MAC Layer Performance with Steerable Multibeam Antenna Arrays

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Abstract— **In this paper, we are concerned with the performance at the media access control (MAC) layer of the protocol stack when multibeam adaptive antenna arrays are employed at the base station site. Specifically, we analyze the performance of slotted ALOHA when the base station receiver uses multibeam antenna arrays capable of *steering* the beams selectively on smaller sectors. The effect of different beamwidths, number of beams, beam steering patterns, and beam service times on the achieved throughput-delay performance of slotted-ALOHA is evaluated. It is observed that under high load conditions steered beams with long beam service times offer better performance, whereas under light load conditions static coverage patterns are better.**

I. Introduction

The growing interest in supporting multimedia and internet applications over wireless medium demands increased capacities of wireless communication systems. Wireless bandwidth being scarce, several techniques, including frequency reuse in cellular systems and spectrally efficient modulation schemes, are employed to increase system capacity on available bandwidths. Also, it is well known that the capacities of wireless systems can be substantially increased by the use of antenna diversity [1]. Different spatial signatures of different mobile users can be exploited to separate multiple co-channel signals even if they share the same time slot or frequency band. The issue of providing adequate suppression of interfering signals at the receiver in spatial diversity reception schemes has been investigated [2, 3]. In [3], an antenna array capable of resolving the angular distribution of the mobile users as seen at the base station is used to direct beams toward either lone mobiles or groupings of mobiles, for both transmit and receive modes of operation has been investigated. Most of the studies on antenna arrays are concerned mainly with signal processing needed to realize spatial diversity by direction-of-arrival estimation and beam forming, optimum diversity combining and equalization, evaluation of outage probability and average probability of error, etc.

In this paper, we are concerned with the performance at the media access control (MAC) layer of the protocol stack when *steerable* multibeam antenna arrays are employed at the base station site. In [4], the performance of slotted ALOHA using an antenna array system where multiple beams capable of being directed on a user with a packet arrival while creating nulls on other users in the system has been studied. In [5], the authors studied the performance of a random access protocol using a single beam antenna capable of illuminating any pointing angle over a given beamwidth. It was shown that adding space selectivity using a single narrow beam does not provide any stable throughput advantage compared to a system using an omni-directional antenna. Here we investigate the benefit of providing simultaneous space diversity using multiple narrow beams, i.e., when the base station uses n beams ($n \geq 1$) each with a beamwidth of θ radians. Specifically, the effect of different beamwidths, number of beams, beam steering patterns, and beam service times on the achieved throughput-delay performance of slotted-ALOHA is evaluated. A simple beam steering pattern which periodically shifts the direction of beam(s) by an angular amount equal to the the beamwidth is considered.

The paper is organized as follows. In Section 2, we provide a brief overview on multibeam adaptive antenna arrays. In Section 3, the system model and the throughput analysis of the steerable multibeam slotted ALOHA system under consideration is presented. Simulation results on the throughput-delay performance are presented in Section 4. Section 5 provides the conclusions.

II. Multibeam Adaptive Antenna Arrays

In an adaptive antenna array, the radiation pattern, frequency response and other parameters are modified based on adaptive control, with the aim of reducing the sensitivity in the direction of unwanted signals (interference) [3],[6]. A typical antenna array consists of a number of antenna elements coupled together via some form of amplitude and phase shifting network to form a single output. An N-element antenna array with associated beam forming network under adaptive control is shown in Figure 1. Several geometries of the antenna elements are common; e.g., uniform line, circular, and planar arrays. In the case of circular array geometry, the beams can be steered through 360° which, in turn, can provide full azimuth coverage from a central base station. The antenna elements are typically placed $\lambda/2$ apart, where λ is the wavelength of the received signal. Greater than $\lambda/2$ spacing improves the spatial resolution of the array; however, it also results in formation of side lobes which is undesirable. The amplitude and phase weighting network can be optimized to steer beams (a radiation pattern maxima of finite width) in a specific direction or directions. Even though the array in Figure 1 shows a single ouput signal, multiple output signals can be obtained from the same set of antenna elements by applying multiple sets of weights. Each set of weights yields a different array output signal, representing a different beam. It has been shown that an N element array has

