Self-Interference in Multi-hop wireless chains: Geometric analysis and performance study

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Abstract. In the presence of interference, two single hop links can interact in a number of different ways, exhibiting significantly different behavior. In this paper, we consider the impact of these two-flow interactions on multi-hop chains. Specifically, we characterize the different types of interactions that arise in chains between hops that do not share a common node. We develop closed formed expressions to estimate the probability of occurrence of these interaction combinations. We use simulation to characterize the performance of the most common types of chains. We make a number of interesting observations: (1) the most destructive types of two-flow interactions do not arise commonly in chains; (2) the throughput of chains does not vary significantly with the types of arising interactions, because of the self-regulating effect of packets in the chain (later hops can only transmit when they receive packets from earlier ones); however, (3) the chains exhibiting destructive interactions suffer frequent collisions and require many more retransmissions. As such, in general scenarios, such chains reduce the available bandwidth within the network.

1 Introduction

Chains are fundamental in multi-hop wireless networks; however, our understanding of their behavior is limited. In multi-hop wireless networks, connections are made across chains of nodes. A chain is a sequence of nodes that a packets travels in order to go from a source node to a destination. The performance of chains is affected both by self-interference (different nodes in the chain transmitting different packets concurrently) [7, 10], as well as interference from other chains. However, due to the complexity of wireless interference our understanding of the behavior of chains remains limited. More accurate characterization of chain behavior, and understanding of what makes an effective or poor chain, is critical for designing routing, QoS and traffic engineering protocols for multi-hop wireless networks.

The CSMA MAC protocol relies on imperfect carrier sense to reduce collisions, which can, even in simple scenarios, lead to a number of different interaction modes some of which exhibit inefficiency and short or long term unfairness. Carrier Sense Multiple Access (CSMA) based MAC protocols like IEEE 802.11 are widely used in multi-hop wireless networks. CSMA MAC protocols suffer from imperfect medium access, giving rise to a class of problems generally called hidden terminal problems [4]; we discuss CSMA MAC protocols in more detail in Section 2. Recent studies have shown that even with a simple scenario of two contending single hop flows, a number of different interaction modes arise [1, 9, 6]. We discuss these *two flow* studies and other related works in Section 3.

Self-interference in chains differs significantly from the two flow interference modes that have been previously studied. The structure of the chain changes the probability of occurrence of the different interaction modes. In addition, the dependent nature of traffic in chains leads to different behavior than that of independent traffic sources.

This paper contributes the following: (1) Classification of the types and frequency of occurrence of chains with respect to self-interaction among the hops; (2) Analysis of the performance of the types that most commonly occur in a 4-hop chain and generalization of this analysis to n-hops. Based on this analysis, we discover the following: (1) Some of the most destructive interaction modes rarely occur because of the structure of the chain (asymmetric interference from an upstream hop to a downstream one); (2) In isolation, there is little difference in throughput obtainable by the different chain types because of the self-dependent nature of the traffic. However, some chains suffer from persistent packet collisions, leading to a large number of retransmissions and therefore, significantly poorer throughput in a general network; (3) Existing routing protocols often pick poor quality chains with respect to self-interference, even in the presence of high quality ones. This places emphasis on mechanisms for detecting destructive self-interference and using that information in routing protocols. We discuss ideas for such mechanisms which form a part of our future work.

2 Background–MAC protocol

In this section, we first briefly review the channel access mechanism and the IEEE 802.11 MAC protocol. We then discuss the modes of interactions that arise among two single hop interfering hops. The goal of this paper is to identify the impact of these interaction modes on a wireless chain.

2.1 IEEE 802.11

The signal power of a wireless transmission attenuates with distance and other environmental factors. A packet is successfully received if the signal strength at the receiver is above the receiver sensitivity threshold. Furthermore, the ratio of the signal to noise and interference power must be above the capture threshold. The *Boolean physical model* is a simplified model of this operation, where a transmission from a node can be sensed by all the nodes that are within a given *Interference Range*(R_i). In the absence of interfering signal, a packet can be received by all the nodes that are within the *Communication Range* (R_c, where $R_c < R_i$). Under this model, packet collisions occur when a node is receiving a packet and an interfering node (within a distance of R_i from the node) transmits a signal.

