Impact of Interference on Throughput in Dense WLANs with Multiple APs

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Abstract—The popularity of wireless local area networks (WLANs) has resulted in their dense deployments around the world. While this increases capacity and coverage, the problem of increased interference can severely degrade the performance of WLANs. However, the impact of interference on throughput in dense WLANs with multiple access points (APs) has had very limited prior research. This is believed to be due to 1) the inaccurate assumption that throughput is always a monotonically decreasing function of interference and 2) the prohibitively high complexity of an accurate analytical model. In this work, firstly we provide a useful classification of commonly found interference scenarios. Secondly, we investigate the impact of interference on throughput for each class based on an approach that determines the possibility of parallel transmissions. Extensive packet-level simulations using OPNET have been performed to support the observations made. Interestingly, results have shown that in some topologies, increased interference can lead to higher throughput and vice versa.

I. INTRODUCTION

WLANs were once thought to be just a replacement for wires in a LAN. Today, it has changed the way many of us communicate, work, play and live. One can find it deployed everywhere including homes, cafes, shopping malls, offices, airports and even in entire cities. The almost ubiquitous WLANs APs are estimated to number in the millions and is expected to grow strongly in the foreseeable future.

One of the reasons for the huge success of WLANs lies in its license-exempt operation. Unburdened by recurrent payments to operators, users can simply purchase WLANs equipment and deploy them. The benefit of deployment in license-free frequency bands is not without its challenges. Managing interference from other users of WLANs and other communication technologies such as Bluetooth is one of its main challenges. Thankfully, the IEEE 802.11¹ (which is the de-facto WLAN standard) has specified a very effective medium access control (MAC) protocol that is based on carrier sense multiple access with collision avoidance (CSMA/CA)² (also known as the distributed coordination function (DCF)). Using this protocol, a node will only transmit if it senses the channel to be idle. If there is transmission or interference, the nodes will wait until the channel becomes clear before transmitting. This protocol makes WLANs particularly robust towards interference.

Due to its popularity, dense deployments of WLANs have started to appear in many parts of the world in recent times. While this can potentially increase capacity and coverage, the corresponding increase in interference can severely degrade the performance of WLANs. Even an excellent MAC protocol such as the DCF is unable to cope with the sharp increase in interference caused by these dense deployments. Realizing this, several techniques such as channel assignment [3-4], load balancing [5] and power control [6] have been proposed in the literature. However, most of these works have the objective of minimizing interference, which in turn infers a maximization of throughput. As shall be seen, the assumption that throughput is a monotonically decreasing function of interference may not be always true. Furthermore, even for techniques that do not employ the interference metric directly, significant insights can be gained from a better understanding of the impact of interference on throughputs.

On the other hand, performance analysis of the IEEE 802.11 DCF has also garnered considerable interests. In [7], Bianchi proposed a novel analytic model based on a two dimensional Markov chain that gives very accurate predictions. However, the paper assumes that all nodes can hear each other. Subsequently, authors in [8] extended the above model to account for hidden nodes. Hidden nodes are nodes that are in the reception range of the receiving node but outside the transmission range of the sending node. Similarly, a symmetric network is assumed (i.e. every node sees the same number of hidden and contending nodes). Clearly, these assumptions severely limit these models' use in dense WLANs deployments with multiple APs. Even if an accurate analytical model can be developed, it is most likely to be prohibitively complex. Coupled with more limiting assumptions, an analytical approach may not be the best way for extracting useful insights.

Therefore, in this work we start by providing useful classification of commonly found interference scenarios in Section II. This is especially helpful in an area of study where the variation of interference scenarios is particularly intractable. This is followed by an investigation into the impact of interference on each class of interference scenarios based on an approach that determines the possibility of parallel transmissions in Section III. In Section IV, extensive packet-level simulations using OPNET are presented to support the observations made. Finally, concluding remarks and future work are given in Section V. Far from being an exhaustive study, this work endeavours to provide practical insights on the impact of interference.
II. CLASSIFICATION OF INTERFERENCE SCENARIOS

In this section, a useful classification of commonly found interference scenarios is presented. The classes are by no means exhaustive but they are sufficient in that they 1) are simple to identify even in a dense network and 2) lend themselves to natural and systematic groupings when investigating the impact of interference on throughput. It is worth mentioning here that only interference from within the transmission range is considered in this paper. This is because interference from the carrier sensing range cannot be known deterministically (i.e. signal strengths are too low for the correct decoding of packets). A basic service set (BSS) (i.e. the collection of an AP and its clients), is said to be interfered by another BSS if its AP or clients can decode transmissions from the AP or clients of the interfering BSS.