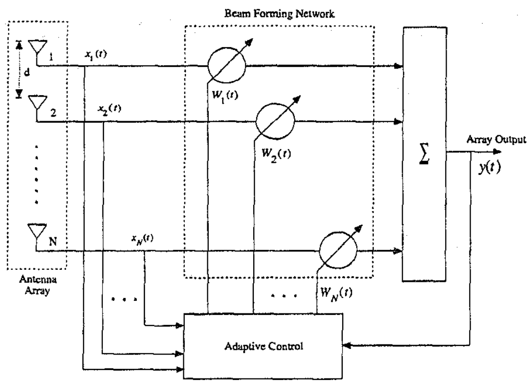

Fig. 1. N-Element Antenna Array with Adaptive Beam Forming Network

$N-1$ degrees of freedom providing up to $N-1$ independent pattern nulls [6].

In principle, multiple beam antenna arrays can be used to track, in azimuth, each mobile (or a group of mobiles) using directive narrow beams. The directive nature of the beams ensures that the interference levels seen by any given user will be far less than when conventional wide coverage base station antennas are employed. In the context of random access protocols at the MAC layer, this would imply reduced probability of collision among packets transmitted from geographically separated mobile users. The focus of this paper would be the evaluation of the throughput-delay performance at the MAC layer when steerable multibeam antenna arrays (with idealized beam patterns) are used at the base station receiver, rather than the issues surrounding antenna array design themselves.

III. System Model and Analysis

We consider a circular cell with its base station located at the center of the cell. Mobile users are assumed to be uniformly distributed over the cell area. A slotted channel is shared by all the mobiles on the reverse link (mobile-to-base station link) for sending data packets to the base station. The base station receives packet transmissions from the mobiles through n, $n \geq 1$, different but spatially separated beams, each having a width of θ radians. The beams are assumed to have idealized, non-overlaping patterns, focusing on perfect 2-dim cones of angle θ in given directions on the two dimensional plane as shown in Figure 2. The beamwidth θ is chosen such that $\theta \leq \frac{2\pi}{n}$.

- If $\theta = \frac{2\pi}{n}$, the entire cell area is illuminated without any "hole" in coverage at any given time; for example, $n = 1$ corresponds to an omni-directional beam pattern covering the full azimuth range from 0° to 360°, and $n = 3$ corresponds to the classical 3-sector scheme with a beamwidth of 120°. We refer to this scenario as the *static beam* scenario, where steering of beams over time is not performed (i.e., the amplitude and phase weights of the array can be fixed).
- On the otherhand, if $\theta < \frac{2\pi}{n}$, the cell area is partially illuminated at any given time, leaving "holes" in coverage. The angular width of the unilluminated holes will be $(\frac{2\pi}{n} - \theta)$. In this case, to achieve full coverage over the cell area, the direction of the beams are to be steered over time, by using appropriate array weights. We refer to this scenario as the *steered beam* scenario. A simple beam steering pattern, in such a case, would be to periodically shift the direction of beam(s) by an angular amount equal to the beamwidth θ. By doing so, the entire cell area can be swept once in $\lceil \frac{2\pi}{n\theta} \rceil$ angular shifts. The time allowed between the angular shifts will then be the service time available to the corresponding illuminated segments in the cell area. The considered beam patterns for $n = 1, 2, 3$ are illustrated in Figure 2.

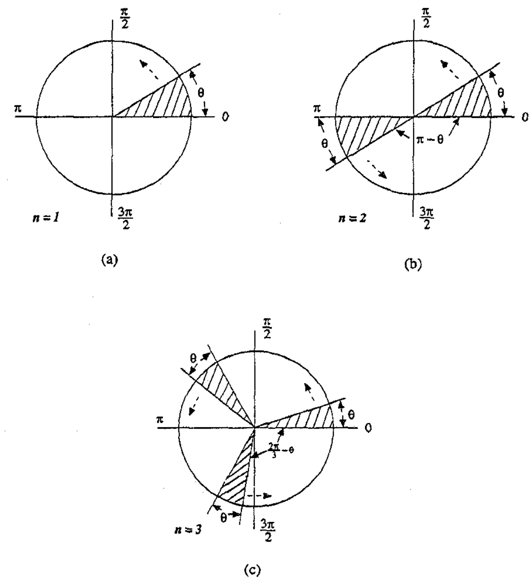

Fig. 2. Antenna Beam Steering Patterns. a) $n = 1$, b) $n = 2$, c) $n = 3$. $\theta < \frac{2\pi}{n}$