The MAC layer protocol regulates access to the channel in an attempt to reduce collisions. IEEE 802.11 uses a Carrier Sense Multiple Access approach, augmented with Collision Avoidance (CSMA/CA). Difficulties arise in wireless settings because carrier sense is carried out at the sender, while correct reception requires the medium to be idle at the receiver. Therefore, IEEE 802.11 optionally uses small control packets to arbitrate the medium (Request to Send sent by the sender before a transmission and Clear to Send sent in response by the receiver if the channel is idle near it) to attempt to reduce collisions. However, since these packets can only block interferer in reception range (those outside cannot receive them), they are of limited use in preventing collisions. Finally, in response to a correctly received packet, the receiver sends an acknowledgement. If the acknowledgement packet is not received, the receiver attempts to retransmit.

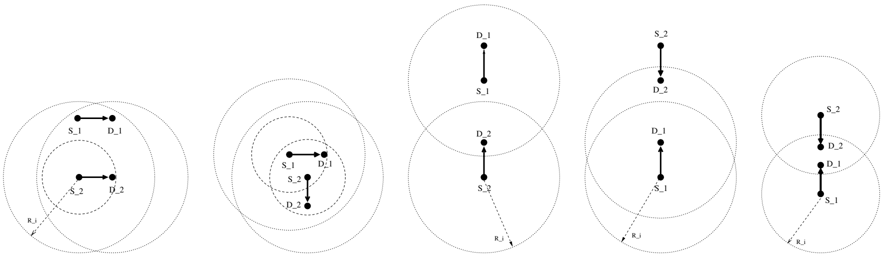
Despite aggressive carrier sense, collisions can still occur between senders that are outside carrier sense range of each other, but that are in interference range of their respective receivers. To regulate the load in the presence of collisions, senders maintains a backoff window (BO) counter. When a collision occurs, the CW is doubled (up to a maximum limit), a backoff algorithm known as Binary Exponential Backoff (BEB).

2.2 Two Flow Interaction Modes

It has been recently shown that a number of different interaction modes arise among two interfering single hop flows [9, 1]. In a two flow scenario, two senders S_1 and S_2 communicate with two receivers D_1 and D_2 respectively. There exist four secondary (or cross-flow) channels that lead to the different modes of interactions; these are S_1S_2 S_1D_2, S_2D_1 and D_1D_2. The connections interfere differently depending on the state of these four secondary links. In this paper we assume Carrier Sense range and Interference range to be the same. Studying interactions with different Carrier Sense and interference ranges is part of our future work. Under a boolean interference model, the interactions can be grouped into five categories as described below [9].

Sender-Connected Symmetric Interference (SCSI): This category includes all scenarios where the two senders are in range and there is symmetric interference between opposite source and destination. An example of this scenarios is shown in Fig 1(a). In this scenario the channel is shared equally among the two flows.

Sender-Connected Asymmetric Interference (SCAI): In SCAI, senders are in communication range and only one destination is in interference range of the other sender. Fig 1(b) shows an example of this scenario. An ACK sent by $D2$ is received by $S1$ as a corrupted packet. $S1$ assumes that it is a DATA



(a) SCSI (b) SCAI (c) AIS (d) IDIS (e) SIS

Fig. 1. Sample scenarios in each category

packet and defers for an Extended Inter Frame Separation (EIFS) period while $S2$ defers for the standard DIFS. Since EIFS is much longer than DIFS, $S2$ wins the channel most of the time. Hence SCAI exhibits severe unfairness problems.

Asymmetric Incomplete State (AIS): In the remaining scenarios the senders are not connected (Incomplete State) and carrier sense cannot prevent collisions. In Asymmetric Incomplete State, as shown in Fig 1(c), only one of the senders interferes with the other destination and only one of the flows experiences collisions, giving rise to unfairness.

Symmetric Incomplete State (SIS): In this category, the senders are not connected and both senders can interfere with the other destination. Fig 1(e) shows an example of this kind of interaction. This causes drops at both destinations and severely affects the throughput of both flows.

Interfering Destinations Incomplete State(IDIS): In this mode only destinations are in range as shown in Fig 1(d). The ACK sent by one destination interferes with packets being received by the other causing packets to be dropped. This scenario affects the throughput of both links.

