Analysis and Impact of Interactions in Chains Under CSMA Protocol

Vinay Kolar†, Saquib Razak‡, Nael B. Abu-Ghazaleh*, Petri Mähönen†, Khaled A. Harras‡

†Department of Wireless Networks,
RWTH-Aachen University
{vko,pma}@mobnets.rwth-aachen.de

*Department of Computer Science
State University of New York, Binghamton, NY
nael@cs.binghamton.edu

‡School of Computer Science
Carnegie Mellon University
srazak@cmu.edu, kharras@cs.cmu.edu

TR-NA-09-02
February 4, 2009

Abstract

Chains or *multi-hop paths* are fundamental communication structures in Multi-Hop Wireless Networks (MHWNs). Understanding chain behavior is critical in order to build effective higher layer protocols. This paper examines the problem of how MAC level interactions influence chain behavior in a general MHWN where multiple chains coexist. We first classify chains based on the MAC interactions observed between its hops when there is no external traffic. Then we identify the interactions across two interfering chains for the most common categories of chains. We study the probability of occurrence, and estimate the effect of MAC interactions on the performance of the chains. We also show that different chains exhibit different transmission patterns; this is an effect that is necessary for accurately estimating chain performance. We observe that destructive interactions arise more frequently among two interfering chains than they do within a single chain. Moreover, chains that have hidden terminals due to self-interference are more prone to have cross-chain hidden terminals. Thus, both intra-chain as well as cross-chain interactions, ultimately provide significant insight into how chains interact.

1 Introduction

Wireless networking is a critical technology that plays a central role for providing connectivity to mobile data and voice users with applications ranging from tactical communications to commercial ubiquitous wireless applications. Multi-Hop Wireless Networks (MHWNs) such as mesh networks, sensor networks, and mobile ad-hoc networks use multi-hop wireless communications to self-organize and provide connectivity among nodes with little or no infrastructure. Designing effective protocols for MHWNs is important due to the increasing pressure on the limited available network bandwidth. However, designing such protocols is challenging due to the complexity of the wireless channel and the dynamic nature of MHWNs.

Interference is a major factor that affects the performance of wireless networks. Existing research studies have proposed approaches to reduce the impact of interference at different layers [1,2]. In the commonly used Carrier Sense Multiple Access (CSMA) MAC protocols, wireless nodes take transmission decisions based on local state of the channel (busy or idle). However, the state of the channel when sensed at a sender may not be representative of the state of the channel at the receiver (which determines whether a collision occurs or not). When a sender senses an idle channel and transmits to a receiver in range with another transmission, a collision occurs (the so called hidden terminal problem [3]). In fact, it can be shown that two links can interfere in a number of different ways that exhibit significantly different behavior [4, 5].

Packets are routed in a MHWN using a sequence of nodes that forms a *chain*. The links of a chain self-interfere, potentially exhibiting destructive MAC interactions, critically affecting the performance of the chain [6]. In our previous work, we analyzed the performance of a single chain based on the type of MAC interactions it exhibits [7, 8]. We classified the chains based on the types of interactions they exhibit, computed the probability of occurrence of each category and empirically studied their performance. However, previous analysis is restricted to single chains and the results cannot be generalized for MHWNs where multiple chains interact. In this paper, we significantly extend this line of work by considering interference across multiple chains.

We analyze the impact of MAC interactions across interfering chains. The paper examines the following three questions: (1) Does the chain type (according to self-interference) influence its vulnerability to destructive cross-chain interference? (2) What is the effect of the transmission pattern in a chain (which we call *pipelining*[1]) and is this pattern different for different categories? and (3) How predictable is performance within each category of interactions? The first contribution of the paper is to extend the analysis of isolated chains to study the throughput of each hop and its vulnerability to hidden terminals. We analyze individual chains in isolation with respect to the questions above and show that each category has a traffic transmission (or pipelining) pattern, predictable and stable effect of MAC interactions, and a predictable performance.

We then extend the analysis to study how two interfering chains interact with each other, which is the main contribution of the paper. First, we characterize the modes of interactions that arise among chains and their impact on

[1]Pipelining describes the way in which the traffic flows across each individual hop while the packets are transmitted from source to destination of a chain. This property is useful to analyze the differences in flow as the traffic advances

the performance of the two chains. Second, we study the how often the cross-chain hidden terminals arise and the vulnerability of different type of links to these hidden terminals. We show that links that have longer hops are susceptible to classical hidden terminal effect, and a milder form of hidden terminal may frequently affect the stable links also. Stable links with reasonable hop-lengths experience significantly high probability of packet drops due to 'capture effect' [9], where a receiver fails to lock to the sender's packet in the presence of even a weak signal from interferer.

Third, we examine the impact of different cross-chain hidden terminals on the link and chain performance. Up to 75% performance penalties are experienced by links due to cross-chain hidden terminals. Finally, the paper infers that self-interference parameters, which accurately predicted the performance of single chains, fail to predict the performance when multiple chains coexist. In such a case, we show that explicitly accounting for cross-chain contention and hidden terminal increases the accuracy of prediction of the chain performance.