Because of spatial diversity, multiple packets sent on the same slot, but from mobiles illuminated by different beams, can be successfully received by the base station. Here we assume that packet losses occur only due to collision among simultaneous packet transmissions on the same beam. Packet losses due to physical layer characteristics like multipath fading and capture will be considered in a future investigation.

A. Throughput Analysis

Consider a infinite user population model with mobile users uniformly distributed over the call area of unit circle. Let the packet arrival process be Poisson distributed with an offered load of G packets per slot into the system. The beamwidth and number of beams (n, θ) are chosen such that $\theta \leq \frac{2\pi}{n}$ (e.g., for $n = 1$, $0 < \theta \leq 2\pi$, and for $n = 2$, $0 < \theta \leq \pi$). The packet arrival process in each beam is also Poisson distributed with an offered load, given by,

$$G' = \frac{\theta}{2\pi} G. \tag{1}$$

Since the beam patterns are considered to be ideal and non-overlaping, packet transmissions from one beam does not in-

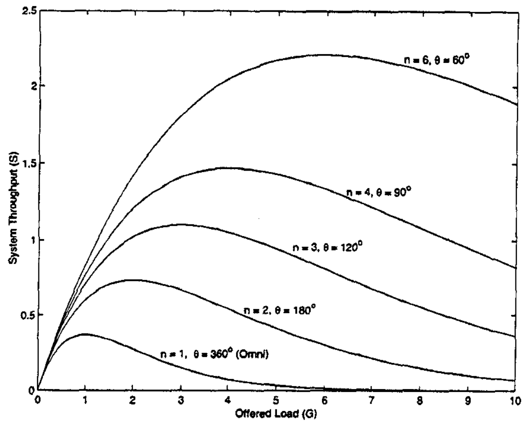

Fig. 3. System throughput (S) versus offered load (G) performance of *static beam* scenario for $(n, \theta) = (1, 2\pi), (2, \pi), (3, \frac{2\pi}{3}), (4, \frac{\pi}{2}), (6, \frac{\pi}{3})$.

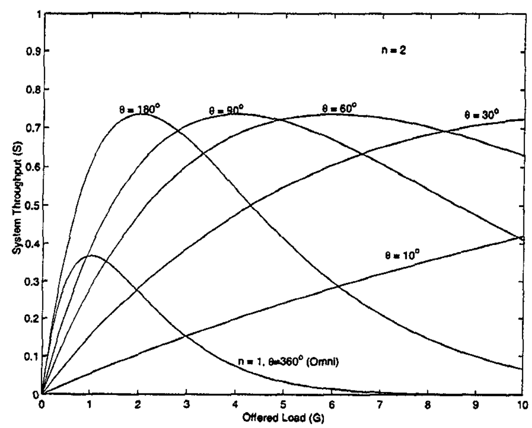

Fig. 4. Throughput performance of *static beams* with no coverege holes ($n = 2$, $\theta = \pi$) versus *steered beams* with holes in coverage ($n = 2, \theta = \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$).

eterfere with transmissions from any other beam, and hence the throughput on each each beam, S', is given by

$$S' = \frac{\theta}{2\pi} G e^{-\left(\frac{\theta}{2\pi} G\right)}, \quad (2)$$

and the aggregate system throughput, S, is given by

$$S = n \frac{\theta}{2\pi} G e^{-\left(\frac{\theta}{2\pi} G\right)}, \quad (3)$$

It is easy to see, from (3), that the offered load at which the maximum throughput occurs is given by

$$G_{max} = \frac{2\pi}{\theta}. \quad (4)$$

Note that for the *static beam* scenario with $\theta = \frac{2\pi}{n}$, the expression for the system throughput becomes

$$S = G e^{-\frac{G}{n}}, \quad \text{and} \quad G_{max} = n. \quad (5)$$

For both the *steered beam* as well as the *static beam* scenarios, the maximum achived system throughout, S_{max}, is given by

$$S_{max} = n e^{-1}, \quad (6)$$

which remains independent of the beamwidth θ.

