Carrier-Sense Protocols for Packet-Switched Smart Antenna Basestations

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Abstract

Researchers have recently considered the use of smart antennas in various packet-switched data networks [1, 2, 3]. In [4], a single-beam system was described which employs a smart antenna basestation operating in carrier-sense (CSMA) mode. Performance improvements are obtained by having the antenna dynamically point pattern nulls in the direction of interfering stations, thus reducing the frequency of channel collisions.

In this paper, we consider the reverse-link performance of stations accessing a smart antenna basestation using multibeam *SDMA. A basic CSMA/SDMA protocol is first proposed for this type of system. Following this, we also present a CSMA/SDMA protocol which incorporates basestation/portable signalling which mitigates the effects of hidden stations. The performance of these systems is characterized and compared using analytical throughput and capacity models. It is shown that when hidden stations are present, the capacity performance of the more sophisticated protocol may be much higher than that of the basic version.*

1. Introduction

In many wireless systems, mobile stations communicate through a basestation which is attached to the wired network. As transmission rates increase, and as networks are deployed in a larger variety of propagation environments, successful systems will have to adapt to a much larger range of operating conditions than is currently the case. In recent years many researchers have shown that smart antennas can improve the link performance in various types of wireless systems.

Recently adaptive arrays have also been considered in packet-switched systems. In [1] smart antennas are used to improve the performance of a slotted ALOHA packet radio network. A multiple-beam adaptive array was proposed in [5] in which each beam-module of the array captures a different packet by automatically pointing its maximum at one packet and nulling out the others. This capability of resolving multiple packets at the same time and frequency is referred to as space division multiple access or SDMA. SDMA has the potential for large increases in system capacity and has recently been studied in [2, 3].

In [4], a single-beam system was described which employs a smart antenna basestation operating in carrier-sense (CSMA) mode. In this system, performance improvements can be obtained by having the antenna dynamically point pattern nulls in the direction of interfering and hidden stations. This effectively suppresses colliding users thus reducing the effects that collisions have on system performance.

In this paper we consider the performance of a set of portable stations communicating with a smart antenna basestation operating in *multibeam* SDMA mode. To accommodate this, the basestation contains several beamforming modules, each of which is capable of directing a beam at a desired packet transmission. Stations access the channel using a form of CSMA which has been adapted to accommodate the smart antenna basestation. We assume that the system operates using time division duplexing (TDD) and focus on the problem of access to the basestation by the portables in the reverse-link direction. The problem of packet-switched TDD operation in the forward link direction has been recently considered in [2].

In [6], a reservation mechanism based on RTS/CTS packet exchanges is combined with CSMA. This may dramatically improve system performance by help-

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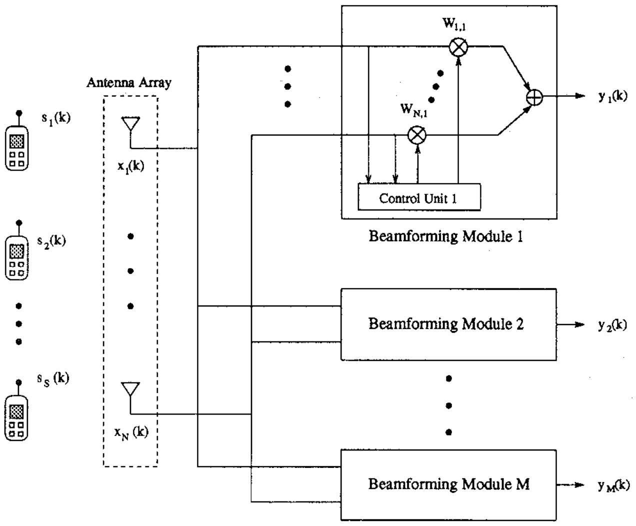

Figure 1. Multibeam Smart Antenna Basestation

ing to prevent packet corruption due to hidden stations. In this paper we also present a new multibeam CSMA/SDMA protocol which incorporates this feature. Corruption due to hidden terminals is alleviated using signalling performed by the basestation. We also give throughput and capacity models for the systems being considered.

