How do Wireless Chains Behave?
The Impact of MAC Interactions

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Abstract—In a Multi-hop Wireless Networks (MHWN), packets are routed between source and destination using a chain of intermediate nodes; chains are a fundamental communication structure in MHWNs whose behavior must be understood to enable building effective protocols. The behavior of chains is determined by a number of complex and interdependent processes that arise as the sources of different chain hops compete to transmit their packets on the shared medium. In this paper, we show that MAC level interactions play the primary role in determining the behavior of chains. We evaluate the types of chains that occur based on the MAC interactions between different links using realistic propagation and packet forwarding models. We discover that the presence of destructive interactions, due to different forms of hidden terminals, does not impact the throughput of an isolated chain significantly. However, due to the increased number of retransmissions required, the amount of bandwidth consumed is significantly higher in chains exhibiting destructive interactions, substantially influencing the overall network performance. These results are validated by testbed experiments. We finally study how different types of chains interfere with each other and discover that well behaved chains in terms of self-interference are more resilient to interference from other chains.

I. INTRODUCTION

Multi-Hop Wireless Networks (MHWNs), which include mesh, sensor, and ad hoc networks, are forecast to play an important role in an Internet that will grow increasingly wireless at the edge. MHWNs reduce infrastructure requirements by having wireless nodes relay traffic towards access points; they are attractive whenever infrastructure is unavailable or costly, or quick deployment is desired [1]–[3]. The complex and dynamic nature of wireless propagation, interference, and user mobility make developing effective networking protocols for MHWNs a significant challenge.

In an MHWN, packets are forwarded from source to destination using a chain of nodes. Starting from the source, a node forwards packets to the next node in the chain forming a path towards the destination. Chains represent a fundamental communication structure in MHWNs, and understanding their behavior is critical to designing effective protocols. In particular, routing protocols must discover efficient chains that can then be used for communication. Early routing protocols used path length to discriminate between chains, favoring the shortest available path [4]–[7]. Recently, individual link qualities have been taken into account in evaluating path quality [8]. However, the behavior of a chain is a complex process that cannot be accurately characterized by looking at the individual links without consideration to how they interact with each other.

Several studies have examined the behavior of chains. Li et al. study the performance of chains as the number of hops are increased [9]. They also study the effect of cross-interference between chains. Xu and Sadaawi analyze TCP instability due to chain self-interference and discover short-term and long-term unfairness issues in cross-chain interactions [10]. Ping et al. present the effect of traffic on routing instability, packet drops, and unfairness due to self interference within chains [11]. These analyses significantly differ from ours in a number of ways, including the fact that they do not consider the detailed processes, such as the impact of the MAC level interactions, on the performance of chains. We review these and other related works in Section II.

Several complex and inter-dependent processes combine to determine the behavior of chains. In particular, the performance of chains is affected by self-interference among the different hops of a chain as they compete to transmit on shared wireless medium. This interference not only reduces the available transmission time at each hop, but also causes packet collisions due to a variety of MAC level interactions that occur in different chains. Moreover, nodes in the middle of the chain experience higher interference than nodes at the edge because they are in interference range with more nodes in the chain; this is a process we call contention unfairness.

Among the different processes that impact chain performance, MAC level interactions play a central role. They also significantly moderate the effect of the other processes. In order to better understand chain behavior, we first analyze the types of interactions that occur most frequently in four-hop chains. We later explore generalizing these results. Although there is a large number of potential interaction configurations that may arise in chains, we discover that only a small number of them occur in practice due to chain geometry restrictions. Specifically, we set up forwarding rules to produce chains in a way representative of how routing protocols work. We use a Signal to Interference and Noise Ratio (SINR) model for packet reception which allows us to account for the effect of capture.

We then evaluate, in Section IV, the effects of the interference interactions within a chain on its overall performance.
We first use simulation to determine the throughput and the number of packet drops for different types of chains. Afterwards, we validate our simulation results by comparing them against results obtained from an experimental testbed.

The next contribution of the paper, discussed in Section VII, is to develop an approach for estimating the performance of general n-hop chains. Specifically, we observe that the best chains are those where senders are in carrier sense range with each other, allowing the MAC protocol to effectively arbitrate the medium. In those chains where this is not the case, the presence of a hidden terminal has a higher impact than a hidden terminal with capture. Finally, the location of the hidden terminal is also a factor in determining the performance; the earlier the hidden terminal, the worse its impact.