The remainder of the paper is organized as follows. Section 2 briefly explains the background, including various forms of MAC and chain interactions. Section 3 describes the related work and explains the specific contribution of the paper with respect to similar research studies. Section 4 presents the extended analysis of single chains. Section 5 studies the cross-chain interactions. Finally, we discuss the future work and conclude the paper in Section 6.

2 Background

In this section, we present the necessary background for the remainder of the paper. First, the section overviews Carrier Sense Multiple Access (CSMA) protocols. It then introduces the types of MAC level interactions that arise between two interfering links. Finally, it discusses how these interactions happen among the links of a chain (self-interference) where the chain geometry limits the types of interactions that can occur.

2.1 CSMA and IEEE 802.11

Carrier Sense Multiple Access (CSMA) based protocols, like IEEE 802.11 [10], are widely used for medium access in wireless networks. In CSMA protocols, each sender waits for the wireless medium to be idle before transmitting in order to avoid packet collision. However, the channel-state at the sender does not accurately reflect the state at the receiver in MHWNs–a channel may appear idle at sender, but the receiver may perceive high interference power, causing a hidden-terminal collision [3]. On the other hand, a node will defer its transmission because of a busy channel although the medium at the receiver might be idle, hence wasting opportunity for channel reuse: the exposed-terminal problem. These two problems affect the overall performance of CSMA based wireless networks.

IEEE 802.11 protocol [10] uses advanced collision avoidance mechanisms like exponential backoff, retransmissions and RTS-CTS packets to counter hidden terminals and congestion. We consider the *basic mode* here (without RTS-CTS) which is the default mode on most commercial radios.

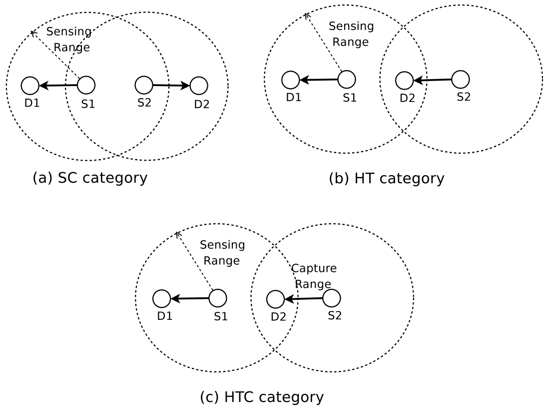


Figure 1: Categories of link interaction.

2.2 MAC interactions between two links

In this section, we introduce the basic MAC level interactions in the context of two interfering links [4, 5]. These interactions are the building block we use to categorize the behavior of chains, and later to understand interference across chains. Given two interfering links S1 - D1 and S2 - D2, the type of MAC interaction that occurs depend on the state of the channel between S1 - S2, S1 - D2, S2 - D1 and D1 - D2. Each of these node-pairs can be in a number of states (in reception range, in carrier sense range, in interference range, or in interference range with capture), resulting in a large number of interaction types [4,5]. Here we summarize the three interaction categories that occur most frequently in chains [8].

2.2.1 Senders Connected (SC):

In this paper, following the convention of MAC interaction studies [4, 5], we refer to two nodes as *connected* when they can sense each other's transmission. SC includes all scenarios where the sources of the two links can sense each other (Figure 1(a)). Thus, CSMA prevents senders from concurrent transmissions; and no collisions occur. A small fraction of collisions may still occur if the senders start the transmission on the same time-slot. Such collisions are unavoidable, and their probability is low due to the randomization of the backoff period.

2.2.2 Hidden Terminal (HT):

The senders are not connected and, hence, can transmit concurrently. As shown in Figure 1(b), a hidden terminal is observed where a transmission from the one sender S1 causes packet collision at the receiver D2 of the other link. The link S1 - D1 is unaffected by signals from S2 to D2. The source S2 observes large backoff values due to repeated packet collision and hence the throughput of S2 - D2 is significantly reduced. This interaction is also referred to as *Asymmetric Incomplete State* (AIS). For simplicity, we denote it as HT in this paper.

2.2.3 Hidden Terminal with Capture Effect (HTC):

In this interaction, two links have *HT* interaction but the destination with the hidden terminal problem is able to capture its packets from its source under interference from the opposite source. Figure 1(c) shows one possible placement of nodes with HTC interaction. In this case, although D2 is within interference range of S1, it is able to capture its packets from S2 as long as the packet from S2 arrives at D2 before S1 starts transmission. Recent studies have shown that a node can capture packets if it has locked on to the packet before the interfering nodes starts transmitting [9]. If the interfering node starts transmitting first, the destination node will lock on to its signal and will not be able to decode the packet. This is known as *capture-effect*.

While other categories exist (for example, symmetric hidden terminals where both packets are lost), they almost never arise in chains due to the geometric structure of chains selected by a forwarding rule representative of MHWN routing protocols [8].

2.3 Interactions observed in isolated chains

In our previous work, we have determined the types of interactions that occur most often between the links of a chain [8].

We also showed that these self-interference interactions play the primary role in determining the performance of these chains in isolation. In this section we summarize our findings since we will be building our cross chain analysis on these results.

