Poster: On the Medium Access Control Problem in Ad-hoc Networks with Smart Antennas[*]

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ABSTRACT

In this paper, we address the problem of medium access control in ad-hoc networks with fully adaptive array antennas. We show that, unlike in the case of directional and switched beam antennas, significant performance improvement can be leveraged with just a simple extension to CSMA/CA that we refer to as CSMA/CA (k). We then provide PHY layer based insights into why a MAC scheme that is smarter than CSMA/CA (k), and hence can achieve significantly better performance, is possible in the target environment. Finally, we propose an idealized protocol called SMART-MAC that builds on the insights.

1. CLASSIFICATION

Smart antennas are multiple-element arrays (MEAs) that can be classified under the following categories: (i) *Directional antennas:* These antennas employ transmissions through directional beams that have fixed radiation patterns. Directional transmission facilitates spatial reuse. However, during reception on a directional beam these antennas do not provide interference suppression along the other beam directions. (ii) *Switched beam antennas:* These have pre-determined and fixed radiation pattern of the beams like the directional antennas. But, they provide interference suppression along other beams when the desired signal is being received along a particular beam direction. Steerable beam antennas are variants of switched beam antennas. But unlike the directional and switched beam antennas, they can steer the beam to continuously track a transmitter or receiver. (iii) *Adaptive array antennas:* These antennas offer the highest degree of flexibility in configuring the beam patterns and achieving interference suppression. Furthermore, the use of multiple antennas at both ends of a wireless link provides significant improvements in terms of spectral efficiency and link reliability, resulting in a technology popularly referred to as *multiple-input multiple-output (MIMO)* wireless systems[1]. Such use of multiple antennas at both ends of the link results in a *multiplexing gain* through the use of multiple data pipes within the same frequency band to yield a linear (in the number of antennas) increase in capacity that comes at no extra bandwidth or power consumption.

We focus on fully adaptive array antennas with MIMO links in this paper.

2. SIMPLE CSMA/CA EXTENSION

A simple extension to CSMA/CA to adapt it to MIMO environment is as follows:. For every transmission (including control and data packets), all the elements at a node are used to speed up the transmission k times (relative to a transmission that uses only one element), where k is the number of elements on the multiple element array (MEA). No further changes are required at the MAC layer except for the adjustment of the different timing constants. We refer to this baseline protocol as CSMA/CA(k). The CSMA/CA(k) scheme can be expected to achieve k times the throughput achieved in a similar network with nodes in the network having only a single omni-directional antenna.

3. MOTIVATION FOR A SMARTER MAC

While a k fold improvement in CSMA/CA's performance is indeed promising, the key question is whether even better performance is achievable through a more MIMO aware MAC protocol. We shed some light on key factors that motivate why a better MAC protocol based on MIMO is indeed possible.

- CSMA/CA(k) does not fully leverage the efficiency of MIMO because it does not exploit knowledge of the channel gains between the links. If two links are close enough to interfere, CSMA/CA(k) would simply prevent one of them from operating so that the other can operate. In contrast, MIMO will allow both links to remain active, and will adapt the array patterns to use the channel gains between links so that interference power is minimized. Furthermore, the performance of MIMO is maximized when the interfering links perform some form of *stream control*, where they voluntarily use only a subset of the maximum allowable number of streams. In [1], the performance gain is presented to be 20% when the number of links is two. Thus, multiple interfering closed-loop links, transmitting simultaneously with appropriate stream control, can achieve better overall network utilization than when a single link operates with the maximum allowable number of streams.

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[1] We consider a specific class of MIMO systems called closed-loop MIMO systems.

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- When the interfering links are positioned such that the interference signals traverse a longer distance than the desired signals ($1 \leq \frac{R}{D} \leq 2$, where D is the distance between the transmitter and the receiver while R is the distance between the interferer and the receiver), the improvement of MIMO over CSMA/CA(k) can increase significantly. The performance gain is shown to be as high as 50% in [1]. This is due to the fact that fewer resources are required to suppress interference when the interfering signals are from far away than when they are from close by. This, in turn results in more of the resources at a node available for improving the performance of the desired transmissions/receptions. In the case of CSMA/CA(k), this scenario is equivalent to a receiver experiencing interference from a signal transmitted by a node within its carrier-sensing range but outside its receive range. However, CSMA/CA(k) by virtue of being a simple extension of CSMA/CA will force the nodes to remain idle as long as there is any transmission in their carrier-sensing range (approximately two-hop neighborhood).

