC/SHAC chain.

In the case of the SC/SC/SHC chain, the SHC interaction is also between Hop1 carrying data traffic and Hop3 carrying ack traffic. However in this case the interaction is symmetric and which ever of nodes 0 and 1 starts transmitting first has a successful transmission. Hence, the collision overhead is much lower at Hop1 in this case causing comparatively better throughput and lower retransmission overhead.

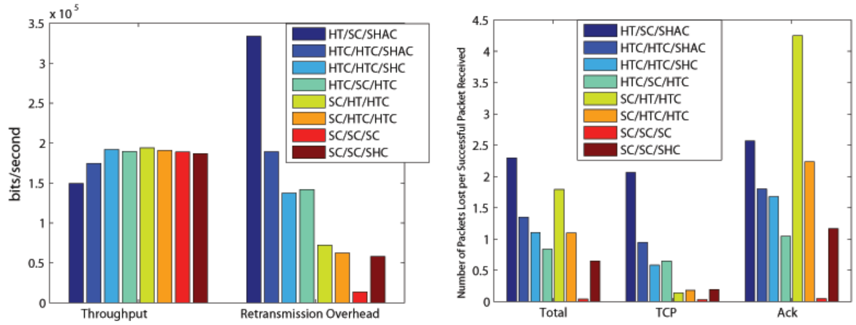
The SC/SC/SC chain is the best in terms of performance and efficiency. It has the lowest overhead since all the sources are sender connected and the medium arbitration is synchronized. The only collisions in this case are synchronized collisions. These collisions are caused when two nodes that are sender connected are ready to transmit a packet, sense the medium as idle and then transmit at the same time. Such collisions occur infrequently [11].

We observe that running TCP over chains that are not sender connected, but have symmetric interactions, may give approximately the same throughput as sender connected chains. However, as demonstrated by the higher overhead in Figure 4(a), they generate much more traffic to give the same throughput. This is undesirable due to the effect this behavior can have on other flows in the network. This effect is discussed in more detail in Section 5.

The performance of a chain worsens if the interaction types in the chain are asymmetric in addition to not being sender-connected. These chains have a large number of collisions, leading to excessive retransmissions, leading to further collisions. This translates to a lower throughput for these chains.

4.2 TCP on Four Hop Chains

Chains in MHWN are not limited to three hops; they can be longer. Hence, studying the performance of four hop chains becomes important for a number



(a) (b)

Fig. 5. Performance of Four Hop Chain.

of reasons. These chains can actually occur in a network, so knowing how they perform is critical to predicting MHWN performance. Furthermore, four hop chains have a variety of interactions that are not sender-connected. Studying TCP behavior over such chains is a critical step towards analyzing TCP behavior over general n-hop chains.

Figure 5(a) presents the throughput of the chains we study. The chains that are not sender-connected and have asymmetric interactions, where the link carrying forward flow is weak, cause severe throughput degradation For all other cases the throughput achieved is comparable. Figure 5(a), however, exhibits that there is a significant difference in retransmission overhead depending on whether the senders are connected or not. Furthermore, the overhead varies significantly based on whether an interaction causes more drops at a link carrying forward flow or the backward flow.

Based on these factors, the chains in a MHWN can be classified into two main classes. Chains (1) where links carrying data flow are the weak links in an interaction and (2) where links carrying ack flow are the weak links in an interaction. Table 2 lists which chains fall in each of these classes. In some chains there are interactions that cause both the data the ack flow to be weak. In such cases, performance of the chain suffers more due to the link carrying data flow being weak. Therefore, these chains are considered in the class (1), described above. We now discuss each of these classes in detail.

1. Chains where the forward going links are at a disadvantage: These chains can be broadly described as having an interaction that causes collisions at an upstream link carrying data packets. The link causing these collisions is a downstream link carrying data or ack packets. The performance of a chain in this category depends on (a) how many such weak links a chain has; and (b) the severity of the interaction.

In Section 4.1 we explained in detail how losses occur in the presence of asymmetric interactions. The same explanation also applies to four-hop chains. If the interaction type is an HT, then the data flow has collisions until all the packets at nodes downstream to this link have been transmitted. After that the data flow can successfully transmit; this pattern keeps repeating. An SHAC is another interaction that causes severe overhead. Anytime the two links that have

Category	Chain Type	Weak Interaction		Interference	Route
		Forward	Backward	Generated	Instability
A	HT/SC/SHAC	Yes	Yes	High	Low
	HTC/HTC/SHAC	Yes	Yes	Medium	Low
	HTC/HTC/SHC	Yes	Yes	Medium	Low
	HTC/SC/HTC	Yes	Yes	Medium	Low
B	SC/HT/HTC	No	Yes	Low	High
	SC/HTC/HTC	No	Yes	Low	Medium
C	SC/SC/SC	No	No	Negligible	None
	SC/SC/SHC	No	Yes	Low	Low

Table 2. The macro-effects shown by each chain type. The third and fourth columns state, for each chain type, whether or not there is a link interaction that causes a forward or backward flow to be weak, respectively. The fifth column qualitatively states the amount of interference generated by a chain of each type. The last column qualitatively states the number of route discovery generated due to consecutive collisions of the same MAC packet. Based on how the interference generated and the route instability caused, the chains are grouped into categories.

an SHAC interaction transmit concurrently, the weaker link loses a packet. This degrades performance by causing excessive retransmissions at the weak link. However, with an HTC interaction the weak link starts transmissions before the stronger link roughly half the time and is successful. The effect of HTC is, hence, not as severe as SHAC or HT.