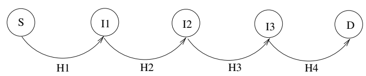


Figure 2: A Chain with 4 hops.

Chains with 4 hops are the smallest unit that has senders that can be out of range with each other, and therefore the possibility of hidden terminals (given carrier sense ranges typical of commercial radios). In a four hop chain, shown in Figure 2, there are three pairs of links that can be active simultaneously (they dont share a node): H1 and H4, H1 and H3, and H2 and H4. As we have determined in our previous work, interactions H1-H3 and H2-H4 will always be sender connected [8]. Therefore, we categorize chains based on the interactions between hops H1 and H4. If this interaction is SC, we call the resulting chains SC-chains: all links have SC interaction. HT-Chains and HTC-Chains have HT and HTC interaction between H1 and H4, respectively. In both HTC and HT chains, the receiver (I1) of the first link suffer from collisions due to transmissions from the source (I3) of the fourth link.

In order to calculate the probability of each chain occurring in a network, we choose an appropriate simulation area where nodes are uniformly distributed [8]. We use NADV, a link quality based geometric routing protocol, to find routes from each node to every other node [11]. NADV uses a greedy approach to pick routes between a source and destination by picking hops that have the best metric for taking the packet closest to the destination. However, typical of the newer generation of routing protocols, NADV also takes the link quality into account when making forwarding decisions. Specifically, the NADV metric is based on the product of link quality and distance covered towards the destination. We evaluate each 4-hop route and determine the chain type based on the link interactions. We discovered that SC-, HTC- and HT-Chains are most commonly, with probabilities 0.46, 0.44 and 0.10, respectively, and every other interaction is very close to 0.0 [8].

3 Related Work

Several studies have analyzed the performance of chains in MHWNs. Xu and Sadaawi analyze TCP instability due to chain self-interference and discover short-term and long-term unfairness issues in cross-chain interactions [12]. Li *et al.* studied the performance of chains as the number of hops are increased [13]. 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. They also studied the effect of cross-interference between chains. Ping *et al.* present a hop by hop analysis of a multi-hop chain and study the effects of hidden terminals on the throughput of a chain topology [14]. They present a quantitative approach towards estimating the throughput of a chain. They provide two main observations about flows in a chain. Firstly the presence of hidden terminals cause packet drops that reduce the throughput of the chain directly, and secondly packet drops cause reporting of broken links to the routing protocol and hence reducing the throughput indirectly. However, while the above work accounts for few MAC interactions, they do not study the general performance of different categories of chain or conclude on the predictability of different chains. Also, as we show later, detailed effects of MAC interactions on pipelining, probability of hidden terminals cannot be accurately studied without the classification of types of chains.

Recently, methodical classification of CSMA based MAC interactions and their effect in MHWNs were studied [4,5]. In our earlier work, we use a simplified two-disc binary model of packet reception to categorize single chains based on the underlying MAC interaction types [7]. Another study, and the one that is most related to this paper, extended this work to enumerate the factors that define chain behavior and then studied the effects of these factors on a single chain [8]. The paper used more realistic propagation models to study the effect of interactions on general chains. While a preliminary analysis of cross-chain interaction effects was described in this work, both the works focus mainly on single chains.

In contrast, the focus of this paper is on detailed analysis of cross-chain interactions. It adds significantly to the above study along three fronts: (1) Studying the performance and its variability of each link in the chain in order to characterize the pipelining for each type of chain; and (2) Examining the effect of hidden terminals on single chains. We also analyze the distance between adjacent nodes in a chain (hop-distance). In addition to providing a detailed insight into the functioning of chains, as we show later, these extensions are important to compare the performance under the cross-chain scenario; and (3) Most importantly, examining interactions between two different chains under various cross-chain categories and analyzing their performance.

4 Extended analysis of single-chains

This section first outlines the methodology used in the analysis and then extends the single chain analysis to study predictability and hop characteristics.

Analysis Methodology Precisely quantifying the performance of chains is a challenging problem because it is influenced by a large number of factors such as the chain's own traffic (which determines self-interference), traffic on the neighboring active links (which determines cross-interference), and the nature of the interference between all these links. In this section, we characterize the behavior of chains as a function of the following properties:

- MAC interactions: We study the vulnerability of the chains and constituent links to detrimental MAC interactions. We analyze the frequency of occurrence of such events and their effect.
- Pipelining: Pipelining refers to the temporal transmission pattern of traffic as it flows down a chain. As we show later, this pattern has implications on the behavior of the chain. The pipelining effect plays an important role in controlling the performance metrics of the chain by propagating the effect observed at the earlier hops of the chain to the later hops. For example, the reduced throughput due to effect of hidden terminal or unfairness at the first hop of the chain may cause an underutilized available capacity at the later hops.
- Predictability of chain performance for each chain type: We study different configurations of chains (of the same type with respect to their MAC interactions) to identify whether the chain type strongly influences performance.

For all the results in this paper, we use the QualNet simulator [15] with default parameters: IEEE 802.11b protocol is used with 2 Mbps channel capacity and approximate carrier sensing range of 560 m. However, since the focus of the study is on generic MAC and routing interactions rather than the PHY modulations, we believe that our conclusions hold for higher transmission rates and advanced modulation schemes.

