E-BAMA vs. RAMA

Under certain conditions, one of these two multiple-access protocols for mobile wireless communication offers superior throughput delay.

Gregory P. Pollini and Zygmunt J. Haas

Multiple-access protocols coordinate access to a common transmission channel(or a set of channels) in environments where there is no direct communication between users. In this article, we use the term "user" to indicate a user's data terminal, phone, or other equipment. Some protocols rely on a separate signaling channel to carry channel access requests for new call set-ups, and handovers between the coverage area of two base stations. Additional messages, such as registrations, also use the signaling channel, although these are not considered in this study.

This article presents a performance comparison of two random access protocols for wireless mobile signaling in which a single channel is dedicated to the signaling function—enhanced beacon-assisted multiple access (E-BAMA) and resource auction multiple access (RAMA). Results are available in [1] for BAMA with multiple signaling channels. Data traffic is transported separately on a set of orthogonal channels. The beacon-assisted multiple access (BAMA) protocol was first presented as a method of providing mobility management functions, e.g., handover, while minimizing the processing burden placed on the mobile [1]. In BAMA, throughout the duration of its call, an active user repeatedly and quasi-periodically broadcasts a beacon containing its ID using the Aloha protocol [2, 3]. Quasi-periodicity prevents a pair of users from repeatedly colliding with each other [1]. When a base successfully receives the beacon and assigns a channel, it uses a separate downstream channel to send to the mobile an acknowledgement that contains the number of the assigned channel. The BAMA protocol includes a scheme to maintain lists of active mobiles in nearby cells and to exchange periodically these lists among the base-stations. A more detailed discussion can be found in [1].

E-BAMA differs from BAMA in two respects. While in BAMA a user always transmits its beacon, in E-BAMA the beacon is transmitted only at call initiation and during a handover. In E-BAMA, a rough measurement of the channel quality is needed to determine when a handover is required. As the accuracy of the channel quality information decreases, the beacon becomes active for longer periods of time.Thus, there is a trade-off between measurement accuracy and channel capacity, which is directly related to the on-period of the beacon.

In the original description of the BAMA protocol [1], it was assumed that data channels were based on the code division multiple access (CDMA) scheme. The channel ID contains the code or hop sequence needed for direct sequence CDMA (DS-CDMA) or frequency hop CDMA (FH-CDMA), respectively. Depending on the available codes and their distribution, new code assignment during a handover might not be necessary. If the code space is very large then only a very small fraction of handovers would require new codes. In this article, we assume that the data channels are implemented using the time division multiplexing (TDM) and frequency division multiplexing (FDM) schemes.

Two different strategies are available to deliver the downstream information (mobile and channel identifiers). In the first, the total bandwidth is divided between the upstream and downstream channels using frequency division duplexing (FDD). The portion assigned to each channel is chosen to maximize resource usage. Users contend on one frequency channel and wait to hear a response from the base on another frequency channel.

When slotted-aloha (S-Aloha) is used, channels can be operated in the FDD mode or the time division duplex (TDD) mode. In the TDD mode, each slot contains an upstream portion and a downstream portion with each proceeded by a guard interval. The feedback information from the base contains only the channel identifier assigned to the contending user. If no user is successful (i.e., no attempt or a collision) then the feedback contains the `no assignment` message.

The RAMA protocol was proposed in [4, 5] as a mechanism for fast resource assignment and handover. It was named in [6], where resource assignments took place on a talkspurt-by-talkspurt basis. In RAMA, users transmit requests to the base on a slotted signaling channel. The signaling channel uses M-ary orthogonal modulation,

GREGORY P. POLLINI is a Ph.D. student at Rutgers University.

ZYGMUNT HAAS is a member of technical staff at AT&T Bell Laboratories.

 0890-8044/94/$04.00

which allows multiple frequencies to be simultaneously received at the base station. Using a collision resolution protocol based on the user's ID and assuming an error-free channel, the base station can uniquely identify a single user in each cycle and grant that user a channel. Each cycle consists of contention and assignment periods: users transmit traffic channel requests to the base station during the contention period; the base allocates available channels during the assignment period. During each cycle, the base identifies a single unique user and assigns it a channel. Those users who fail to obtain allocation try again in the next cycle. Thus as long as there is a user contending for a channel and there are free channels available, there is one assignment every cycle.