2. Smart Antenna Basestation

Figure 1 shows a block diagram of the system considered. The basestation has a smart antenna with N elements, and communicates with a set of portable stations. The portable stations are much simpler in design and use single omnidirectional (OMNI) antennas. We will assume that the system considered uses time division duplexing (TDD). In this paper we focus on the operation of the system in the reverse link (i.e., portable to basestation) direction.

When there are a number of simultaneous transmissions, the basestation attempts to receive up to M packets simultaneously by forming multiple antenna beam patterns, one optimized for each received signal. This is illustrated in Figure 1 which shows M parallel beamforming modules operating independently. The receiver maintains a different set of weights in each beamforming module and each attempts to optimize that beam performance for one particular station. In the following discussion, we focus on the activities of a single module.

From Figure 1 the received basestation signal vector at time sample k is defined by

$$\mathbf{x}(k) = [x_1(k)\, x_2(k) \cdots x_N(k)]^T. \tag{1}$$

For the beamforming module of interest, the received signal $\mathbf{x}(k)$ is the superposition of the desired signal, interfering signals, and noise. If the signal transmitted by station j is $s_j(k)$, and the channel is not varying with time, then the received signal can be written as

$$\mathbf{x}(k) = \underbrace{\mathbf{v}_d s_d(k)}_{\mathbf{x}_d(k)} + \overbrace{\sum_{\substack{i=1\\ i\neq d}}^{S} \underbrace{\mathbf{v}_i s_i(k)}_{\mathbf{x}_i(k)} + \mathbf{x}_\eta(k)}^{\mathbf{x}_u(k)}, \tag{2}$$

where $\mathbf{v}_d$ and $\mathbf{v}_i$ are referred to as the $N \times 1$ station signature (or station code) vectors of desired station d and the i^{th} interfering signal, respectively. Here $\mathbf{x}_\eta(k)$ is additive white Gaussian noise (AWGN). Note that in general, the station signatures result from a superposition of transmitted multipath components. The interfering and noise signals collectively form the undesired signal $\mathbf{x}_u(k)$, so $\mathbf{x}(k)$ can be written as $\mathbf{x}(k) = \mathbf{x}_d(k) + \mathbf{x}_u(k)$. We assume that the transmitted signal has unit power and is uncorrelated with other transmitted signals.

The mean signal to mean interference plus noise power ratio after beamforming is

$$\text{SINR} = \frac{E[|\mathbf{w}^T \mathbf{x}_d(k)|^2]}{E[|\mathbf{w}^T \mathbf{x}_u(k)|^2]}, \tag{3}$$

where $\mathbf{w}$ is the $N \times 1$ complex weight vector. The value of $\mathbf{w}$ which maximizes (3) is

$$\mathbf{w}_{opt} = \mathbf{\Phi}_u^{-1} \mathbf{v}_d^*, \tag{4}$$

where $\mathbf{\Phi}_u = \sigma_\eta^2 \mathbf{I} + \sum_{\substack{i=1\\ i\neq d}}^{S} \mathbf{v}_i^* \mathbf{v}_i^T$ is the $N \times N$ undesired signal covariance matrix [7]. Here, σ_η^2 is the noise power per element. In the ensuing sections we use the optimal SINR beamforming defined above to evaluate the performance of the smart antenna basestation. SNR is defined to be the mean signal power to mean noise power ratio at each antenna output before beamforming.