The interference scenarios are classified by the distance, $D$ between the APs. As shown in Fig.1, Class-I, Class-II and Class-III interference scenarios correspond to $D \leq R$, $R < D \leq 2R$ and $2R < D \leq 3R$ respectively, where $R$ is the transmission range. For $D > 3R$, there is no interference between both BSSs. Before delving further into the characteristics of each interference class, we introduce a few helpful notations.

Using Fig.1 as a reference, the region of interest will be divided into 3 regions, namely region A, region B and the overlapping region O. AP1 and its clients are located in region A or region O while AP2 and its clients are located in region B or region O. Transmissions from APx to clients in region $y$ will be denoted by $APx \rightarrow Client_y$ and transmissions from clients in region $y$ to APx will be denoted by $Client_y \rightarrow APx$ (e.g. transmissions from AP1 to clients in region A will be denoted by $AP1 \rightarrow Client_A$). Furthermore, even in the same interference class, different topologies can be formed depending on the location of the clients. A convenient way to refer to different topologies will be to specify the number of clients from each BSS that is in the overlapping region O, in the form Class$_i$ nco1_nco2 where $i$ is the interference class, nco1 $\in \{0, 1, ..., nc1\}$ and nco2 $\in \{0, 1, ..., nc2\}$ are the number of clients in region O that are associated with AP1 and AP2 respectively (e.g. the topology in Fig.1(a) will be denoted as Class$_{I_1_1_1_1}$). In this paper, we have used the case where $nc1 = nc2 = 3$ clients, where $nc1$ and $nc2$ are the total number of clients of AP1 and AP2 respectively.

In Class-I, an AP can receive direct transmissions from the interfering AP and some or all of its clients. The problem faced by Class-I interference scenario is that its own clients, the interfering AP and its clients can become potential hidden nodes to the ongoing transmission. For example, as shown in Fig.1(a), when there are $Client_A \rightarrow AP1$ transmissions, $AP2$ and some clients in region O become hidden nodes. On the other hand, for $AP1 \rightarrow Client_O$ transmissions, some clients of AP2 in region B become hidden nodes. For $Client_O \rightarrow AP1$ transmissions, some of its own clients in region A become hidden nodes.

For Class-II, the APs are not within transmission range of each other and therefore cannot receive each other’s transmitted packets. However, the APs can hear from the clients of the interfering AP. The possibility of its own clients, the interfering AP and its clients becoming hidden nodes are also present here. Referring to Fig.1(b), for $Client_A \rightarrow AP1$ transmissions, clients in region O become hidden nodes. In $AP1 \rightarrow Client_O$ transmissions, $AP2$ and some clients in region B become hidden nodes. For $Client_O \rightarrow AP1$ transmissions, its own clients in region A become hidden nodes.

Finally in Class-III, the AP cannot hear transmission from the interfering AP or its clients. Only its clients can hear the interfering clients. This means that only the interfering clients can become potential hidden nodes. In Fig.1(c), it can be seen that AP2’s clients in region O are hidden nodes for $AP1 \rightarrow Client_O$ transmissions.

III. IMPACT OF INTERFERENCE ON THROUGHPUT

In the previous section, common interference scenarios have been classified and the characteristics of each interference class have been presented. Although the approach used was to highlight transmissions with potential hidden nodes, the throughput of various interference scenarios in dense WLANs with multiple APs cannot be obtained from just extending the results from the analysis of classical hidden node problem (i.e. a topology consisting of a source node, a destination node and a hidden node as shown in Fig.2). This is due to 1) the potential hidden nodes in multiple AP scenarios behave differently from classical hidden nodes and 2) the AP is either the source or the destination in all transmissions. For example, in the former, as is shown in Fig.1(b), AP2’s clients in region O are hidden...
nodes for Client_A \rightarrow AP1 transmissions but they have a high probability of being prevented from transmitting due to parallel AP2 \rightarrow Client_B transmissions.

Therefore in this section, we adopt an approach that focuses on the possibility of parallel transmissions to predict the impact of interference on throughput in a qualitative manner. Parallel transmissions can result in the doubling of throughputs and this is expected to be the most important factor in determining the impact of interference on throughputs in multiple APs scenario. Consequently, the following condition for parallel transmissions is given.

**Condition 1**: Parallel transmissions can take place if there exist at least two unique pairs of source and destination that is not within transmission range of each other.