We now extend previous single-chain analysis [8] by examining the end-throughput. The impact of the pipelining is then explained by observing the link-level throughputs. We then analyze the distance between adjacent nodes (henceforth referred as *hop-distance*) in each chain category. In addition to providing a detailed insight into the functioning of chains, as we show later, this new analysis is necessary to understand performance in cross-chain scenarios.

4.1 Throughput analysis

The end-throughput of the various categories of chains is shown in Figure 3. The throughput is represented in a box-plot notation. The box-plot summarizes the groups of data points (in our case, the throughput) by a box that bounds the upper and lower quartiles of the data. The median is represented by a

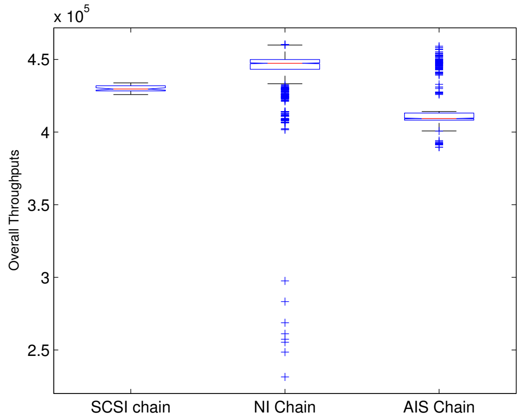


Figure 3: Throughput study in a single chain: SCSI chains hardly have any variance. Variance of HTC and HT chains is also very small thus demonstrating a very predictable self-interference pattern.

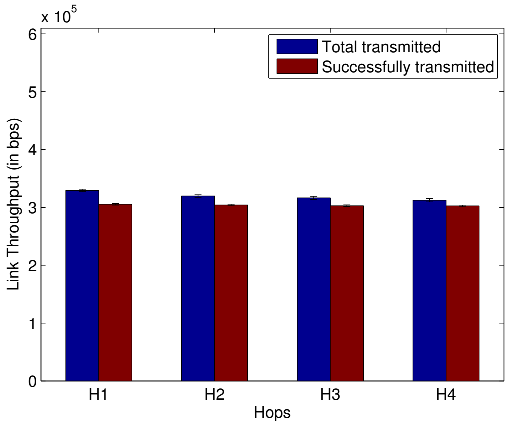
horizontal line that lies within the box. The outliers are represented by '+' symbols. As seen in the Figure 3, all the chains have very low variance and, hence, categories of single chains are very predictable. Hence, identifying the category of the chain is sufficient to accurately predict the performance of the chain and other accurate measures, such as distance between the hops, do not assist in enhancing the accuracy of prediction. As we demonstrate in Section 5.4, these chain categories fail to accurately capture the performance of the chain when multiple chains interact.

4.2 Pipelining in single-chains

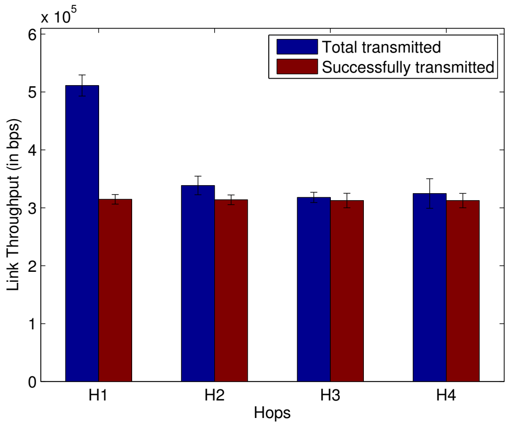
We now examine the link level throughputs of the chain to study the pipelining effectiveness and predictability of the chain. We generate random 4-hop chain scenario, classify them into different chain categories, and study the performance of each of the category. Figure 4 shows the link-throughputs of different categories of chains. The figure plots the mean link throughput and the standard deviation of the the total data transmitted and the amount of data successfully transmitted at each hop, thus showing the entire transmission behavior of a chain. SC-chains have perfect pipelining where the data transmitted on each link is successfully forwarded to the next hops. However, it can be seen that the fraction of the data that is successfully transmitted on H1 is very low in HT-chain (and HTC-chain) since H1 suffers from HT- (and HTC-) interaction from H4. The variance of the link throughputs are quite low suggesting that the performance of an isolated chain is predictable.

4.3 Hop-distance analysis

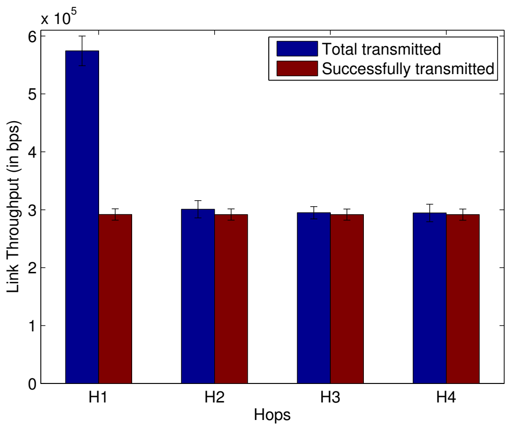
We are using the log-normal shadowing model; under this model, link quality varies with the distance between the sender and the receiver. Figure 5 shows the



(a) SC Chain



(b) HTC Chain



(c) HT Chain

Figure 4: Link throughputs for different chain types: SC chains exhibit little performance variance even when viewed at each link.