3. Multibeam SDMA/CSMA Protocols

In the systems considered, a set of portable stations access a single reverse link channel. The basestation attempts to resolve as many simultaneous transmissions as possible using its smart antenna and multiple beamforming modules. In this case, the normal CSMA

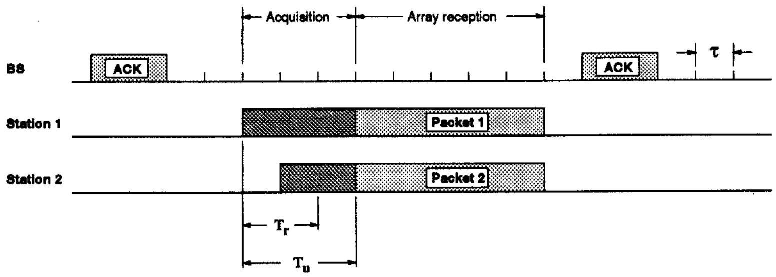

Figure 2. Basic Multibeam CSMA

objective of isolating a single active station is not desirable. Instead, we would like to resolve several simultaneous transmissions and carrier-sensing is used to synchronize the acquisition process for the smart antenna basestation.

To assist in the acquisition of multiple transmissions, we use a variation of the method first described in [5]. In [5], each transmitted packet is prepended with three or more periods of a preselected pseudo-noise bit sequence (PN). The sequence is chosen so that it is highly uncorrelated with time-shifted versions of itself. When multiple stations transmit, the incoming signal is correlated with the PN sequence. Each time a new packet is detected by the correlator, antenna beamforming is performed based on the PN sequence itself. When this acquisition phase is completed, the antenna beams are frozen and multiple packet reception is possible.

In the design considered in this paper, a set of R PN sequences is used for this purpose. As in certain CDMA designs, the sequences are chosen so that they have a high degree of mutual orthogonality. When a station accesses the channel, it randomly chooses a PN sequence from this set and uses it in the acquisition procedure discussed above. It should be noted that the technique proposed in [5] may not be efficient here, since two or more stations using the same PN code and whose transmissions overlap exactly at the basestation will be correlated and improper beamforming will occur. The additional diversity provided by the code set is used to reduce the chances of this happening. However, the basestation must now have R matched filter receivers, as discussed below. These aspects of the system are in addition to that proposed in [4], where only a single beam is formed. The advantage here however, is that unlike [4], multiple packets can be received at the basestation simultaneously. We now describe the basic CSMA/SDMA protocol.

Basic Multibeam CSMA (MB-CSMA): In Figure 2 an example is shown of the basic multibeam CSMA protocol. In the figures we assume that the protocol operates with a mini-slotted time base. This is done for convenience only and a non-slotted version of the protocol would typically be used in practice.

As in conventional CSMA, stations must first sense the channel to be idle prior to transmitting. In this version however, when the channel becomes busy, this transition defines the start of an "uncertainty interval" of duration T_r seconds. During this interval any station generating a packet is free to commence transmitting. The intent is to accumulate a set of packets for the basestation antenna to resolve and to randomize their starting times so that acquisition may occur. Once this acquisition phase is over, carrier-sensing inhibits other stations from transmitting, as in conventional CSMA. This is to prevent them from corrupting transmissions which are being successfully received at the basestation. Note that timing skews associated with the start of the uncertainty interval are not critical, and may in some cases improve performance by staggering simultaneous transmissions.

In the example in Figure 2, Station 1 senses the idle channel and starts a busy period. Upon seeing this activity, the other stations become aware that the T_r uncertainty interval has begun. Any station generating a packet in this interval is still free to transmit. As shown, Station 2 generates a packet and starts transmitting one minislot later. Following the T_r interval, stations revert to carrier-sensing to determine when to transmit. Note that each station transmits its chosen PN sequence repeatedly until a time T_u beyond the start of the busy period. Antenna beamforming takes place during the interval between the ends of the T_r and T_u time intervals.

At the basestation, a set of R matched filters continually correlates the incoming signal (received in OMNI mode) with the PN sequences. An output from a correlator will be generated when the first PN sequence occurs in the input. In response to this, the first beamformer begins adapting its antenna beam to this desired signal. Subsequent appearances of PN sequences in the input trigger each successive beamformer, which begins adapting its beam pattern for the appropriate packet.

Note that a packet can only be acquired if the offset in time between it and all others exceeds one transmitted bit-time or if the offset is less than one bit and it is using a different PN code. In [5] further details of this process are discussed. In this paper we assume that the length of the PN sequences and R are chosen so that the probability of non-acquisition due to code collisions is small compared to the probability that beamforming cannot be achieved.

