Performance evaluation of Directional Antenna-assisted MAC Protocols in the presence of Mobility

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***Abstract*— The basic feature of the emerging IEEE 802.11n and other standards for high throughput is the presence of directional antennas at network nodes. In this work, we evaluate the performance of media access control protocols in envisioned IEEE 802.11n wireless LANs that operate in point coordination function (PCF) mode. The Access Point (AP) is equipped with an adaptive antenna array. An underlying objective of the access control protocol is to identify and localize individual users in order to transmit information to them. The performance metric is the required time for localization of all users. In an earlier work [3], access control protocols are studied, that employ directional transmissions with contention-based or contention-free polling methods to locate users residing in or out of coverage range of the AP. However, the location of users is oftentimes subject to changes due to mobility. In this work, we present two schemes to alleviate the potentially large delays that are anticipated due to user mobility. The first scheme is based on user location caching at the AP. That is, the most recent location of each user is maintained at a cache memory at the AP, so that in a future time the AP selects an appropriate sector to start the search from. The second alternative attempts to reduce the required time by employing multiple transceivers. Numerical results show significant achieved performance benefits for these two schemes.**

Keywords: Adaptive antenna arrays, access conttol protocols, user mobility, location caching, multiple transceivers

I. INTRODUCTION

The emerging IEEE 802.11n standard for high throughput demonstrates the need for efficiency and high-data rates in wireless networks. The basic feature of these standards is the presence of directional antennas at the APs and the mobile nodes. Adaptive antenna arrays are also considered to be a necessary addendum to the evolving standards for Broadband Wireless Access (BWA) such as WiMax. Such protocols will contain several recently proposed innovations, yet they are likely to rely also on readily available access control protocols in the IEEE protocol suite and elsewhere in order to allow for backwards compatibility. The first step towards establishing a connection to a user in such an environment involves the identification of users that are located in the neighborhood of an AP. This is the topic of this work.

Up-link access to a Base Station (BS) with an antenna array with the help of a protocol based on Carrier Sense Multiple Access (CSMA) is studied in [1]. The AP can request information about the spatial signature of a user by broadcasting a polling message intended for that user in the down-link. Upon reception of the poll, the user transmits a given sequence of symbols. The BS measures the received signal strength and uses it to compute the spatial signature and gradually steer a beam towards the direction of the user [2].

In an earlier work [3], access control protocols were proposed for extending the coverage range of the AP. The performance was measured in terms of required delay for acquiring the location of each user so as to initiate information transmission. Such protocols primarily serve the purpose of identifying the location of users that are out of broadcast range, yet they can also be combined with existing media access protocols that are designed for coping with users within broadcast range. The protocols presented in that work employed successive directional transmissions in conjunction with contention-free or contention-based polling methods in order to acquire location information for users. The AP essentially scans the area around it sequentially in an effort to identify users. The study in [4] includes a simulation model in OPNET of a system with adaptive antennas. It also suggests several configurations for transmission such as directional transmission of ACK or DATA packets. A protocol for a wireless LANs in distributed coordination function (DCF) operation mode is proposed in [5]. An important common characteristic of these approaches is that they consider mostly static networks and do not take into account network dynamics due to mobility.

In wireless environments, user mobility raises new issues and challenges in identifying and tracking users. The AP may not be able to effectively locate users and thus it cannot efficiently employ the access control protocol. In such cases,

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additional functionalities need to be implemented at the AP. In this work, we build upon the work in [3] and propose two means for coping with user mobility. We maintain the protocol machinery of [3] in order to have a basis for evaluating the performance benefits of our approach.

The underlying idea of the first solution is the existence of a cache memory in the AP, which is easy to implement in both hardware and software. The most recent location of each user is maintained at the cache. If the AP transmits to a user in a future time, it will not need to start scanning the area from the beginning. Instead, it will start from the location that corresponds to the most recent entry in the cache. The second solution relies on the capabilities of the AP to form more than one beam simultaneously. Each beam is formed by a dedicated transceiver, namely a hardware unit that is used to form a distinct beam. Both schemes imply significant performance benefits in locating users and are used in an effort to alleviate large expected delays under user mobility.

The paper is organized as follows. Section II presents the system model and Section III describes the employed media access protocol. Simulation results are presented in Section IV. Finally, Section V concludes the study.

