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Efficient Media Access Protocols for Wireless LANs with Smart Antennas

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***Abstract*— The use of smart antennas in extending coverage range and capacity of wireless networks dictates the employment of novel media access control protocols, with which the base station (BS) or access point (AP) provides access to users by learning their locations. We consider the class of protocols that employ beamforming and use contention-based or contention-free polling methods to locate users residing in or out of coverage range of the AP. Such protocols allow rapid media access and can be embedded in existing MAC protocols.**

I. Introduction

The increasing need for providing fast wireless access and high-speed wireless links to users has become the driving force for active research in the telecommunications area. The advent of services such as home networking, video conferencing, wireless internet access and multimedia transmission is only the first sign of the projected demand for rapid and reliable access to information sources of any kind. The requirement for ubiquitous coverage in personal, local and wide area networks and the demand for mobility necessitate the deployment of efficient protocols for wireless access in indoor and outdoor environments. In such systems, the final interface between the mobile user and the network is wireless through APs or base BSs that are wired to the backbone network.

A major challenge in the design of wireless systems is quality of service (QoS) provisioning to users. Different notions of QoS are available in different phases of the link establishment procedure and in different communication layers. When a link needs to be established between an AP and a user, QoS is expressed in terms of link setup time delay and can be ensured with efficient media access control (MAC) protocols. After link establishment, QoS at the physical layer is given in terms of an acceptable signal-to-interference and noise ratio (SINR) or bit error rate (BER) at the receiver of a user or in terms of minimum throughput guarantees at higher layers. QoS is then provided with appropriate resource allocation techniques. Space division multiple access (SDMA) with smart antennas at the AP constitutes perhaps the most promising means for ensuring these notions of QoS and increasing system capacity [1]. SDMA enables intra-cell channel reuse by several spatially separable users by pointing a beam towards the direction of a user and nulling out other users. However, the employment of antenna arrays at the physical layer affects resource allocation methods and MAC protocols of higher layers. With respect to the impact of SDMA on resource allocation, some heuristics for time slot assignment to users in a SDMA/TDMA system are proposed in [2] and [3].

In order to exploit the benefits of SDMA in MAC protocols, the BS needs to know the location of each user, which is captured by its spatial signature. In reception mode, the BS obtains information about spatial signatures of users by making use of the preample of received packets. Each preample is used by the BS to train the array to compute beamforming weights that effectively steer the beam towards the intended user. In [4], the authors describe a slotted ALOHA network with a single-beam adaptive array at the BS. By exploiting a pseudo-random sequence in the packet preample, the BS computes a beam and locks it onto the first received packet in a slot, while nulling subsequently received packets. A similar system with multi-beam capabilities is presented in [5]. The BS again uses packet preamples to form a beam for each received packet from a different user, so that several users are captured. Up-link access to a base station with an antenna array with the help of a modified carrier sense multiple access (CSMA) protocol is addressed in [6]. In transmission mode, the BS can request information about the spatial signature of a user by broadcasting a polling message intended for that user in the down-link [7]. Upon reception of the poll, the user transmits a given sequence of symbols. The BS measures the received signal and uses it to compute the spatial signature and gradually steer a beam towards the direction of the user.

The common characteristic of these approaches is that they are all designed for users that reside within the omni-directional transmission range of the AP or BS. When required, the AP broadcasts polling requests to users and receives response packets from users within broadcast range by having its antenna in omni-directional mode. It then uses packet preamples to steer beams to appropriate directions. In this setting, the basic feature of SDMA to extend coverage range essentially remains unexploited. In this paper, we address the problem of extending the coverage range of an AP with smart antennas, by devising efficient media access protocols. Such protocols are primarily meant for detecting the location of users that are out of broadcast range, but they can also be integrated with existing media access protocols that are designed for coping with users within broadcast range. We present protocols that use directed beamforming and employ contention-free or contention-based polling methods to acquire location information of users. In devising the protocols, some essential characteristics of the IEEE 802.11 standard for wireless local area networks [8] were adopted. However, our treatment is general enough to encompass other wireless networks as well.

The rest of the paper is organized as follows. In section II we provide the model and main assumptions and in section III we present our protocols and analyze their performance. Numerical results are presented in section IV. Finally, section V concludes our study.