- While the above two factors directly help a MIMO aware MAC achieve improved performance over CSMA/ CA(k), there exists one facet of CSMA/CA(k) that allows it to perform better than a purely MIMO aware MAC under some circumstances. In CSMA/CA(k), since there can be only one active transmitter in any *contention region*, the other passive receivers in the same region can be *overloaded* with more streams than they can receive. This paves the way for a higher degree of spatial reuse. Hence if a passive receiver belongs to more than one otherwise non-overlapping contention regions, then there can be an active transmitter in each of those contention regions. On the other hand in a MIMO MAC employing stream control, all the transmitters within a contention region use the best subset of their streams such that no receiver in the region is overloaded. But if any of the receiver nodes belong to other contention regions, then this prevents the nodes of those contention regions from transmitting since this will overload an active receiver. This in turn reduces the degree of spatial reuse, and can potentially degrade performance. Hence it becomes critical to distinguish between the links that belong to multiple contention regions (red links) and those that belong to a single contention region (white links). To avoid the potential under-utilization caused due to the inability of overloading the receivers, it is necessary that stream control be performed on only the white links with the red links operating on all the streams.

4. CENTRALIZED SMART-MAC

Having motivated the need for a MIMO aware MAC protocol, we now outline the key components of a centralized SMART-MAC protocol.

- *Coloring:* The first step of the SMART-MAC protocol is the task coloring wherein, the links are all colored red or white. It addresses the problem of receiver overloading. To be able to color the links as red or white, SMART-MAC first identifies all the contention regions in the network and the member links of each contention region. This is achieved by determining all the maximal cliques in the flow contention graph induced by the network topology [2]. Thereafter, all the links that belong to multiple contention regions, with white links present in atleast two of them, are colored red, while the other links are colored white.

- *Fair Allocation:* Once the links have been appropriately colored the next step is to allocate a fair share of the network resources to the contending links. For this purpose SMART-MAC has a *global transmission allocator* with which every link in the network, that has a packet to transmit, registers. The allocator having global information of the location of the links, allocates the number of streams to be used by the links based on their color for every transmission slot as follows: The allocation begins with the red links which are the bottleneck links. Every red link when scheduled, is allocated all *k* streams. Any link can be allocated a stream provided it has enough resources (after suppressing unwanted streams) to transmit a stream and its neighbors also have enough resources to suppress this stream. In verifying if a link has enough resources, the interference based on distance is taken into account. At every slot, the algorithm also attempts to maximize the utilization, i.e. after scheduling a red link with *k* streams, the algorithm checks to see if any other red links can be scheduled in the same slot with *k* streams. Then, it checks to see if any white links can be scheduled in the same slot with atleast one stream. Once all possible links have been scheduled for that slot, the allocator moves to allocate the schedule for the next slot. The scheduling of the red links is stopped when the red link with the minimum service has received greater service than that of the white node with the minimum service. The allocator then switches to scheduling the white links which in turn involves stream control. We elaborate on this in the remaining part of this section.

- *Stream Control:* The allocation is done on a stream by stream basis to all the white links that can be scheduled in the same slot. This results in a fair allocation of streams to all the white links that can be scheduled in the same slot. Thus, the resources in any contention region are shared in a fair manner amongst the white links in that contention region, thereby facilitating stream control. The allocator switches the scheduling back to the red links once the white link with minimum service has a value greater than or equal to the red link with maximum service.

Thus, the various components of the SMART-MAC protocol helps us leverage the advantages of MEAs with MIMO links without incurring the degradation due to the incapability of performing receiver overloading. For further details on the components and algorithm of the SMART-MAC protocol, the readers are referred to [3].

5. REFERENCES

[1] M.F. Demirkol and M.A. Ingram, “Control Using Capacity Constraints for Interfering MIMO Links,” in *Proceedings of IEEE Symposium on Personal, Indoor and Mobile Radio Communications*, Sept 2002.

[2] T. Nandagopal, T. E. Kim, X. Gao, and V. Bhargavan, “Achieving MAC Layer Fairness in Wireless Packet Networks,” in *Proceedings of ACM International Conference on Mobile Computing and Networking,* Aug 2000.

[3] K. Sundaresan and R. Sivakumar, “On the Medium Access Control Problem in Ad-hoc Networks with Smart Antennas,” *GNAN Research Group Technical Report, Georgia Institute of Technology,* Apr 2003.