II. System Model

In an environment with user mobility, users may enter and leave the broadcast region. We assume however that users remain within the maximum range achieved with directional transmission. Every time the AP needs to transmit information to the user, it needs to learn the user location. When the user is within the AP broadcast region, the AP does not need to possess the exact location of the user. However, if the user is out of the broadcast region, the exact location of the user is needed in order to trigger an appropriate directional transmission that covers the user location.

The location of each user is captured by its spatial signature. The identification of location of each user is performed through spatial signature acquisition and location caching. The AP maintains a cache that maps user terminal IDs (namely MAC addresses) to spatial signatures. Whenever the user is located using the procedure outlined in Section III, and a packet is received, the user location is updated in the cache. When the mobile enters the broadcast region, the AP may switch to broadcast mode. However, this will incur the additional cost of trying to find the location of the user whenever it moves out of the broadcast region again. When a packet is to be transmitted, the MAC address of the receiver is matched to the cache entry and the corresponding spatial signature is used for transmission of the packet. When the receiver is not in the cache, then the procedure for spatial signature recovery [3] is initiated.

For users that have moved into another area or beam, contention-free or contention-based polling schemes are applied. See Section III for a description of the employed MAC protocols. In both cases, omni-directional or directional transmission can take place. In contention-free directional transmission, the space is scanned beam by beam until a certain user is located. Then, the procedure is repeated for the next user. In contention-based polling schemes, contention among users in a beam is resolved before the AP proceeds to steering the next beam. The contention-free method has the advantage of absence of contention but, depending on the number of beams, it may require more time to locate all users. A small number of large beams favors the contention-free scheme since less time is needed to cover all space and therefore to locate all users. On the other hand, in contention-based polling, the width of the beam that scans the space plays a significant role. If a large beam width is used, fewer beams are needed to scan the space and the required time to scan the area with successive directed transmissions is smaller. However, with a large beam width, the number of users that receive the message is larger on average and hence the contention resolution for users in a beam lasts longer. From that point of view, a large beam width does not contribute to reduction of time delay to locate all the users.

The second alternative relies on the existence of several transceivers at the AP. Several beams are formed, each one by a dedicated transceiver. Each beam scans the area and attempts to identify users and resolve transmissions to them.

III. MAC Protocol Description

A. Basic Procedures

In this section, the basic machinery of the access control protocol presented in [3] is outlined.

When contention-based polling is employed, the AP forms successive directed beams and scans all space. The AP attempts to locate all users within the beam before proceeding to the next beam. Time is divided in slotted intervals, called Contention Resolution Intervals (CRI). Each CRI consist of L slots. At the beginning of each CRI, the AP sends a polling message that does not contain user ID. Each user that receives the message responds by sending a polling acknowledgement (P_ACK) message that contains a preamble and the user ID. If only one user in a beam sends a P_ACK message the AP responds to him with an ACK message with his address. If several users in a beam send a P_ACK, a collision occurs and the AP does not broadcast any ACK, so that users are aware about the collision. A simple collision resolution scheme with each of the collided users retransmitting its P_ACK with fixed probability p is used in [3] in each of the L slots in the CRI. If the CRI expires and the AP does not have any indication that all users have been resolved, it initiates a new CRI by sending a new polling message. The procedure is repeated for the rest of the users in the beam.

When contention-free polling is used, the polling messages include the ID of a user for which they are intended. The AP sends a polling message for each specific user in a beam. If the user does not reside in the beam, the AP does not receive any P_ACK and it repeats the same procedure in the next beam. If the user resides in a beam, it responds by sending a P_ACK message. The AP responds to this message by transmitting an ACK message to the user in order to inform him that his location is found. The same procedure is repeated for all users.

In [3], the performance of four schemes was compared:

- Contention-Free Broadcast/Beam-forming

First, the AP uses contention-free polling messages to locate users within broadcast range. Then, it uses contention-free polling messages with beam-forming to locate users outside of broadcast range.

- Contention-Free Beam-forming/Beam-forming

This scheme is similar to the previous one, but the AP only uses directional transmissions. The procedure does not have two different phases and all users (inside or outside the broadcast region) are treated equally.

- Contention-Based Broadcast/Beam-forming

The AP uses contention free-polling messages for users in the broadcast region and contention-based messages for the users located outside of that range.

- Contention-Based Beam-forming/Beam-forming

The AP sends contention-based polling messages regardless of users' location with respect to broadcast region.

