MAC layer Issues and Challenges of using Smart Antennas with 802.11

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***Abstract*— Traditionally IEEE 802.11 systems have used omni directional antennas. Omni-directional antennas are most suitable for the CSMA/CA based 802.11 MAC protocol. Recently increased market penetration of 802.11 is demanding higher range and higher capacity Access Points (AP). The use of smart antennas to enhance the coverage and capacity of 802.11 systems has become a compelling application. In an AP that uses smart antennas, each transmission is in the form of a beam, with the main lobe directed to a particular station (STA). Thus the coverage area is no longer omni-directional, which causes some undesirable side effects to the 802.11 MAC. The directional nature of transmissions and receptions and the interaction between them introduce certain characteristic problems. The problems such as the hidden terminal problem, the hidden beam problem and the 'ACK Suicide' problem along with some other problems involved are described in this paper. The impact of the problems is quantified using simulations. Some possible solutions to the above problems are discussed.**

Keywords; Beam-forming, Smart Antennas, 802.11, Wireless LAN, DCF, Hidden-Terminal, Hidden Beam, ACK Suicide

I. INTRODUCTION

In recent years the use of 802.11 wireless LAN has widely proliferated both in the home and enterprise market. However, the short range of 802.11 WLAN is becoming the limiting factor for many applications. The use of smart antennas allows a significant increase in range. This allows the APs with smart antennas to attain significantly higher coverage compared to ones that use omni-directional antenna.

Although smart antennas can be applied to clients, the higher cost makes it impractical. Most commonly available clients use omni-directional antennas. Thus the smart antenna enhanced APs have to support standard clients.

The 802.11 MAC is originally designed for omni-directional operation. The directional nature of smart antennas introduces certain characteristic problems to the 802.11 MAC. Although certain proprietary changes to the client can resolve some of the problems. Such approaches are not considered in this paper.

This paper focuses on the commonly used infrastructure mode of 802.11, also known as the Basic Service Set (BSS)[1]. In a BSS, an AP provides services that distribute frames originating from STA to the rest of the network, including STAs in the same BSS or wired stations. In the BSS mode, all traffic originating at STA is directed towards the AP, which then transmits the frames that it receives to the final destination.

Typically, a smart antenna system uses an array of antennas. The antenna-array can form directional beams[5,7] to the intended STAs to improve signal to interference and noise ratio (SINR). Beam-forming may use either switched beams or adaptive beam-forming [6,7].

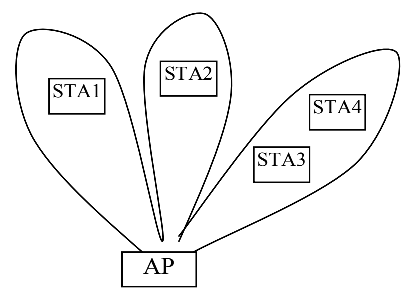

Figure 1 Beams at the AP

The problems caused by the smart antennas are addressed in the following sections. The remainder of the paper is organized as follows: In section II, some characteristic problems introduced by smart antennas are described. In section III, several solutions to the problems are proposed. In section IV, simulation results to evaluate the impact of the problems are presented. The conclusions and discussions are provided in section V.

II. IMPACT OF DIRECTIONAL OPERATION ON THE MAC

The directional nature of transmission and reception, as well as the interaction between transmission and reception on different beams introduce certain characteristic problems described below.

A. *Hidden Beam Problem*

Figure 1 illustrates an AP using smart antennas communicating with several STAs. In an AP that uses smart antennas, each transmission is in the form of a beam, with the main lobe directed towards a particular STA. STAs that are located in the coverage area of a beam will receive that transmission, while STAs located outside the coverage area of the beam will not sense the beam and may start transmitting a frame during the ongoing transmission. Since the AP cannot receive a frame from any beam when it is transmitting on a chosen beam, this frame sent to the AP will be lost. The phenomenon is called "hidden beam problem". This problem is similar to the exposed terminal problem [9].

B. *Hidden Terminal/ACK Suicide*

Two STAs that are outside the coverage area of each other are hidden from each other [8]. The 802.11 protocol use the RTS-CTS mechanism to avoid hidden terminal problems [1,9]. However a CTS frame transmitted on one beam of the AP is received only by STAs in the coverage area of that beam, and not heard by other STAs outside the coverage of the beam. Also, because of the increased range, the STAs on different beams are likely hidden from each other. Thus, the RTS-CTS can not prevent a STA from transmitting when another hidden STA is transmitting. Although an AP with more than one receiver can receive multiple frames simultaneously, the 802.11 protocol requires the AP to send an acknowledgement (ACK) immediately. The ACK responding to the first successful fame destroys the other going frame, causing an 'ACK suicide'. Since an ACK is required to be transmitted right away (within SIFS duration) by the receiver after receiving the frame or the frame is regarded as lost at the sender, there is no way to defer the ACK of the first frame to avoid the 'ACK suicide' of the second frame. In 802.11, the frames have different durations. The smaller frames statistically have higher chance of being ACKed. This introduces unfairness in uplink transmissions.

