Polling Based Media Access Protocols for use with Smart Adaptive Array Antennas

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Abstract

Use of an adaptive antenna array or a space-time processor at each base station of a wireless network can substantially abate the effects of multipath fading and co-channel interference. Among the expected benefits are higher data rates, greater frequency re-use factors, and, overall, higher capacity systems as needed to enable wireless multimedia services.

Media access control (MAC) protocols which facilitate the deployment of such a processor have been previously proposed and studied. These MAC protocols invoke the delivery of a pilot tone from each *packet access unit* in the network as needed, so that the array antenna at the associated base station may rapidly adjust its weighting co-efficients, or its per branch equalization co-efficients, thereby ensuring subsequent reliable communication between the access unit and the base station. This paper considers two modifications to these earlier protocols, both based upon the notion of *piggybacking* information requests on to the actual information messages and both intended to improve utilization efficiency and mean delay performance. Results show that a maximum link utilization efficiency[1] of 97 % is readily achieved with either modification, and that this maximum utilization efficiency is independent of the number of remote users in the network. The modifications also help in achieving a considerable reduction in the average delay in low load regimes: for typical system parameters,

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[1] Note that the utilization efficiency refers to the throughput at maximum loading i.e., when the remotes always have queued requests.

the average delay at low-load is only about 10 % of that produced by the original schemes.

1 Introduction

Recently, the topic of Wireless Access to the Internet has emerged as the focus of considerable worldwide interest [1]-[10]. An important issue in Wireless Access concerns the reduction or elimination of the time-varying impairments typical of a wireless channel. The use of smart adaptive array antennas at base stations can help abate both multipath fading and co-channel interference, thereby ensuring "good" received signal quality [11]-[12]. In the receive direction, the signals appearing at each branch of such an array are appropriately phase and amplitude weighted, and subsequently combined such that some objective function, perhaps the signal to interference ratio, of the composite signal is maximized. As an example maximum ratio combining might be performed [13], [14] (Figure 1)[2]. For broadband operation, some combination of space and time processing might be used whereby the signal arriving at a given branch is "equalized" prior to combining with the "equalized" signals arriving at other branches. In either case, an adaptive mechanism is needed to enable the base station to dynamically cope with the time varying effects of the channel and to obtain the correct set of complex weighting co-efficients (different for different users) as needed. If Time Division Duplexing (TDD) is used, then a reasonably effective base-to-remote transmission link can also be produced by a base station transmit array, since, with TDD, the multipath channel is symmetric. Thus, "equalized" (for broadband operation), in the base-to-remote direction, the power transmitted by the base station might be split among the branches, and re-phased in accordance with the complex weighting coefficients derived from the receive direction measurements. However, the transmit channel quality may not be as high as that of the receive channel since the interference arising at the remote is different from that arising at the base station. Note that in this paper we do not consider issues related to the synchronization of time-slots between adjacent cells or the hand-off of remotes between cells. We assume the presence of a signaling channel [6] that helps achieve these functionalities.

Media access protocols providing a base station with a means of obtaining receive weighting co-efficients have been proposed and studied in [15], [16] and [17]. The base station relies on *polling mechanisms* to obtain the weighting co-efficients from the remote users within its cell and

[2]Note that the remotes users are not equipped with antenna arrays and no attempt is made to perform space division multiple access.

hence, we will name these **P**olling **B**ased **M**edia **A**ccess (PBMA) protocols. In [15] a token based protocol is proposed for a pedestrian oriented wireless network. The protocol allows a base station to periodically update its space-time weighting co-efficients by sequentially polling each remote. A remote responds to a poll with either *an information request* (defined as a request for a specific text or graphic data file) or an *unmodulated* pilot tone. Either response helps the base station to appropriately update the weighting co-efficients of its array antenna to be used for communication with that remote. It was shown in [15] that, with a polling cycle of about 50 ms (typical in a pedestrian-oriented wireless system setting [18]), this protocol can yield an overall channel utilization efficiency of over 80 %. While this protocol adequately serves the needs of pedestrian traffic, it is unsuitable for vehicular traffic, since a polling cycle of 50 ms does not permit rapid adaptation of the antenna weighting co-efficients as needed to cope with the faster changes in fading characteristics expected by the possibly increased velocity of each remote user.

A new media access protocol was proposed in [16],[17] to facilitate much faster array or array-time adaptation and thereby extend the domain of support to include *vehicular* remote users (in addition to pedestrian and fixed point users). The scheme includes a polling mechanism whereby each transmission, in either direction is immediately preceded by a remote-to-base unmodulated pilot signal used to immediately adapt the base-station's space-time processor to that remote. This media access protocol assumes *frames* of fixed length, and each remote is polled exactly once every frame. It was shown in [16] that a maximum utilization efficiency of as high as 95 % can be achieved if appropriate frame sizes are chosen. Note that the *utilization efficiency* is defined as the the fraction of the time that useful information is being transmitted over the channel, where, by definition the useful information consists only of information requests and replies to such requests. At very low loads, the utilization efficiency will be poor since the channel is carrying no useful information for most of the time due to the lack of traffic. As such, only the maximum utilization efficiency i.e., the utilization efficiency at very high loads, is of significant interest.

However, the MAC protocol proposed in [16] has a serious limitation which may be readily identified. If the frame size is chosen so as to optimize the maximum utilization efficiency, the frame size will increase linearly with the number of users in the cell, and this may result in long delays (since a remote user is polled only once every frame) at low traffic intensity (low load conditions). If, instead, the frame size is reduced, maximum utilization efficiency suffers due to an increase in the number of polling slots per frame as the number of users admitted into the cell increases. Therefore optimizing the maximum utilization efficiency might result in poor delay performance and improving delay performance might hurt the maximum utilization efficiency. In the remainder of this paper, we shall refer to this protocol as the "Polling Based Media Access protocol with Fixed Frame size" or PBMA-FF.

In this paper, modifications are suggested to the PBMA-FF MAC protocol to address this issue. It is recognized that at the time of completion of an information transfer, a remote may *piggyback* any new information requests in the remote-to-base direction, since the array antenna weights are still valid at this time. The users who piggyback requests in a particular frame need not be assigned polling slots in the immediately following frame. This reduces the overhead due to polling and, at heavy loads, every user uses piggybacking to relay requests to the base station; thus, there would be no polling slots in any frame.

The frame size is no longer kept fixed and the base station continuously polls the remotes when it has no requests to serve. Thus, at very low loads, a request would reach the base station with minimal delay. Further, the traffic model considered in this paper is more general than the one considered in [16].

Analytical models are developed for two variants of the protocol from which approximations for the effective utilization efficiency and expected message delay may be found. It is shown that the maximum utilization efficiency is independent of the number of users in the cell and can be as high as 97 % for typical system parameters for both PBMA-LP and PBMA-EP. Furthermore, it is seen that, at low loads, the average delay experienced when the modified protocol is used is approximately about one tenth of the average delay experienced when PBMA-FF is used. The average delay remains relatively unchanged for utilization efficiencies of up to 90 %.

We begin in Section 2 by briefly revisiting the protocol described in [16]. In Section 3, two variants of the modified media access protocol are described. The first variant uses limited polling wherein, when polled, a remote can send at most one outstanding request to the base station. The second variant is based on exhaustive polling which allows a remote, when polled, to send all its outstanding requests, sequentially, to the base station. We refer to the first variant as PBMA-LP (Limited Polling) and the second variant as PBMA-EP (Exhaustive Polling). In Section 4 analytical models are developed for the two variants of the protocol, and using reasonable approximations, expressions for the utilization efficiency and mean turn around delay are computed. The results are discussed in Section 5 and the conclusions are presented in Section 6.

2 PBMA-FF: A Brief Description

Consider a microcell containing a single base station and a plurality of remote packet access units. The communication between the base station and remotes is assumed to be time-division duplexed over a single high speed radio channel. As described in Section 1, the base station is equipped with an adaptive array antenna (for narrowband operation) or a space-time processor (for broadband operation) to abate multipath fading and co-channel interference. As these impairments may rapidly change, the media access protocol provides the base station with a pilot signal sent by a remote, prior to information transfer to or from that remote.

A timing or framing diagram of PBMA-FF appears in Figure 2. The frame consists of two segments: a polling segment and a data segment. The polling segment contains N polling slots, one for each remote within the radio cell. The data segment contains $J > N$ information transfer slots and is further subdivided into two subfields. Subfield 1, containing N slots, is used for transferring *information requests* from remote-to-base, and may, under certain circumstances, be used to transfer *information replies* from base-to-remote. Subfield 2 is used exclusively for base-to-remote information replies. Notice, that the frame consists of a fixed number of polling (N) and a fixed number of data slots (J).

The polling segment is used to signal an intent to send an information request (remote-to-base) or reply (base-to-remote). Multipath and interference-robust direct sequence spread spectrum signaling is used during the polling slots, unprotected by the array. Each polling slot is *owned* by a particular remote and consists of two parts (Figure 2). In the first part of its polling slot, if the *owner* remote has a queued information request to send, it sends in its *own* spreading sequence which occupies the entire channel bandwidth[3]. The base station immediately recognizes this polling signal, and acknowledges receipt using the same spread spectrum signal in the second half of that polling slot. Corresponding to each polling slot, there exists a data slot in Subfield 1 of the data segment. The above mentioned acknowledgement from the base station, transmitted in the second half of a polling slot, notifies the remote that the data slot in Subfield 1, corresponding to that polling slot is available for that remote to send its information request. Just prior to that particular

[3]Note that, during the data segment, information is sent at a rate which consumes the entire spectrum; the chip rate during the polling segment is therefore equal to the data rate during the data segment, and a spreading sequence of say, 200-300 chips should be adequate to distinguish the remotes, suppress the interference, and abate multipath. Note further that we do not consider the practical issues of synchronizing the correlator needed at the base station and each remote, or implementation of the requisite matched filter if synchronization is to be avoided.

data slot, the remote would then send a short pilot tone (Figure 2) to be used by the base station for rapid acquisition of the currently correct set of antenna array combining weights to be used for that remote. If the remote does not have a queued information request, it does not send its spread spectrum sequence in its polling slot, thereby notifying the base station that the corresponding data slot in Subfield 1 of the data segment is free and may be used for transfer of an information reply packet (one packet among the many which might compose the entire information response message, which in turn might consist of a text or graphic data file) to any remote. To do so, the base-station transmits the spread spectrum sequence of the chosen remote, using the base-to-remote portion of the polling slot; this notifies the remote that the corresponding data slot in Subfield 1 of the data segment has now been allocated to it for receiving a base-to-remote information reply. The chosen remote, then, sends a pilot tone just prior to that slot, allowing the base station to acquire the correct set of antenna array weights to be used for that information reply.