B. *Enhanced scheme with cache memory in the AP*

Suppose that the scheme with the cache memory at the AP is incorporated in the protocol. In the first scan, the AP uses one of the schemes above to locate the users. In the second scan, the AP sends contention-free polling messages containing the users' ID in the broadcast region for those users that had an entry in the cache indicating that they were in that region. For users outside the broadcast region, the AP operates in directional mode by sending contention-free polling messages to the direction that corresponds to the location stored in the AP cache memory. The following schemes are used for those users that may have changed area or beam:

- Contention-Free Broadcast/Beam-forming

The AP uses the contention-free Broad/Beam method in the second round of scanning. For the non-identified users with an entry indication in the broadcast region, the AP sends a directional contention-free polling message to the beam that corresponds to the previous location. This means that the AP assumes that the user has moved out of the broadcast region. Subsequently, it sends contention-free polling messages to the beams located left and right of the aforementioned beam. This procedure is shown in Figure 1.

In the case of a user with an entry indication in the specific sector area, the AP sends a contention-free polling message left and right of that beam. Afterwards, contention-free polling messages are sent by the AP to the other beams. Upon receiving the P_ACK message, the AP sends to that user an ACK in order to inform it that its location has been found and the procedure for that user is terminated. The procedure is depicted in Figure 2.

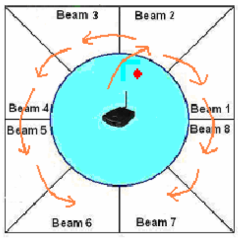

Figure 1. Second round of scanning for non-identified users with an entry indication in the broadcast region.

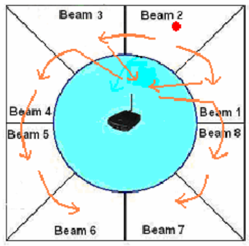

Figure 2. Second round of scanning for non-identified users with an entry indication outside of the broadcast region.

- Contention-Free Beam-forming/Beam-forming

In this case, the AP uses contention-free directional transmission towards the last position stored in the cache memory. If a user does not respond to this message, the AP uses the contention-free Beam/Beam method and tries to find its location by sending contention-free polling messages to the beams left and right of the previous stored beam. As before, the procedure for a user is completed whenever the AP receives the P_ACK and it sends an ACK message to the mobile terminal.

- Contention-Based Broadcast/Beam-forming

Contention-based beam-forming transmission is applied for users that have not been identified in the region stored in the cache memory. The procedure starts from the last indicated sector for each user. In the case that a user other than the requested one sends a P_ACK, the AP updates his entry in the cache memory and continues the procedure.

- Contention-Based Beam-forming/Beam-forming

The AP transmits directional contention-free polling messages in the area indicated by the last location in the AP´s memory. Similarly to the users that have moved into another beam, the contention-based Beam/Beam procedure is used.

C. *Enhanced scheme with multiple transceivers in the AP*

For the case when two transceivers are employed at the AP, we study two scanning strategies.

In the first strategy (M1), each beam scans half of the area for all users, e.g. beam 1 scans the first half area A1 and beam 2 scans the other half area A2. Then they exchange areas. We assume that each transceiver operates in different frequency and the mobile terminals are able to receive the signal at any one of the available frequencies. Therefore, when the AP transmits a directional polling message, the users of the beam are synchronized with the AP for a period equal to the CRI. Since the polling message transmission is directional, no interference occurs among the two transceivers. Furthermore, the P_ACK transmission from a terminal to one of the transceivers does not affect the communication in the area of the second transceiver. The methods analysed in [3] are used in each case. For the users located in the broadcast region, broadcast polling messages are transmitted. Ideal synchronization between transceivers is assumed.

In the second strategy (M2), each beam scans half of the area (say A1) for a subgroup of users S1 and the other one scans the other half (say A2) for a subgroup S2, simultaneously. In our model, the subgroups S1 and S2 are arbitrary. Then they exchange areas (i.e. they scan for users in group S1 in area A2 and for users in S2 in area A1). It is assumed that beams move simultaneously. Furthermore, we suppose that each subgroup knows the frequency of the beam where it belongs. In this case, the four methods analysed in [3] are used. It is worth noting that contention-free polling messages are used in the broad/beam methods for users residing in the broadcast region.