A cycle starts with the base station sending a "polling" signal. Each user replies with a short burst on the frequency that corresponds to its first ID digit. The base chooses one of the busy frequencies, and echoes it back to the mobile. A mobile that hears the base echo back any symbol other than its own, drops out of the contention for this cycle. The remaining users continue in this collision resolution cycle by sending a short burst on the frequency corresponding to their second ID digit. This process continues until all the digits are sent. The single remaining user is assigned a channel in the assignment period that follows the contention period. This protocol requires TDD operation on a symbol-by-symbol basis during the contention period. Thus although one channel is assigned every slot (if one is free), there is wasted bandwidth associated with the TDD operation.

The next section evaluates the capacity and delay performance of E-BAMA and RAMA. Then, we present a numerical comparison with parameters suggested in [1, 4-6]. Finally, the results are summarized qualitatively. Some additional derivation is included in the Appendix.

Performance Evaluations

This section develops expressions for the capacity and access delay of E-BAMA and RAMA. We define capacity as the number of active mobiles (mobiles engaged in a call) per cell. The capacity of the access protocols is limited by the total number of new call originations (i.e., call set-ups) and handovers, denoted as the number of channel accesses. (Here, we do not distinguish between call set-ups and handovers.) We determine the number of channel accesses supported by a single random access channel, and then use a model of user mobility to find the number of users per cell.

For both protocols, we assume that the user identifier is composed of I_d digits and a channel identifier of C_h digits. In general, i decimal digits can be coded as

$$i\ [\textit{decimal digits}] = i\log_M(10)\ [\textit{M-ary symbols}]. \quad (1)$$

Thus, the user and the channel identifiers are coded as $I_d\log_M(10)$ and $C_h\log_M(10)$ M-ary symbols.

For E-BAMA, we use on-off keying (OOK) and transmit a continuous binary (M=2) bit stream. For RAMA, orthogonal modulation is required. We use M-FSK and choose the M that minimizes the total time to transmit the beacon.

The symbol duration depends upon the modulation scheme. In OOK the symbol duration, T_S, is simply $1/BW\ (= \gamma)$, where BW is the channel bandwidth. For M-FSK the symbol duration is

$$T_S = \frac{M}{BW} = \gamma M, \quad (2)$$

where M is the number of frequencies. This relation assumes that noncoherent detection is used [7]. (For coherent detection, the symbol duration is $T_S/2$, i.e., the MSK separation of frequencies.)

Throughout this article, we assume error-free transmission. Under the assumptions outlined above (and subject to the same maximum power constraint), the symbol error rate of RAMA (with M-FSK) is less than the symbol error rate for BAMA (with OOK) over the same additive white gaussian noise (AWGN) channel. However, an error in RAMA may affect several allocations in that cycle, where an error in BAMA affects at most a single allocation.

Capacity of BAMA

In this article, we do not discuss the techniques used to evaluate the capacity of the BAMA protocol. For access delay over the range of practical interest, RAMA supports more users then BAMA. BAMA was designed to offload as much processing as possible from the mobile. This was achieved by having every active user continuously transmit its quasi-periodic beacon at an average frequency of f_{beacon}. If each beacon takes t_{beacon} seconds to transmit, then the maximum number of users is restricted to $1/(t_{beacon}f_{beacon})$.

For BAMA to support a large number of users, the beacon frequency must be made extremely slow, on the order of seconds. The access delay is a multiple of the beacon period ($1/f_{beacon}$).

Upstream Capacity of Enhanced BAMA

In E-BAMA, each user activates a quasi-periodic beacon with average period T_p when a call set-up or a handover is required. The mobile repeats the same beacon over and over again. The E-BAMA signaling channel uses either the Aloha or the S-Aloha protocols; the calculations here assume the Aloha protocol. Results for S-Aloha require only trivial modification.

The throughput of Aloha, S, is described by the characteristic equation given as

$$S = Ge^{-2G}, \quad (3)$$

where G is the offered traffic [3].

