S3: Slotted Sectored Scheduling in WLANs

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ABSTRACT

In this paper, we introduce a system for using steerable directional antennas to improve the capacity of Wireless LANs. In a WLAN with multiple access points (APs), a steerable antenna can be employed at each access point to restrict the power dissipated by the access point in a narrow area to just reach the intended client. Such an approach provides two main advantages: a) higher delivery ratio because of improvement in link quality, and b) higher spatial reuse because of increased simultaneous transmissions between APs and clients. However, using directional antennas in a dense WLAN environment is challenging because of hidden node *and* deafness *problems. In this paper, we present a novel slotted sectored scheduling framework (S3) that addresses the above challenges by coordinating packet transmissions in the network. Our approach does not require any client modifications and MAC modifications on the APs. Preliminary results show that in a network of two APs and five clients, the network throughput is almost doubled using directional antennas.*

1. INTRODUCTION

This paper considers the use of steerable directional antennas for spatial reuse in *managed* wireless LAN deployments— the word *managed* refers to deployments in which all access points (APs) are under the same administrative domain. Such managed deployments are common today at multiple scales, from small-range corporate networks [14] and campus-wide networks [2], to hot-spot networks such as T-mobile [5], and city-wide muni-wifi networks such as Google's Wifi [3], MIT's roofnet [8], and Houston's urban network [9].

To provide maximal coverage, these wireless networks often contain multiple APs with overlapping transmission and interference ranges. Greater overlap leads to increased contention to transmit and increased packet collisions, thereby reducing the overall network throughput. As WLANs become ubiquitous and users adopt the wireless medium as their first-class last-mile access network, network administrators are forced to increase the capacity of their wireless networks. Unfortunately, the capacity of an 802.11 network is limited due to the interference among network nodes and the availability of limited number of channels. Consequently, several research efforts are being focused on mitigating interference as much as possible to get maximum throughput out of these networks. Two major directions for capacity improvement have been toward exploiting channel diversity through efficient channel allocation [7] and spatial reuse through power control [6].

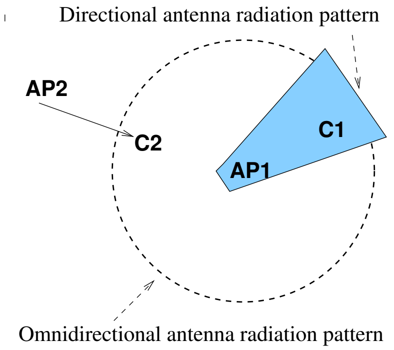
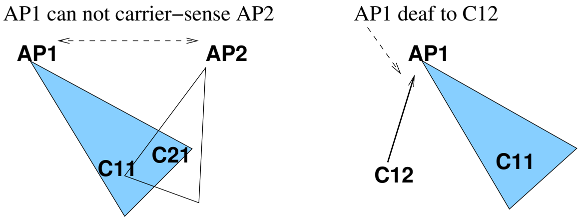


Figure 1: Qualitative Benefit of a directional antenna over omni.



(a) Hidden terminal problem (b) Deafness problem

Figure 2: Challenges with steerable directional antennas in WLANs.

In this work, we explore a new dimension—of using steerable directional antennas —to restrict the transmit power dissipated from an access point in a narrow area by forming directional beams to just reach the intended client, thereby reducing interference to other transmissions and increasing spatial reuse. To illustrate this idea, consider two APs and two corresponding clients as in Figure 1. While AP2's transmission to C2 gets interfered when AP1 transmits using an omnidirectional antenna to C1, the interference is avoided when AP1 uses a directional antenna. The advent of steerable directional antennas [1, 4] makes it possible for each AP to form such directional beams for each of its clients to restrict interference.

Exploiting the benefits of a steerable directional antenna, however, engenders two challenges—hidden node and deafness problems. Figure 2 illustrates the two problems.

- *Hidden terminal:* Figure 2(a) shows that two APs using directional beams may not carrier-sense each other, thereby causing interference at the clients when transmitting simultaneously.
- *Deafness:* Figure 2(b) shows that an AP using directional beam to transmit to client C11 may

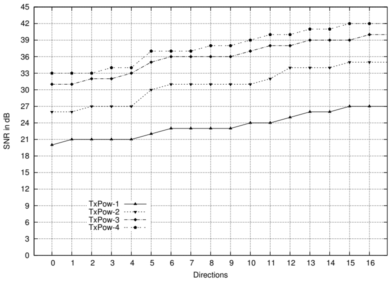


Figure 3: Impact of beamsteering and transmit power control in Indoors.

not be able to hear another client C12's simultaneous transmission. This can lead to increased number of retransmissions and, in the extreme case, disassociation from an unmodified client.

The above challenges are partially addressed in adhoc networks [11], where changes are proposed to the 802.11's virtual carrier sensing mechanism. Such MAC level modifications make the solution harder to deploy both because of the need to modify the MAC implementations and because of client modifications.