After characterizing how a single chain self-interferes in isolation, we look at the problem of how multiple chains interfere with each other. In a general MHWNs, multiple connections are active simultaneously, interfering with each other. In Section VII we evaluate cross-chain interactions and study their effects on the performance of chains. Again, we discover that the presence of hidden terminals significantly affects performance and fairness. Moreover, we discover that well behaved chains in terms of self-interference are more resilient to destructive interference from other chains. Finally, we summarize our contributions and present some concluding remarks in Section VII.

II. RELATED WORK

Several researchers have developed framework to characterize the behavior of wireless networks [12]–[14]. They develop models to predict the behavior of networks but do not consider factors affecting chains in multi-hop networks. Works like MACA, MACAW and FAMA added MAC level packet exchange combined with Carrier Sensing to mitigate hidden terminal problems [15]–[17]. These protocols do not solve the hidden terminal problems under realistic models for wireless interference and packet reception.

Jain et al. model interference in a network as a conflict graph and estimate throughput achievable in a given network and load [18]. They utilize global knowledge of network and interference to determine routes that maximize throughput. They do not analyze self interference between chain links and do not consider chain effects while evaluating these routes.

Recently, Gollakot and Katabi present an interference cancellation technique that uses information from successive collisions to decode collided packets [19]. Their techniques assume symmetric hidden terminals that causes same packets to collide several times. Garetto et al. and Razak et al. show that most interactions in ad-hoc networks in general and chains in particular have asymmetric interference hence this interference cancellation technique is not applicable in most cases [20]–[22].

Li et al. studied the performance of chains as the number of hops are increased [9]. 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 nodes on the throughput of a chain topology [11]. 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 nodes 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.

In earlier work, Razak et al. use a simplified two-disc binary model of packet reception to categorize interactions between self interfering links of a chain [22]. The current paper advances this earlier study in several important ways: (1) Enumerates factors that are instrumental in affecting chain behavior; (2) it uses the SINR propagation model, which allows us to more accurately model interactions, and include the important impact of capture; (3) it presents experimental validation of the results; (4) it contributes a more accurate approach for estimating chain probabilities taking into account the effect of routing protocols and the node density; (5) it presents a generalization to n-hop chains; and (6) it presents a study of interactions across chains.

In summary, most of the work that analyzes chains concentrates on observing the behavior of chains and then identifying and evaluating the effects that cause these behaviors. Our approach, studies the factors that determine chain behavior from first principles, identifies the factors that have high impact and then evaluates the effect of these factors on chain performance.

III. MAC INTERACTIONS IN CHAINS

In this section, we first discuss the different factors that impact chain behavior. We identify that MAC interactions between chain links have the highest impact on chain performance. We then study the frequency of occurrence of the different sets of interactions in 4 hop chains, under representative routing protocols.

A. Factors that Determine Chain Behavior

It is well known that the throughput of a chain decreases as the number of hops increase [9]. In this section we outline the factors that affect the performance of chains of a given length. Contention Unfairness: As nodes in a chain compete for channel access, the ones in the middle of the chain may contend with more nodes within the chain than those at the edges. These middle nodes have a smaller chance to transmit, which results in longer packet queues, ultimately leading to packet drops. We term this effect contention unfairness which affects the overall performance of the chain and is similar to the flow in the middle problem [23].

MAC Level Interference Interactions: One of the factors that affects the performance of chains is the types of MAC interaction between hops of the chains that do not share a
common node. For example, if the source of one hop is a hidden terminal to the receiver of another, the performance of the chain is significantly influenced.

**Pipeline Effect:** In a chain, earlier hops feed data to later ones. As a result, later hops can never transmit more packets than earlier ones. This effect has important implications: if there is an interaction leading to unfairness in favor of later hops, it cannot be sustained. On the other hand, unfairness in favor of earlier hops leads to rate mismatch at intermediate hops and packet drops in queues. This effect moderates the impact of hidden terminals and contention unfairness, preventing unfairness in some cases.

**Cross-chain Interference:** Chains do not exist in isolation within a network. Links in a chain can have different interactions with links within other chains affecting the overall performance of the network. The effect of this cross chain interference is an important factor to consider while characterizing the performance of chains.

Of the factors above, the MAC level interactions play a defining role in the overall performance of the chain. Contention Unfairness, Pipelining Effect and Cross-chain interference may exist in all chains to varying degrees but the MAC interactions significantly influence the impact that these other effects have. We show examples of this behavior in Section [VII]. Thus, the first and most important step in understanding chains is to understand the occurrence probability and impact of the different MAC interactions within chains.