As described, each slot of Subfield 1 serves two purposes. If a slot *owner*, say the j th, has a queued information request, the j th slot in Subfield 1 is used to transfer that request. Otherwise, the base station may use that slot for transferring an information reply packet to *any* particularly chosen remote. In Subfield 1, data packet transfer must be preceded by a pilot tone since the base station must acquire the correct set of antenna array weights to be used for each packet. By contrast, the slots of Subfield 2 are used exclusively for base-to-remote information replies. Here, it is possible for the base station to schedule a long multi-slot reply to one particular remote, and it will not, therefore, need to re-acquire the antenna weights prior to each slot. Rather, the transfer of information can continue without pilot tones until the long message ends. In such a case, the base station would *asynchronously* send polls to the recipient of the next long message, stimulating a pilot tone for re-acquisition purposes as needed (See Figure 2). The base station would then rapidly acquire the weighting coefficients for its antenna array and transfer of the long information reply would continue. Note that it is possible to embed in each time slot a signaling segment to be used to indicate the beginning, end, or continuation of a message.

In [16] it was shown that for a given cell population N, it was possible to choose the optimal value for J (for a given traffic type) such that the utilization efficiency was maximized. However, this requires a continuous computation of the appropriate frame duration to be chosen. Furthermore, if the value of N increases, the optimal frame size would increase as well. This would result in polling latency since the users are polled once a frame. If instead, the frame size is reduced, the utilization efficiency suffers. In the following section we propose modifications to PBMA-FF so that both of these limitations are avoided.

3 PBMA-LP and PBMA-EP Variants

As in [16], the communication between the base-station and remotes is assumed to be time division duplexed (TDD) over a single high speed radio channel. As discussed in Section 1, the base station is equipped with an adaptive array antenna or space-time processor to combat impairments due to multipath fading and co-channel interference.

The basic framework of the protocol remains the same as for PBMA-FF. The polling signal uses a multipath fading and interference-robust direct sequence spread spectrum modulation scheme which obviates the need for a base station to possess the correct set of array weights (narrowband) or equalization weights per array element (broadband) while polling. In response to a poll, the remote can either reply with an information request at some pre-determined future time or remain silent. Prior to any information transfer (the information may consist of a request from a remote or a response from the base station), a preamble or pilot tone is sent by a remote to enable the base station to rapidly acquire the correct set of weights to be used for that particular information transfer. However, unlike in PBMA-FF, polling is no longer done periodically. A remote can now piggyback its information requests to any information transfer between the base-station and itself.

We consider two variants of the protocol. In the first variant, the base station uses *limited* polling (LP) i.e., at each poll, exactly one information request is retrieved from any remote. In the second variant, the base station will *exhaustively* poll (EP) each remote. For the case of exhaustive polling, if the traffic was just of the request response type as described earlier, there is a possibility that the a single user may *unfairly* flood requests and hence, keep using the channel continuously without allowing for the other users to transmit their requests. This may be overcome by inserting intermediate polling segments at regular periods. In our analysis, we assume that there is an additional type of traffic which consists of messages destined for users within the cell, but those that originate from other sources from within the entire network consisting of a multitude of other wireline and wireless users (*Class 2* messages). The message length distribution for this Class 2 traffic is assumed to be the same as that of the message length distribution of an information response message described earlier. The presence of this type of messages provides an inherent notion of fairness since each message may be intended for any remote user with equal probability. This type of traffic is not considered when we analyze the LP variant since it is inherently fair. The presence of Class 2 traffic does not change the performance of the scheme significantly, since a Class 2 message has the same message length distribution as that of an information response message.

3.1 The Protocol with Limited Polling (PBMA-LP)

In the Limited Polling (LP) variant of the protocol, each remote can send only one request at a time. Each request invokes exactly one information reply from the base-station. A framing diagram for the LP variant of the protocol is shown in Figure 3. Each frame consists of three *segments* as shown in the figure. Consider an arbitrary frame, say frame K. The base station explicitly polls a remote using *a polling slot* if either,

(a) the remote did not get a chance to send a request by piggybacking in frame $K-1$ since it did not get any information reply messages in that frame, or,

(b) the remote did not have any request to piggyback at the time it got its information reply message in frame $K-1$.

This polling is done in the first segment of the frame which, as in PBMA-FF, we call the *polling segment.* Spread spectrum signaling is used for this purpose. Thus, out of the N users in the cell, if L users were able to piggyback requests in frame $K-1$, we would require $R = N - L$ polling slots in frame K. Each polling slot is divided into three portions. In the first portion of the polling slot, the base station transmits a spread spectrum sequence uniquely identifying the remote to be queried for an information request. If the particular remote has a request to send, it responds to the query in the second portion of the polling slot (Figure 3) by sending a spread spectrum sequence back to the base station. If that remote does not have a request to send, it ignores the query and sends nothing. In the third portion of the slot, the base station would broadcast one of two *reserved* spread spectrum signals. One of these would be used to indicate that a response to the query was received, and the other one to indicate that a response was *not* received. Each of the R remotes keeps count of how many responses the base station has received, so that when a remote receives its query, it knows the number of remotes which have asked for *information request* slots prior to it. For example, if after j polling slots, $(1 \leq j \leq R-1)$, i $(i \leq j)$ remotes have responded to the queries, the $(j+1)$ st remote would know (if it had a request) that the $(i+1)$ st request slot in the first field of the *data segment* belongs to it.

The first field of the data segment consists of slots for getting *information* requests from remote users. We call this the *requesting segment.* If κ remote users responded to queries in the polling segment, then there would be exactly κ request slots in the first field of the data segment. At the end of the request segment, the base station could indicate the beginning of the next segment which we call the *reply segment*, by broadcasting an ending delimiter (another reserved spread spectrum ID). The reply segment is used for information transfer (in the base-to-remote direction for a request response type of system) between the base station and the remote users. Prior to each message transfer, the base station station transmits the spread spectrum sequence unique to the remote to which the information is to be sent. In response, the remote transmits a pilot tone. Subsequently, information transfer begins, and continues until the message ends. At the end of the message, the base station queries the remote for new requests (this time the query is protected by the array and hence, no spread spectrum signaling is used). The remote will then piggyback a new request if its request queue is non-empty, or will indicate that it has no new requests. Requests which were either piggybacked in the $(K-1)$ st frame, or directly made in the request segment of the K th frame are served in the K th frame. Requests made through piggybacking in the K th frame will be served only in the $(K+1)$ st frame.

It is to be noted that at very high loads where remotes' queues are seldom empty, requesting is done almost entirely using piggybacking and the polling segment is either very short or non-existent. Hence, we expect thtat the maximum utilization efficiency should be high.

3.2 The Protocol with Exhaustive Polling (PBMA-EP)

Instead of using limited polling, one may use exhaustive polling whereby a remote, upon being polled, sends all its queued information requests to the base station. As discussed earlier, in order to provide a realistic model which ensures the fairness of PBMA-EP, we will consider this protocol when two types of traffic are present. The first is of request response type as described in the previous subsection and is referred to as *Class 1* traffic. The second consists of *independent*, unrequested messages (such as e-mail) in the base-to-remote direction, which we call *Class 2* traffic. Note that the two types of traffic can be integrated with the limited polling scheme as well. In that case, the base-station will have to explicitly indicate to a remote (by means of a spread spectrum slot) that it has a message destined for it.

A timing diagram of the protocol is depicted in Figure 4. When the base-station queue is non-empty, i.e., it has queued information messages (either Class 1 or Class 2 messages), the base station delivers the messages to the appropriate remotes until the queue becomes empty. There are no polling cycles inserted until and unless the base-station queue empties. Prior to each delivery, the base-station transmits the spread spectrum sequence of the remote to which the message is to be sent, and, in response, the remote immediately sends a pilot tone. This pilot tone enables the base-station to quickly adjust its array weights appropriately for reliable information transfer. At the end of each message, the remote to which this message was delivered can *piggyback* all the requests in its queue.

When the base-station queue is empty, the base-station continually and sequentially polls the remotes. As in PBMA-LP scheme, spread spectrum modulation is used for polling and each remote is assigned a unique spread spectrum sequence. A polling slot consists of two portions. In the first portion, the base-station transmits the unique spread spectrum sequence of the remote it wants to poll. If this remote has requests to send, it responds by echoing the sequence in the second portion of the slot. This is immediately followed by a pilot tone, and the remote transmits all its queued requests, one by one, to the base station, until its queue is empty. When its queue becomes empty, it transmits an *End of Transmission (EOT)* signal to indicate that it has nothing else to send. The base-station then polls the next remote. In a *polling cycle* the base-station polls all the remotes in the cell. At the end of the polling cycle, if the base-station queue is non-empty, it continually delivers either Class 1 or Class 2 messages to the remotes as mentioned earlier [4]. As long as the base-station is non-empty, the transfer of information messages continues and there are no polling cycles. If the base-station queue becomes empty, a polling cycle is immediately inserted.

Note that, for both variants of the protocol, a signaling field is needed to admit users to a cell and to accommodate hand-off [6]. We do not consider such a field in this paper but, rather, consider protocol performance only for a fixed number of users admitted to the cell.

3.2.1 Fairness when PBMA-EP is used

As mentioned earlier, in the presence of a single traffic type, i.e., when the traffic just consists of query-response type of messages, it is possible for a single remote user to dominate the channel by continuously piggybacking requests. In that case the base-station queue never becomes empty and other remotes will never be polled. Hence, it would be essential to limit the maximum number of consecutive requests that a user can make. If this number is reached, the base station will immediately insert a polling segment in order to provide the other remote users with a chance to send in their requests. Note however, that the exhaustive polling is especially useful if only a few remotes have information to send and dominate the channel. In such a case, it might be wasteful to consume overhead to poll the remaining mobiles. Thus, PBMA-EP might be expected to outperform the PBMA-LP scheme in such scenarios.

In this paper, as mentioned earlier, we include two types of traffic when we analyze the exhaustive polling scheme. The first type is inquiry-response. The second type consists of messages destined for remote users, and these messages arrive at the base station from within the underlying wireline network. These messages are independent of remote requests. However, each remote can piggyback a request at the end of each Class 2 message transfer in the base-to-remote direction. It

[4] We assume that both Class 1 and Class 2 messages arrive to a common queue.

is to be noted that these types of messages would typically exist in any broadband wireless data network. The presence of these Class 2 messages would provide an inherent notion of fairness since each may be intended for any remote user with equal probability.