In this paper we study the existence of different interference groups in a multi hop chain and its effects on chain throughput and goodput. We denote the absence of any interaction between two hops as NI (No Interaction).

3 Related Work

Analysis of throughput in chains has been studied extensively. Authors in [7, 5, 3, 2] compute the theoretical upper bounds on throughput of multi-hop ad hoc network. In [11], the authors evaluate the performance of TCP over a mulithop chain. They demonstrate that TCP traffic in a chain has instability problems that degrade the throughput of the chain.

In [8] the authors 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. 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.

Our observations in this study show that in a four-hop chain, packet drops have very little effect on the throughput of a chain both directly by extra transmissions or indirectly by way of rerouting because of false link breakage information. Extra lost transmissions come at a cost of decreased goodput of a chain hence introducing extra noise in the network. We also extend this analysis to an n-hop chain and conclude that chain interactions do not play vital role in determining the throughput but effect only the goodput of the chain. Cross chain interference is effected more by these interactions since different chains produce similar throughput but very different overall transmission levels.

Most of the studies are focused on finding the macro level behavior of chains in order to estimate the overall throughput of the network. Our study is focused on the micro level interactions in a multi-hop chain between different hops in order to better understand the interference present in a chain topology. In this paper we study the patterns of self interference in a chain. We feel that a better understanding of self interference is critical in understanding cross interference between chains.

4 Chain Self Interference

Links in a chain topology exhibit different modes of interference among hops, leading to significant impact on performance. We use, as the base for classifying the different chains, the two flow interference modes presented in an earlier work [9]. Given the restrictions of chain connectivity, the probability of the different cases changes. Moreover, given the nature of the traffic, it is likely that the impact of these modes will be different as well.

4.1 3-Hop Chains

Figure 2 shows a chain with 3 hops. In this chain, hops H1 and H3 are two link level flows within this chain that interact with each other according to the probabilities shown in Figure 3.

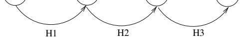


Fig. 2. A Chain with 3 hops

The plot in Figure 3 is obtained by creating different 3-hop chains using a Monte Carlo approach and then analyzing the existing interference interactions amongst the flows. It can be seen from the plot that at typical carrier sense/interference range of more than twice the communication range, only SCSI interactions are possible. But at lower ratios of carrier sense to communication the AIS group is the dominant interaction. AIS interaction has much lower throughputs than SCSI groups in two flow settings [9] but increasing the carrier sense range in a network exacerbates the exposed node problem.

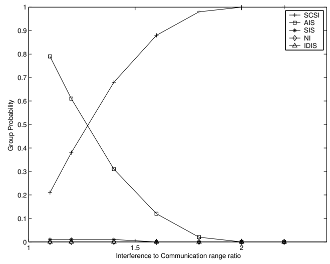


Fig. 3. Interaction Probabilities for a 3-Hop Chain

4.2 4-Hop Chains

A 4-hop chain as shown in Figure 4 presents more interesting problems. In this chain we have three different sets of two flow links that can interfere; note that links that share a node cannot be active at the same time and hence do not interfere with eachother. Node S can potentially transmit to Node I1 at the same time when Node I3 is transmitting an older packet to Node D. This makes hops H1 and H4 one set of simultaneous flows. Similarly H1 and H3, and H2 and H4 make up the other sets of two-flows. Hence in 4-hop chain we can have three different groups of interactions between the three sets of flows.

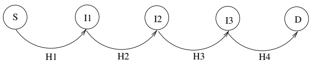


Fig. 4. A Chain with 4 hops

Mathematically there can be 5^3 kinds of interactions in a chain. To determine those interactions that are probable in a 4-hop chain topology we perform an exhaustive enumeration of all possible scenarios. More specifically, we fix the location of the source node S and move node $I1$ around it in a circular disc starting from radius 0 to a radius of Communication Range (250m in this case). Then we move node $I2$ around $I1$ in a circle making sure that $I2$ does not enter the communication range of node S. Similarly node $I3$ is moved around

$I2$ and the destination D is moved to all possible locations around $I3$. For each position of these five nodes, we evaluate the scenario that occurs in this chain. The following interactions occur non-negligible percentage of times in a chain. The interactions are referred to in the format A/B/C where A is the interaction between H1 and H4, B is the interaction between H1 and H3 and C is the interaction between H2 and H4.