II. SYSTEM MODEL

We consider the down-link of a single AP and focus on down-link access to N users. The AP is equipped with a uniform linear array of M antennas. The broadcast range of the AP is specified by a maximum transmission power level when the array operates in simple omni-directional mode. Users can reside in or out of broadcast range of the AP. Due to mobility, they can also move in or out of range at different time instants. A snapshot of the system is considered, where users remain either within or out of range. The AP has C available transceivers and each transceiver is perceived as a distinct communication unit that is capable of forming one beam. In this work, we consider the class of protocols with $C = 1$, so that one beam can be formed at each time instant. A beam is described by an $M \times 1$ beamforming vector $\mathbf{w} = (w_1, \ldots, w_M)^T$, where w_i's are complex numbers and $\mathbf{w}^H \mathbf{w} = 1$, so that the beam has fixed power. Alternatively, a beam is specified by its beam width δ and its angular position ϕ. We assume that a beamforming vector uniquely specifies the pair (δ, ϕ) and vice versa. The space can be covered by B beams of beam width $\delta = 360/B$ degrees and each user is covered by at least one beam. Depending on parameter B, the patterns of two successive beams can partially overlap.

The location of a user is captured by its spatial signature. In line-of-sight (LOS) transmission, this is a vector that points towards the physical location of the user, while in multi-path environment it is formed as a superposition of components corresponding to different directions. We assume that the user association phase with the AP is completed, so that the AP knows the number of users and their addresses but not their instantaneous locations. Packetized data arrive from higher layer queues for transmission over the channel. If the AP uses beamforming and not broadcasting to transmit data to users, it needs to know their spatial signatures.

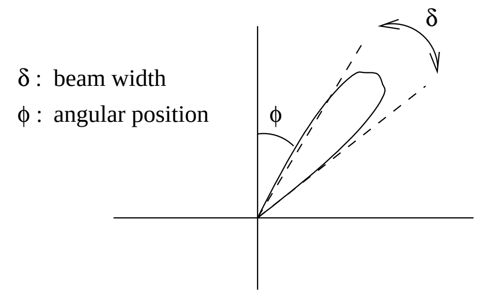

Fig. 1. Beam width and angular position of a beam.

The AP can obtain information about the location of a user by using the following two methods. According to the first one, it first sends a polling message that contains the address of the intended user. Upon receiving the poll, the user responds by sending a known sequence of bits in the up-link. The AP uses these bits to train the array so as to steer the beam towards the direction indicated by the spatial signature of the user. This polling/response method is used to acquire the spatial signature of each user. We refer to this method as contention-free polling, since it does not involve any kind of user contention. Alternatively, the AP can acquire information about user locations by sending a beacon message that is not intended for a specific user. If the message is received by more than one users, their simultaneous responses will collide at the AP. The AP then initiates a contention resolution procedure to resolve users and obtain their spatial signatures. We refer to this method as contention-based polling. The AP can send polling messages with omni-directional or directional transmission. After the spatial signature acquisition process is completed, data can be transmitted to users.

III. MEDIA ACCESS PROTOCOLS WITH SMART ANTENNAS

A. Problem Statement

When the AP needs to obtain information about the spatial signature of a user residing within its broadcast range, it can poll the user by using broadcast or directed transmission with contention-free or contention-based polling. Contention-free broadcast polling is the method that results in the smallest time delay in locating all users.

However, when the user is out of broadcast range, it cannot be reached by a simple broadcast transmission. The AP needs to concentrate all transmission power into a narrower directed beam so that it reaches the user. An arising issue concerns the polling protocol that should be devised, such that the AP acquires the spatial signatures of users out of broadcast range in a fast and reliable manner. Towards this end, the AP can use beamforming to send polling messages with long range directed transmissions. The AP sequentially steers the beam towards different directions, so that the entire space is covered. In this case we have maximum range polling through successive directed transmissions that scan the space. The objective of the protocol is to locate all users as fast as possible.

The AP can select between contention-free and contention-based polling with directed transmissions in order to locate users out of broadcast range. In contention-free polling, the space is successively scanned by a beam until the user is located and the procedure is repeated for all users. In contention-based polling, the space is successively scanned by a beam in a different direction and the contention among users in a beam is resolved before proceeding to the next beam. The absence of contention in contention-free polling is the advantage of this method over contention-based polling. However, the time consumed in scanning the space to locate each user separately may be larger than the corresponding time with contention-based polling. A significant issue that arises in contention-based polling is that of the width of the beam that scans the space. If a large beam width is used, fewer beams are needed to scan the space and the required time to scan the space 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 users. A similar tradeoff holds for small beam widths as well.