When a multibeam transmission is finished, the basestation broadcasts an ACK in OMNI mode, which acknowledges those packets which have been correctly received. Those stations which were unsuccessful then randomly backoff and try again, as in conventional CSMA. The proposed CSMA protocol includes a low priority inter-frame space (LIFS) of the kind used in IEEE 802.11 [6]. Stations which access the channel in CSMA mode use LIFS which is defined to be large enough so they do not interfere with high priority frames. ACKs are transmitted using a zero-length IFS so that they cannot be collided with.

It is apparent that in the MB-CSMA protocol, the intended operation is only assured if all stations hear at least one of the transmitted packets. However, in many wireless networks the stations may have very poor inter-station connectivity due to various fading and shadowing effects [8]. For this reason, transmissions by hidden stations may corrupt otherwise successfully transmitted packets. In IEEE 802.11 [6], a technique for improving performance in the presence of hidden terminals is used. Rather than transmitting a complete packet, stations transmit a short RTS packet first. Following this, the station waits for a CTS acknowledgement. If hidden stations see either of these packets, then they will differ their own transmission until the transmission period has completed. In the protocol described next, we use a similar mechanism to prevent hidden terminals from transmitting in the multibeam smart antenna case.

MB-CSMA with Hidden Station Blocking (MB-CSMA-HSB): In this protocol, hidden terminals are prevented from interfering with packet acquisition and transmission. To coordinate things, the basestation explicitly signals the start of each possible contention interval. It is during a contention interval that stations may access the channel using CSMA, thus competing for transmission. The signalling of contention intervals is done in two different ways. The first is by setting a "Beacon" bit in an acknowledgement packet at the end of a transmission interval. When this ACK is used it is referred to as a B-ACK and is broadcast to all stations in OMNI mode so that receiving stations are aware of the start of the new contention interval. In addition to the B-ACK mechanism, the basestation may broadcast a short "Beacon frame", or B-FRAME which signals the same information. Note that when the channel is idle, the time period used between successive B-FRAME transmissions is just *greater* than the "coherence time", t_c, of the channel [8]. This time period is such that channel conditions are relatively constant over this interval. In indoor channels operating in the 1 GHz range for example, t_c would typically be 10's to 100's of msecs [9]. After receiving a successful B-ACK or B-FRAME, any station is enabled to transmit in accordance with the usual rules for CSMA. However this permission to transmit is only valid for a timeout interval of t_c seconds, after which the station is inhibited from transmitting until it receives another B-ACK or B-FRAME.

The intent of the above procedures is that only those stations which are currently within OMNI reception range of the basestation are enabled for channel acquisition. Stations which are experiencing local channel fades must wait until they have B-ACK/B-FRAME connectivity with the basestation. It can be seen that with these procedures in place, stations cannot inadvertently corrupt basestation receptions which might otherwise occur. This is because the protocol strongly restricts contending stations to those which are currently within range of the basestation. After timing out, a station must ensure that it still has this connectivity before attempting to transmit.

During the period the B-ACK or B-FRAME packets are being sent, each portable also measures its received power. When engaging in the acquisition process discussed below, stations transmit so that their received power at the basestation is the same.

An example of channel activity for this protocol is shown in Figure 3. In top diagram of Figure 3 the basestation has just transmitted a B-FRAME as described above. Following this, the channel is made available to stations using CSMA. When an enabled station generates a packet, it transmits a Reservation Beacon (RB) in the next minislot. In the figure we assume that two stations initially generate packets to be transmitted and both transmit RB's simultaneously as shown. The RB is a carrier signal burst that informs the basestation that the channel is to undergo the acquisition process. The channel is then made available for acquisition for a predetermined time period.