Using Eq. (1) with $M = 2$, the duration of a beacon containing I_d decimal digits transmitted over a channel with a bandwidth of $BW = \frac{1}{\gamma}$[Hz] is:

$$I_d\gamma\log_2(10)\ \left[\frac{\textit{seconds}}{\textit{beacon}}\right]. \quad (4)$$

When a user wishes to access the channel, it transmits its beacon until it is able to get through. This requires on average $\bar{k}$ attempts. First, considering only upstream transmissions, the time that a single user holds the channel is

$$\bar{k}I_d\gamma\log_2(10)\ \left[\frac{\textit{seconds}}{\textit{channel access}}\right]. \quad (5)$$

An access is for a handover or a new call setup.

RAMA may affect several allocations in that cycle, where an error in BAMA affects at most a single allocation.

■ ■ ■ ■ ■

The downstream channel is slotted and functions as a first-in first-out (FIFO) queue. We assume that the arrival of upstream channel access requests is a Poisson process.

The average number of handovers per second for each mobile is labeled HO_M. The average call arrival rate to/from a mobile second is λ_M. Thus, there are $HO_M + \lambda_M$ channel accesses per second per mobile. It has been shown [8] that using the fluid model of mobility [9] gives the average handover rate of a mobile as

$$HO_M = \frac{V}{\sqrt{A_C}} E_{term} \left[\frac{handovers}{sec \cdot mobile} \right], \qquad (6)$$

where V is the average mobile's velocity, A_C is the cell area, and E_{term} (in Erlangs) is the activity factor of a user, i.e., *Prob*[*a user is on*] as defined in [10].

The total offered traffic on the signaling channel from N_{cell} users in a cell is given by

$$G = N_{cell}[HO_M + \lambda_M]\bar{k} I_d \gamma \log_2(10) \left[\frac{Erlangs}{cell} \right] \qquad (7)$$

We assume that the process of user activity is ergodic, i.e., the percentage of time a user is active equals the percentage of active users at any time. The average number of active users at any given time in a cell is

$$n = E_{term} N_{cell} \ [active\ users]. \qquad (8)$$

The average number of attempts until success, $\bar{k}$, is equal to $\frac{G}{S}$ [3]. Substituting Eqs. (7) and (8) into Eq. (3) and using the relation $\gamma\bar{x} = E_{term}$ (where $\bar{x}$ is the average call duration in seconds) allows for calculation of the average number of active users supported by an E-BAMA channel as

$$n = \frac{Ge^{-2G}}{I_d \left[\frac{V}{\sqrt{A_C}} + \frac{1}{\bar{x}} \right] \gamma \log_2(10)} \left[\frac{active\ users}{cell} \right]. \qquad (9)$$

This equation assumes that all of the available bandwidth is used by upstream transmissions. To account for the effect of downstream transmissions, we need to determine the distribution of the bandwidth between the upstream and downstream channels.

Upstream Delay Performance of E-BAMA

Assume that the first beacon is transmitted as soon as the mobile realizes that a handover or call set-up is required. Let the access delay include the time interval from the first access attempt to the time of the final (i.e., first successful) attempt, but it does not include the transmission time of the final attempt. When the upstream channel is an Aloha channel, the access delay for upstream transmission in E-BAMA is

$$t_{acc}(unslotted\ E-BAMA) = \left[e^{2G} - 1 \right] T_p \left[\frac{seconds}{access} \right], \qquad (10)$$

where $e^{2G} = \frac{G}{S}$ is the average number of tries to succeed and T_p is the average time between each try. (Appendix A presents a more formal derivation based on other results [3].)

If the upstream channel is an S-Aloha channel, the access delay is given then by:

$$t_{acc}(slotted\ E-BAMA) = \left[e^{G} - 1 \right] T_P + \frac{T_{slot}}{2} \left[\frac{seconds}{access} \right] \qquad (11)$$

where $T_{slot}/2$ is the average time until the first attempt for a randomly arriving request, since an attempt must wait until the beginning of the next slot. (We assume Poisson arrival of attempts.)

In practice, it is often the case that $T_p \gg T_{slot}$. Thus neglecting the second term in Eq. (11) has little effect on the evaluated performance.

Downstream Delay Performance of FDD E-BAMA

The downstream channel is slotted and functions as a first-in first-out (FIFO) queue. We assume that the arrival of upstream channel access requests is a Poisson process.