4 Performance Analysis

In this section, we use reasonable approximations to obtain expressions for the *utilization efficiency* and *mean turn around delay*. The utilization efficiency is defined as the fraction of time that useful information is being transmitted over the channel where, by definition, the useful information consists of only information requests and replies. As such, the utilization efficiency at low loads will be poor due to the low volume of traffic being carried over the wireless channel. Only at high loading is the utilization efficiency of significant interest; here the utilization efficiency is a function of the overhead. The mean turn around delay refers to the average duration between the generation of a request by a remote and the receipt by that remote of a reply to that request. We should emphasize here that the performance metrics are gathered at the MAC layer. Higher layer protocols at the network and transport layers might further degrade the utilization efficiency (by inserting additional overhead) and increase the mean delay.

4.1 Performance Analysis of PBMA-LP

Due to interdependence between the arrival process and the service process of the base station's queue [5] it is extremely difficult to analyze the PBMA-LP protocol. Hence, we shall present an analytical model and use this to derive close approximations to the channel utilization efficiency and mean turn around delay. The validity of these approximations has been confirmed by simulation studies, to be described later.

Let each remote generate requests according to a Poisson Process, with a mean arrival rate of λ. We define the following :

- N: The number of remotes in the cell at a given time.
- F_N: The frame size in number of slots, given that there are N remotes in the cell.
- Y_N: The number of response messages per frame, given that there are N remotes in the cell.

[5] Longer frames are likely to have a greater number of arrivals than smaller frames. On the other hand, if the number of arrivals in a frame is large, the subsequent frame will be longer. Thus, there is an inherent interdependence between the arrival and service processes.

- X_N: The number of request messages per frame, given that there are N remotes in the cell.
- R_N: The number of polling slots per frame, given that there are N remotes in the cell.
- P_0: The steady state probability that a particular remote's queue is empty.
- $M(z)$: The probability generating function of the number of ATM cells per reply message.
- D: The number of ATM cells in a request message.
- P: The number of ATM cells in a Polling Slot
- S: The number of ATM cells in a Pilot Tone.
- I: The number of ATM cells in a partial poll in the base-to-remote direction preceding a reply message.

4.1.1 Utilization Efficiency

At the outset, we assume that the lengths of the different remote users' queues are statistically independent random variables[6]. With this assumption , the probability distribution of the number of request messages in a particular frame is the same as the distribution of the number of non-empty users in the previous frame and is given by,

$$P(X_N = i) = \binom{N}{i}(1 - P_0)^i P_0^{(N-i)}. \tag{1}$$

Since each request message invokes exactly one reply, the number of reply messages per frame has the same distribution i.e.,

$$P(Y_N = k) = \binom{N}{k}(1 - P_0)^k P_0^{(N-k)}. \tag{2}$$

In a given frame, the remotes which did not piggyback requests in the preceding frame are assigned polling slots. Therefore, the distribution of the number of polling slots in a frame is given by:

$$P(R_N = j) = \binom{N}{j} P_0^j (1 - P_0)^{N-j}. \tag{3}$$

[6]This approximation certainly holds at low loads, since the arrival processes to different queues are independent processes and the service time consists of mainly single message transmissions. Simulation results presented in Section 4 suggest that the approximation also remains valid at higher loads. Analysis is intractable without this simplifying assumption.

Thus, in steady state, the frame size is given by the following expression:

$$F_N = \sum_{i=0}^{Y_N} M_i + X_N D + R_N P + \{Y_N + (X_N - Y_N(1-P_0))\}S + Y_N I, \tag{4}$$

and the *probability generating function (pgf)* of F_N is given by:

$$F_N(z) = E(z^{Y_N(P_0 S+I)+\sum_{i=0}^{Y_N} M_i}) E(z^{X_N(D+S)}) E(z^{R_N P}). \tag{5}$$

We first find $E(z^{Y_N(P_0 S+I)+\sum_{i=0}^{Y_N} M_i})$. This may be represented as:

$$E(z^{Y_N(P_0 S+I)+\sum_{i=0}^{Y_N} M_i}) = z^{(P_0 S+I)Y_N} E(z^{M_1+M_2+\ldots M_{Y_N}}) = (z^{(P_0 S+I)} M(z))^{Y_N} \tag{6}$$

since M_i ($i \in \{1, Y_N\}$) are independent and identically distributed with *pgf* $M(z)$. Similar expressions may be found for $E(z^{X_N(D+S)})$ and $E(z^{R_N P})$.
Thus, equation (5) may be rewritten as:

$$F_N(z) = Y_N(z^{(P_0 S+I)} M(z)) X_N(z^{D+S}) R_N(z^P). \tag{7}$$

Further, using equations (1),(2) and (3) we obtain:

$$F_N(z) = (z^{(P_0 S+I)} M(z)(1-P_0) + P_0)^N (z^{D+S}(1-P_0) + P_0)^N (z^P P_0 + (1-P_0))^N. \tag{8}$$

Differentiating this expresssion and setting z to unity yields the average frame length

$$\overline{F} = N(1-P_0)(\overline{M} + P_0 S + I + D + S) + N P_0 P. \tag{9}$$

Each of the remote queues may be modelled as an M/G/1 queue with a mean service time of $\overline{F}$. The steady state probability that a remote's queue is empty is then given by [19]:

$$P_0 = 1 - \lambda \overline{F}. \tag{10}$$

The utilization efficiency may be expressed as:

$$\rho = \frac{N(1-P_0)(\overline{M}+D)}{\overline{F}}. \tag{11}$$

At very high loads $P_0 \equiv 0$, and the maximum utilization efficiency is:

$$\eta = \frac{(\overline{M}+D)}{(\overline{M}+D+S+I)}. \tag{12}$$

4.1.2 Mean Turn Around Delay

More requests are likely to arrive in long frames than in short frames. Furthermore, the length of a frame depends on the number of arrivals in the previous frame. Thus, one would see alternating bursts of long frames and short frames. The length of a burst of *non-empty* frames[7] is equal to a busy period of an M/G/1 queue with an arrival rate of $N\lambda$, since the burst would continue until the remotes' queues are empty. This average length of a burst of non-empty frames [8] is then given by:

$$\overline{BP} = \frac{\overline{M}+1}{1-N\lambda(\overline{M}+1)}. \tag{13}$$

The average length of an empty frame would be NP.

The probability that a given frame is empty is approximately P_0^N and the probability that the given frame is non-empty is therefore $1 - P_0^N$. From renewal theory, the probability that a *tagged* request arrives during a burst of non-empty frames is given by [20]:

$$P_{BP} = \frac{\overline{BP}(1-P_0^N)}{\overline{BP}(1-P_0^N)+NPP_0^N}. \tag{14}$$

The probability that a tagged request arrives in an empty frame is $P_{IP} = 1 - P_{BP}$. Since requests are more likely to be generated during a burst of long frames, the average time that a request stays at the head of a remote's queue (*average service time*) will be longer than the average frame length during a non-empty burst.

[7]A non-empty frame is a frame which contains at least one information reply.

[8]This is an approximation since it excludes the pilot tones and the polling slots which form a part of this burst of non-empty frames.

It is difficult to get an exact expression for the average service time. Instead, an approximate expression will be found[9].

Let P_1 be the probability that, during a burst of non-empty frames, a frame contains exactly one reply message. If we know that the previous frame was of length F, then

$$P_1 = P_0^{N-1} e^{-N\lambda F} + P_0^N N\lambda F e^{-N\lambda F}. \tag{15}$$

The first term in the above expression accounts for the case where (a) there was exactly one non-empty remote at the beginning of the previous frame [10] and (b) the previous frame had no arrivals. The second term accounts for the case where (a) there were no non-empty remotes at the beginning of the previous frame and (b) there was exactly one arrival. Since F is unknown, this expression is difficult to compute, and we use the following approximation:

$$P_1 \approx P_0^{N-1} e^{-N\lambda \overline{M}} + P_0^N N\lambda \overline{M} e^{-N\lambda \overline{M}}. \tag{16}$$

In the above expression, $\overline{M}$, the average length of a reply-message, is substituted for F. Since we are considering a non-empty burst of frames, each frame has at least one reply-message and, hence, this approximation is reasonable. The approximation simply means that we assume that the prior frame consisted of exactly one reply-message of average length. If the prior frame were much longer, the probability that the current frame will have exactly one message would be much smaller and could be set to zero.

Using this expression, an approximation for the probability generating function of the service time during a burst of non-empty frames is:

$$S_{NE}(z) = P_1(M(z) z^{D+S} R_N(z^P)) + (1 - P_1)((M(z) z^{D+S})^2 F_{N-2}(z)). \tag{17}$$

The first term represents the case where there is exactly one reply message in a non-empty frame. The second term takes into account that there are at least two reply messages in a non-empty frame containing more than one reply message. Each of the remotes can be modelled as an

[9] The expression for the distribution of the service time seen by a tagged packet is extremely difficult to compute since it requires the computation of the probabilities P_k, for $k \in \{1, N\}$). P_k is the probability that a frame in a burst of non-empty frames contains k reply-messages.

[10] It should be noted that by the *beginning* of a frame we mean the instant just before the reply segment.

M/G/1 queue and, hence, the mean delay experienced by an arriving request in reaching the base station would be:

$$\overline{D_0} = \overline{S_{NE}} + \frac{\lambda \overline{S_{NE}^2}}{2(1 - \lambda \overline{S_{NE}})}. \tag{18}$$

On reaching the base station, the request must wait for the duration of a frame before the base station sends a reply. In addition, the transmission time of the reply message is to be included in the computation of the mean turn around delay. Thus the total turn around delay, on average, experienced by a request packet arriving during a burst of non-empty frames is given, approximately by:

$$\overline{D_{NE}} = \overline{D_0} + \overline{F} + \overline{M} + S + I. \tag{19}$$

If the request packet arrived during an empty frame, the delay experienced would be given by:

$$\overline{D_E} = \overline{M} + D + S + NP. \tag{20}$$

Thus, the mean turn around delay experienced by any request is given by:

$$\overline{D} = P_{BP}\overline{D_{NE}} + P_{IP}\overline{D_E}. \tag{21}$$

4.2 Performance Analysis of PBMA-EP

Each of the N remotes in the cell is assumed to generate Class 1 requests at a *Poisson* rate of λ_1 requests per slot (each request fits exactly into one *slot*), and invokes an information reply from the base-station with a geometrically distributed message length (in terms of slots). In addition, the base-station also generates a second class of traffic, Class 2, with *Poisson* arrivals at a rate λ_2 per remote, per slot, to be delivered from the wireline network to the remotes. For simplicity, it is assumed throughout that both Class 1 and Class 2 messages have the same message length distributions. Let us define $\lambda = \lambda_1 + \lambda_2$.