### B. MAC interactions between two links

In this section, we introduce MAC level interactions in the context of two interfering links [20], [24]. This scenario is the simplest case in which links interfere at the MAC level. It provides a basis for identifying the different interaction cases, which we then use to classify interactions that occur within chains.

In a wireless network, the state of the channel at the receiver determines whether a reception occurs successfully or not. However, carrier sensing is carried out at the sender in Carrier Sense Multiple Access (CSMA) protocols. Accordingly, if the receiver channel is busy but the sender channel appears idle, a collision can occur. The geometry of the interfering links (more accurately, the state of the channels between them) determines what MAC level interactions arise. These interactions can significantly impact performance or cause short term or long term unfairness.

Given two interfering links $S_1 - D_1$ and $S_2 - D_2$, the type of MAC interaction that occurs depends on the state of the secondary (or unintended) channels between $S_1 - S_2$, $S_1 - D_2$ and $D_1 - D_2$. Each of these channels 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 [20], [24]. Garetto et al. identify 5 categories of interactions in a simplified unit-disc model of interference [20]. Razak et al. identify 10 categories of basic interactions under SINR model. We next summarize the three interaction categories that occur most frequently in chains [24].

1. **Senders Connected Symmetric Interference (SCSI or SC):** SCSI 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 other than those arising when the two senders start transmission at the same time will occur (not giving CSMA a chance to work). Such collisions are unavoidable, and their probability is low due to the randomization of the backoff period. We will henceforth refer to the SCSI interaction as SC for simplicity.

2. **Asymmetric Incomplete State (AIS or HT):** The senders are not connected in AIS scenarios and, hence, can transmit concurrently. Each sender has incomplete information about the state at the respective receivers. As shown in Figure 1(b), an asymmetric interference is observed where a transmission from the one sender $S_1$ causes packet collision at the receiver $D_2$ of the other link. The link $S_1, D_1$ is unaffected by signals from $S_2$ to $D_2$. The source $S_2$ observes large backoff values due to repeated packet collision and hence the throughput of $S_2, D_2$ is significantly affected. For simplicity, we henceforth refer to the AIS interaction as HT since it experiences severe Hidden-Terminal effect.

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 $D_2$ is in interference range of $S_1$, it is able to capture its packets from $S_2$ as long as the packet from $S_2$ arrives at $D_2$ before $S_1$ 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 [25]. 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.

While other categories exist (for example, symmetric hidden terminals where both packets are lost), we show in the next section that they almost never arise in chains due to the geometric structure of chains selected by a forwarding rule
C. What interactions occur most frequently in chains?

In this section, we determine the probabilities of different types of interactions that occur between links in multi-hop chains. We start with a uniform deployment of the nodes in a fixed-size area. We considered using shortest path routing to select the chains. However, since modern routing protocols incorporate link quality in evaluating paths, we decided to use the following forwarding rule instead to generate paths. We start from the source and pick as the next hop the neighbor that is expected bring the packet the closest to the destination taking into account both distance and link quality. This expected distance is the product of the actual distance travelled towards the destination divided by the expected number of retransmissions necessary to delivery the packet (ETX [26]). Link qualities were assumed to be distributed as a function of distance between the sender and receiver according to the log-normal shadowing distribution. This forwarding rule is identical to that implemented by the NADV routing protocol [27].

![Fig. 2. A Chain with 4 hops.](image)

We conduct our analysis of interactions on chains with 4 hops. We choose 4-hop chains because they have multiple interactions between their links and provide insights that are helpful in generalizing our evaluation to n-hop chains as we will show in Section V. In a four hop chain as depicted in Figure 2 there are three different sets of links that can be active at the same time. These sets of links result in four-hop chains exhibiting three types of interference interactions. We denote this set of interactions as INT1/INT2/INT3, where INT1 represents interaction between hops H1 and H4, INT2 represents interaction between H1 and H3, and INT3 represents interaction between hop H2 and hop H4.

In order to evaluate routes picked by NADV-like forwarding rule, we generate a topology with nodes uniformly distributed in a 1500 x 1500 meters area. We study the impact of node density by increasing the number of nodes deployed in the same area. We observe that the interaction probabilities stabilize as density of nodes increases and are not significantly different at lower densities. Next we calculate the route from each node to every other node using the forwarding rule and evaluate the interference interactions between links of all 4-hop routes. Figure 3 shows the probability of the different types of interactions in 4-hop chains for different node densities. In this figure, we omit some very rare interactions that occurred to avoid clutter.