IV. NUMERICAL RESULTS

In order to evaluate the aforementioned schemes, computer simulations have been carried out using a C++ simulator. We consider a scenario of a flat square in 500x500 space units with an AP located in the centre of the area. Users are uniformly distributed in the area with an initial relation N_{OUT}/N_{IN}, where N_{IN} is the number of users in the omni-directional coverage area, and N_{OUT} is the number of users that are reachable only with directional transmission of the AP. The users can reside either in or out of the AP broadcast region. At each time, only one beam is formed towards a certain direction. It has been assumed that the area is covered by B beams. In our simulation setup, we assume that the AP selects to poll users within the broadcast region either by broadcast or by directional transmission, while for users out of this region only directional transmission is used. For the case of several transceivers, we do not assume user mobility in order to facilitate performance comparison.

The performance of the schemes described in Section III has been evaluated. The polling and the ACK messages contain an address field and each of the messages is assumed to have a length of one time unit. The P_ACK message includes a preamble for spatial signature acquisition in addition to the address field and it occupies two time units.

Ideal transmission with no channel errors is assumed. CRIs consist of L=6 slots. Unlimited cache memory of the AP is also assumed. The second round of scanning starts immediately after the end of the first one.

A scenario where users move slowly within the coverage zone has been considered. We do not adhere to a mobility model such as one from [6] but we use the following simple model. Each user selects randomly a direction of movement based on a uniform distribution from 0 to 2π radians. Then, it moves in a straight line with this direction with constant speed 0.01 length units per time. When it reaches the border of coverage zone, it changes direction so as to return to the area. The performance of all techniques has been evaluated in terms of the required time delay to resolve all users in the system.

The use of cache memory at the AP significantly reduces the required time to identify all users. This is shown in Figure 3 and Figure 4, which depict the comparative results about mean delay with and without cache memory as a function of number of users for B=20 beams. The ratio of users out and within the range, N_{in}/N_{out} in the first scan was fixed to ½. In these plots, the retransmission probability p is fixed to 0.4. In Figure 3 the contention-free schemes are compared, while in Figure 4 the contention-based ones are presented. When cache memory is considered at the AP, 41% less time is needed to identify all users with the contention-free Broad/Beam method and 71% less time is needed with contention-free Beam/Beam when there are 51 users in the system. Similar results hold for contention-based schemes. In this case, 58% less time is required in the Broad/Beam and 35% in the Beam/Beam schemes when a cache memory is used.

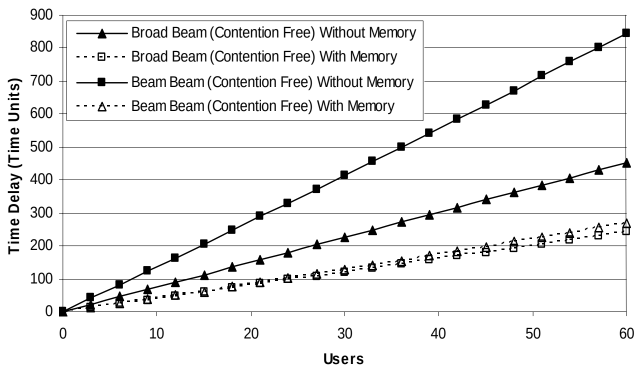

Figure 3. Time delay versus number of users for contention -free schemes when cache memory in the AP is considered.

Figure 5 and Figure 6 show results when two transceivers are considered. Significant improvement is achieved in terms of time delay both for contention-free and contention-based schemes. It can be seen that the second method (M2) needs less time to identify all users. This is because fewer users receive the contention message and, as a consequence, fewer collisions occur. As a benchmark figure we can see that for 51 active users in the system, the two transceivers need in the worst case (contention-based Broad Beam) 6% less time to resolve all the users.

By comparing the results from Figure 3-Figure 6 it can be seen that the cache memory in the AP is a more effective means for reducing location acquisition delay than the employment of two transceivers, since it reduces the required time by 1% in the worst case (contention-based Broad/Beam) and by 30% in the best case (contention-free Beam/Beam).