Under the constraint of not modifying the clients or the MAC level functionality, we present a novel *slotted sectored* scheduling framework for using steerable directional antenna in a WLAN; the framework is compatible with existing 802.11 implementations, can be overlayed on top of the MAC layer on the APs, and requires no modifications to clients. Preliminary results show that in a network of two APs and five clients, the network throughput is almost doubled using directional antennas.

The rest of the paper is organized as follows. Section 2 provides background on steerable antennas and the feasibility of using them in WLANs. Section 3 describes our approach to best utilize steerable antennas while addressing the involved challenges. Section 4 presents initial performance results. Section 5 discusses related work, and Section 6 concludes.

2. BACKGROUND

Our work is motivated by the recent availability of steerable beam antenna systems [1, 4]. In this paper, we employ Fidelity Comtech's [1] phocus array antenna system that uses eight antenna array elements to form various directional beams by controlling the phase and amplitude of RF signal input to each element. This system is capable of *steering* the beam at a fine granularity of 1°, and incur a switching delay of about 150μs from beam to beam. The system also forms an omnidirectional beam to transmit signals equally in all directions if needed. The gain with directionality is almost 4 times that of omnidirectional.

Understanding Directionality: Figure 3 shows the signal strength received by a client when an AP equipped with a directional antenna system transmits with different beams. The different beams are sorted and numbered in the increasing order of signal strngth. We consider 16 different pre-configured beams that together cover all directions. We also vary the amplitude (in terms of transmit power) given as input to the array elements. The graphs demonstrates the directionality achieved by the antenna—the client receives lower than half the power in more than 60% of the directions when compared to the direction with maximum SNR. Also, the SNR received reduces significantly with decreasing amplitude. This graph leads us to conclude that by controlling the direction and the amplitude to a level sufficient enough to reach each intended client, the interference caused to clients and APs in other directions can be reduced significantly.

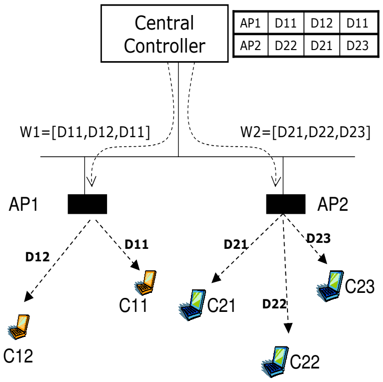


Figure 4: (a) Example scenario depicting $S3$ framework.

Switching Overhead: One hardware limitation of these antennas for consideration is the delay incurred in switching from one beam to another. For example, the above system incurs a switching delay of 150μs. With such a system, in 802.11g mode at a fixed rate of 24Mbps, per-packet beam switching reduces the throughput from 16Mbps to 11Mbps. However, the cost of switching can be amortized over multiple packet transmissions.

3. SLOTTED SECTORED SCHEDULING

In S3, the APs follow a synchronized slotted timeline. One way to achieve synchronization is to use a GPS receiver at each AP, and synchronize the realtime clocks on APs using GPS signals. Our implementation of the GPS-based technique synchronizes APs to within 200μs.

With the APs synchronized, we assume that each AP uses a specific "sectored" beam pattern to communicate with each of its clients. For each slot duration, the beam pattern to be used by each AP is defined. The basic idea of maximizing spatial reuse is to choose beam patterns at all APs in each slot such that the number of simultaneous transmissions is maximized, while adhering to some fairness objective to ensure that no client starves.

More specifically, a window of slots W defined by $[D_1, D_2, \ldots, D_k]$ specifies the beam pattern D_i used in the ith slot of a window. Each AP$_j$ repeats through W_j starting at a specified real-time to ensure that APs are synchronized within each slot. S3 constructs W_j

for each AP$_j$ to meet two requirements: a) all client traffic for AP$_j$ is served and b) no two beam patterns conflict at the clients. W is computed at the centralized controller and communicated to the corresponding AP. Note that commonly deployed WLANs that follow the thin AP architecture have the provision of a centralized controller managing the APs. The computation of W_j takes into consideration the conflict graph among the directional links and the traffic requirements. W_j is recomputed if there is a change in client association, variation in conflict graph, or change in traffic. This approach of scheduling based on conflicts allows S3 to get rid of the hidden terminal problem.

The conflict graph determination problem is orthogonal to our work and can be solved in various ways. For instance, the conflict graph can be determined apriori using extensive measurements during WLAN installation based on interference characteristics at actual positions in the physical space, or can also be reactively learnt through feedback from the clients and APs while the system is in operation. We do not address this problem in this paper.