By its definition, both APs in Class-I are within each other’s transmission range. Using the fact that the AP must be either the source or destination in all transmissions, it can be deduced that condition 1 is always not satisfied. This proves that parallel transmission is not possible in Class-I for all topologies. This means that at most, only a single transmission can take place successfully at any time. On the other hand, based on the characteristics of Class-I, hidden nodes are reduced when the number of clients in region A and region B are reduced. Therefore, we expect the throughput to increase from Class-I_0_0 to Class-I_3_3 topology as the total number of clients in region O increases. In fact, hidden nodes are eliminated completely in the case where all clients are in region O. The corresponding topology (Class-I_3_3 as shown in Fig.3(a)) gives the maximum throughput for Class-I interference scenarios.

In Class-II, note that clients in region O cannot be part of the two unique pairs of source and destination in condition 1 because they are in the transmission range of both APs. Therefore, the unique pairs of source and destination must be found from \(P(AP1, Client_A)\) and \(P(AP2, Client_B)\) where \(P(m,n)\) refers to \(m\) and \(n\) source and destination pair. This leads us to deduce that condition 1 is satisfied if there is at least one pair of \(P(AP1, Client_A)\) and at least one pair of \(P(AP2, Client_B)\). This is equivalent to saying that parallel transmissions are possible if not all of AP1’s clients or AP2’s clients are in region O or mathematically \((nc1 \neq nc1) \lor (nc2 \neq nc2)\). For Class-II topologies, hidden nodes are reduced if there are less clients in region O. Therefore, within each subset of topologies that have possible parallel transmissions and those that do not, the throughput is expected to decrease from Class-II_0_0 to Class-II_2_2 topology and from Class-II_3_0 to Class-II_3_3 topology as the total number of clients in region O increases. Consequently, when there are no clients in region O, there are no hidden nodes. This corresponds to Class-II_0_0 topology shown in Fig.3(b) that gives the maximum throughput for Class-II interference scenarios. The discussion above runs counter to the widely held assumption that throughput is always a monotonically decreasing function of interference. For example, Class-II_2_2 experiences higher interference than Class-II_3_0 topology but it is predicted that the former’s throughput will be higher than the latter’s.

Finally, for Class-III, recall that only the clients in region O can interfere with each other. This means that clients in region O from both APs cannot be part of the two unique pairs of source and destination at the same time. However, even if all clients from one AP is in region O, condition 1 can still be satisfied from \(P(AP1, Client_O)\) and \(P(AP2, Client_B)\) or \(P(AP1, Client_A)\) and \(P(AP2, Client_O)\) pairs. Obviously, \(P(AP1, Client_A)\) and \(P(AP2, Client_B)\) pairs can also satisfy condition 1. From this, we can deduce that the only Class-III topology where parallel transmission is not possible is the Class-III_3_3 topology. As mentioned before, clients in region O are hidden nodes. Therefore, throughputs are expected to decrease from Class-III_0_0 to Class-III_3_3 topology as the number of clients in region O increases. Class-III_0_0 topology as shown in Fig.3(c) gives the maximum throughput for Class-III interference scenarios.

![Figure 2. Classical hidden node topology consisting of a source node, a destination node and a hidden node.](image)

![Figure 3. Topologies corresponding to maximum throughput for each interference class with nco1 = nco2 = 3.](image)
IV. SIMULATION RESULTS

Extensive packet-level simulations using OPNET have been performed to validate the observations made in the previous section. In the simulations, we have used the IEEE 802.11b standard specifications and additional parameters as shown in Table I. IEEE 802.11b uses direct sequence spread spectrum (DSSS) physical layer (PHY) [1] and is the most commonly deployed WLANs. All nodes are in the saturated condition (i.e. they always have packets to transmit). Each topology has been simulated for 30 seconds for which more than 10000 packets have been successfully received. All throughputs shown are normalized to the data rate, i.e. Normalized Throughput = Packet Payload/ (Time x Data Rate). Unless mentioned otherwise, we have used the basic access mode of the DCF MAC, which consists of a two-way handshake (i.e. DATA-ACK). This is because the RTS/CTS (Request to send/Clear to send) mode which consists of a four-way handshake (i.e. RTS-CTS-DATA-ACK) has been shown to be inferior when used in high speed WLANs where the data rate is significantly higher than the control rate, even in the presence of hidden nodes [9].

In Fig. 4, the throughput of Class-I topologies with various nco, the total number of clients in region O (nco = nco1 + nco2) is shown for both basic access and RTS/CTS modes. As an example, nco = 1 corresponds to the Class_I_1_0 topology (note that Class_I_0_1 is not considered because it is symmetrical to Class_I_1_0 topology). For nco = 2, 3 and 4, we have shown the average total throughput for (Class_I_2_0 and Class_I_1_1), (Class_I_3_0 and Class_I_2_1), and (Class_I_3_1 and Class_I_2_2) topologies respectively. From the figure, it is clear that the basic access mode gives superior throughput when compared with the RTS/CTS for all possible topologies, which is consistent with existing research. Furthermore, for Class-I, recall that parallel transmission is not possible and the throughput is expected to increase for topologies with higher nco. Although quite marginal, it can be observed from the figure that higher throughputs are obtained for topologies with higher nco for both modes.