1. SCSI/SCSI/SCSI
2. AIS/SCSI/SCSI
3. NI/SCSI/AIS
4. AIS/AIS/SCSI
5. NI/AIS/AIS

Fig 5(a) plots the occurrence probabilities of the scenarios as carrier sense range is increased.

4.3 Geometric Models

We develop geometric models for computing the probability of occurrence of the five chain interactions listed above. Here we present the complete derivation of NI/AIS/AIS group while the rest of the groups are derived in a similar fashion.

NI/AIS/AIS In this set of interactions nodes S and I1 are out of range of Nodes I3 and D. This Scenario has AIS interaction between H1 and H3, which requires that I1 to be out of range of I3 (Source of H1 is out of range of destination of H3). The last interaction AIS between H2 and H4 requires I1 to be out of range of Node D. This is already implied by the NI interaction between H1 and H4. For this chain we find the probability that for a given distance between nodes S and I1, I2 lies in an area that is outside the area of interference of S. Also given the distance between I1 and I2, we find the probability that I3 lies outside the area of interference of I1.

The derivation uses the following terminology: interference range and communication range are represented by r_i and r_c respectively. $C(X)$ refers to the area of communication range of Node X (circle of radius r_c around X) and $T(X)$ refers to the interference range of Node X (circle of radius r_i around X).

The probability that I1 is on a circle of radius x around S where x is always less than r_c is given by

$$p_1 = \int_0^{r_c} \frac{2x}{r_c^2}\, dx \tag{1}$$

Next we find the probability that I2 is out of range of S. Lets say that I2 is on a circle of radius y from I1. The arc length of circle with radius y around I1 that is intersected by circle with radius r_i around S gives us the portion of circle y that is within range of S. Subtracting this arclength from the perimeter of circle y will give us the portion that is out of range of S.

The minimum value of y has to be $r_i - x$ to guarantee that some portion of the circle is out of range of S. The maximum value of y is r_c.

$$p_2 = \int_{(r_i - x)}^{r_c} (2 * pi * y) - 2ycos^{-1}(\frac{y^2 + x^2 - r_i^2}{2xy})\ dy \tag{2}$$

Now we calculate the probability that I3 is out of range of I1. I3 has to be within the communication range of I2. We find $AreaR_iR_cy$ the area of intersection of circle r_i around I1 and r_c around I2 given the distance y between I1 and I2,. This is the portion of Communication range around I2 that is within range of I1. Subtracting this common area from $C(I2)$ gives the area that is out of range of I1. Let $AreaR_cR_cy$ be the area of intersection of circle of radius r_c around I1 and I2. Subtracting this area from $C(I2)$ will give us the area which is within communication range of I2 but outside the communication range of I1. Note that since I3 is the next hop for I2, it can only be in $C(I2)$ - $AreaR_cR_cy$. Hence probability of I3 being out of range of I1 is given

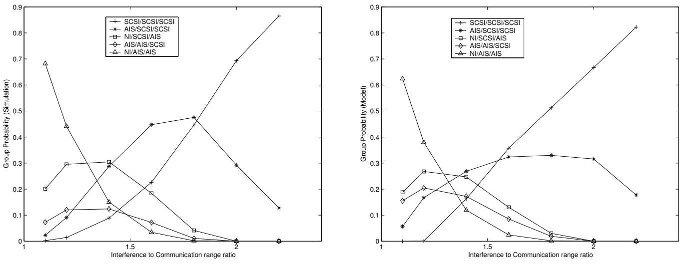
$$p_3 = \frac{C(I2) - AreaR_iR_cy}{C(I2) - AreaR_cR_cy} \tag{3}$$

The overall probability of NI/AIS/AIS is calculated by multiplying Eq[1,2,3]

$$p = \int_0^{r_c} \int_{(r_i - x)}^{r_c} p_3 \frac{2x}{r_c^2}((2 * pi * y) - 2ycos^{-1}(\frac{y^2 + x^2 - r_i^2}{2xy}))\ dy\ dx \tag{4}$$

4.4 Model Validation

We validate the geometric models for each interaction by comparing against exhaustive enumeration of all interactions in a chain.