In order to ensure that the APs are not deaf to the uplink traffic from clients, APs make use of CTS transmissions to prevent clients from transmitting when APs are directed elsewhere. This framework enables the clients to transmit to the APs frequently enough (small slot size) to ensure that clients do not disassociate from the APs. The framework also ensures that all management frames are sent in omni-directional mode to ensure that existing clients do not disassociate and new clients are still able to associate with the APs.

An example scenario for our solution is shown in Figure 3 where there are two APs. AP1 with two clients and AP2 with three clients. For AP1, traffic demand of C11 is twice that of C12, while for AP2, all clients have equal demand. Further, with directional beams used $AP1 \rightarrow C12$ conflicts with $AP2 \rightarrow C21$. In this scenario the W_1 and W_2 computed by controller is shown.

4. EVALUATION

To provide a flavor of the benefits of using directional antennas, we consider the example scenario in Figure 3 with two APs and five clients. AP1 has two clients and AP2 has three clients. We consider only downlink traffic in this experiment. For AP1, the traffic demand of C11 is twice that of C12; while for AP2, all clients have equal demand. Further, with directional beams, $AP1 \rightarrow C12$ conflicts with $AP2 \rightarrow C21$.

The above scenario is simulated using modified ns2 that models steerable directional beams and compared with use of omni-directional antenna. We modified ns-2.29 version to model the radio propagation characteristics of a steerable beam antenna that is capable of creating 45 degree beams along a specified direction. Figure 4 depicts the throughput obtained for each client for the two schemes. The graph shows that clients benefit both because of decreased inter-AP interference and better link quality. The throughput of APs almost doubles with directional antennas when compared to omnidirectional antennas. This benefit can be higher with more number of clients and APs in different directions. Exploration of the benefits under different WLAN settings is a part of our ongoing work.

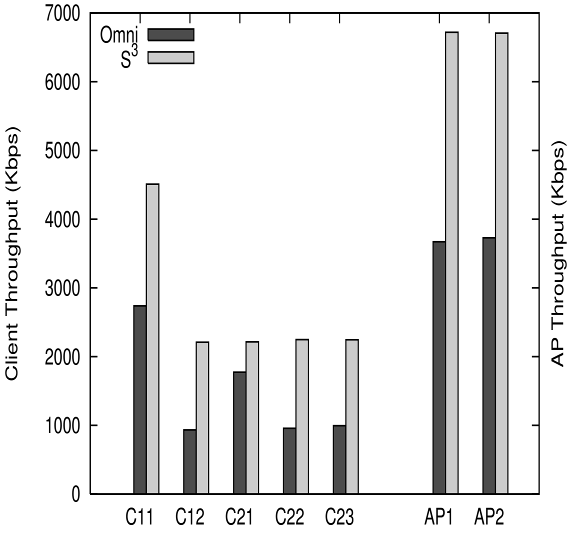


Figure 5: Shows improvements of $S3$ over traditional WLANs.

5. RELATED WORK

Several works in the literature address the design of new MAC protocols for using directional antennas in ad-hoc network settings [12, 17, 10]. In [12], the authors describe hidden node and deafness issues that arise due to the use of directional antennas, and propose a multiple-hop RTS message exchange to establish a directional link between two distant nodes. The proposed MAC protocol requires modifications of the MAC layer, and hence can not be used under our constraints of not modifying the clients and the MAC layer.

In [15], the authors propose the use of directional antennas for achieving topology control in static multihop mesh networks and improving spatial reuse. They assume that the antenna can enable multiple beams in different directions simultaneously. This solution, however, is not applicable is WLAN setting as clients can be mobile and thus APs have to adapt the directions over time. In addition, the number of clients can vary over time.

In [10], the authors show that directional antennas can improve spatial fairness with standard 802.11 DCF by reducing the number of contending nodes. They assume that APs are equipped with sectorized directional antennas and are capable of simultaneous transmission and reception along different sectors.

Slot assignment problem [16, 13] has been well studied in literature. [16] proposed a centralized collision-free slot assignment algorithm for multi-hop wireless networks using maximal clique algorithm. The assignment is done to reduce the average delay to service each link in the network. These works do not satisfy the unique fairness constraints that arise in WLAN networks.

6. CONCLUSION

In this paper, we introduce a system for using steerable directional antennas to improve the capacity of Wireless LANs. In a WLAN with multiple access points (APs), a steerable antenna can be employed at each access point to restrict the power dissipated by the access point in a narrow area to just reach the intended client. Such an approach provides two main advantages: a) higher delivery ratio because of improvement in link quality, and b) higher spatial reuse because of increased simultaneous transmissions between APs and clients. However, using directional antennas in a dense WLAN environment is challenging because of *hidden node* and *deafness* problems. In this paper, we present a novel slotted sectored scheduling framework that addresses the above challenges by coordinating packet transmissions in the WLAN. Preliminary results show that in a network of two APs and five clients, the network throughput is almost doubled using directional antennas.

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