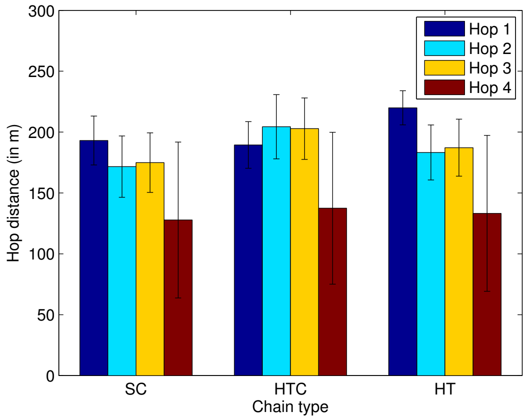


Figure 5: Hop-distance study: All chains have small, but highly varying, last hop-distance. The effect of the distance between receiver(R) and sender(S)/interferer(I) causes hidden terminal in single chains. Stable chains (SC-chain) have low SR distance. HT chains have noticeably large SR distance. factors to hidden terminals. Capture effect (HTC) occurs when S and I are unconnected and there is a smaller distance between them.

distances between each hop in the commonly occurring categories of the chain. SC-chains have smaller hop-distances for all hops.

For HT-chain, the distance between sender S and receiver R of H1 is relatively high and the distance between R and interferer I (R of H1 to S of H4) is low. This leads to HT-interaction at H1 of HT-chain.

Eventhough, the H1 of HTC-chain is relatively strong (hop-distance is equal to that of H1 of SC-chain), it still suffers from HTC-interaction from H4. The reason for HTC is that the interfering signal is high since the distance between the R and I is smaller due to longer hop-distances of H2 and H3.

From these observations, we start the analysis with the following two hypothesis:

- **Hypothesis 1:** *Longer R-S distance is a key factor for HT-interaction.*
- **Hypothesis 2:** *HTC-interactions have lesser R-I distance and can occur for even reasonable R-S distance.*

Obviously, another inherent condition is that S and I cannot sense each otherm, since otherwise there are no concurrent transmission and hence no possibility of a collision. We empirically show that the above factors are consistently true even in cross-chain interactions.

Figure 5 also shows that the last hop of all the chains has significantly lesser distance and higher variability. This effect occurs since greedy geography based routing protocols try to forward the packet as far as possible towards the receiver. Since the end destination of the chain is fixed, on average, the last hop has to cover relatively smaller distances. The fact that this hop is short (and therefore more stable), has implications on the behavior of the chains; we discuss this impact in more detail later.

4.4 Effect of MAC interactions

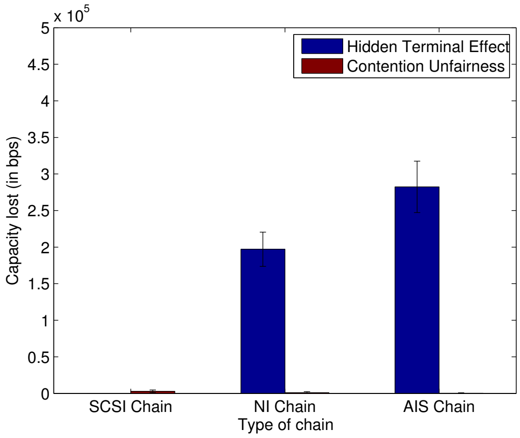


Figure 6: Comparison of the lost capacity due to hidden terminals and contention unfairness: HT and HTC has a greater detrimental effect than contention unfairness. Contention unfairness is controlled due to pipelining in single chain.

In this section, we examine the impact of HT-interaction, HTC-interaction and contention unfairness on prominent categories of chains. As shown in Figure 6, the effect of HT and HTC is very high in respective chains. However, the contention unfairness is controlled due to pipelining in single chain. The traffic to all the nodes is only fed by the previous hops due to absence of external traffic. Hence, contention unfairness will occur only when a link starves due to contention unfairness from more than one link with high traffic. Since, single pipelining controls traffic through the chain, the possibility of having two high traffic links that starves a link of the same chain is very low. However, as we describe in Section 5.3, the effect of contention unfairness is higher when there is an independent high-traffic cross-chain link.

5 Cross chain interactions

In this section, we analyze the interference interactions across two chains. We examine the effect of cross-chain hidden terminals, pipelining and the variability of chain performance.