Let the number of remotes in the cell be N. The base station queue may be modelled as an M/M/1 queue with an Poisson arrival rate of:

$$\Lambda = N\lambda = N(\lambda_1 + \lambda_2) \tag{22}$$

per slot. Let $M(z)$ denote the probability generating function of the message length (which is geometrically distributed with a mean of $\overline{M}$ slots). Then, the external load on the system is given by

$$\rho = \Lambda(\overline{M} + \frac{\lambda_1}{\lambda}), \tag{23}$$

since a message will be of Class 1 with probability $\frac{\lambda_1}{\lambda}$. It is easy to find the utilization efficiency for the EP variant of the protocol. If we assume the polling slot size to be P units and a pilot tone to be of duration S units, the utilization efficiency is given by:

$$\gamma = \frac{(1 - P_0)(\overline{M} + \frac{\lambda_1}{\lambda})}{\overline{M} + \frac{\lambda_1}{\lambda} + S + P}, \tag{24}$$

where $P_0 = 1 - \rho$ is the probability that the base station queue is empty.

The maximum utilization efficiency is given by

$$\eta = \frac{\overline{M} + \frac{\lambda_1}{\lambda}}{\overline{M} + \frac{\lambda_1}{\lambda} + S + P}. \tag{25}$$

Note that this quantity is independent of the number of remotes in the cell N.

The delay experienced by a message essentially consists of two parts. The Class 2 messages will experience only the delay at the base-station. However, the Class 1 traffic will experience an additional delay equal to the time taken by a request to reach the base station, which we shall refer to as the *Holding Time*.

The mean delay at the base-station is the mean delay experienced by a message in an M/M/1 queue and is given by:

$$\overline{D_{BS}} = \frac{\overline{M} + \frac{\lambda_1}{\lambda}}{1 - \rho}. \tag{26}$$

An approximate expression for the average holding time of the Class 1 packets is obtained by considering a tagged request generated by a tagged remote. This tagged request may arrive during the idle period of the base station queue or during the busy period of the queue. The average busy period of the base station queue is given by

$$\overline{BP} = \frac{\overline{M} + \frac{\lambda_1}{\lambda}}{1-\rho}. \tag{27}$$

The average duration of the idle period seen by a tagged request arriving during an idle period may be approximated by:

$$\overline{IP} \approx NP. \tag{28}$$

From renewal theory, the probability that the request arrives during a busy period is thus given by:

$$P_{BP} = \frac{(1-P_0)\overline{BP}}{P_0\overline{IP} + (1-P_0)\overline{BP}}, \tag{29}$$

and the probability it would arrive during an idle period is given by

$$P_{IP} = 1 - P_{BP}. \tag{30}$$

Let us assume that the tagged request arrives during the busy period. After the tagged request arrives, if the base station queue should become empty before the tagged remote receives a Class 1 reply or Class 2 message, the tagged request must be sent to the base station during the following polling cycle. Otherwise, it can be piggybacked to the next Class 1 reply or Class 2 message.

Let L be the random variable representing the number of slots before the tagged remote gets a *piggybacking* slot[11]. Let E be the random variable representing the number of slots before the base-station queue becomes empty after the tagged packet's arrival.

The probability that an arbitrarily chosen slot either does not belong to the tagged remote or is not a piggybacking slot is given by:

$$\alpha = 1 - \frac{1}{N(\overline{M} + \frac{\lambda_1}{\lambda})}. \tag{31}$$

[11] Let us define a piggybacking slot to be the slot immediately following the last packet of a Class 1 reply or Class 2 message (where a remote can piggyback its request)

Thus, the probability that a given slot is a piggybacking slot for the tagged remote is $(1-\alpha)$.

We need to compute the probability that the base station's queue becomes empty before the tagged remote gets a piggybacking slot, i.e., $P(L > E)$. The conditional probability $P(L > e/E = e)$ is given by:

$$\begin{aligned} P(L > e/E = e) &= \sum_{i=e}^{\infty} \alpha^{i-1}(1-\alpha) \\ &= 1 - \sum_{i=1}^{e} \alpha^{i-1}(1-\alpha). \end{aligned} \tag{32}$$

Then, removing the conditioning we obtain:

$$\begin{aligned} P(L > E) &\approx \sum_{e=1}^{\infty} P(L > e/E = e)(1-P_0)^{e-1}P_0 \\ &= \frac{\alpha P_0}{1-(1-P_0)\alpha}. \end{aligned} \tag{33}$$

Simplifying this expression yields:

$$\begin{aligned} P(L > E) &= \frac{(N(\overline{M} + \frac{\lambda_1}{\lambda}) - 1)P_0}{1 + (N(\overline{M} + \frac{\lambda_1}{\lambda}) - 1)P_0} \\ &= \frac{\xi}{1+\xi}, \end{aligned} \tag{34}$$

where $\xi = (N(\overline{M} + \frac{\lambda_1}{\lambda}) - 1)P_0$. We note that $P(L < E) = \frac{1}{1+\xi}$.

The expected value of the holding time of a tagged request, given that it arrived in a busy period and reached the base station during a polling cycle, can be approximated by:

$$E(H/L > E) = \frac{1}{P_0}. \tag{35}$$

We need to find $E(H/L < E)$, i.e., the average holding time of the tagged request, given that it arrived in a busy period and reached the base station using a piggybacking slot. Let J represent the random number of slots between the exhaustive polls to a tagged remote during a busy period. The probability generating function of J given that there were k messages in between is given by:

$$J(z/k \text{ messages in between}) = z^{[\sum_{i=1}^{k} M_i + X_i]}, \tag{36}$$

where M_i is the ith message length and X_i is the number of requests piggybacked by the *owner* remote of the i th message. The number of requests piggybacked by the owner remote of a message i is equal to the number of new requests generated by that remote since its last exhaustive poll. Hence, we have:

$$P(X_n = i/J = l) = \frac{e^{-\lambda_1 l}(\lambda_1 l)^i}{i!}. \tag{37}$$

Thus, the probability generating function of X_n (or X, since it is identically distributed for all remotes) is given by:

$$\begin{aligned} X(z) &= \sum_{l=0}^{\infty}\sum_{i=0}^{\infty} z^i \frac{e^{-\lambda_1 l}(\lambda_1 l)^i}{i!} P(J = l) \\ &= \sum_{l=0}^{\infty} P(J = l) e^{-\lambda_1 l(1-z)} = J(e^{-\lambda_1(1-z)}). \end{aligned} \tag{38}$$

Further, by assumption, all M_i have identical distributions and have probability generating functions given by $M(z)$.

Thus, Equation (36) reduces to:

$$J(z/k \text{ messages in between}) = (M(z)J(e^{-\lambda_1(1-z)}))^k. \tag{39}$$

Since the probability that a message belongs to a given remote is $\frac{1}{N}$, we can find the unconditional *pgf* of J as follows:

$$\begin{aligned} J(z) &= \sum_{k=1}^{\infty}(M(z)J(e^{-\lambda_1(1-z)}))^k(1-\frac{1}{N})^{k-1}\frac{1}{N} \\ &= \frac{M(z)J(e^{-\lambda_1(1-z)})}{N-(N-1)M(z)J(e^{-\lambda_1(1-z)})}. \end{aligned} \tag{40}$$

Differentiating Equation (40) and setting $z = 1$ yields the mean duration between polls of a tagged remote which is given by:

$$\overline{J} = \frac{N\overline{M}}{(1 - N\lambda_1)}. \tag{41}$$

The average holding time of the tagged request, given that it arrived in a busy period and reached the base station through piggybacking is $E(H/L < E)$. Then, given by:

$$E(H/L < E) = \frac{\overline{J}}{2}. \tag{42}$$

Thus, the average holding time of the packet may be expressed as:

$$\overline{H} = P_0 \frac{NP}{2} + (1 - P_0)(\frac{\overline{J}}{2} P(L < E) + \frac{1}{P_0} P(L > E)). \tag{43}$$

The mean turn around delay $\overline{T}$ for a Class 1 packet is then given by:

$$\overline{T} = \overline{H} + \overline{D_{BS}}. \tag{44}$$

5 Results and Discussion

For illustrative purposes, we assume that a request message fits exactly into one *slot* which is assumed to consist of 3 ATM Cells. Each slot in the polling segment (for both the LP and EP schemes) is assumed to be of duration equal to 1 ATM Cell. Reply Messages (both Class 1 and Class 2 messages in the EP case) are assumed to have a geometrically distributed number of *packets* (each of which fits exactly into one slot) with a mean size of 34 packets ($\approx$ 100 ATM Cells). A pilot tone is of duration equal to 1/2 an ATM cell. Further, we assume a channel data rate of 20 Mbps. (Note that we have *arbitrarily chosen* this rate; the results, of course, hold for any other data rate.) The parameters used are listed in Table 1. It is to be noted that the Poisson models used in these paper may not be realistic and thus, the absolute values for throughput and delay may be different if other models (such as self-similar traffic models [21]) are used. However, the trends seen may be expected to be similar.

Figures 5,6, and 7 illustrate results for PBMA-LP. Figure 5 shows the utilization efficiency versus the arrival rate per remote per second. We see that a maximum utilization efficiency of up to 97% may be achieved. Figures 6 and 7 show the variation of the average turn around delay with utilization efficiency for 30 and 50 remotes, respectively. The base station continuously polls the remotes when it is empty, thereby ensuring low delays at low loads. The performance of the LP protocol is compared with the performance of PBMA-FF for the same parameters. The gain in both the maximum utilization efficiency and the mean turn around delay are evident. Figures 6 and 7 show that the maximum utilization efficiency improves by about 5 % as compared to maximum

Table 1: System Parameters

Parameter	PBMA-FF	PBMA-LP	PBMA-EP
Polling Slot Size	1 ATM Cell	1 ATM Cell	1 ATM Cell
Pilot Tone Size	1/2 ATM Cell	1/2 ATM Cell	1/2 ATM Cell
Data Slot Size	3 ATM Cells	3 ATM Cells	3 ATM Cells
Average Reply Message Length	100 ATM Cells	100 ATM Cells	100 ATM Cells
Reply Message Distribution	Geometric	Geometric	Geometric
Assumed Data Rate	20 Mbps	20 Mbps	20 Mbps
Portions in Polling Slot	2 Portions	3 Portions	2 Portions

utilization efficiency achieved by PBMA-FF and that the mean turn around delay, at low loads, is reduced by 90 %. Also shown in figures 6 and 7 are simulation results which confirm the accuracy of the analytical approximations.

Figures 8 through 12 depict the performance of the EP variant of the protocol. We assume that 50 % of the traffic belongs to Class 1 while the other 50 % belongs to Class 2. In Figure 8, the overall utilization efficiency is plotted versus the arrival rate per remote when there are 30 remotes in the cell. The utilization efficiency increases linearly with the external load (as seen from Equation (24)). In Figures 9 and 10, the mean delay at the base-station is plotted versus the arrival rate per remote. It is seen that a utilization efficiency of 97% is achievable. The average holding time experienced by Class 1 requests is plotted versus the arrival rate per remote in Figure 11, where 50 remotes are present in the cell of interest.