The problems of interaction between the transmissions and receptions of different beams are illustrated in the following example scenario. Here an AP and two STAs C1 and C2 have connectivity as shown in Figure 2, where C1 and C2 are on beam1 and beam2 respectively and they are hidden from each other.

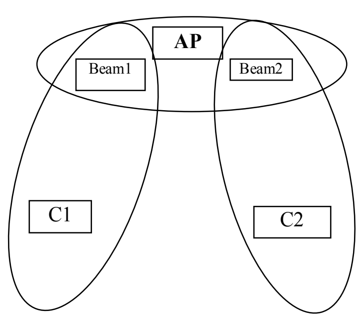

Figure 2 Example Problem Scenario

The interactions are shown in Table 1, with each entry representing the result when transmission of the device on the column starts after transmissions of the device on the row. The normal 802.11 collisions are ignored. In the table, 'x' means no problem caused by directional beam; 'Scheduled' indicates a situation which the AP schedules both the transmissions. 'Deferred' indicates a situation where the AP defers a downlink transmission after sensing an uplink transmission on another beam; 'Hidden beam' indicates the hidden beam problem; 'ACK suicide' indicates the ACK suicide problem.

Table 1 Beam Problem Scenario Matrix

Row transmit before column	AP Beam1	AP Beam2	C1	C2
AP Beam1	x	Scheduled	x	Hidden Beam
AP Beam2	Scheduled	x	Hidden Beam	x
C1	x	Deferred	x	ACK Suicide
C2	Deferred	x	ACK Suicide	x

For example; consider the entry corresponding to the second row and third column, this represents a condition where a frame is lost because of the hidden beam problem. Here STA C1 transmits towards the AP while AP is transmitting to STA C2 on a beam hidden from STA C1.

C. *Automatic PHY Rate Switching*

The 802.11 standard supports several PHY rates with different SNR requirements[1,2,3,4]. Several STA implementations perform dynamic rate switching with the objective of improving performance. The algorithm for performing dynamic rate switching is vendor dependent. Most implementations use simple algorithms based on the number of successive unacknowledged data packets, or number of frames dropped. Many of these algorithms do not clearly identify that the cause of packet loss is actually the link quality, and do not clearly separate the impact of hidden terminals. With the use of smart antennas there is a potential for increased frame losses, caused by the MAC problems described above. This could cause several client implementations to fall back on their transmission PHY rate in spite of having sufficient SINR to use a higher PHY rate.

D. *Near Far capture problem*

Increased range results in greater difference (dynamic range) in received signal strengths between STAs at the AP. A transmission by a nearby STA that is hidden from a far away STA may start during an ongoing uplink transmission, possibly even on the same beam. If there is a significant difference in signal strength, the AP will capture the second frame from the nearby STA. STA closer to the AP may be located in the side lobe of several transmissions and can avoid the hidden beam problem, and have an advantage over STA that are far away which are exposed to hidden beam problems. The far away STA receive a smaller share of the channel access than the near

STA. Such capture phenomenon results in unfair distribution of bandwidth among STAs and the far away STA may even be completely denied service.

III. Possible Solutions

A smart antenna based solution should reduce the impact of the above described problems to achieve acceptable throughput over its coverage area. The AP can sense transmissions by STAs within the coverage area of the beam, as well as other ongoing receptions on other beams thereby preventing collisions with ongoing receptions. Unlike ACK frames, the transmission of RTS, or Data frames can be deferred. CTS frames may be avoided so as not to interfere with on going receptions.

The impact of automatic rate fall back can be improved by managing the uplink retransmission schemes. Also clients that implement better rate fall back solutions are beneficial, for example clients may identify the optimal PHY rate for the link by considering received signal strength and the presence of hidden terminals instead of depending only on unacknowledged frames. Small modifications to the 802.11 protocol could provide a better rate fall back scheme that completely avoids the smart antenna problems.

The impact of the problems can be handled to certain extent using load limiting algorithms in conjunction with STA Fair Sharing schemes.

An effective approach to reduce the impact of hidden beam problem is complementary beam-forming(CBF)[10]. CBF uniformly raises the side lobe of the beams with little compromise on the range of transmission . This reduces the number of STAs that are hidden from the beam, thereby improving performance. This approach would maximize performance of all the STAs in the coverage area, that communicate with the AP.