We model the downstream as an M/D/1 queue with vacations. The average waiting time in the M/D/1 queue with vacations is

$$t_{acc}(downstream\ FDD\ E-BAMA) = \frac{\bar{y}}{2(1-\lambda\bar{y})} \left[\frac{seconds}{access} \right], \qquad (12)$$

where $\bar{y}$ is the mean service time, and λ is the mean arrival rate. These are given by

$$\lambda = n \left[\frac{V}{\sqrt{A_C}} + \frac{1}{\bar{x}} \right] \left[\frac{accesses}{hour \cdot cell} \right], \qquad (12a)$$

and

$$\bar{y} = (I_d + C_h)\gamma_{down} \log_2(10) \left[\frac{seconds}{access} \right], \qquad (12b)$$

with $\gamma_{down} = 1/BW_{down}$, the reciprocal of the bandwidth used by the downstream channel.

Capacity and Delay of FDD E-BAMA with Aloha

In order not to transmit more than the minimum required number of beacons on the upstream, the delay on the downstream must not exceed the average beacon period, T_p. (We assume that this delay equals T_p. Since the portion of the tail of the distribution of the access delay on the downstream exceeding T_p represents the probability that additional unnecessary upstream beacon will be sent, the downstream access delay may need to be shorter than T_p, requiring larger downstream bandwidth. Thus, we understate the required capacity of the downstream and overstate the available capacity of the upstream thereby providing an upper bound on upstream capacity.) We must solve

$$t_{acc}(downstream\ FDD\ E-BAMA) = T_p \qquad (13)$$

for the downstream bandwidth, BW_{down} and find that

$$BW_{down} = (I_d + C_h)\log_2(10) \left[\frac{1}{2T_p} + n \left[\frac{V}{\sqrt{A_C}} + \frac{1}{\bar{x}} \right] \right] [Hertz] \qquad (14)$$

The bandwidth available for the upstream channel, BW_{up} is just $BW - BW_{down}$. Now define $\gamma_{up} = 1/BW_{up}$. Replace γ in Eq. (9) by γ_{up} and solve for n. Thus the number of active users supported by an FDD E-BAMA system using pure Aloha is

$$n=\frac{BW-\frac{I_d+C_h}{2T_p}\log_2(10)}{\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]\log_2(10)\left[\frac{I_d}{G}e^{2G}+I_d+C_h\right]}\left[\frac{\textit{active users}}{\textit{cell}}\right]. \tag{15}$$

The average access delay is given by Eq. (10), with G given by Eq. (7).

Capacity and Delay of FDD E-BAMA with S-Aloha

Modify Eq. (4) to include the additional beacon length (in time) associated with separating each upstream transmission by a guard of length $t_G/2$. The total offered traffic on the upstream channel is

$$G_{up}=n\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]e^{G_{up}}\left[I_d\gamma_{up}\log_2(10)+t_{G_{up}}\right]\left[\frac{\textit{Erlangs}}{\textit{cell}}\right]. \tag{16}$$

Since $\gamma_{up} = 1/(BW - BW_{down})$ substitute Eq. (14) into Eq. (16) and solve for n to get

$$n=\frac{\left[-b-\sqrt{b^2-4ac}\right]}{2\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]}, \tag{17}$$

where

$$a = 1 \tag{17a}$$

$$b=\frac{1}{2}T_P-e^{-G_{up}}\frac{1}{t_{G_{up}}}-\frac{A_{I_d}}{A}\frac{1}{t_{G_{up}}}-\frac{BW}{A} \tag{17b}$$

$$c=G_{up}e^{-G_{up}}BW\frac{1}{t_{G_{up}}}\frac{1}{A}-G_{up}e^{-G_{up}}\frac{1}{t_{G_{up}}}\frac{1}{2T_P}, \tag{17c}$$

and with the shorthand notation

$$A_{I_d} = I_d\log_2(10) \tag{18a}$$

$$A_{C_h} = C_h\log_2(10) \tag{18b}$$

$$A = A_{I_d} + A_{C_h}. \tag{18c}$$

The average access delay is given by Eq. (11), with G_{up} given by Eq. (16).