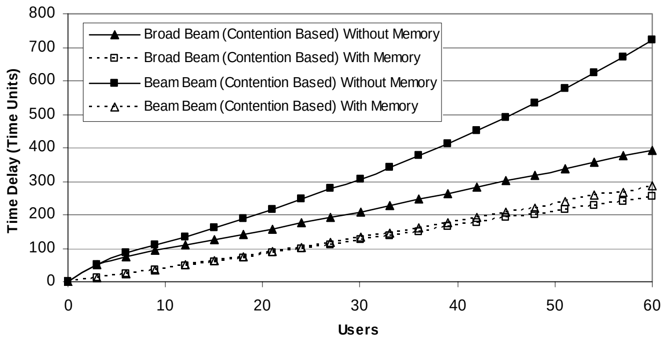

Figure 4. Time Delay versus number of users for contention based schemes when cache memory in the AP is considered.

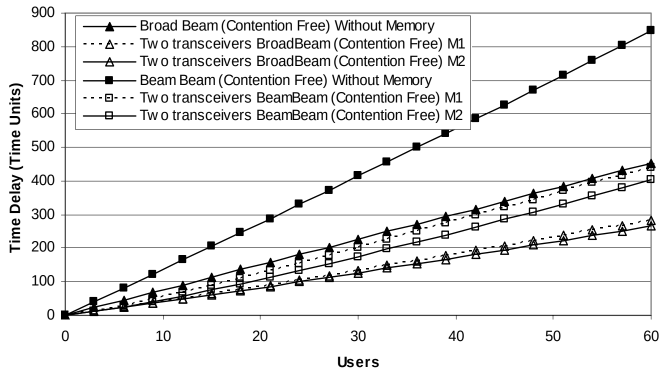

Figure 5. Time Delay versus number of users for contention free schemes when two transceivers are considered in the AP.

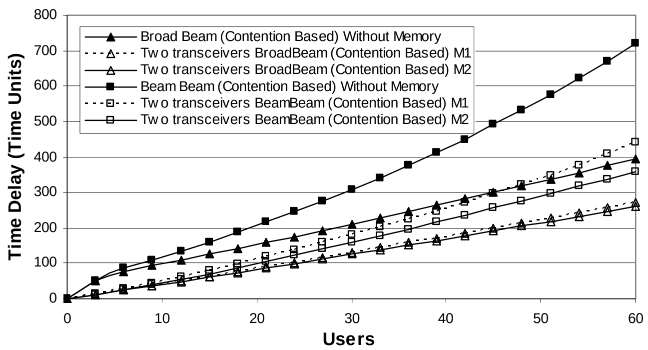

Figure 6. Time Delay versus number of users for contention based schemes when two transceivers are considered in the AP.

V. CONCLUSION

We presented two methods for coping with user mobility in a wireless network in PCF operation mode, in which the AP is equipped with directional antennas. The objective was to localize all users and transmit data to them with small delay in the presence of mobility scenarios. To this end, we suggested two alternatives that provide significant performance with the expense of additional hardware and software implementation. In the first alternative, the AP performs user location caching in a local cache. Alternatively, the AP is equipped with the necessary hardware to form more than one beam simultaneously. Our work can be considered as a prelude for the emerging IEEE 802.11n standard or other evolving wireless broadband access standards.

Our approach was presented in the context of wireless networks operating in PCF mode. This implies that there are no memory limitations. Nevertheless, additional issues arise when ad-hoc distributed coordination function (DCF) operation is considered. In this latter case, the nodes are resource-constrained and they have limited amount of buffer to allocate to store user locations. The decision regarding the users whose locations will be cached at each node is an issue. Nodes may employ collaborative caching, in the sense that each of them caches locations of certain number of nodes, so that no duplicate caching occurs. On the other hand, the existence of location information for a node in caches of more than one nodes improves the chances of successful localization of the user. The solution with multiple transceivers needs additional consideration, since small-size mobile devices operate under hardware constraints.

Another issue for future work is the incorporation of additional adaptation capabilities in the protocols. The protocol can become adaptive in the following sense: Each user may adapt its channel access probability each time a collision is experienced. For instance, in the collision resolution procedure, the user may reduce the access probability by a small amount in the case of collision at the previous attempt. In the case of a successful attempt, the access probability can be increased. All or some of users could perform this adaptation. Along the same lines, the beam-width B of the beam could be adapted, depending on the outcome of the previous collision resolution procedure. For instance, if several users out of a total of N have been resolved in the previous beam with beam-width B, the beam increment could be higher by an amount depending on the remaining users that need to be resolved. Implicit here is the effort to try to balance the times needed from different beams to resolve users.

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