As shown in Figure 3 in sparse networks, routing protocols are forced to pick longer hops, leading to a higher percentage of hops with Hidden Terminal interactions. Given a density, the occurrence of interactions are a function of Carrier Sense range, as we have more senders connected with higher Carrier Sense range. As we decrease the Carrier Sense range, more nodes can transmit together causing a higher number of hidden terminal problem. We observe from this figure that there is a substantial number of hidden terminal interactions for all values of Carrier Sense range. For values of Carrier Sense range representative of those used on commercial wireless cards, interactions SC/SC/SC, HT/SC/SC, and HTC/SC/SC occur most often.

IV. CHAIN PERFORMANCE

In this section we evaluate the performance of 4-hop chains with different interference interactions. We pick interactions: SC/SC/SC, HTC/SC/SC, and HT/SC/SC since they occur most commonly at realistic values for Carrier Sense range. We evaluate the performance in terms of throughput achieved and the percentage of dropped packets to achieve this throughput. Chain throughput demonstrates the amount of traffic successfully transferred per unit time where as packet drops determine how efficiently this traffic was transferred.

![Fig. 4. Simulation based Performance Analysis of 4-hop Chains vs Channel Saturation.](image)

We first carry out simulation based studies using Network Simulator (NS2) [28] to study the performance of these chains in an environment with repeatable results. We then conduct the same experiments in a wireless testbed in order to study the accuracy of our results in a more realistic environment.

A. Simulation Based Performance Analysis

We simulate scenarios with 4-hop routes. We use a fixed distance of 250m for transmission range and disable RTS/CTS mechanism. All transmissions are based on 802.11 DCF mode.
at data rates of 6Mbps and packet size of 1500 bytes. Our choice for 6Mbps was based on our testbed evaluation. In our testbed since we are using 802.11a to get interference free channels the minimum supported rate is 6Mbps. We change the saturation level of the channel by altering the rates at which the source pumps Constant Bit Rate (CBR) traffic into the chain. We perform this analysis using the standard two-ray ground wireless propagation model with SINR model for packet reception and capture effects. We fix the Carrier Sense range at 550 meters.

Figure 4(a) shows that for all interactions, chains behave similarly at low saturation levels. Saturation levels determine how often a source transmits a packet; at full saturation, the sender will always have a packet to transmit. At low levels of saturation, a packet transmitted from the source makes it to the destination before the next packet is transmitted at the source. Hence, there is no interference between the links. The reason for the sudden jump in packet drops for HT cases is that as soon as we cross the saturation threshold, a packet sent on the first hop will collide with the transmissions on the last link. That packet will be successfully retransmitted. When this packet is eventually transmitted on the last hop, it causes the new packet being transmitted on the first hop to be dropped. This way each packet will be dropped once on the first link before it is successfully transmitted. Hence, we see almost 100% drops as soon as we cross the saturation threshold.

As saturation increases, the level of contention between links also increases causing throughput to eventually level-off, we call this the chain effect. As we see from Figure 4(a) the chain effect has a higher impact on throughput than self-interference interactions since all three interactions show similar performance.

The interesting observation, however, is that the three chains consume different amounts of channel bandwidth to obtain this same throughput as shown in Figure 4(b). At lower saturation, the behavior of each chain is the same; as none of the chains experience any packet drops. As saturation levels increase, the interactions between links start to affect chain performance. For chain with Hidden Terminals, more packets are dropped resulting in extra bandwidth usage. The reason why these packet drops do not substantially effect the throughput of the chain is that these packets in Hidden Terminal (HT) chains are transmitted at times when Sender Connected (SC) chains are waiting to transmit because of channel contention. Hence waiting periods in Sender Connected chain are used to transmit packets that are dropped in hidden terminal chains. Percentage of packets dropped in Hidden Terminal with Capture (HTC) cases is better than HT cases, as several packets sent by the source are captured on the first link.

B. Testbed Evaluation

We validate the results for chain performance obtained from simulation using a wireless testbed to confirm whether our observations will hold in a real network. Our testbed consists of 8 nodes that are placed in offices on the same floor of our building as shown in Figure 6.