When the basestation detects that one or more stations have transmitted a RB, it "re-enforces" the RB by transmitting a carrier burst (in OMNI mode) for at least two minislot periods. We refer to this as an RB re-enforcement or RBR. This is to ensure that any stations hidden from other mobiles are aware of the

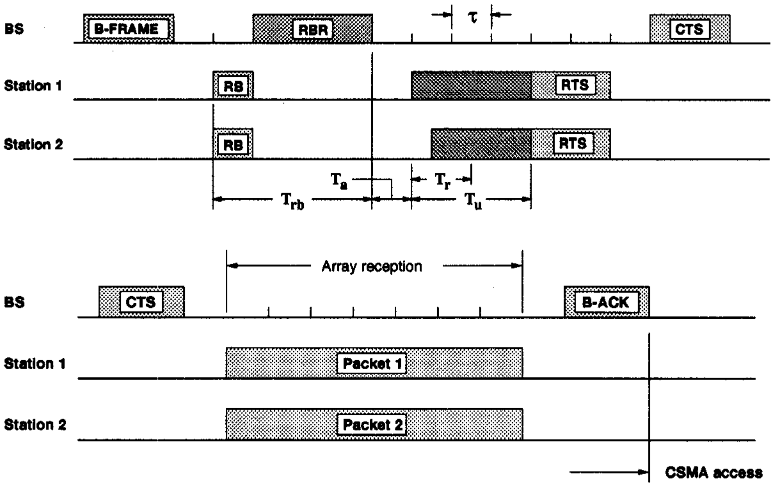

Figure 3. MB-CSMA with Hidden Station Blocking

RB so that acquisition occurs properly. The end of the RBR starts an accumulation period, T_a, during which any arrivals to the system can participate in the current acquisition cycle. After this time period expires, all non-transmitting stations are blocked from transmitting until the next contention period. At the end of the accumulation period, all participating stations then randomize the start of their RTS packet transmissions over an interval of time referred to as T_r. This is so that antenna acquisition can be attained as discussed previously. When transmitting during this interval the stations transmit by repeating their chosen PN bit sequences. This is continued for the time shown after which the RTS packet is transmitted.

Following these actions, the basestation acknowledges the successfully received packets using a CTS packet containing the identities of the stations authorized to transmit. The identified stations are then free to transmit their packets to the basestation. As discussed before, the basestation uses the antenna beams formed previously. The transmission phase of the protocol is shown in the bottom diagram of Figure 3. Upon receiving the CTS broadcast, the identified stations transmit immediately. Note that since the beamforming has already been accomplished for each of these packets, they may be transmitted immediately without any randomization in their starting times. This is followed by a single broadcast B-ACK which acknowledges the successful packets and initiates the next round of CSMA access. Note that we assume that the full busy period occurs within the coherence time of the channel, so that the beam weights can be used successfully for all acknowledged transmissions [9].

There are a number of variations to the above procedures. For example, it is possible to transmit the actual data packets in place of the RTS packets discussed above. The advantage of using the RTS/CTS scheme is that it approximates the effects of collision detection [6]. Note that in the above protocols each packet must be received with a large enough signal-to-interference-plus-noise power ratio (SINR), after beamforming, to provide for proper signal reception. For a packet to be received with a reasonable bit-error rate performance, the SINR for the packet must exceed some preselected limit, denoted by SINR_{min}.

4. Non-persistent Multibeam Throughput and Capacity

In this section we derive a throughput model for non-persistent multibeam CSMA/SDMA. The model is an extension of that first considered in [4] for the single-beam case. We first start with the MB-CSMA protocol. It is assumed that transmission arrivals to the channel occur according to a Poisson Process with mean arrival rate G'. Under this assumption, the number of stations transmitting during an uncertainty interval T_u is Poisson distributed. As in a conventional non-persistent CSMA throughput analysis, the throughput may be written as

$$S = \frac{\bar{U}}{\bar{B} + \bar{I}}, \tag{5}$$

where $\bar{U}$, $\bar{B}$ and $\bar{I}$ are the mean success time per busy period, mean busy period length and mean idle period length, respectively. In this case it can easily be shown that

$$\bar{I} = \frac{\tau e^{-\tau G'}}{1 - e^{-\tau G'}}. \tag{6}$$

We first define **A** to be the event that at least one successful beam is formed at the start of a busy period. We also define $P_L = \Pr\{\mathbf{A}\}$. The mean busy period length can be calculated as follows.