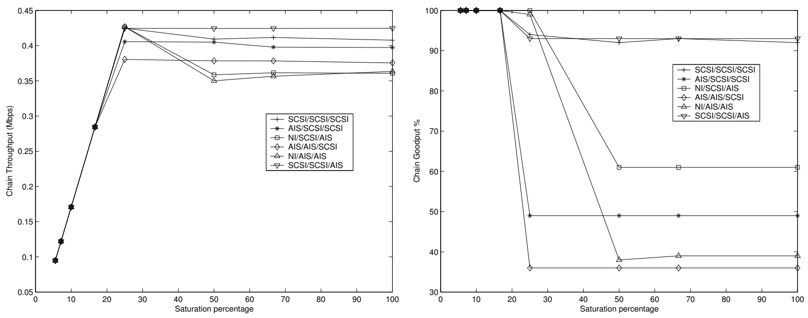
(a) Simulated (b) Predicted

Fig. 5. 4-Hop Interaction Percentages

Figures 5(a), and 5(b) show the probability of each interaction obtained using enumeration, and geometric model prediction. The plots indicate that the models closely match the results of simulation as the ratio of interference range and communication range is increased. As the ratio increases, the interactions move towards having all interacting hops Sender Connected. At lower ratios we have an increased percentage of interactions with hidden terminals.

5 Simulation Study of Throughput

In this section we analyze the throughput of a 4-Hop chain under different interactions using NS2 Network Simulator. 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 2Mbps and packet size of 1000 bytes. We change the saturation level of the channel by altering the rates at which the source pumps Constant Bit Rate (CBR) packets into the chain. We perform this analysis using the standard two-ray ground wireless propagation model which results in fixed communication and interference/carrier sense ranges.



(a) Throughput

(b) Goodput

Fig. 6. Throughput and Goodput of a 4-hop Chain vs Channel Saturation

Fig 6(a) shows the throughput achieved at different saturation rates for the different chains. The throughput of a chain increases as we increase the saturation rate until it reaches an asymptotic limit. The limit represents the highest throughput possible in a chain topology as has been determined to be 1/4 of total bandwidth [7, 11, 8]. Figure 6(b) shows the percentage goodput of each chain. Goodput in our case is calculated as percentage of packets that are successfully transmitted. We analyze these plots of each chain separately.

5.1 SCSI/SCSI/SCSI

In this chain, all the hops are Sender Connected. As the source node competes for the channel with three other nodes (I1, I2 and I3), it is able to transmit at one fourth of the total bandwidth. The only drops in this interaction are due to two sources transmitting within very short duration of each other. Since the probability of these collisions is very little we see a goodput of more than 90%.

5.2 AIS/SCSI/SCSI

The chain effect dominates the throughput performance of this chain. In the AIS interaction between the first and the last hop, the first hop is the weak link and last hop is the strong link. Packets transmitted together on H1 and H4 cause the packet on Hop 1 to be dropped. Hence the lack of sender connectedness in the first group just increases the noise produced by wasted transmissions by Node S. This is depicted in the goodput curve of AIS/SCSI/SCSI in Figure 6(b). This chain transmits lots of packets on hop1 that are dropped.

5.3 NI/SCSI/AIS

In this chain, several packets are dropped at the AIS connection. The throughput is not affected severely because of the presence of SCSI in the middle that limits the transmission of packets from Source and $I2$ and hence limits the concurrently active packets in the chain. The goodput of this chain is affected by the lack of coordination between the hops.