Each numbered circle represents a single wireless node. Each node consists of a soekris board [29] with mini-PCMCIA wireless card running atheros chipset [30] and madwifi device driver [31]. We operate the wireless cards on 802.11a to avoid interference with our resident 802.11 b/g network. There is also an 802.11a network inside the building but it uses four channels at the lower end of the spectrum so we set our wireless cards to operate on channel 157 (5.785GHz). We use a bit rate of 6Mbps and disable RTS/CTS handshake.

We start each node and check the kind of interactions that occur between nodes. Nodes 3 and 7 can sense each others transmission so they are Sender Connected (SC). To make sure that links 3-4 and 7-8 are Sender Connected (SC), we start transmission from node 3 to node 4 and from node 7 and node 8. We observe that both links equally share the channel. We create a chain by adding static routes so that packets being sent from Node 3 to Node 8 are routed through nodes 4, 6 and 7 making a four-hop route 3-4, 4-6, 6-7, and 7-8. This creates an SC/SC/SC chain since all nodes are in Carrier Sense range.
To create an HT/SC/SC interaction we pick the source to be node 1 and destination to be node 8. The 4-hop route between these two nodes goes through nodes 3, 5, and 7. Nodes 1 and 7 are out of range so they can transmit together. When node 7 transmits, node 3 is unable to capture packets from node 1 creating a hidden terminal interaction between links 1-3 and 7-8. To verify this interaction, we start transmitting packets from node 1 to node 3 on link 1-3. We see the maximum throughput on this link. Now we start transmitting packets from node 7 to node 8 on link 7-8. The throughput on link 1-3 drops substantially and we see most of the packets on this link being dropped [21]. Hence chain 1-3-5-7-8 represents an HT/SC/SC interaction.

To create an HTC/SC/SC interaction we use the same chain that gave us an HT/SC/SC interaction: 1-3-5-7-8 and start reducing transmission power on node 7 until node 3 is able to capture packets from node 1. Figure 7 show results obtained from the testbed. We see that the results closely match those obtained from simulation although the throughput from testbed is slightly lower than simulation. We attribute this to the physical hardware delays in the real network.

Current routing protocols do not consider the interaction between links of a chain while making routing decisions. Metrics that try to maximize throughput of a route will consider chains with these different interactions to be similar and will pick routes irrespective of their efficiency. This will cause suboptimal usage of network bandwidth; an already limited resource, hence causing lower throughput in the whole network. Inefficient routes also require more transmits for each successful transmission, which also wastes the limited energy resources of wireless nodes.

V. GENERALIZATION TO N-HOPS

In this section we use our results from 4-hop chains to generalize to n-hop chains. In a chain, each hop can possibly interact with every other hop within the chain. Therefore in an n-hop chain, the first hop will interact with n − 1 hops, second hop will interact with the subsequent n − 2 hops, and so on. The total number of interactions \( N_i \), between hops is thus given by the following equation:

\[
N_i = \frac{n(n - 1)}{2}
\]  

(1)

Previously, we had determined that there are 10 different types of interactions between two flows [24]. Consequently it is possible to have each of the interactions to be one of the 10 states. This makes the total number of possible interactions between hops of a chain to be \( 10^{N_i} \). Clearly this is an intractable number to analyze. We have observed in our evaluation of 4-hop interactions that out of the 10 interactions possible, 3 occur most frequently in chains because of the their geometric nature. Hence we can reduce the number of considered interactions to \( 3^{N_i} \).

To further reduce the \( N_i \) term, we make the following observations:

- The destination of each hop is the source of the next subsequent hop. Since nodes within a hop are always within communication range of each other, each hop has an SC interaction with its neighboring hop.
- For commonly used values of Carrier Sense ranges in commercial radios (equal to two times the Communication Range or more) two hops separated by a single hop are always going to have SC interaction as well. The reason for this is that the sources of these two hops share a common neighbor i.e. the source of the middle hop, and since neighbors can be at most Communication Range apart. Therefore, the distance between the source of two hops separated by a single hop can be at most two times the Communication Range.

- All chains start from a source and go towards a destination. Hence each hop of the chain goes further away from the source and gets closer to the destination. This causes enough distance between links such that if there are enough hops between two links, the links will not have any interaction between them. By analyzing routes with more than 4 hops we observe that in more than 99% cases, there is no interaction between links that are 3 hops apart using the NADV forwarding rule.