$$\begin{aligned}\bar{B} &= (T_u + T + \tau + T_{ACK} + 2\tau) \cdot P_L \\ &\quad + (T_u + T + 2\tau) \cdot (1 - P_L). \end{aligned} \tag{7}$$

Here, T is the packet transmission time. Note that under the mode of operation described, the overhead due to acquisition is fixed regardless of the number of stations. The probability P_L can be written as follows.

$$P_L = \sum_y \Pr\{\mathbf{A} |\ y \text{ Xmt}\} \Pr\{\text{y Xmt}\}, \tag{8}$$

where $\Pr\{y \text{ Xmt}\}$ is the probability that y transmissions occur in the randomization interval. Note that this probability is conditioned on the fact that there is at least one transmission in the interval since the busy period must be started by at least one transmission. The number of distinct intervals which are available for acquisition are given by $r = T_u/T_b$, where T_b is the data bit period. Using Bayes Theorem it is easy to show that

$$\Pr\{\text{y Xmt}\} = \frac{1 - (\frac{T_u - T_b}{T_u})^y}{1 - e^{-T_b G'}} \frac{(T_u G')^y e^{-T_u G'}}{y!}. \tag{9}$$

In a similar way, we can perform the computation for $\bar{U}$ as follows.

$$\begin{aligned}\bar{U} &= \sum_v \sum_y (v \cdot \Pr\{v \text{ beams resolved} \mid y \text{ Xmt}\} \\ &\quad \Pr\{y \text{ Xmt}\}). \end{aligned} \tag{10}$$

As discussed for a similar analysis [5], the first probability in Equation 10 is very difficult to obtain in closed form. This is especially true in our case since this probability is a function of the optimum SINR beamforming described in Section 2. As in [5], we derive this term by Monte Carlo simulation using a large number of randomly generated spatial codes [9].

The throughput calculation for the MB-CSMA-HSB case is very similar. In this case however,

$$\begin{aligned}\bar{B} &= (T_{RB} + T_{RBR} + \tau + T_a + T_u + T_{RTS} \\ &+ \tau + T_{CTS} + \tau + T + \tau + T_{ACK} + 2\tau) \cdot P_L \\ &+ (T_{RB} + T_{RBR} + \tau + T_a + T_u + T_{RTS} \\ &+ \tau + T_{CTS} + \tau) \cdot (1 - P_L). \end{aligned} \tag{11}$$

For the MB-CSMA-HSB protocol, the calculations performed above are almost identical. In this case however, arrivals in the interval T_a are "compressed" into T_r. This achieves the same effect as a Poisson Process with rate $G'' = G'T_a/T_r$ impinging on T_r. The calculation is done using G'' in the above expressions, in place of G'.

Mean Signal Power	1W
Mean Noise Power	0.1W
SINR_{min}	10 dB
B	1 Mbps
T_b	1/B sec
PN length	25 bits
T_u	$75T_b$
T_{RTS}	$150T_b$
T_{CTS}	$100T_b$
T_{ACK}	$100T_b$
T_{RB}	$10T_b$
T_{RBR}	$10T_b$
T_a	$18T_b$

Table 1. Parameter Values

We now discuss the throughput and capacity results using the model formulated above. In the graphs we plot the throughput vs applied Poisson load, $G = G'T$, impinging on the basestation. Unless otherwise stated in the graph, the parameter values used are given in Table 1.

In Figures 4 and 5 we show the throughput versus applied load for the MB-CSMA and MB-CSMA-HSB protocols. In both graphs similar curves are plotted for various noise power (NP) levels as indicated. In both sets of curves a 6-element smart antenna array is used with optimal SINR beamforming as discussed in Section 2. All stations are assumed to transmit with the same power and are subject to flat Rayleigh fading as discussed in [10]. This is representative of what can be found in harsh indoor multipath environments. The data packet length used is 1000 bits.