Figure 3 shows the throughput performance plots for *static beam* scenarios, obtained from (5), when $(n, \theta) = (1, 2\pi)$, $(2, \pi)$, $(3, \frac{2\pi}{3})$, $(4, \frac{\pi}{2})$, $(6, \frac{\pi}{3})$, in which maximum throughputs of ne^{-1} are seen to occur at offered loads of n. Figure 4 shows a performance comparison between *static beam* versus *steered beam* scenarios when $n = 2$. Note that in Figure 4, $\theta = \pi$ corresponds to two static beams with no coverage holes, and $\theta = \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$ correspond to two steered beams with holes in coverage. The performance achieved using one omni-directional beam ($n = 1$, $\theta = 2\pi$) is also illustrated. From Figure 4 it can be seen that static beams with no coverage holes offer better throughput compared to steered beams with holes in coverage, when the offered load is low. However, at high offered loads the steered beams results in better throughput compared to static beams. This is mainly because, at high loads, the spatial separation of beams becomes increasingly beneficial due to no interference from mobile users in the holes.

The offered load at which the static beams versus steered beams performance crossover occurs varies as a function of number of beams n, and beamwidth θ. From (3) and (5), this crossover load $G_{crossover}$ at which both static beams and steered beams offer same system throughput can be derived as

$$G_{crossover} = \frac{2\pi n}{n\theta - 2\pi} \ln\left(\frac{n\theta}{2\pi}\right). \quad (7)$$

Figure 5 shows the variation of achieved throughput at $G_{crossover}$, as a function of beamwidth θ for $n = 1, 2, 3, 4, 6$. In the context of the above performance crossover, a drift analysis [8] of the system to address the stability issues is the topic of an ongoing investigation.

IV. Simulation

The static and steered beam scenarios with different number of beams, beamwidths and beam service times have been simulated. In the simulations, a finite user model with M mobile users uniformly distributed over the circular cell area is considered. The beams are illuminated, in a given direction, continuously for K slots time. After this beam service time (BST) of K slots in a given direction, the direction of the beam(s) are shifted (counter clockwise) by an angular shift equal to the beamwidth. This beam shifting process is carried out periodically, synchronous to the slot timing, once every K slots. New packets arrive at each user node with probability p in each slot. Users in illuminated areas whose packet transmissions are lost due to collision, and users who get new packet arrivals when they are not illuminated (i.e., user in a hole) enter into a backlogged mode. In the backlogged mode, users make retransmission attempts with probability p_r in each slot. Users in backlogged mode reject new packet arrivals until the backlogged packet is successfully sent to the base station.

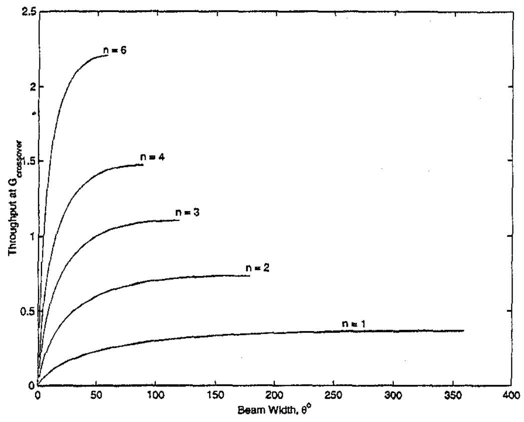

Fig. 5. Throughput achieved at $G_{crossover}$ versus θ (in degrees) for $n = 1, 2, 3, 4, 6$.