In Figures 12 and 13, the mean base-station delay and the mean holding time experienced by the Class 1 packets are plotted versus the utilization efficiency. Since the utilization efficiency is a linear function of the external load, these figures show that for a given external load i.e., $N\lambda\overline{M}$, there is almost no change in mean delay with a change in the number of remotes N. These results further indicate that the utilization efficiency and the expected delay are functions of the overall arrival rate $N\lambda$. Thus, for a given value of λ, to meet a particular mean delay objective, it is easy to obtain the number of admissible remotes into the radio cell. Simulation results once again are shown in all the graphs, confirming the accuracy of the analytical approximations.

In Figures 14, 15 and 16 we compare the performance of PBMA-LP and PBMA-EP. The results presented in these graphs are obtained via simulation, and for all results presented, we assume that the number of remotes within a cell is 30. For the PBMA-EP variant, we consider two cases: in the first case the entire traffic belongs to Class 1 and in the second case the total traffic is equally divided into the two classes.

In Figure 14 we compare the expected delay of the PBMA-EP and PBMA-LP variants. The performances of both variants are seen to be almost identical. The expected delay of the Class 2 type of traffic (in the second case considered) is slightly lower than the expected delay of Class 1 traffic since there is no delay incurred in transmitting a request to the base station for this class. From Figures 7 and 14, it can be inferred that both PBMA-EP and PBMA-LP outperform PBMA-FF at all loads in terms of expected delay while simultaneously producing higher utilization efficiency.

In Figure 15 we compare the variance of PBMA-LP and PBMA-EP. For the latter, we assume that only Class 1 traffic is present. It is seen that the variances are almost identical; this is expected, since we assumed that the traffic is homogeneous among remotes. However, if there is non-uniformity in the traffic, i.e., if there are a few dominating remotes that generate traffic at a much higher rate than the others, then, as discussed earlier, a policy might be needed to ensure fairness. In the absence of such a policy, it is possible that the variance of the delay for PBMA-EP increases significantly in the presence of non-uniform traffic.

The variance of the delay for PBMA-EP is depicted in Figure 16 for both cases considered. It is seen that when the traffic is comprised of two classes, the variance of the delay of each class is slightly higher than the variance when a single class is present. However, this increase is not significant.

6 Conclusions

Two new polling-based media-access protocols for use in conjunction with space-time processing smart adaptive array antennas have been proposed. A basic issue in the use of such an array for packet switching is the need to train the array prior to transmission of a packet in either direction. The proposed protocols solve this problem by means of a training pilot sent with each remote-to-base transmission and stimulated from the remote prior to each base-to-remote transmission. A further feature of these protocols is the use of piggybacking as a mechanism to transfer information requests (generated by remote users) to the base-station; this helps reduce the overhead caused by the signaling needed to facilitate these training pilots. Thus, the overall achievable utilization efficiency is higher than that produced by an earlier version of these protocols that did not include such piggybacking. At very high loads, the use of piggybacking virtually eliminates the signaling overhead. Thus, unlike the earlier protocol, the maximum achievable utilization efficiency is independent of the number of remotes in the cell. Furthermore, by allowing for variable frame sizes, the high turn around delay experienced at low load with the earlier protocol is substantially reduced.

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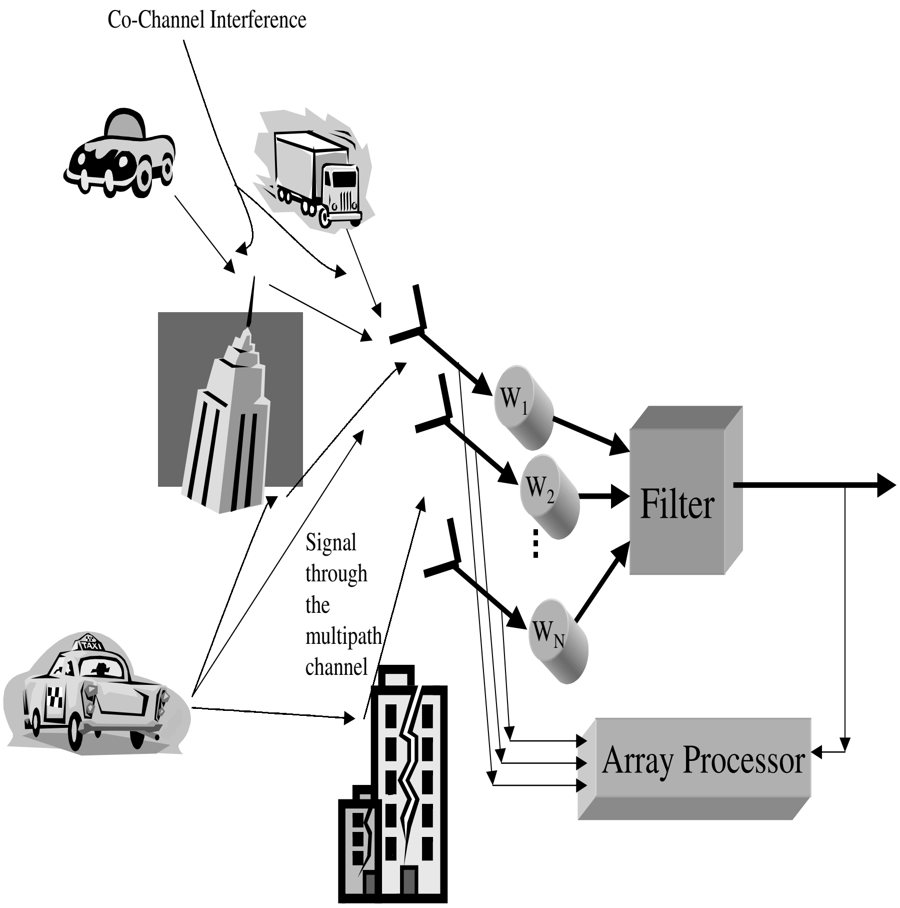