We address the problem of extending the coverage range of the AP by providing media access to users that are located out of its broadcast range. We describe contention-based and contention-free protocols and analyze their performance with respect to several involved parameters.

B. *Contention-based polling with directed transmissions*

When contention-based polling is employed, the AP forms successive directed beams and scans all the space. The AP attempts to locate all users within a beam before proceeding to the next beam. For now assume that the AP employs directed transmission for all users, regardless if they are in or out of broadcast range.

Time is divided in slotted intervals that are referred to as contention resolution intervals (CRI). Each CRI consists of L contention slots. At the beginning of a CRI, the AP sends a polling message by using directed transmission. The polling message does not contain the address of any user. Each user that is illuminated by that beam receives the message and responds by sending back a polling acknowledgement (P_ACK) message that contains a preample and the user address. If only one user sends a P_ACK, the message is received correctly by the AP and the spatial signature of the user is obtained with the help of the preample. In that case, the AP informs the user that his spatial signature is known, by sending him an ACK message with his address. However, if there are multiple users in the beam, their P_ACK messages collide at the AP. The AP then does not issue an ACK to users in the beam and users are informed about the collision and the upcoming contention. A simple method is used for resolving the collisions: each user with a collided P_ACK retransmits with probability p in each of the subsequent L slots in the CRI. If one user happens to transmit alone in one slot, the message of this user is resolved. Then, the AP informs the user that his P_ACK is obtained (and hence his spatial signature is known) by sending an ACK message to the user, so that he defers from transmission in the next slots. If no user sends a P_ACK in a slot following the polling message, the AP assumes that no user is located in the beam or that all users have been resolved in previous slots. It then proceeds by forming the next beam. If the CRI expires and the AP does not have any indication that all users have been resolved, it initiates the next CRI by sending a polling message again. The procedure is repeated for the remaining unresolved users, until the AP has an indication that all users in the beam are resolved.

Our assumption for using a fixed retransmission probability p in each slot is justified as follows. Assume that there exist n unresolved users in a beam. The probability that one user transmits in a slot and therefore succeeds in transmission is $p_s(n) = np(1-p)^{n-1}$. This probability is maximized for $p^* = 1/n$, which depends on the number of unresolved users. Ideally, the AP could instruct users to retransmit with probability p^*, so as to improve the chances of a successful transmission. The problem is that the AP is not aware of the number of users in a beam and therefore it does not know the number of unresolved users at each step of the procedure. Thus, we resort to a fixed value p.

Let us now compute the expected time $d(n)$ to obtain the spatial signature of n users in a beam. Let X_p, X_{p_a} and X_a denote the time length of poll, P_ACK and ACK messages respectively. Define $p_{i,n,L}$ as the probability that i out of n users have already been resolved successfully in L contention resolution slots. Then, $p_{1,n,1} = p_s(n)$ and $p_{i,n,L} = 0$ if $i > n$ or $i > L$. For all other cases, $p_{i,n,L}$ can be computed with the recursive equation,

$$p_{i,n,L} = p_s(n)p_{i-1,n-1,L-1} + (1-p_s(n))p_{i,n,L-1}. \quad (1)$$

For the time delay $d(n)$, we have $d(0) = L_p$ and $d(1) = L_p + L_{p\_a} + L_a$, while for $n \geq 2$ it is

$$d(n) = \sum_{k=0}^{n} p_{k,n,L}\left[X_p + X_{p\_a} + LX_{p\_a} + kX_a + d(n-k)\right]. \quad (2)$$

In the beginning of a CRI, a polling message is sent and the polling response from users (collided or not) is received. If k out of n users are resolved in L contention slots, this means that the AP has received P_ACKs from users that retransmit in the intervals following each one of the L contention slots and it has sent k ACKs to resolved users. The term $d(n-k)$ accounts for the fact that $n-k$ users still need to be resolved.