Fig. 5 shows the throughput of Class-II topologies with various nco. In order to highlight the trend in the throughputs, two groups of topologies have been formed, those that have possible parallel transmissions and those that do not. Recall that for Class-II, topologies that do not have all its clients in region O have possible parallel transmissions while others only have single transmissions. As an example, for the single transmissions topologies, nco = 3, 4, 5 and 6 corresponds to Class_II_3_0, Class_II_3_1, Class_II_3_2 and Class_II_3_3 topologies respectively. From the figure, it can be clearly seen that topologies that have possible parallel transmissions have much higher throughputs than those with only single transmissions. The throughputs of the former can be as high as twice the latter's. When a comparison is made within each group of topologies, the throughputs decrease for topologies with higher nco, as expected. The results also show that the throughput for Class_II_2_2 (parallel transmissions group, with nco = 4) is evidently higher than Class_II_3_0 topology (single transmissions group with nco = 3), which validates our assertion that the assumption that throughput is a monotonically decreasing function of interference may not be always true. Furthermore, it is also interesting to note that the throughput decrements in the parallel transmissions group are
been investigated for each class of interference scenarios. Based on an approach that determines the possibility of parallel transmissions, observations are made that allow one to predict the relative throughputs for a large variation of topologies possible within each class of interference scenarios. The observations made are supported by extensive packet-level simulations using OPNET. It is shown that topologies with possible parallel transmissions exhibits significantly higher throughputs than those that only have single transmissions. Also interestingly, results have shown that in some topologies, increased interference can lead to higher throughput and vice versa.

The insights gained from this work not only lead to a better understanding of the impact of interference on throughput in dense WLANs with multiple APs but also can be used to design improved channel assignment, load balancing and power control techniques. Future work includes developing a simple analytical model that has acceptable accuracy for predicting the throughputs based on the possibility of parallel transmissions, the factor that has the largest impact.

much higher than the single transmissions group as $nco$ increases. This can be explained by the number of unique pairs of source and destination for parallel transmissions. As $nco$ increases, the number of unique pairs of source and destination for parallel transmissions decreases, which in turn decreases the probability of parallel transmissions. On the contrary, additional clients in region O does not have such serious effect on the single transmissions group.

In Fig. 6, the throughput of Class-III topologies with various $nco$ is shown. A similar observation can be made that throughputs are significantly higher for topologies that have parallel transmissions when compared to those with only single transmissions. For Class-III, recall that only Class_III_3_3 topology does not have possible parallel transmissions, which explains the single bar in the single transmissions group. Furthermore, as is similar to Class-II, it can be noted that the throughputs decrease for topologies with higher $nco$, which is as predicted in Section III. However, the throughput decrements as $nco$ increases is evidently smaller when compared to Class-II. Again, this can be explained by considering the number of unique pairs of source and destination for parallel transmissions. Consider the case when a client is moved from region A/B to region O. In Class-II, it ceases to be a candidate for the unique pairs of source and destination because it is in the transmission range of both APs. On the other hand, in Class-III, it can still be a candidate for unique pairs as long as the other pair does not consist of another client in region O. Therefore, Class-III topologies suffer less throughput degradation when compared to Class-II topologies when $nco$ increases.

V. CONCLUSIONS

In this paper, a useful and practical classification of interference scenarios has been presented. The classes are easily identifiable and they have similar interference characteristics. The impact of interference on throughput has been investigated for each class of interference scenarios. Based on an approach that determines the possibility of parallel transmissions, observations are made that allow one to predict the relative throughputs for a large variation of topologies possible within each class of interference scenarios. The observations made are supported by extensive packet-level simulations using OPNET. It is shown that topologies with possible parallel transmissions exhibits significantly higher throughputs than those that only have single transmissions. Also interestingly, results have shown that in some topologies, increased interference can lead to higher throughput and vice versa.

The insights gained from this work not only lead to a better understanding of the impact of interference on throughput in dense WLANs with multiple APs but also can be used to design improved channel assignment, load balancing and power control techniques. Future work includes developing a simple analytical model that has acceptable accuracy for predicting the throughputs based on the possibility of parallel transmissions, the factor that has the largest impact.

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