5.4 AIS/AIS/SCSI

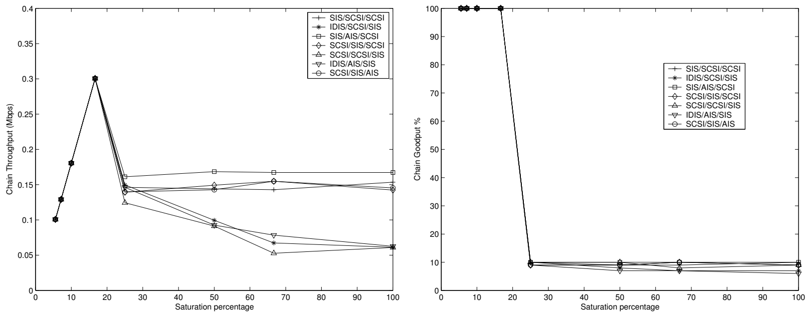
In this chain, the packets are sent in bursts because of the two AIS connections. The connection starts sending packets. When the packet reaches node I3, transmissions from I3 to node D cause packets to be dropped on Hop 1. For every packet sent successfully on Hop1, the next packet will be dropped, increasing the backoff at Node S. Hence the goodput for this chain is always less than 50%.

5.5 NI/AIS/AIS

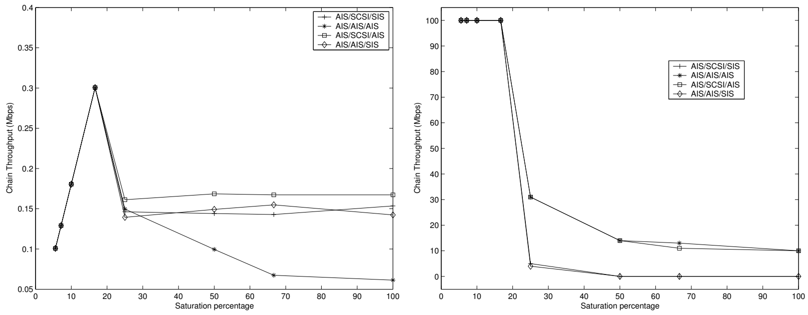
This interaction is also dominated by the AIS group in terms of goodput. Since senders of all interactions are out of range, they will transmit together. This causes many wasted transmissions without any gain in throughput.

5.6 SIS cases

In this section we consider those chains that have SIS interaction between any two hops. The probability of these interactions is really small using the default NS-2 parameters. Figure 7(a) shows the throughput of seven possible categories with SIS interactions. This type of interaction is really destructive as packets are dropped from both links and the throughput is drastically reduced. As can be seen in Figure 7(b), although the chain transmits many packet, few of these are successful.



(a) Throughput with SIS (b) Goodput with SIS



(c) Throughput with Reverse AIS (d) Goodput with Reverse AIS

Fig. 7. Throughput and Goodput of Chains with SIS and Reverse AIS interactions

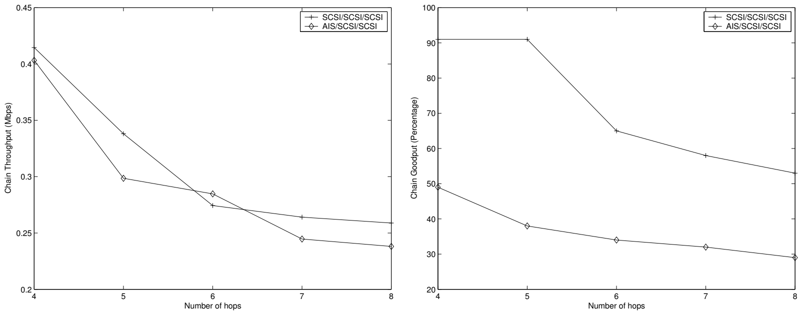
5.7 Reverse AIS cases

Another interaction that is possible in a chain (although the probability is low because of the geometry restrictions) is an AIS interaction between the first and the last hop where the first hop is the strong link and last hop is the weak link. The first hop transmits packets causing collisions at the last hop, which cannot empty packets as fast as it receives them (leading to queue drops). Figures 7(c) and 7(d) show the throughput and goodput of chains with Reverse AIS interaction.

6 Towards Generalization to n-hop Chains

In this section we make some observations about generalizing the results from 4-hops to general chains via an inductive argument. In the future, we will attempt a more systemic generalization. First we add one more hop to our chain. The fifth hop can have two possibilities - it either interferes with the first hop or it does not. In the first case, the fifth hop interferes with the first, second, and third hops in either AIS or SCSI interactions because of symmetry. Our simulation results indicate that the throughput of all these scenarios is within 2.5% of each other.