We now compute the expected time $D(N,B)$ to resolve all N users and obtain their spatial signatures when the space is covered by B successive directed transmissions. Let $q_{i,N,B}$ be the probability that i out of N users reside in a beam. Assuming that users can reside in each of the B beams with probability $1/B$, $q_{i,N,B}$ is given by

$$q_{i,N,B} = \binom{N}{i}\left(\frac{1}{B}\right)^{i}\left(1-\frac{1}{B}\right)^{N-i} \tag{3}$$

and the delay $D(N,B)$ can be computed recursively as,

$$D(N,B) = \sum_{i=0}^{N} q_{i,N,B}\left[d(i) + D(N-i,B-1)\right] \ . \tag{4}$$

where the first term in the brackets denotes the delay to resolve i users in a beam and the second term indicates that $N-i$ users need to be resolved in the remaining $B-1$ beams.

C. Contention-free polling with directed transmissions

When contention-free polling is used, the AP again forms successive directed beams to poll users. However, polling messages now include the address of a user and are intended for that user. The AP attempts to locate one user by sequentially scanning the space with successive directed transmissions. The AP starts by sending a polling message for a user in a beam. If the user does not reside in the beam, the AP does not receive any reply and proceeds with the formation of the next beam to locate the user. If the user is found to reside in a beam, it responds by sending a P_ACK message. Upon receiving P_ACK, the AP finds its spatial signature and sends an ACK message to the user to inform him that his location is found. It then starts scanning the space for another user. The order in which users are sought is arbitrary.

The advantage of this scheme is the absence of contention among users in a beam, since only one user responds to the polling message. However the time delay to locate all N users is highly dependent on the distribution of users in the area around the AP. Clearly, the minimum time delay is achieved when all users reside in the first beam that is formed while scanning the space, while the maximum time delay occurs if all users reside in the beam that is formed last. The expected delay $D'(N,B)$ to obtain the spatial signatures of N users when covering the space with B beams is,

$$D'(N,B) = N\left(\frac{B+1}{2}X_p + X_{p\_a} + X_a\right) \ . \tag{5}$$

Indeed, for each user the AP issues $(B+1)/2$ polls on average, receives one polling response when the user is located and sends one ACK to the user.

IV. Numerical Results

A. Simulation Setup

We consider a scenario where N users are uniformly distributed in an area around an AP, so that they can reside either in or out of the AP broadcast range. The AP needs the spatial signature of all users and can poll users with omni-directional or directional transmission. At each time one beam can be formed towards a certain direction and the area around the AP is covered by B beams. For users within broadcast range, the AP may select to poll users by broadcasting or directional beamforming and can use contention-based or contention-free transmission. For users out of broadcast range, the AP can use only beamforming to poll users. The time lengths of the polling, P_ACK and ACK messages were chosen to satisfy the ratios $X_p : X_{p\_a} : X_a = 1 : 2 : 1$. This selection is justified by the fact that all messages have an address field and the P_ACK message also has a preample for spatial signature acquisition. CRIs consist of L slots. The intervals between transmission of polling messages, reception of polling responses and transmission of ACKs were not considered in the analysis.

B. Comparative Results

The performance measure is time delay until spatial signatures of users are acquired. We evaluate the performance of four schemes:

- Broadcasting/Beamforming (Broad/Beam) scheme. The AP uses contention-free broadcast polling for users in broadcast range and uses polling with beamforming for users out of range. The latter can be contention-based or contention-free.
- Beamforming/Beamforming (Beam/Beam) scheme. The AP uses polling with beamforming for all users, regardless if they reside in or out of broadcast range. The polling can again be contention-based or contention-free.

In figures 2 and 3, we illustrate the performance of the aforementioned schemes for $N = 20$ users for $B = 5$ and $B = 15$ beams. The time delay is plotted as a function of the number of users N_{out} that reside out of broadcast range. A first observation is that the performance of the Beam/Beam contention-based and contention-free schemes is independent of N_{out}, since these schemes treat users residing in and out of range the same. The time delay for contention-free schemes increases linearly with the number of users, as can be seen from (5). For $B = 5$, the Broad/Beam and Beam/Beam contention-free schemes perform better than corresponding contention-based ones. This is because the small value of B results in fast enough contention-free polling and because beams are wide enough, so that time latency due to user contention is large. When $N_{out} < 14$, Broad/Beam contention-free scheme yields the best performance. Beam/Beam contention-free scheme is more preferable when $N_{out} > 15$, because in the Broad/Beam scheme time is wasted in issuing broadcast polling messages that are not received by users residing out of range. When $B = 15$, the behavior is reversed, namely contention-based schemes incur smaller delay than contention-free ones. The large value of B makes contention-free polling time-consuming, while at the same time user contention within each beam becomes low, since beams are narrow. Broad/Beam contention-based polling yields the smallest delay when $N_{out} < 17$, while Beam/Beam with contention achieves the best performance in all other cases. From other conducted experiments for $B > 10$, it seems that Broad/Beam with contention should be selected when users out of range represent less than $75 - 80\%$ of the total number of users. Similar conclusions can be drawn from figure 4, where the ratio of number of users out of and within range, N_{out}/N_{in} was fixed to $1/2$.