Capacity and Delay of TDD E-BAMA with S-Aloha

Using Eqs. (6) and (8) and rewriting Eq. (7), the offered traffic to the upstream channel is

$$G_{up}=n\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]\bar{k}I_d\gamma\log_2(10)\left[\frac{\textit{Erlangs}}{\textit{cell}}\right]. \tag{19}$$

The downstream information consists of only the channel identifier. Between the upstream and downstream transmissions, there must be a guard interval. There is one upstream and one downstream transmission per slot, so there are two guard intervals per slot, each of duration t_G. The offered traffic to the downstream channel, including both guard periods is

$$G_{down}=n\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]\bar{k}\left[C_h\gamma\log_2(10)+2t_G\right]\left[\frac{\textit{Erlangs}}{\textit{cell}}\right]. \tag{20}$$

Adding together Eqs. (19) and (20) and solving for n gives the number of active users on a TDD E-BAMA S-Aloha channel as

$$n=\frac{G}{\left[\frac{V}{\sqrt{A_C}}+\frac{1}{\bar{x}}\right]\bar{k}\left[(I_d+C_h)\gamma\log_2(10)+2t_G\right]}\left[\frac{\textit{active users}}{\textit{cell}}\right]. \tag{21}$$

The average access delay can be now obtained by substituting $G = G_{up} + G_{down}$ into Eq. (11) with the values of G_{up} and G_{down} from Eqs. (19) and (20).

Capacity of Resource Auction Multiple Access

This section follows the RAMA evaluation presented elsewhere [4, 5], and it extends those results by providing an expression for the optimum number of orthogonal signals for M-FSK as a function of the guard interval.

The number of supported channel accesses is inversely proportional to the cycle time, which is the time to allocate a single channel to a mobile. The total cycle time,

$$t_{tot} = 2I_d t_X + C_h T_S, \tag{22}$$

consists of two adjacent periods: the contention period $I_d t_X$, and the assignment period $C_h T_S$, where t_X is the time to transmit a single user ID digit (one out of I_d decimal digits) and T_S is the time to transmit one symbol (out of C_h decimal digits) of the assigned channel number on the downstream channel.

In the contention period, each user transmits its I_d symbols of its user ID on a symbol-by-symbol basis. After each symbol, the base echoes the winner. Mobiles not hearing their symbol drop out. A guard interval of length t_G is required after each symbol; it must be sufficiently long to allow on/off time of the transmitter and to allow for the processing and propagation delays between consecutive upstream and downstream transmissions. (In RAMA, an inactive transmitter must be turned off to avoid interference with other active transmitters.) Thus the time for the transmission of a single symbol is:

$$t_X = T_S + t_G \text{ [sec]}, \tag{23}$$

where T_S is a time to transmit a user ID symbol.

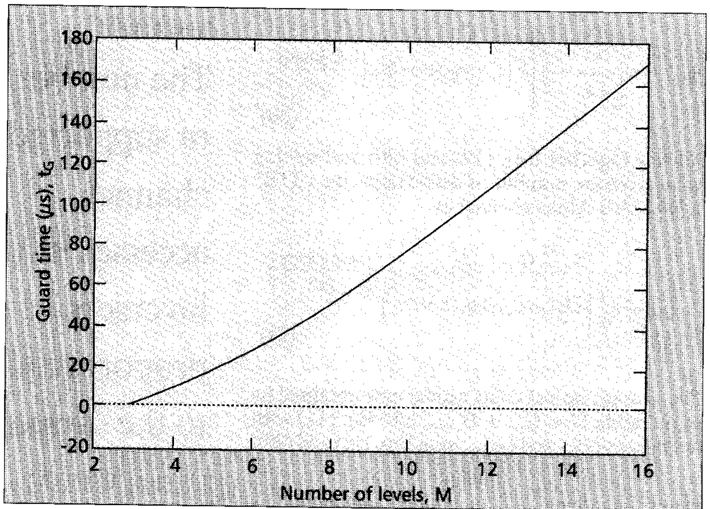
A channel is allocated to the winner of a contention during the assignment period. The base assigns a channel by broadcasting the channel's C_h symbol long ID. The duration of each channel ID symbols is also T_S.