In the second case where the fifth hop does not interact with the first hop, the situation is similar to evaluating a four hop chain where the second node of the chain is acting as the source of the 4-hop chain. As we have seen in section 5 the throughput of a chain does not depend on the type of interaction, hence the type of interaction between the 4 hops starting from the second node of the 5-hop chain would not effect the chain throughput. Hop count is the only dominating cause that effects the throughput of the chain. The goodput of the chain on the other hand is directly effected by the interactions amongst the hops. Chains with a higher number of AIS interactions will have higher drops hence lower goodput, while SCSI dominated chains will produce a higher goodput. Figure 8 shows the throughput and goodput of 8-hop chains. In the SCSI/SCSI/SCSI chain, each group of 4-hops as obtained by shifting down the chain by one hop has SCSI/SCSI/SCSI interaction while in AIS/SCSI/SCSI has the same interaction for all sets of four-hops within the 8-hop chain.



(a) Throughput

(b) Goodput

Fig. 8. Throughput and Goodput of 8-Hop Chains

7 Discussion

We have seen in this section that for all different interactions in a chain, the throughput of the chain with AIS and SCSI interactions depends only on the number of hops. Chains with SIS and Reverse AIS have very little throughput. The goodput of the chain is more influenced by the type of interaction. For chains with higher goodput, the channel utilization is more efficient which translates into less cross chain interference. Low goodput chains waste a lot of bandwidth for transmissions that in the end are dropped and hence wasted. Throughput of a chain should not be the only criteria for determining its performance. As we have seen from Figures 6(a) and 6(b) that chains that have similar throughput might have substantial difference in goodput. In routing decisions it is important to pick routes that minimize not only the interference within the chain but also across different chains in order to better utilize available channel bandwidth. Designing routing protocols that take consider chain interaction and pick high goodput routes is an area of our future research.

In chain interactions that occur more often, the type of interaction does not substantially affect the throughput of the chain although it does effect the amount of traffic generated. This observation leads us to believe that evaluating cross-chain interference and its effects on throughput are more important than self-interference in a chain.

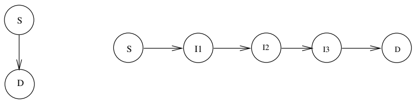
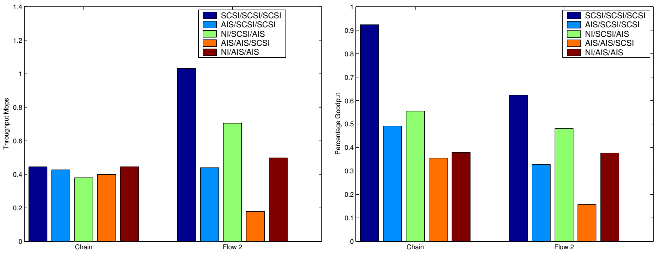


Fig. 9. A chain and an external flow

We consider the effect of noise from a chain on the throughput of other flows. Fig 9 shows a chain in close proximity to another flow. We determine the effect of this chain on the flow when the chain has different self interference patterns while the source of the chain has an AIS relationship with the second flow. In this AIS interaction, the second flow is the weaker link. Fig 10(a) and 10(b) show the effect of the chain on the throughput and goodput of an external flow. These are some preliminary results, a detailed study of cross-chain interference is a topic of our future research.



(a) Throughput (b) Goodput

Fig. 10. Effect of a chain on throughput and goodput of an external flow

8 Conclusion

This paper makes several contributions to the analysis of interference interactions multi-hop wireless chains. Specifically, we classify and study of all possible interactions within a chain and their effects on chain throughput and interference generated to other chains. We identify that some chains that produce high throughput in isolation, also experiences substantial drops hence wasting the available channel bandwidth with retransmissions and causing cross chain interference. The characterization of chains is important for routing protocols to be able to more intelligently select routes.

Our immediate goal is to extend this study to include a more realistic model where capture effects are taken into consideration. We would like to take the analysis performed in this paper to develop interference aware routing protocols that can look at a route and determine the types of interaction within the routes. Based on this study the protocol then decides on picking the best mix for throughput and goodput from all routes that are available.

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