IV. Simulation

As discussed in previous sections, the use of smart antennas with 802.11 MAC protocol violates the protocol design assumptions and thus necessitates a detailed study of interaction between them. We have developed simulation models to characterize performance of MAC and higher layer protocols (e.g. TCP) in APs using beam-forming antennas.

We used ns-2 as the simulation platform. ns-2 is an open source discrete event simulator [11] and provides an extensive library of networking protocol (e.g. TCP-UDP/IP, 802.11 MAC) and wireless channel models.

The modeled AP system (called as a panel) has *N* beams operating on the same frequency. We modified the wireless models available in ns-2 to provide capability for operation using smart antennas.

The model allows the user to specify the number of beams in the panel and the spatial location of panel and clients. The modeled system operates under following constraints.

- At any given time, the panel can either correctly receive or transmit a frame from one beam
- Clients connected to the panel are standard clients i.e. they use omni-directional antennas and unmodified 802.11 MAC protocol.
- Most clients lie in coverage area of a singe beam, i.e. they are able to listen to only a single beam from the panel.
- Clients covered by separate beams can only hear each other with a small probability.

Since the extent of hidden beam depends on the deployment scenarios (i.e. in indoor deployments, clients may be able to listen to multiple beams), the simulations are performed with varying extent of hidden beam. The performance is characterized by varying following parameters in each simulation run.

- The percentage of clients using TCP vs. UDP at the transport layer
- The traffic load offered to the AP (downlink) and clients (uplink).
    - A traffic source/sink is associated with each client MAC instance, corresponding to which there is a peer traffic source/sink associated in the panel.
    - The traffic source is modeled using a 2-state ON-OFF model. The traffic generation parameters (on-state duration, off-state duration and on-state packet-interarrival time) are exponential distributions
    - The packet size distribution for each traffic source can also be specified

To characterize MAC performance, we use following metrics.

- Failure Rate – Percentage of frames dropped by the MAC layer (frames are dropped after the retransmission attempts exceed the retry-threshold)
- Efficiency – Ratio of delivered load (by MAC to higher layers) vs. offered load (to MAC by higher layers)
- Latency – Delay seen by application layer

The simulations are performed with 50 active clients and the panel is configured with 16 beams. The performance graphs are shown for uplink only as downlink performance is not affected significantly due to the hidden-beam/terminal problems.

The first graph (Figure 3) shows uplink performance in case of an omni-AP. As shown, uplink throughput efficiency degrades gracefully as uplink load is increased.

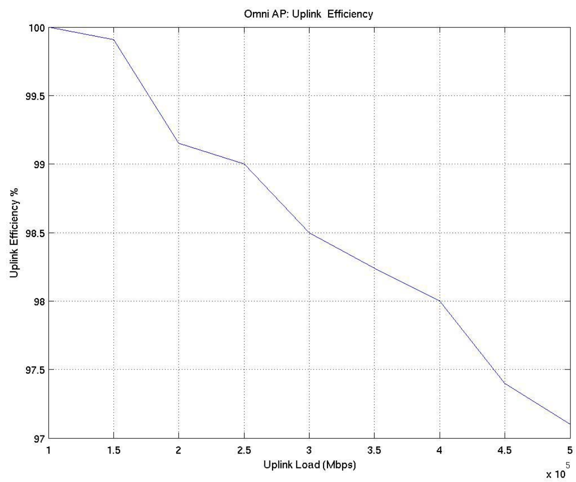

Figure 3: Omni AP – Uplink Efficiency

Next, we consider the performance of the smart-antenna based panel in various scenarios. Figures 4 & 5 show impact of increasing downlink load on uplink performance.