Combining Eqs. (1), (2), (22), and (23) gives a final expression for the cycle time as

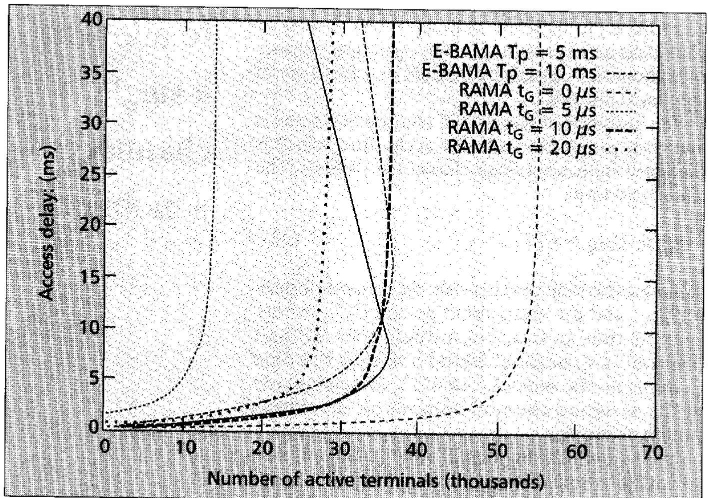
$$t_{tot} = 2I_d(\alpha\gamma M + t_G)\log_M(10) \text{ [sec]}, \tag{24}$$

where α is a constant which depends only upon the lengths of the user and channel IDs,

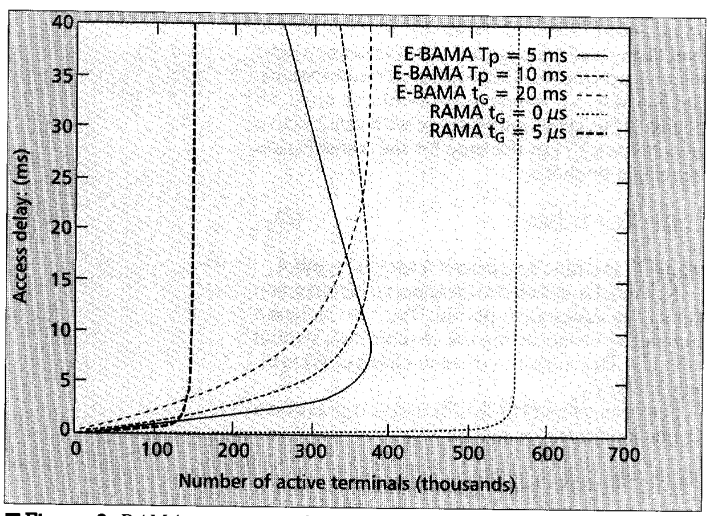
The number of supported channel accesses is inversely proportional to the cycle time, which is the time to allocate a single channel to a mobile.



■ **Figure 1.** *Optimum M versus guard time for RAMA.*



■ **Figure 2.** *RAMA vs. pure Aloha E-BAMA. (BW = 200 kHz; Ac= 1 km x 1 km).*



■ **Figure 3.** *RAMA versus pure Aloha E-BAMA. (BW = 2 MHz; Ac= 1 km x 1 km).*

Parameter name	Variable	Value	Unit
User identifier	N_{I_d}	10	digits
Channel identifier	N_{C_h}	4	digits
Cell size	A_C	1	km²
Mobile velocity	V	55	km/hr
Mean call duration	$\bar{x}$	120	sec
User traffic	E_{term}	0.1	Erlangs

■ **Table 1.** *Fixed parameters used in the comparative study.*

$$\alpha = \frac{2I_d + C_h}{2I_d} \quad . \tag{25}$$

Practically, the number of channels will be less than the number of users ($I_d \geq C_h$), meaning that $\alpha \in [1, 1.5]$.

The number of channel accesses per second is simply the inverse of the total cycle time. (This assumes there is no restriction on how cycles can be mapped into frames. Others assume there is an integer number of cycles per frame and the leftover is wasted [4-6]. Neglecting this provides a bound on capacity.) Using Eqs. (6) and (8), the channel accesses are distributed between new call setup requests and handover requests to find the number of active users per cell as

$$n = \frac{\frac{1}{t_{tot}}}{\frac{V}{\sqrt{A_C}} + \frac{1}{\bar{x}}} \left[\frac{\text{active users}}{\text{cell}}\right], \tag{26}$$

where t_{tot} is given by Eq. (24).