5.1 Methodology

We simulate a large number of two 4-hop chain scenarios in a 1500 m × 1500 m network. For each scenario, we evaluate the type of interaction between two chains. We ignore those scenarios where two chains have no interaction between each other since this results in isolated chains. We discover that even across two chains, the three most prominent interactions are HT, HTC and SC. We denote two interacting chains as Ch1 - Ch2, where Ch1 is the type of first Chain and

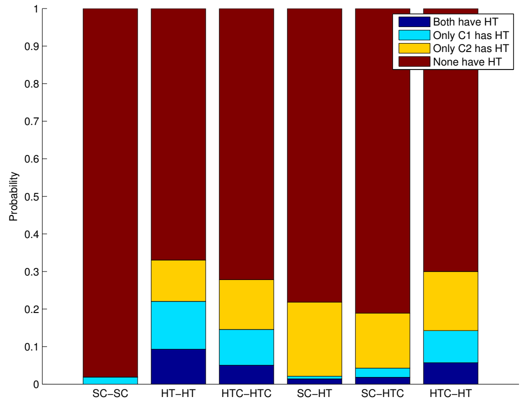


Figure 7: Cross-chain HT-interaction occurrence probability: SC-chains are protected against HT-interaction, HTC-chains are vulnerable.

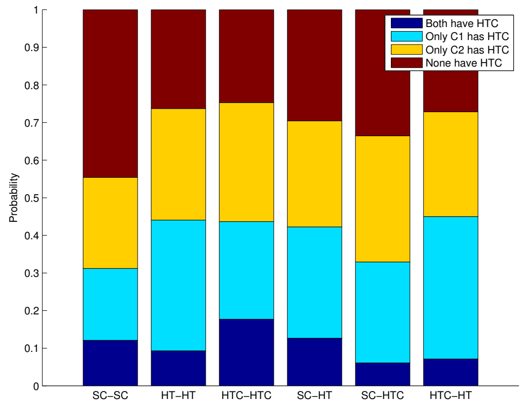


Figure 8: Cross-chain HTC-interaction occurrence probability: HTC occurs significantly in all type of chains.

Ch2 is the type of second Chain in terms of self interference interaction. For example, *HT-SC with HTC-interaction* refers to an HT-Chain and an SC-Chain experiencing an HTC-interaction with each other.

5.2 Occurrence probabilities of hidden terminals

This section studies how often different types of cross-chain hidden terminals arise. Figures 7 and 8 show the the overall probability of a chain having at least one HT- or HTC-interaction.

Vulnerability of SC-chains Figure 7 shows that SC-chains are well protected against HT interactions with other chains; SC-chains have 1.9%, 2.1% and 4.2% of HT-interaction in SC-SC, SC-HTC and SC-HT scenarios, respectively. This supports *hypothesis 1* in Section 4.3. However, even the stable

	p_c(HT)								p_c(HTC)					
	Ch1				Ch2				Ch1					
Category	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2	H3	H4	H1	H2
SC-SC	-	-	-	-	-	-	-	-	0.71	0.55	0.55	0.02	1.00	0.4
HTC-HTC	0.04	1.00	0.26	0.00	0.28	0.52	0.52	0.00	0.67	0.54	0.32	0.13	0.63	0.5
HT-HT	0.89	0.19	0.08	0.08	1.00	0.21	0.21	0.00	0.90	0.42	0.36	0.06	0.67	0.6
SC-HTC	-	-	-	-	0.22	0.74	0.22	0.04	0.65	0.46	0.32	0.07	0.72	0.6
SC-HT	-	-	-	-	1.00	0.17	0.13	0.07	0.70	0.40	0.32	0.07	0.50	0.6
HTC-HT	0.10	0.80	0.25	0.10	1.00	0.20	0.03	0.03	0.76	0.59	0.22	0.06	0.55	0.3

Table 1: Conditional probabilities of link having HT or HTC given that the chain had HT or HTC, respectively: Data largely supports hypotheses 1 and 2. Last hops (H4), which are generally shorter, have very low HT probabilities even if the chain has HT.

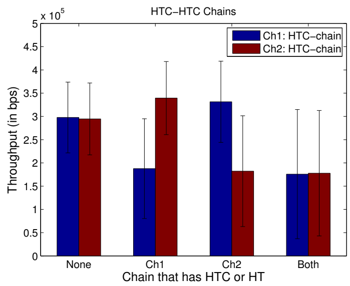
SC-chains can suffer from significant HTC effect as shown in Figure 8; around 55%, 42% and 39% of SC-chains had cross-chain HTC interactions. This confirms a part of *hypothesis 2* that even links of SC-chains, which have reasonable hop-distances, are vulnerable to HTC-interaction.

In order to verify these hypotheses in greater detail, we compute the conditional probability that a link has a particular type of cross-chain hidden terminal given that the chain had that cross-chain interaction. This probability is denoted by p_c(interaction type). Table 1 shows the values of p_c(HT) and p_c(HTC) for hops of both the chains. It shows that all links in SC-chains have negligible probability of cross-chain HT. However, HTC-interaction occurs significantly across first three hops (strengthening *hypothesis 2*). It is to be noted that last hops of all the chains have very low probability for HT-interaction since the hop-distance of H4 is very small (Figure 5). However, SC-chains have reasonable occurrence probability of HTC-interaction (again verifying *hypothesis 2*).