Among the chains in this class, HT/SC/SHAC behaves the worst in terms of throughput and overhead. This result is intuitive since this chain has two interactions where a link carrying data flow is weak, one HT and one SHAC. The HTC/HTC/SHAC chain has the HT replaced with an HTC interaction resulting in slightly better performance. However, the performance is significantly lower than the other chains.

The HTC/HTC/SHC and HTC/SC/HTC chains are similar to each other and better than both HT/SC/SHAC and HTC/ HTC/SHAC in terms of achieved throughput. The interactions of the links carrying TCP data packets in these two chains are similar. The only difference is that in HTC/SC/HTC Hop1 carrying forward flow is competing with both Hop3 and Hop4 carrying backward flow. However, HTC/HTC/SHC has Hop1 carrying forward flow competing with Hop3 carrying backward flow and Hop2 carrying forward flow competing with Hop4 carrying backward flow. So node0 in an HTC/SC/HTC chain has both node3 and node4 as hidden terminals causing TCP data packet drops while in the HTC/HTC/SHC chain node0 has only one hidden terminal. This difference causes HTC/SC/HTC to have more TCP packet drops at Hop1 resulting in worse performance, in terms of transmission overhead.

2. Chains where the backward going links are at a disadvantage: These chains have interactions that cause collisions at links carrying ack traffic. The collisions could be from other links carrying ack traffic or from links carrying data traffic. The chains that are affected on the most part by this category of interactions are SC/HT/HTC, SC/HTC/HTC and SC/SC/SHC. Qualitatively, the affects caused by HT, HTC and SHC on the ack traffic is the same as what was described above for the case where links carrying TCP packets were at a disadvantage. There are two main differences here however. (1) Ack packets are smaller and hence there is a lower probability (compared to TCP packets) that they will collide with another transmission. However, it is also possible for multiple retransmissions of the same ack packet to collide with a single TCP packet. The smaller size of ack packets causes their transmissions to be shorter and hence retransmissions can be scheduled faster. This effect causes the number of collision drops per delivered packet in the SC/HT/HTC, SC/HTC/HTC and SC/SC/SHC chains (depicted in Figure 5(b)) to be higher than the case where links carrying TCP data packets are at a disadvantage. (2) Due to the much smaller size of the ack packets the overhead of ack collisions is much lower. This is the reason the overhead observed in Figure 5(a) is much lesser for these chains even though the number of ack collisions are close.

The only chain that does not fit in either of these categories is the SC/SC/SC chain. As described in Section 4.1 the transmitters in an SC/SC/SC chains have a complete view of the medium and can arbitrate it in a way to avoid all the affects that cause performance degradation in the other chains.

5 Discussion

This section discusses the impact of chain behavior on a MHWN. We first discuss the interference effect of different chains due to retransmission traffic. We then discuss route instability caused by the behavior of different chains. Table 2 presents the qualitative impact of chain interactions on network interference and route stability. Finally, we categorize chains according to their performance and describe the behavior of each category.

Interference Effects: Figures 4(a) and 5(a) illustrate the retransmission overhead of the chains we analyzed. In the three-hop case, SC/SC/SC gives 25% better throughput, compared to SC/SC/SHAC, using only 5% of the retransmission overhead. Since the overhead is measured in terms of unsuccessful transmissions, this means that by avoiding all of those additional transmissions the SC/SC/SC chain kept the medium busy for a smaller duration – still achieving better performance. The difference is even more pronounced in the four-hop case when comparing SC/SC/SC with HT/SC/SHAC. In this case the HT/SC/SHAC chain has a very high retransmission overhead and a 25% lower throughput. Therefore, in a MHWN limiting connections to use chains that have low retransmission overhead would significantly increase network throughput by facilitating medium reuse. On the other hand, using chains with undesirable interactions greatly increases interference in the network while providing similar or lower throughput to the sender-connected chains.

Route Instability: As mentioned in section 4.1 and 4.2, SHAC and HT interactions affect TCP performance due to numerous collisions. Some routing protocols decide that a route is lost if a certain number of consecutive MAC transmissions lost [12, 13]; the routing protocol then initiates route discovery. In the absence of RTS/CTS this number is set to seven. In chains that cause nu-

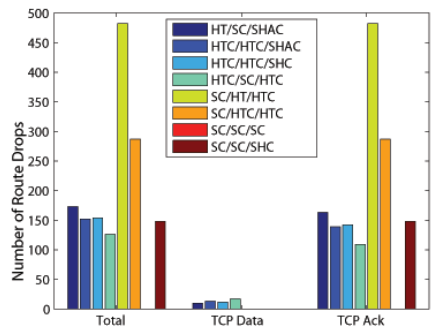


Fig. 6. Route Instability

merous collisions such protocols would initiate route discovery numerous times. Since the route is not lost, the same route will be found every time. Figure 6 shows the number of such route drops in each chain and then breaks up the route drops depending on whether they were caused by TCP data packet collisions or TCP ack packet collisions. Notice that even though ack collisions do not cause significant overhead in terms of bits/second retransmitted, their effect on initiating route discovery is significant. Recall from section 4.2 that due to smaller size collisions of TCP ack packets are significantly higher in number.