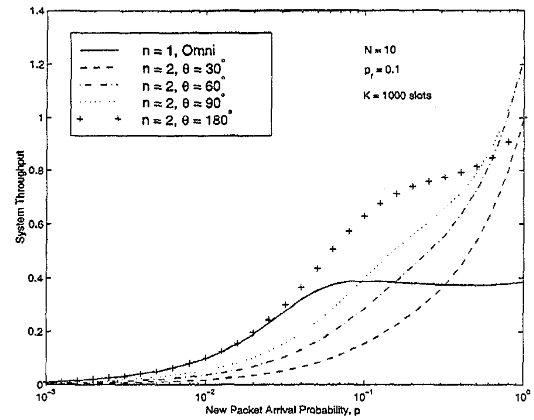

Fig. 6. System throughput versus new packet arrival probability p, for $n = 2$ at different values of θ. $N = 10$, $p_r = 0.1$, $K = 1000$ slots.

Figure 6 shows the system throughput performance as a function of new packet arrival probability p when $N = 10$, $p_r = 0.1$, and beam service time $K = 1000$ slots. The p_r value of 0.1 implies an average of 10 slots delay between retransmission attempts by the backlogged nodes. Figure 6 shows the performance plots for $n = 1$, $\theta = 2\pi$ (i.e., omni-directional beam pattern) as well as for $n = 2$ with different values of θ, namely π, $\frac{\pi}{2}$, $\frac{\pi}{3}$, $\frac{\pi}{6}$. The plot corresponding to $\theta = \pi$ corresponds to the *static beam* scenario, whereas the plots for other θ values less than π correspond to the *steered beam* scenario. For the same set of parameters in Figure 6, Figure 7 gives the system throughput versus mean packet delay performance plots. As in the anlytical performance plots in the previous section, a performance crossover between static versus steered beam scenarios is observed in Figure 6. That is, at low values of p, static beams ($\theta = 180°$) offer larger throughputs than steered beams. On the other hand, steered beams (e.g., $\theta = 60°, 90°$) offer larger throughput at high values of p. From the throughput and delay performances in Figures 6 and 7, it can be seen that, for the 2-beam system considered, 60° beams ($\theta = \frac{\pi}{3}$) is a good choice for $p > 0.5$ and 180° beams ($\theta = \pi$) are desired for $P < 0.5$.

Figures 8 to 11 illustrate the efect of beam service time K on the system throughput and mean delay performance for $N = 10$, $p_r = 0.1, n = 2$ and $\theta = \pi, \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$. Figures 8 and 9 show the plots for $p = 1$ (high arrival rate), and Figure 10 shows the plots for $p = 0.01$ (low arrival rate). It can be seen that long beam service times are preferred at high arrival rates, whereas short beam service times are desired at low arrival rates.

V. Conclusions

The throughput-delay performance of slotted ALOHA was evaluated when steerable multiple beam antenna arrays are used at the base station site. Performances achieved using multiple static beams versus multiple steered beams were compared. A simple beam steering pattern that periodically shifts the direction of beam(s) by an angular amount equal to the the beamwidth was considered. Preliminary investigations showed that, under light load conditions, static beams without coverage holes offered better throughput than steered beams with holes in coverage. However, under heavy load conditions, steered beams with long beam service times performed better. This is because spatial steering of beams was increasingly beneficial, due to no interference from mobiles in the unilluminated areas (holes). In the context of the above performance crossover of static beam versus steered beam scenarios, a drift analysis to address the stability issues is being pursued. The effect of physical layer characteristics like fading and capture, and design of smart MAC protocols that jointly consider beam steering patterns and access rules are useful topics for further investigation.

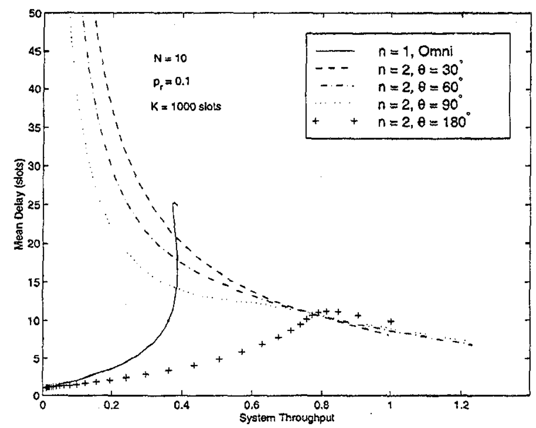

Fig. 7. Throughput-delay performance for $n = 2$ at different values of θ. $N = 10$, $p_r = 0.1$, $K = 1000$ slots.