The graphs illustrate the loss in capacity as the basestation array's ability to resolve multiple stations decreases. It can also be seen that there is about a 10%-20% loss in capacity between the MB-CSMA and MB-CSMA-HSB protocols. This loss is attributed to the overhead associated with the additional signalling used in the more sophisticated protocol. These losses become higher as the noise floor increases. Also included in the graphs is the performance of single-antenna CSMA using the noise powers indicated. It can be seen that a smart antenna basestation with a 6-element array can obtain a capacity of roughly 5 times that which can be obtained without the smart antenna. It is clear from the graphs that there is much to be

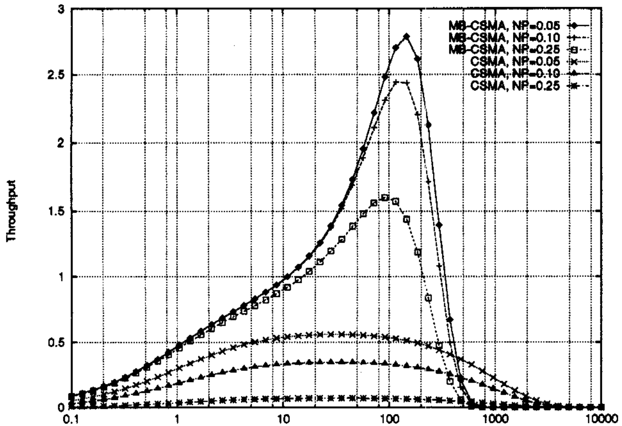

Figure 4. Throughput vs Applied Load, MB-CSMA

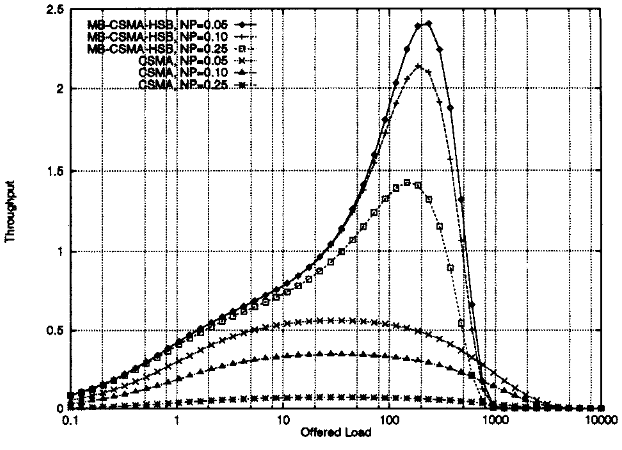

Figure 5. Throughput vs Applied Load, MB-CSMA-HSB

gained from a capacity standpoint by using a smart antenna at the basestation.

In Figure 6 the protocols are shown for 1000, 2000 and 5000 bit packet lengths. It can be seen from this curve that when larger packet lengths are used, the capacity loss due to overhead in MB-CSMA-HSB is reduced. In this case the capacity performance of the later protocol slightly exceeds that of MB-CSMA. This is attributed to the fact that the RTS/CTS mechanism acts as a collision detection mechanism by terminating unsuccessful busy periods.

In Figure 7 we compare the two protocols in the presence of hidden stations. For these results we extended the analytical model for MB-CSMA to include an upper bound on throughput due to the effects of hidden stations. This is outlined as follows.

We assume that any station generating a packet while there are z transmissions in progress will be "hidden" from each of the z stations independently with the same probability p. Therefore, an arriving packet will be considered hidden with probability p^z, i.e., it is hidden to all stations. For a transmission period during which the basestation attempts multiple receptions for t_B minislots, we calculate the distribution of the number of hidden station arrivals at the *end* of that interval. From a beamforming viewpoint, the t_B period will have accumulated hidden stations for the duration of that time. The required calculation is performed by finding the t_B-step state occupancy probabilities of a Markov chain. The states of the chain represent the number of simultaneous transmissions occurring during each slot of the period considered. The final state, at time t_B, gives the total number of transmissions in progress. The transition matrix for this system may be easily written and using this information we can also calculate the average stretching of the busy period due to hidden stations which arrive during this t_B slot interval. This information allows us to determine a lower bound on the length of the busy period and to calculate the distribution of the number of received packets that are lost at the basestation due to hidden station transmissions. In the interests of brevity we have not included all the details of the calculations made. Note that although the model determines the "first-order" busy period stretching, it does not include any additional loss in performance due to hidden arrivals beyond this.