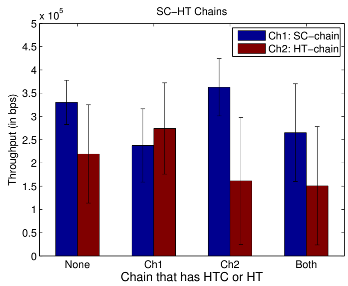
Vulnerability of HTC-chains Figure 7 shows that HTC-chain is more vulnerable to HT-interactions. The reason for this higher probability is clearly seen from Table 1. Most vulnerable links for HT-interaction is H2, which has larger hop-distance (Figure 5), thus again supporting *hypothesis 1.* But, H3 which has the same hop-distance as that of H2 does not observe severe HTC-interaction. This is the only instance where hypothesis 2 is not strongly supported. Similar to SC-chain, H1, H2 and H3 are vulnerable to HTC-interaction.

Above result shows that links with higher hop-distance are vulnerable to HT-interaction, thus supporting *hypothesis 1.* However, HTC-interaction depends upon the *R-I* distance(which is independent of the chain since interferer belongs to another chain).

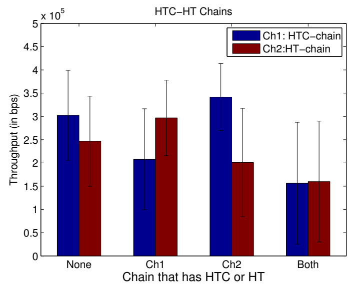
Vulnerability of HT-chains HT-interactions occur frequently in HT-chains (Figure 7). At link level, Table 1 shows that links that had HT-interaction under self-interference are the ones who are most affected by cross-chain HT-interaction, strengthening *hypothesis 1.*



(a) HTC-HTC



(b) SC-HT



(c) HTC-HT

Figure 9: End throughput v/s presence of hidden terminal: Under identical category interaction, chains lose almost half of their throughput when hidden terminal occurs. Variance of chains with cross-chain hidden-terminal is higher.

5.3 Effect of MAC interactions on end-throughput

Unlike the case of single chains, categories of cross-chain scenarios had very high standard deviation (comparable to respective means) for the link and end throughputs. The greater variance is because of the additional interference parameters that are introduced due to the effect of traffic from independent cross-chain transmitters. This was absent in single chain because the interactions between links and the traffic are controlled by a single pipeline. In the next two subsections, we isolate the causes for the variance by recognizing the primary parameters and summarize the pipelining effect by observing detailed link-throughputs.

We study the effect of cross-chain hidden terminals and, due to space limitation, we demonstrate the throughputs of only 3 out of 6 cross-chain categories. We do not mention notable standalone effects of HT- and HTC-interaction on chains. Interested reader is pointed to the technical report for details [**?**]. Figure 9 shows the throughput of both the chains when none of the chains, one of them or both have HT- or HTC-interaction.

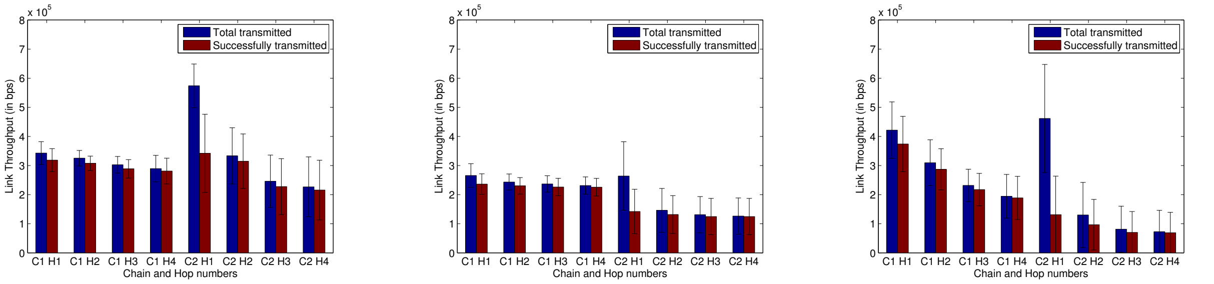
When identical chains interact (see e.g. Figure 9(a)), *the chain with the hidden terminal loses approximately 50% of the throughput* when compared to a scenario without any hidden terminal. When a particular chain has a hidden terminal, HT- and HTC-chain observe comparatively larger throughput losses than the SC-chain. This is attributed to a lower probability of success and larger backoff delays in chains with hidden terminals.

Comparing the chain throughputs in Figure 9 with those observed in single chain scenarios (Figure 4), it is clear that the *variability of end-throughput during cross-chain interactions is significantly higher.*

5.4 Link-throughputs and pipelining

We now analyze the pipeline to obtain a deeper understanding of the effect of interactions on link-throughput. Due to space limitations, we summarize our conclusions on predictability and pipelining of chains through one example.