From the above observations we make the approximation that a hop \( a \) will have SC interactions with hops \( a + 1 \) and \( a + 2 \), one of the three interactions with hop \( a + 3 \) and no interaction with any subsequent hops. This simplification reduces the total number of interactions to \( n - 3 \), since the last three hops don’t have an \( a + 3 \) neighbor to interact with. Hence an n-hop chain can have a total of \( 3^{n-3} \) interactions.

To determine the behavior of n-hop chains, we make the following observations based on our results:

- The throughput of a chain is independent of the type and number of self-interfering interactions.
- In contrast, the performance of a chain in terms of number of dropped packets, depends upon the types of interfering interactions between links of the chain as well as the location of these interactions. The kind of interaction towards the beginning of a chain will have a higher impact on the performance than the later interactions.
- Chains with SC interactions perform better than those with HTC or HT interactions. Chains with HTC interactions perform better than those with HT interactions.

\[ \text{Fig. 7. Performance Analysis of 5-hop Chains with Different Interaction Combinations: HT interactions cause worst performance in terms of packet drops followed by HTC and then SC. Throughput is mostly independent of interference interaction.} \]
Figure 8 illustrates the performance of a 5-hop chain, with different link1-link4 and link2-link5 interactions. In the figure, the terminology SC-HT means that there is an SC interaction between the first and fourth hops and an HT interaction between the second and fifth hops. The plot shows that the difference between the best and worst throughput is less than 15%. We also observe that SC interactions perform better, especially when they occur at the beginning of the chain. HT interactions at the start of the chain have the worst performance.

Figure 8 illustrates the performance of 8-hop chains that have HT interactions at varying distances from the beginning of the chain. We observe that HT interactions at the beginning of the chain are much more pronounced than in later hops, with the effect being minimized after the chain throughput stabilizes after the first few hops. These observations allow us to analyze the first few interactions in a chain and compare their performance. Quantifying the effect of these interactions and applying them as metrics for routing is part of our future work.

VI. INTERACTIONS ACROSS CHAINS

This section considers the problem of interactions that occur across different chains. Clearly, the number of possible interactions that general chains can have with each other is overwhelming, preventing a systematic analysis such as the one we attempted with a single chain. Instead, the study presented in this section examines the following questions: (1) Does the type of chain (from a self-interference perspective) affect its susceptibility to cross chain interference? (2) Do different types of chains interact differently with each other? (3) What is the effect of cross chain hidden terminals and hidden terminals with capture on different types of chains?

For simplicity, we denote the SC/SC/SC, HTC/SC/SC and HT/SC/SC chain categories as SC, HTC and HT respectively. We simulate cross-chain interactions by randomly choosing two chains of a particular category that were selected by the NADV forwarding rule. This approach leads to 6 possible combination of cross-chain interactions: 2 SC chains, 2 HTC chains, 2 HT chains, SC & HTC chains, SC & HT chains and HTC & HT chains. We analyzed more than 200 different scenarios under each category. We analyze the number of cross-chain interactions that occur when two chains interact. We then study the effect of hidden terminal interactions on different combinations of chains.

Cross-chain hidden terminals: We empirically study the occurrence probability of a hidden terminal on two chains. Figure 9(a) shows occurrence probabilities of a hidden terminal (HT or HTC interaction) in two chain scenarios. We observe that the occurrence of Symmetric HT (or Symmetric HTC), where a pair of links have HT (or Symmetric HTC), to each other, are very rare. We refer to the first and second chains in each interaction category as chain 1 and chain 2, respectively. Figure 9(a) shows that weaker chains like HT or HTC chains are more vulnerable to cross-chain hidden terminal interactions than the SC chain. It can be observed that the probability of occurrence of hidden terminal in at least one of the chains is very high: a value of 0.55 in the 2 SC chains and 0.8 in weaker chains. The reason that HT and HTC chains suffer more cross chain hidden terminals is that the link with a HT in self-interference has low SINR at the receiver, meaning that it is susceptible to interference from another chain as well. The average throughput values of representative scenarios are shown in Figure 9(b).

We illustrate the general effects of hidden terminals through representative scenarios due to space limitations. In general, severe unfairness from hidden terminals result when a strong chain like SC interacts with a weaker ones like HTC and HT chains. Weaker chains with cross-chain hidden terminal interactions are prone to severe throughput degradation. This is highlighted when HT & HTC chains interact and both have cross-chain hidden terminals: the presence of hidden terminals reduces the throughput of both chains to approximately half the original value. The amount of throughput degradation is dependent upon the placement of the two links that are involved in the hidden terminal and the type of self-interference observed. The average throughput of two interacting chains are equal when two similar chains have no hidden terminals. Even under such stable scenarios, we observed a large variation of throughput due to contention unfairness. We move on to explain this effect.