In Figure 7 we show the degradation in performance of MB-CSMA as p increases. In the figure we also plot the performance for MB-CSMA-HSB which is unaffected by the hidden station arrivals. As can be seen in the graphs, there are clearly large improvements in performance possible using this protocol. An important factor to consider is also the general robustness that such a protocol can provide compared with one such as MB-CSMA. In certain situations the likelihood of hidden stations may be very low. However, when there is significant hidden traffic, network operation may very well be reduced to unacceptable levels.

5. Conclusions

In this paper we consider the reverse link capacity achieved by a set of stations communicating with a smart antenna basestation operating in *multibeam* SDMA mode. A multibeam CSMA/SDMA protocol is introduced which permits efficient operation in this type of system. Stations access the channel us-

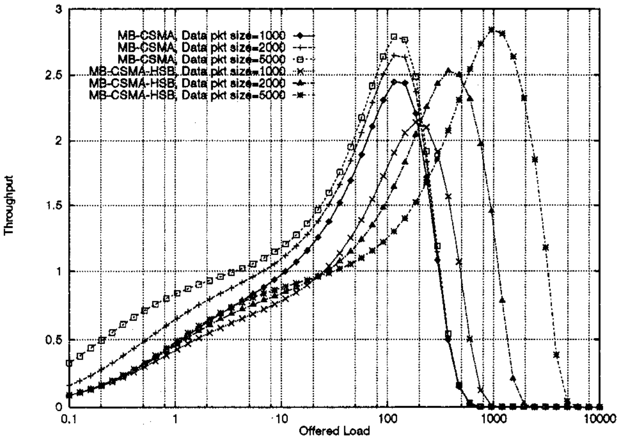

Figure 6. Throughput vs Applied Load, MB-CSMA and MB-CSMA-HSB

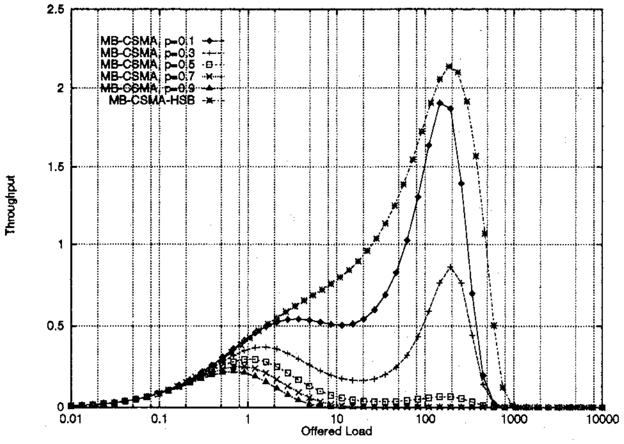

Figure 7. Throughput vs Applied Load, MB-CSMA and MB-CSMA-HSB Comparison

ing a form of CSMA which has been adapted to accommodate the smart antenna basestation. In this paper we also proposed an extension to this protocol that uses more advanced basestation/portable signalling to reduce the effects of hidden stations in multibeam CSMA/SDMA. We present throughput and capacity models for the systems being considered. We find that when there are no hidden stations, the capacity of the basic MB-CSMA protocol exceeds that of the hidden station blocking version when packets lengths are short. With longer packets, the converse is true and MB-CSMA-HSB has higher capacity. When hidden stations are present, the performance of the basic MB-CSMA protocol can deteriorate very rapidly. In this case MB-CSMA-HSB can perform much better than MB-CSMA.

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