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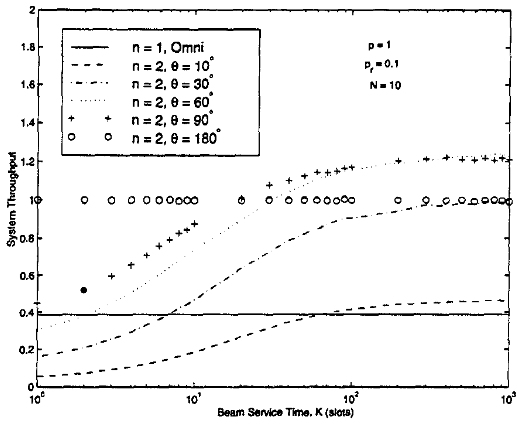

Fig. 8. System throughput versus beam service time K, for $n = 2$ and $\theta = \pi, \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$. $N = 10, p = 1, p_r = 0.1$.

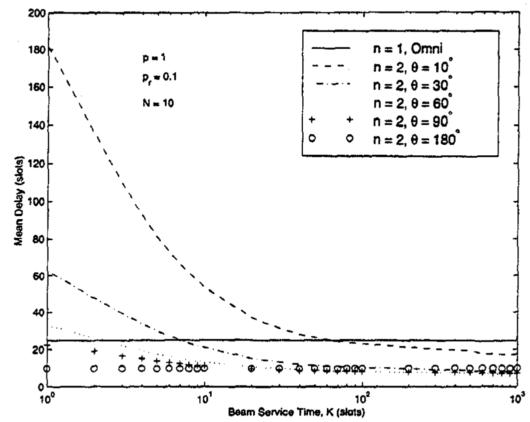

Fig. 9. Mean delay versus beam service time K, for $n = 2$ and $\theta = \pi, \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$. $N = 10, p = 1, p_r = 0.1$.

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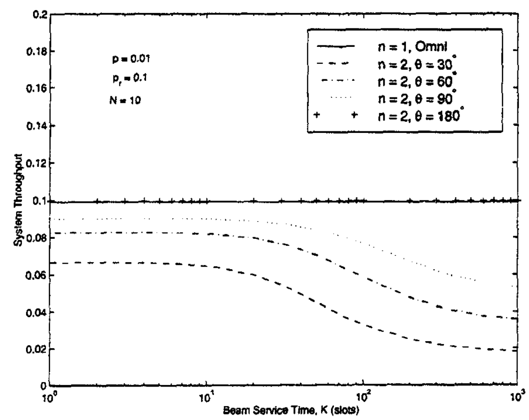

Fig. 10. System throughput versus beam service time K, for $n = 2$ and $\theta = \pi, \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$. $N = 10, p = 0.01, p_r = 0.1$.

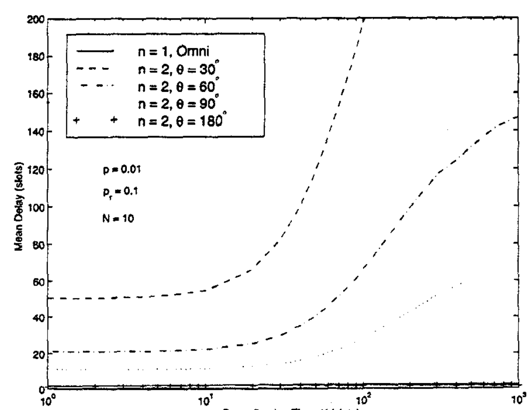

Fig. 11. Mean delay versus beam service time K, for $n = 2$ and $\theta = \pi, \frac{\pi}{2}, \frac{\pi}{3}, \frac{\pi}{6}, \frac{\pi}{18}$. $N = 10, p = 0.01, p_r = 0.1$.