Figure 1: An array antenna deployed at a base station

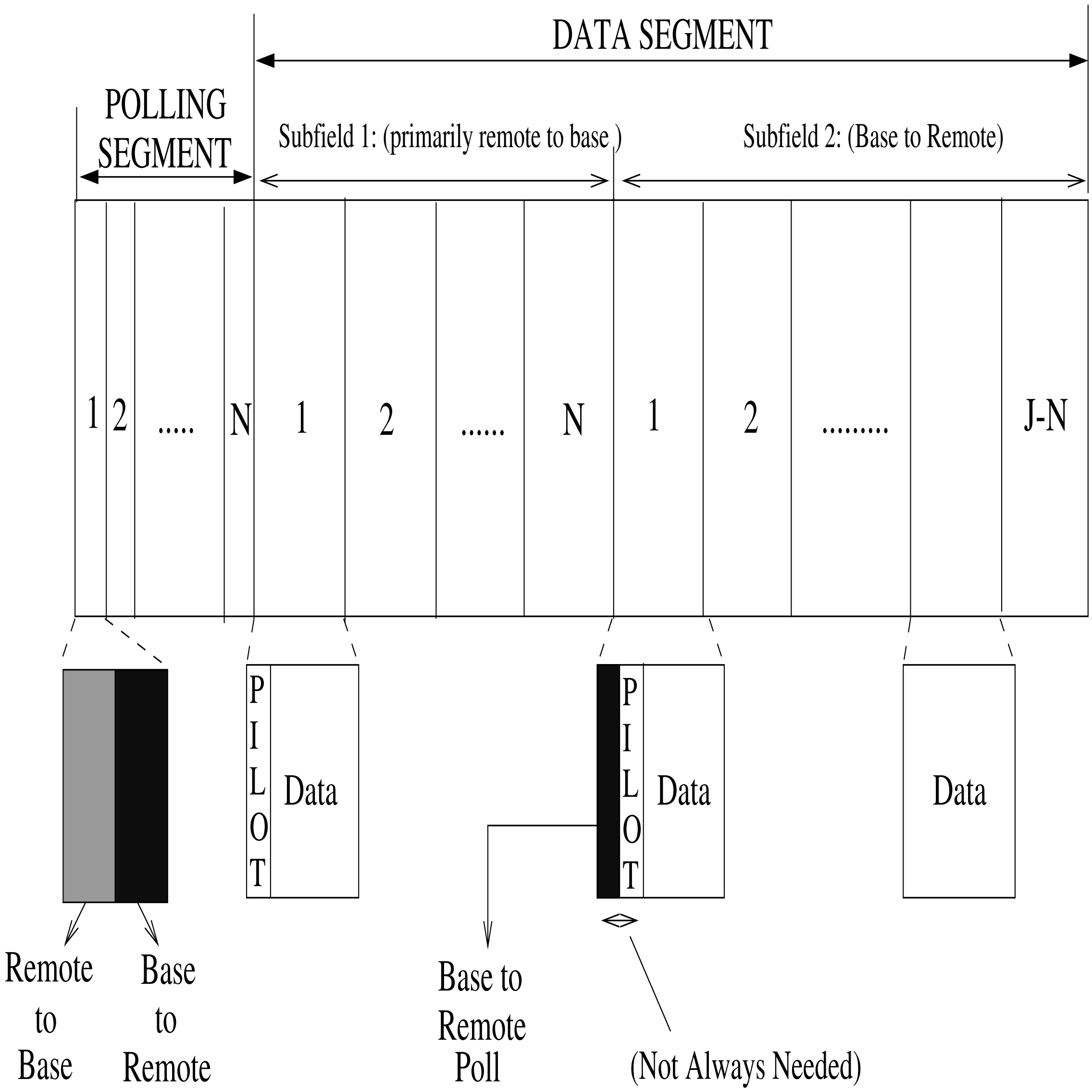

Figure 2: Basic Timing Diagram for PBMA-FF

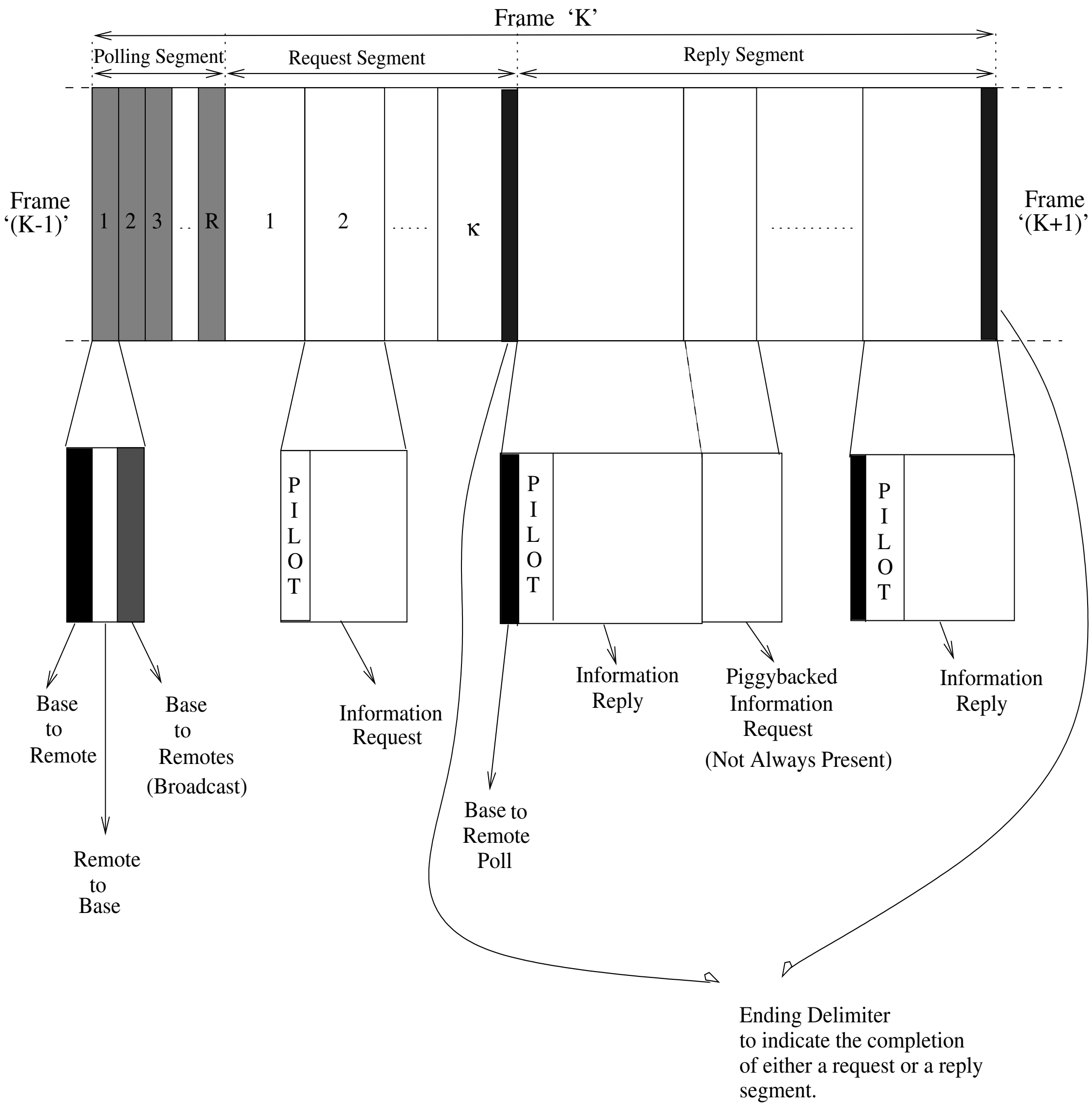

Figure 3: The Limited Polling Scheme

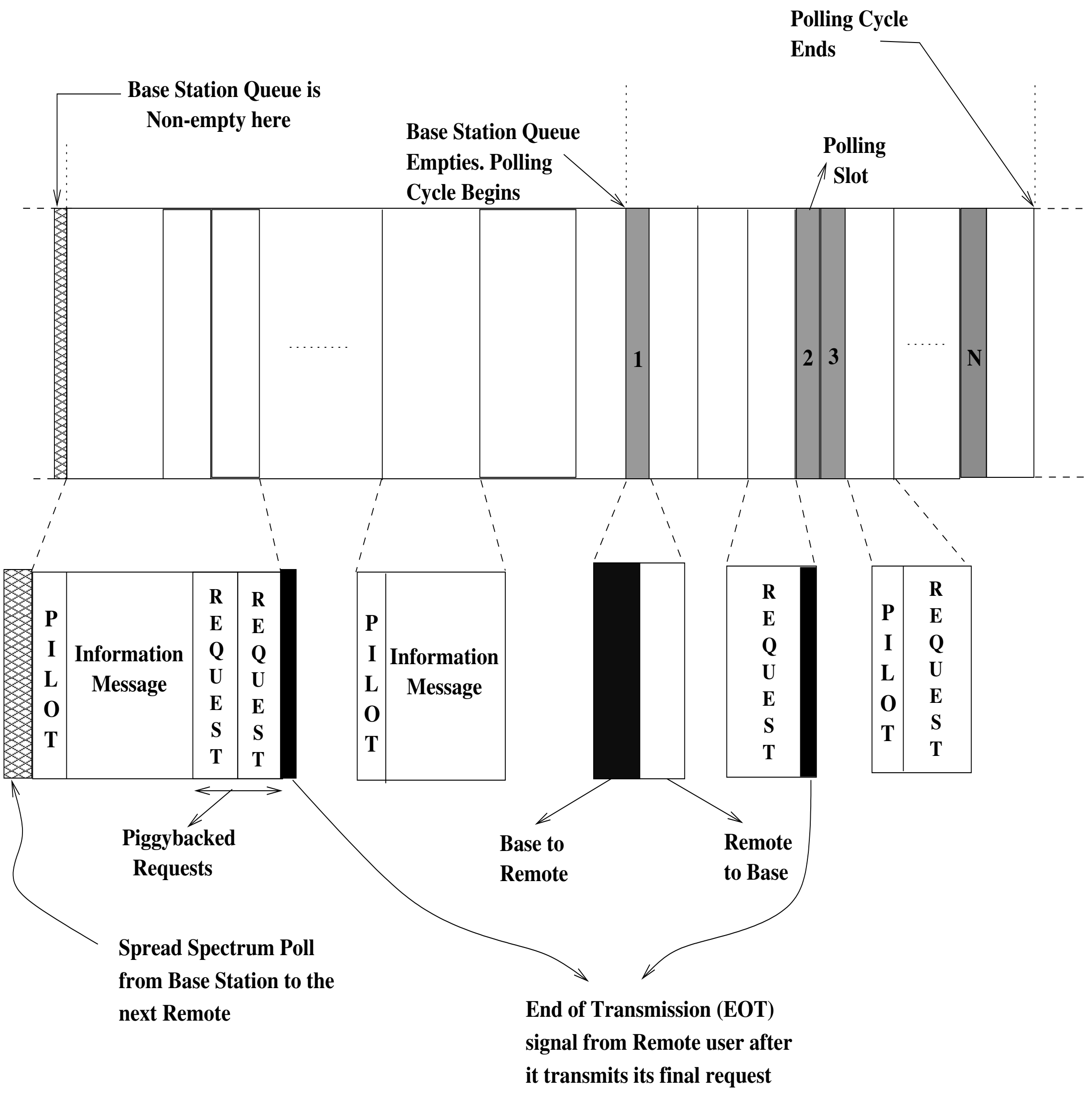

Figure 4: The Exhaustive Polling Scheme

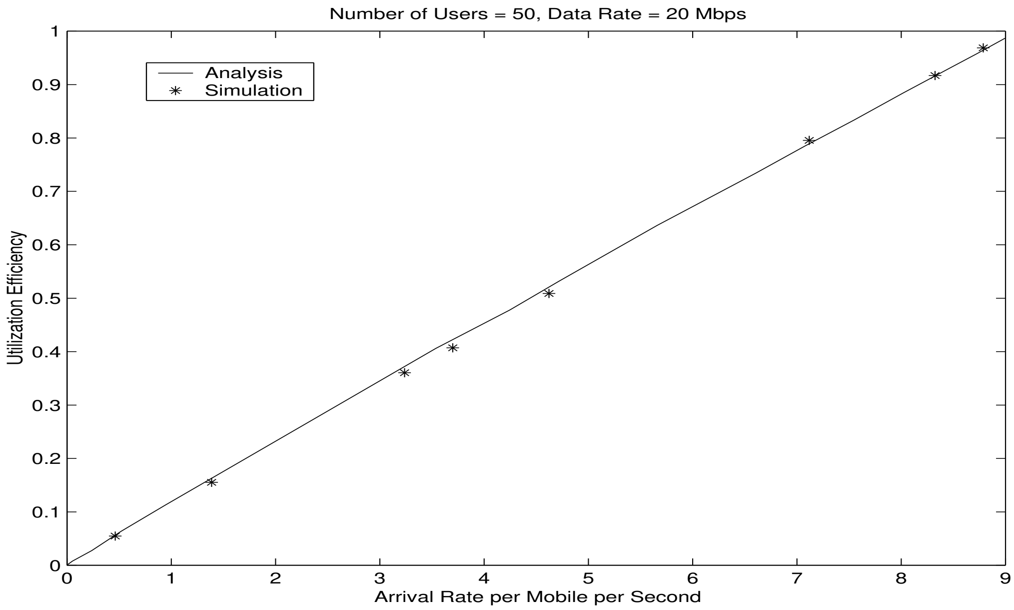

Figure 5: Limited Polling: Utilization Efficiency vs Arrival Rate per Mobile for 50 remotes in a cell

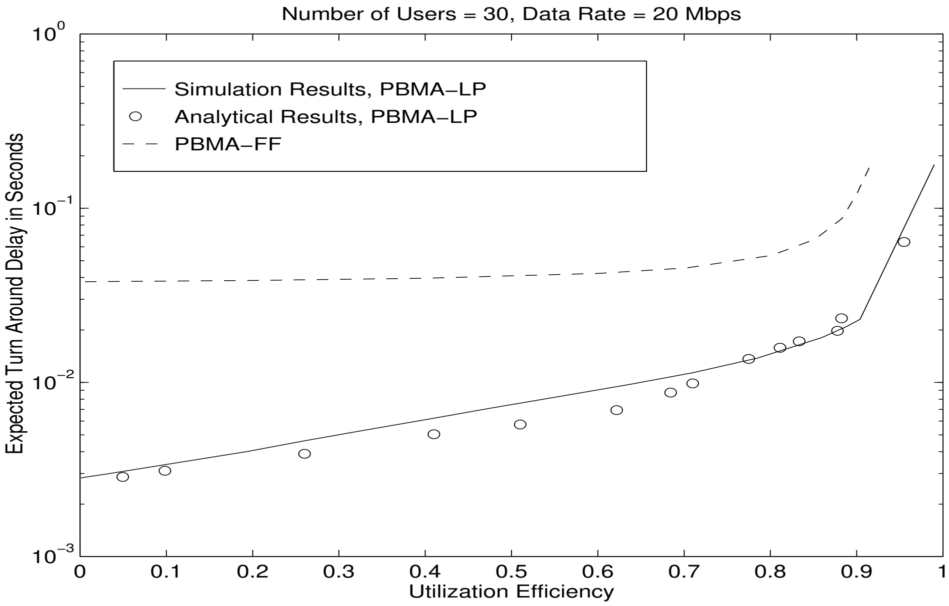

Figure 6: Limited Polling: Expected Turn Around Delay vs Utilization Efficiency for 30 remotes in a cell