Ranking Interactions: Table 2 separates the four-hop chains in categories based on how each chain affects the network. From the table we can see that chains that have interactions where the link carrying data traffic (forward flow) is at a disadvantage generate more retransmission traffic; keeping the medium busy longer. This is due to the high retransmission cost of TCP data packet collisions. The chains in category A are of this type. These links also have interactions where the link carrying ack traffic (backward flow) is at a disadvantage. However, the forward flow being at a disadvantage causes a larger affect and so these chains show relatively lower route instability compared to category B. Category B is the set of chains that have interactions where the links carrying backward flow are at a disadvantage. This causes a large number of route drops and hence higher route instability.

The attractive category in terms of performance is category C. It has the least amount of interference generated, due to retransmissions, and minimal route instability. From table 1 we see that nearly 40% of the chains in a random network are of this category. Therefore, when a MHWN carries TCP traffic, the link interactions in the forward and backward path both enable efficient communication. Therefore, routing protocols should pick routes that are sender connected in the forward as well as the backward direction. Furthermore, assymetric interactions significantly affect throughput and the routing protocol should, as much as possible, avoid chains with such interactions.

6 Conclusions and Future Work

In this paper, we have demonstrated that wireless chains, that otherwise appear identical to higher layers, can have very different MAC interactions. This difference in MAC interactions between the links of these chains can cause up to 25 percent difference in throughput performance. Furthermore, in some cases, even if the throughput is not affected by these interactions, inefficient chains require a significantly higher number of MAC transmissions to achieve the same throughput. These retransmissions keep the medium busy and degrades throughput of the network. Based on the observed interactions, we have proposed a ranking of the chains in a MHWN. Sender-connected chains provide high throughput with low retransmission overhead and ought to be favored by higher layers.

The analysis and results we have presented in this paper represent a first step towards a better understanding of how chains behave in a general network setting and how performance is affected by cross chain effects. For future work, we plan to extend our analysis to larger n-hop chains. Furthermore, we would like to evaluate and develop routing protocols that exploit this knowledge to improve network performance.

References

1. S. Razak and N. Abu-Ghazaleh, "Self-Interference in Multi-hop wireless chains," in *Proc. ADHOC-NOW*, 2008.
2. S. Razak, V. Kolar, N. Abu-Ghazaleh, and K. A. Harras, "How do wireless chains behave? the impact of mac interactions," *Technical report under arxiv.org: cs.NI arXiv:0903.1002v1*, 2009. [Online]. Available: http://arxiv.org/abs/0903.1002v1
3. S. Xu, T. Saadawi, and M. Lee, "On tcp over wireless multi-hop networks," *Military Communications Conference MILCOM. Communications for Network-Centric Operations: Creating the Information Force. IEEE*, vol. 1, pp. 282–288 vol.1, 2001.
4. L. Kleinrock and F. Tobagi, "Packet switching in radio channels," in *IEEE Transactions on Communications*, 1975, (Part I and Part II).
5. J. Li, C. Blake, D. DeCouto, H. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *MobiCom*, 2001, pp. 61–69.
6. P. Ng and S. Liew, "Throughput analysis of 802.11 multi-hop ad hoc networks," *IEEE/ACM Trans. Netw.*, vol. 15, no. 2, pp. 309–322, 2007.
7. M. Garetto, J. Shi, and E. W. Knightly, "Modeling media access in embedded two-flow topologies of multi-hop wireless networks," in *MobiCom '05*, 2005.
8. S. Razak, N. B. Abu-Ghazaleh, and V. Kolar, "Modeling of two-flow interactions under sinr model in multi-hop wireless networks," in *Proc. LCN*, 2008, pp. 297–304.
9. A. Kochut, A. Vasan, A. U. Shankar, and A. Agrawala, "Sniffing out the correct physical layer capture model in 802.11b," in *ICNP '04*, 2004, pp. 252–261.
10. S. Lee, B. Bhattacharjee, and S. Banerjee, "Efficient geographic routing in multihop wireless networks," in *MobiHoc*, 2005, pp. 230–241.
11. G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Comm.*, vol. 18, no. 3, 2000.
12. D. Johnson, D. Maltz, and Y.-C. Hu, "The dynamic source routing protocol for mobile ad hoc networks (DSR)," in *IETF draft*, 2003.
13. C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *WMCSA '99: Proceedings of the Second IEEE Workshop on Mobile Computer Systems and Applications*. IEEE Computer Society, 1999, p. 90.