Effect of contention unfairness: We now examine a collective interaction that significantly affects the performance of the links. Even in the absence of hidden terminals, some links may suffer starvation due to very low channel access probabilities due to contention from other links. The contention unfairness problem can be explained by a simplified topology that highlights its effect. In the Flow-in-
A significant number of hidden terminals emerge during cross-chain interactions. HT and HTC chains are more vulnerable to hidden terminals than SC chains.

Throughput (in bps)

(a) Occurrence probability of cross-chain hidden terminals in chains:

(b) Effect of hidden terminals on throughput in some representative scenarios: Severe unfairness results when hidden terminal is present in a HT or HTC chain, but absent in a competing SC chain.

Fig. 9. Hidden terminals in cross-chain interactions.

Fig. 11. Capacity wasted due to hidden terminals and contention unfairness: The effect of contention unfairness is significant in cross-chain interactions.

The-middle topology shown in Figure 10 Link A and C do not sense each other and can transmit in parallel. However, link B can only transmit when neither A nor C are transmitting. Due to the fact that A and C are out of range, and unsynchronized, B experiences large busy times on the channel, as the channel is mostly busy with transmissions from either A or C (or both). This leads to severe starvation. The other links capture a large share of transmission time. We call such interactions “contention unfairness” since individual links experience unfairly different contention levels.

The pipeline effect of traffic on a single chain reduces the impact of contention unfairness. However, when independent chains compete, contention unfairness may arise, leading to queue drops and unfairness.

Combined impact on chain performance: Figure 11 compares the effect of hidden terminals and contention unfairness in terms of the lost capacity. Contention unfairness significantly reduces capacity for all chains. The large variance indicates that the effect of hidden terminals and contention unfairness cannot be accurately predicted in the aggregate; rather, a case-by-case analysis is required.

Chain type and vulnerability to cross chain interactions: The next experiment studies the vulnerability of the different chain types to destructive cross-chain interactions. Considering the types of interactions in order of severity (HT, HTC followed by SC), we label a link in a chain according to the most severe interaction it suffers. For example, if a link has an HT interaction from one link, HTC from another link and SC with some others, the link is labeled HT. We then empirically calculate the conditional probability that the link has an interaction X from the other chain given that it had interaction Y. This metric quantifies the vulnerability to cross-chain interactions for the link with X interaction under self-interference.

Figure 12 shows this conditional interaction probability. It can be seen that weak links (ones having HT or HTC) have much greater probability to have detrimental interactions than the links that have only SC interactions.

VII. CONCLUSIONS AND FUTURE WORK

Chains are a fundamental communication structure in multi-hop wireless networks; understanding their performance is important for building efficient protocols. The behavior of chains is complicated because of a number of complex processes that arise as different hops of a chain interfere with each other. We first identify these different effects and argue that MAC level interactions are the most important. We analyze the frequency of occurrence of the different types of chains, classified by the types of MAC interactions they exhibit. There is a large number chain types possible in four hop chains when we consider the different interaction combinations that can arise.
However, the analysis shows that only a small number of these interactions occurs in practice.

We also study the performance of chain types that occur. We find that, even though the different chains show similar throughput when considered in isolation, different chains experience significantly different number of packet drops. These packet drops, require retransmissions, increasing the overall performance of the network. We validate these results using testbed experiments. We also generalize the results we obtained four-hop chains to n-hop chains.

The paper then analyzes the link level interactions that occur across two interfering chains. The number of potential interactions grows exponentially, preventing a systemic analysis. However, we make a number of interesting observations: (1) MAC level interactions also play a primary role in how multiple chains interact. Other factors such as contention unfairness play a smaller role. For example, the presence hidden terminals (with or without capture) across chains significantly hinders performance and fairness; and (2) A chain that is well behaved with respect to self-interference is more immune to interference from another chain.

Our future plans include deeper analysis of cross chain interactions. We also plan to develop routing protocols that leverage the observations made about chain behavior. Another intriguing possibility is to explore changing MAC parameters such as transmission power and carrier sense range to change chains that have destructive interference into better chains that do not.

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