V. Discussion

We addressed the problem of extending the coverage range of the AP by providing media access to users out of broadcast range with beamforming. Our primary goal was to design protocols that can be easily integrated with existing polling protocols that use omni-directional transmission. We considered the class of media access protocols with contention-based and contention-free polling and evaluated their performance in terms of required time so that the AP becomes aware of user locations and grants access to the system.

There exist several directions for future study. An interesting situation arises if the AP is equipped with several transceivers. Then, multiple beams can be formed to scan the space simultaneously towards different directions, so that the time required to locate users is reduced. A synergy between beams could further improve protocol performance. Furthermore, the possibility of adapting beam width in different stages of the algorithm, depending on the outcome of the contention resolution process is another issue that deserves further investigation.

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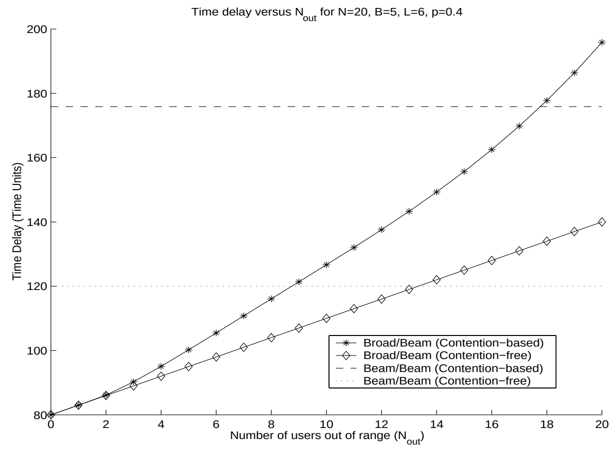

Fig. 2. Time delay as a function of number of users out of broadcast range for $N = 20$ users when $B = 5$ beams scan the space.

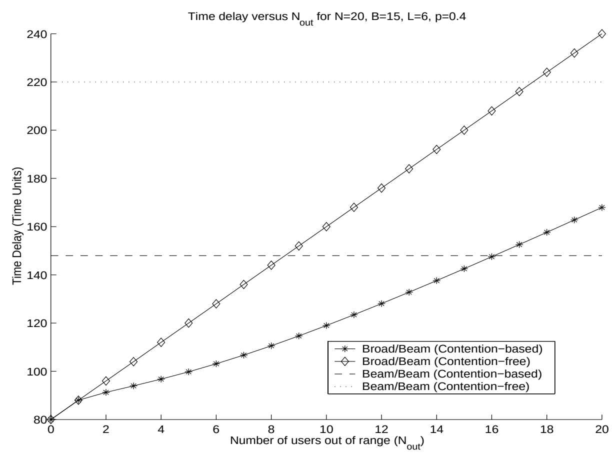

Fig. 3. Time delay as a function of number of users out of broadcast range for $N = 20$ users when $B = 15$ beams scan the space.

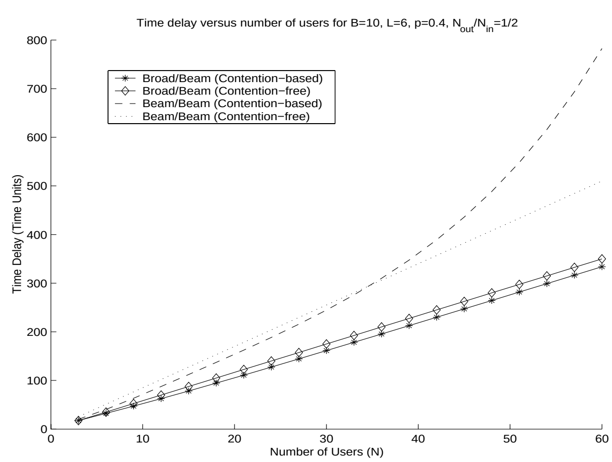

Fig. 4. Time delay as a function of number of users, when ratio $N_{out}/N_{in} = 1/2$ and $B = 10$ beams scan the space.