In addition to classifying the scenarios based on the cross-chain categories,



(a) When H1 of HT-chain does not interact with SC-chain

(b) When H1 of HT-chain is connected to H1 of SC-chain

(c) When H1 of HT-chain has a cross-chain HT interaction with SC-chain

Figure 10: Effect of hidden terminal and interfering traffic when SC-HT chains interact:

we observed that classifying it based on the below parameters decrease the variability of chain performance. First, the amount of contention forms a key parameter. The cross-chain links that are within sensing range to the source node of the other chain experience higher busy channel times since the traffic of the chain near the source node is much higher than the traffic near the destination nodes (especially for HTC- and HT-chains). This significantly reduces the available capacity of the link, even in the absence of hidden terminals. Moreover, some scenarios suffer excessively from starvation [8]. Second, as we saw in the previous subsection, the presence of cross-chain hidden terminal influences the performance of the chain. In addition, the traffic of the interferer and the traffic on the link that suffers from hidden terminal has a significant effect on the chain performance.

We illustrate these through one example of SC-HT cross-chain category. Figure 10 shows the pipelining and link-throughputs in three cases. Figure 10(a) shows the pipeline when H1 of HT-chain has no interaction with SC-chain. In this case, due to non-blocking of the weaker HT-chain, it transmits greater traffic and, thus, obtains reasonable end-throughput.

However, the end-throughput of HT-chain is reduced to half when the H1 of HT-chain is *connected* to H1 of SC-chain (Figure 10(b)). The pipeline clearly illustrates that H1 of HT-chain is unable to transmit enough packets due to the high contention from the traffic from H1 of SC-chain.

Figure 10(c) shows another extreme case where H1 of HT-chain has a cross-chain HT interaction with a link from SC-chain (in addition to self-interference HT interaction). It is to be noted that such scenarios occur often since cross-chain HT interaction for H1 of HT-chain has a very high probability (c.f. Figure 7 and Table 1). In such scenarios, the throughput of HT-chain degrades to 25% of its original value with a large number of collisions at H1.

To summarize, in this section, we showed the probability of occurrence of hidden terminal in different configurations of chains. We verified our hypotheses that: (1) Links that suffer from HT are relatively longer than the stable links; (2) The occurrence of HTC is mainly a function of distance between the receiver and the interferer for links with reasonable hop-distance. We then demonstrated the end-throughput when various categories of chains interact under presence and absence of cross-chain hidden-terminals. Finally, we demonstrated the various causes of throughput degradation by analyzing the complete chain pipeline and concluded that the effect of contention and hidden terminals is dependent upon the traffic on the link and the interferer.

6 Conclusions and Future Work

Chains are fundamental units to route packets from source to destination in multi-hop wireless network. Precise characterization of chains is a challenging since it is influenced by a large number of factors such as the chain's self-traffic, traffic on the neighboring active links, and the nature of the MAC interactions between all these links. In this paper, we provided a detailed analysis of the chains with respect to the pipelining effect, predictability and the effect of MAC interactions. We first analyzed the the above three properties and hop-distance in a single chain and showed that the behavior is highly predictable in isolated chains.

The paper then studied the emergence of new cross-chain interactions and its impact when multiple chains interact. It was shown that links with longer hop-distance were very vulnerable to cross-chain hidden terminals. Even stable links were prone to the *capture effect* when multiple chains interact. Our analysis of hidden terminals showed that, while self-interference patterns is sufficient to predict the throughput of the chain under a single chain scenario, it is inadequate when multiple chains interact. Accounting for additional cross-chain parameters that capture the contention and hidden terminals increases the predictability of the chain performance. We verified it through examples of detailed analysis of the pipeline.

Extension of the observation in realistic network requires measurement-based methodology to infer the MAC and chain interactions. Design and development of such a realistic measurement tool is our immediate future work. Interaction-aware routing protocol follows as the next step to utilize the observations made in this study.

Acknowledgements

This work was in part financially supported by European Union (ARAGORN project). We acknowledge also the partial support from DFG and RWTH Aachen through UMIC-research center facility.

References

[1] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media access protocol for wireless LANs," in *SIGCOMM*, 1994.

[2] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless performance," in *MobiCom*, 2003.

[3] F. A. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part II–The Hidden Terminal Problem in Carrier Sense Multiple-Access and the

Busy-Tone Solution," *IEEE Trans. on Communications*, vol. 23, no. 12, pp. 1417–1433, 1975.

[4] 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.

[5] 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.

[6] C. Barrett, A. Marathe, M. V. Marathe, and M. Drozda, "Characterizing the interaction between routing and MAC protocols in ad-hoc networks," in *MobiHoc '02*, 2002.

[7] S. Razak and N. Abu-Ghazaleh, "Self-Interference in Multi-hop wireless chains," in *Proc. ADHOC-NOW*, 2008.

[8] 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

[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] The IEEE Working Group, "IEEE 802.11 Wireless Local Area Networks," 2002. [Online]. Available: http://grouper.ieee.org/groups/802/11/

[11] S. Lee, B. Bhattacharjee, and S. Banerjee, "Efficient geographic routing in multihop wireless networks," in *MobiHoc*, 2005, pp. 230–241.

[12] S. Xu and T. Saadawi, "Revealing the problems with 802.11 medium access control protocol in multi-hop wireless ad hoc networks," *Comput. Networks*, vol. 38, no. 4, pp. 531–548, 2002.

[13] J. Li, C. Blake, D. DeCouto, H. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *MobiCom*, 2001, pp. 61–69.

[14] 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.

[15] "Qualnet network simulator, version 3.8," http://www.scalable-networks.com/.