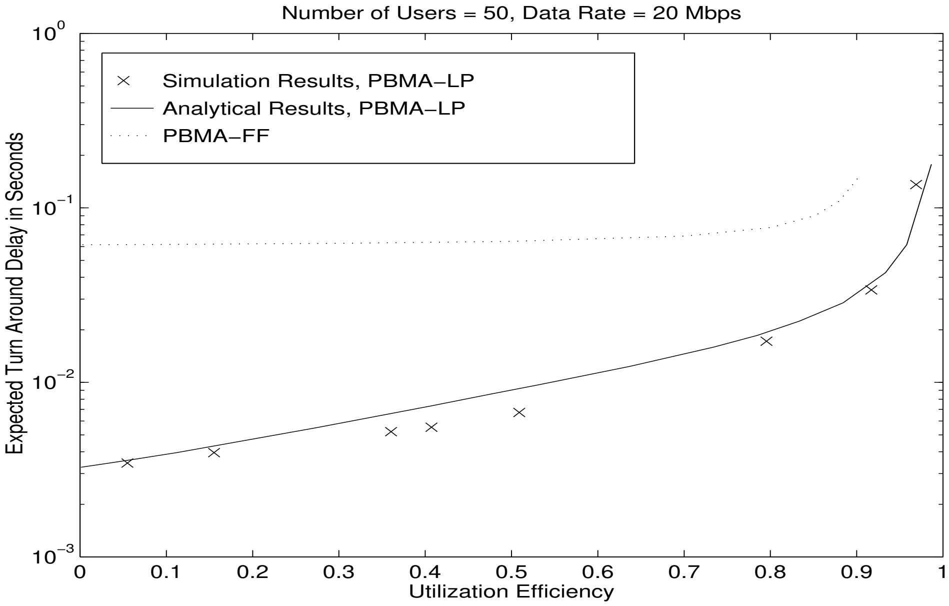

Figure 7: Limited Polling: Expected Turn Around Delay vs Utilization Efficiency for 50 remotes in a cell

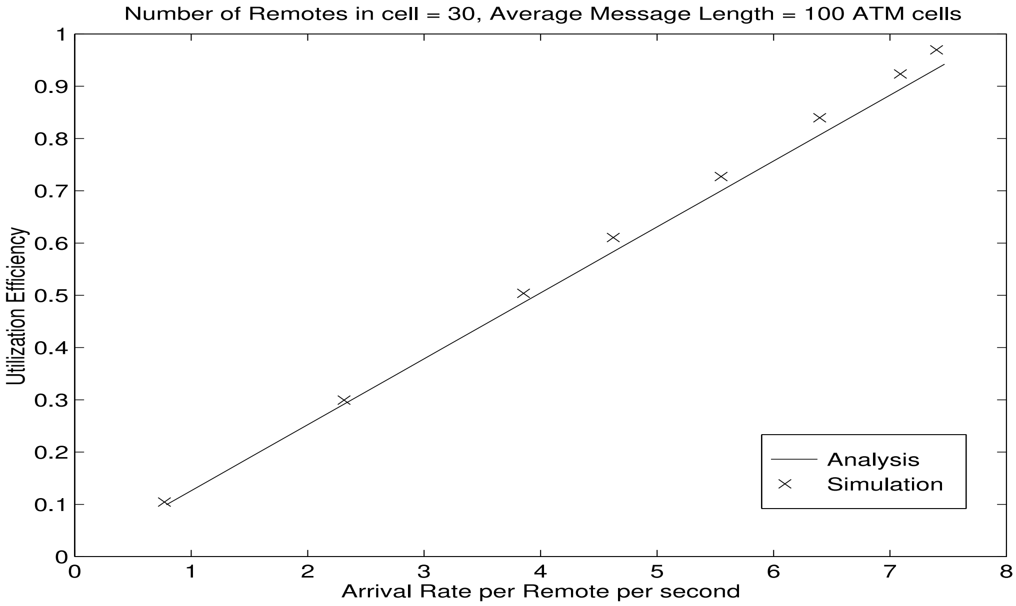

Figure 8: Exhaustive Polling: Utilization Efficiency vs Arrival Rate per Remote for 30 remotes in a cell

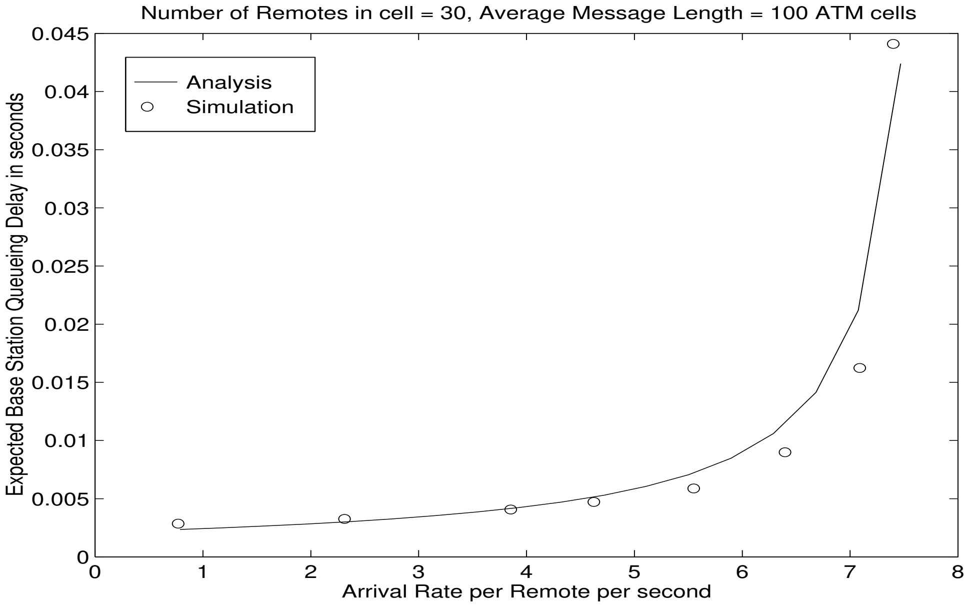

Figure 9: Exhaustive Polling: Expected Base Station Delay vs Arrival Rate per Remote for 30 remotes in a cell

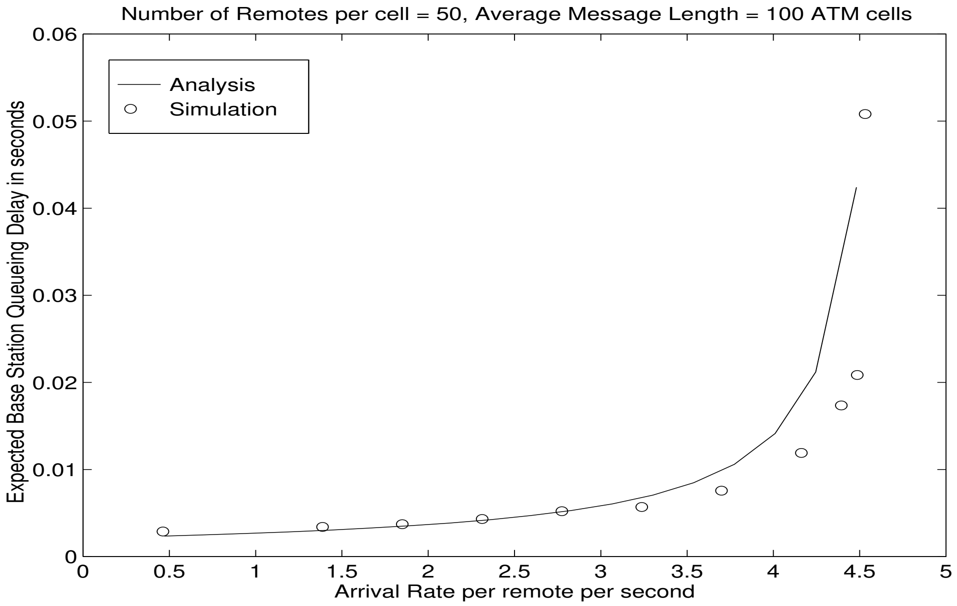

Figure 10: Exhaustive Polling: Expected Base Station Delay vs Arrival Rate per Remote for 50 remotes in a cell

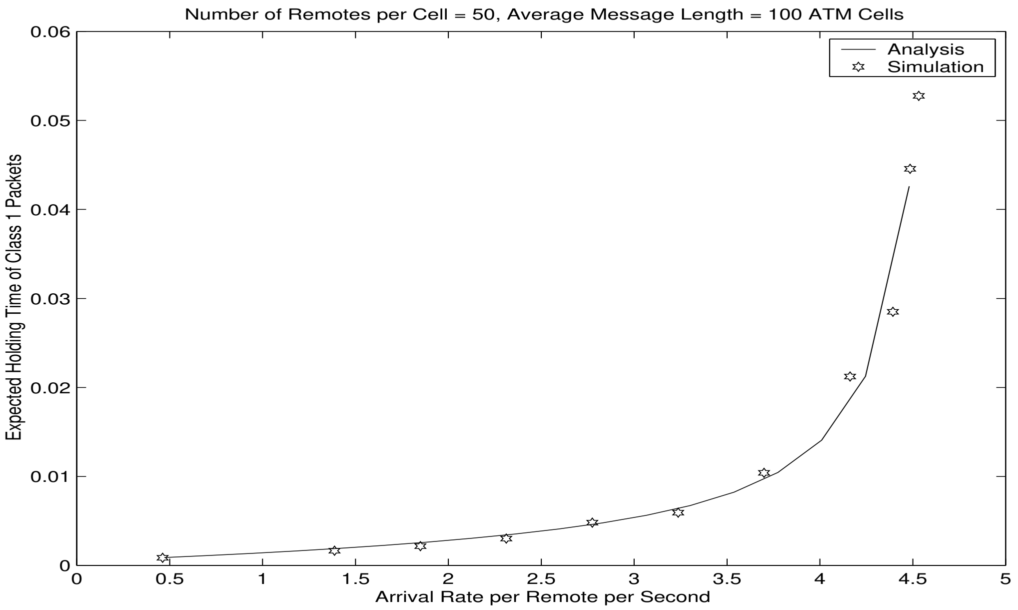

Figure 11: Exhaustive Polling: Expected Holding Time for Class 1 requests vs Arrival Rate per Remote for 50 remotes in a cell