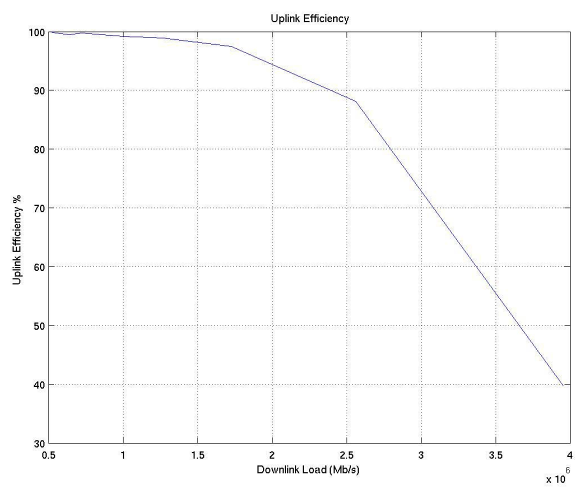

Figure 4: Panel Uplink efficiency vs. Downlink load

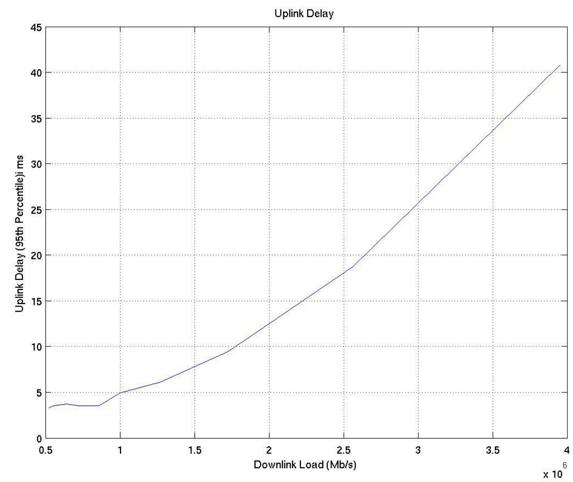

Figure 5: Panel uplink delay vs. downlink load

The impact of hidden-beam and hidden-terminal problems can be observed here. As downlink load is increased, uplink throughput efficiency reduces while delay increases. Similarly, increased load in uplink also negatively impacts uplink performance, as depicted in Figures 6 & 7.

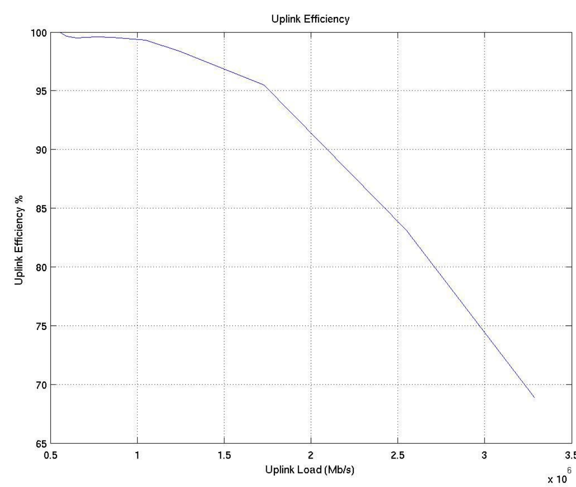

Figure 6: Panel uplink efficiency vs. uplink load

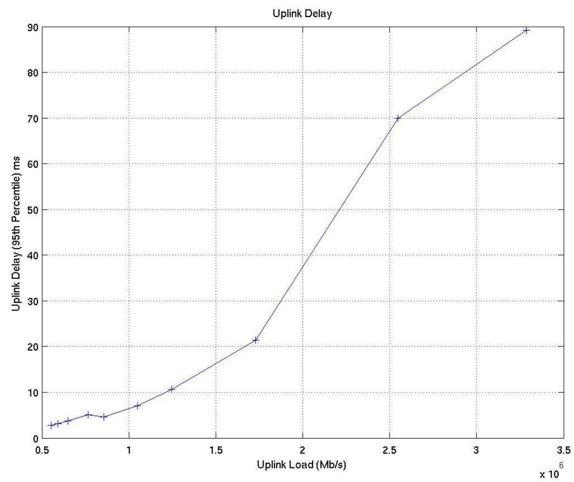

Figure 7: Panel uplink delay vs. uplink load

Figures 8 depicts unfairness seen by clients in case of heavy uplink traffic. As discussed earlier in the paper, the unfairness occurs due to the hidden-terminal/beam problem and near-far capture effect.

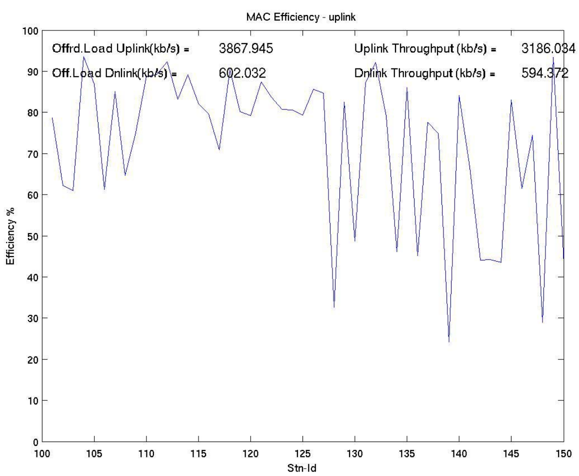

Figure 8: Unfairness seen by clients in case of heavy uplink traffic

V. CONCLUSIONS

In this paper several problems of using smart antennas with 802.11 APs were identified. The impact of the problems were quantified through simulations. The simulation results show that directly using smart antennas without any modification causes significant degradation to the performance especially under heavy traffic conditions. Although smart antenna solutions can increase the range of an AP, changes have to be made to the AP, the client or the protocol. Some solutions are suggested in the paper.

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