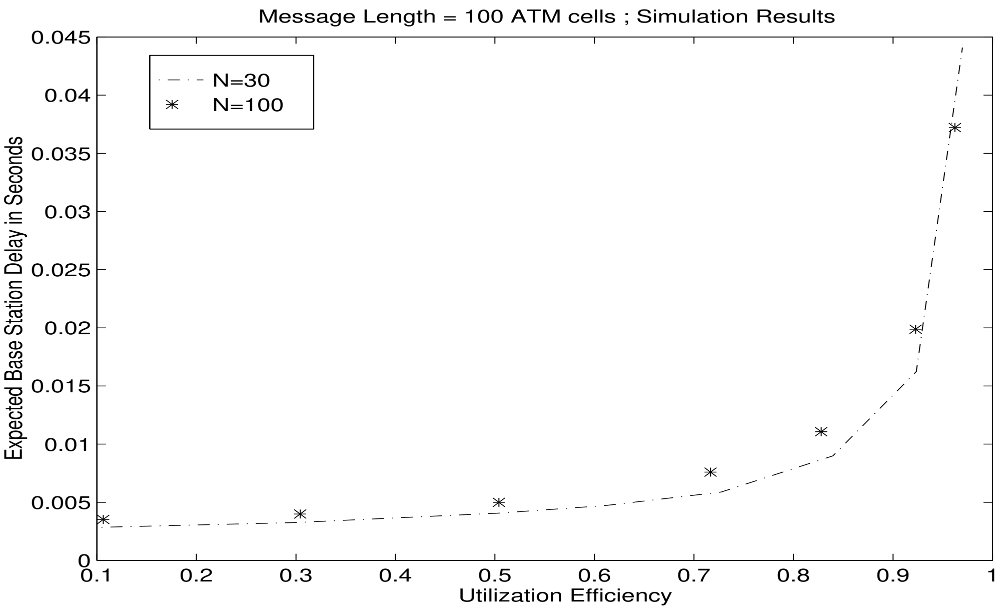

Figure 12: Exhaustive Polling: Expected Base Station Delay vs Utilization Efficiency

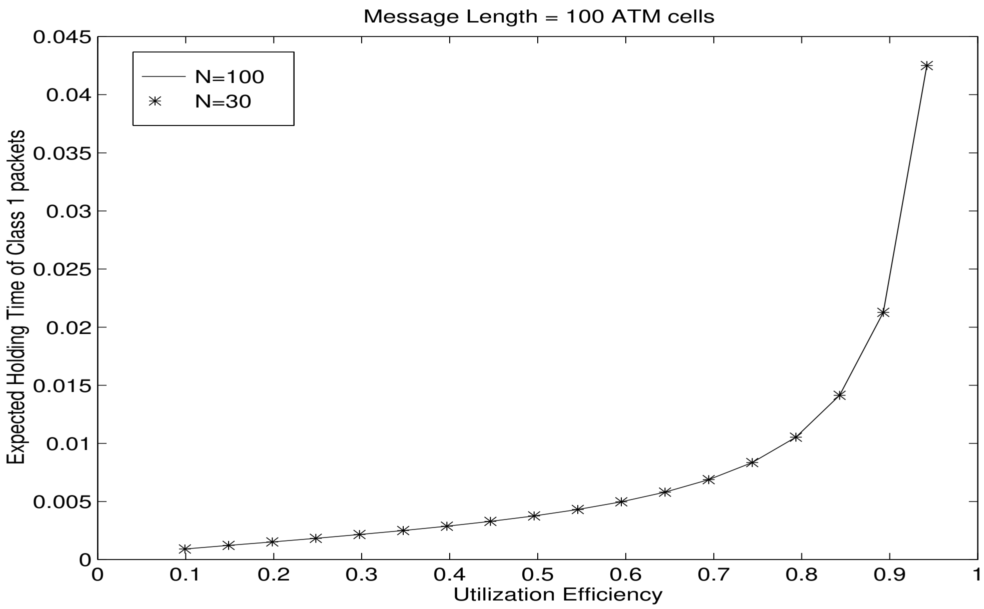

Figure 13: Exhaustive Polling: Expected Holding Times for Class 1 requests vs Utilization Efficiency

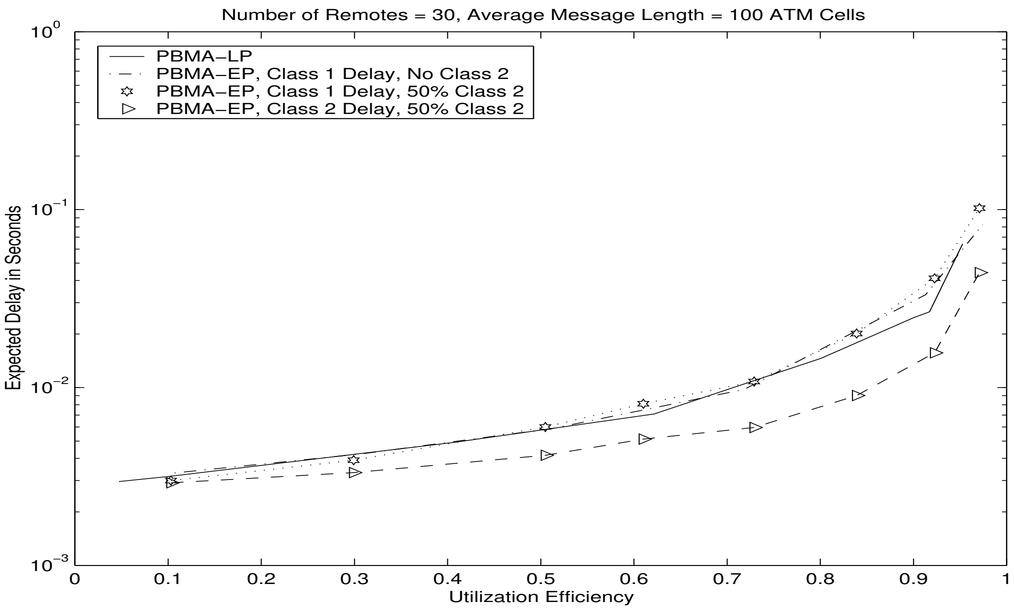

Figure 14: Comparing the Expected Turn Around Delay for PBMA-LP and PBMA-EP

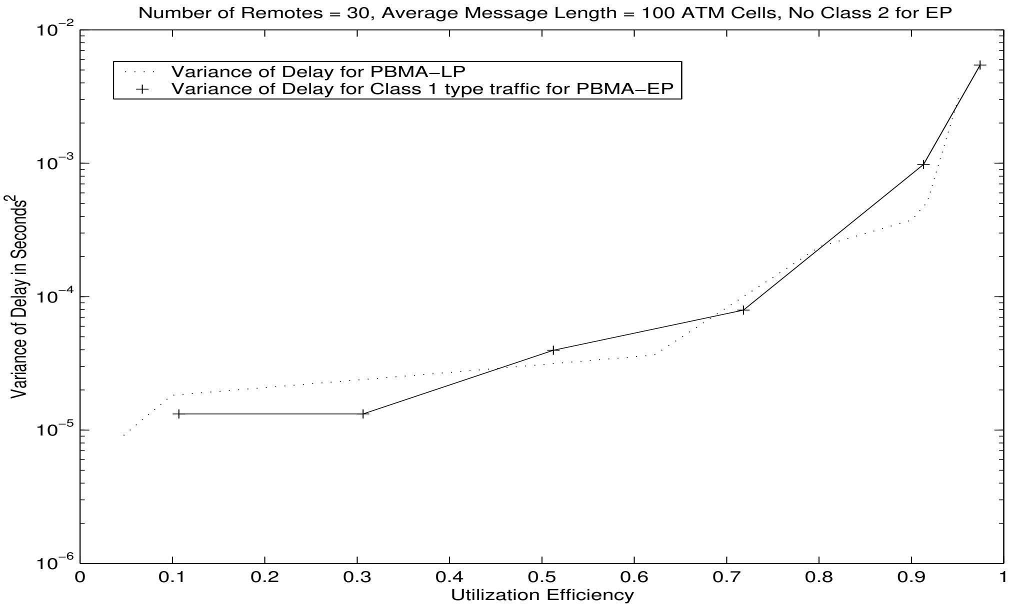

Figure 15: Variance of the Turn Around Delay for PBMA-LP and PBMA-EP

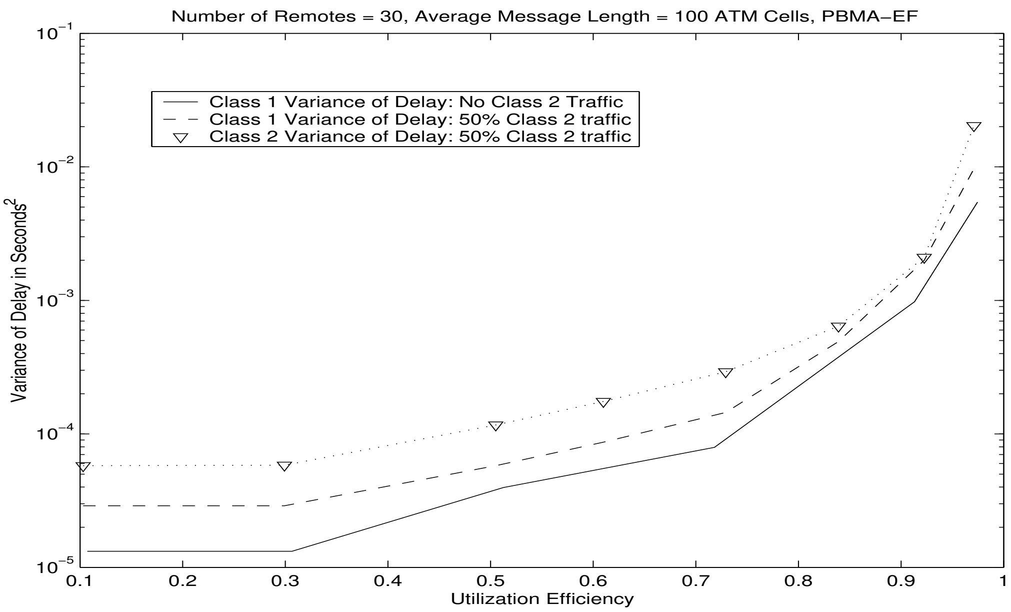

Figure 16: Variance of the Delay for PBMA-EP for different fractions of Class 2 traffic