Theorem 1: there is an M^{opt} which minimizes the total cycle time t_{tot}, given as

$$t_G = \gamma\alpha M^{opt}(\ln M^{opt} - 1) \, . \tag{27}$$

Since $t_G \geq 0$, M^{opt} is always greater than two. Thus 2-FSK or FSK is never the optimum choice.

Proof: minimize Eq. (24) with respect to M and rearrange to get (27). Note that $t_G = 0$ when $M = 0$ or $M = e < 3$.

It has been suggested by example that $M = 4$ is best over the important range of t_G [4,5]. For M=4, C_h=4, I_d=10, and BW=200 kHz, the range is 5.13 μs ≤ t_G ≤ 13.3 μs. For shorter guard intervals M=3 should be used. For E-BAMA we use M = 2, since we assume on-off keying.

Figure 1 shows Eq. (27). All numerical examples that involve RAMA use the optimum M found from this graph.

Delay of Resource Auction Multiple Access

Just like the downstream channel of E-BAMA, RAMA is modeled as a M/D/1 queuing systems with vacations. Use Eq. (13) with

$$\bar{y} = t_{tot} \, , \tag{28}$$

Parameter name	Variable	Values
Channel bandwidth	BW	20 kHz, 200 kHz, 2 MHz
Beacon period	T_p	5, 10, 20 msec
Guard interval	t_G	0, 5, 10, 20, 50 usec

■ **Table 2.** *Variable parameters used in the comparative study.*

and

$$\lambda = (HO_M + \lambda_M)N_{cell} = \left[\frac{V}{\sqrt{A_C}}E_{term} + \lambda_M\right]N_{cell}. \quad (29)$$

to get the average access delay for RAMA as

$$t_{acc}(RAMA) = \frac{t_{tot}}{2 - 2\left[\frac{V}{\sqrt{A_C}}E_{term} + \lambda_M\right]N_{cell}t_{tot}} \; [seconds].$$

Comparisons and Examples

This section compares the protocols by presenting numerical examples based on realistic parameters. We choose parameters consistent with previous work [1,4-6].

By varying the values of these parameters, we observe how they affect the relative performance of E-BAMA and RAMA. Mostly, these variations affect the performance of the two protocols roughly the same way, e.g., linear dependence on velocity, square root dependence on cell size. These are summarized in Table 1.

The channel and user identifiers exhibit slightly different behavior, i.e., reducing the user ID improves RAMA performance more than E-BAMA. Their effect is not studied in these examples, however.

Several parameters are varied in this study because they affect the relative performance of RAMA and E-BAMA in a very significant way. The examples characterize this dependence. They are summarized in Table 2.

E-BAMA with Aloha versus RAMA

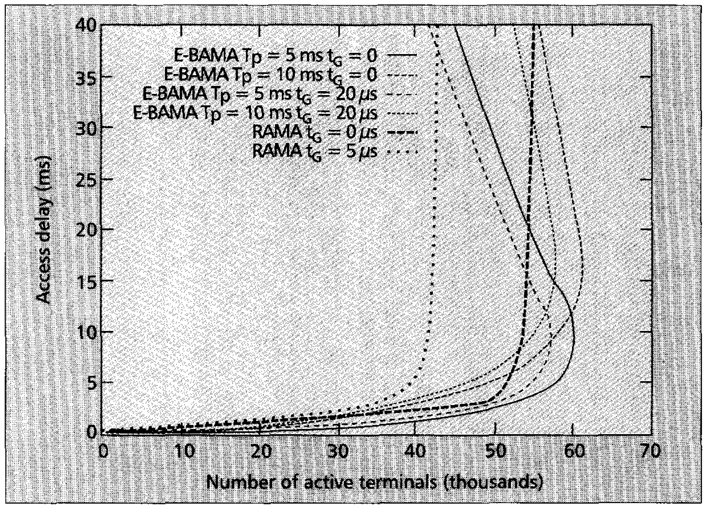
First we compare the delay throughput characteristics of Aloha based E-BAMA and RAMA (Figs. 2 and 3).

For a channel bandwidth of 200 kHz, RAMA is better than E-BAMA unless the guard time is greater than 5 μs (Fig. 2). When the bandwidth is increased by a factor of 10 to 2 MHz, E-BAMA is better than RAMA unless the guard time is much less than 5 μs (Fig. 3). Thus, for larger bandwidths the guard plays a more pronounced role in the comparison.

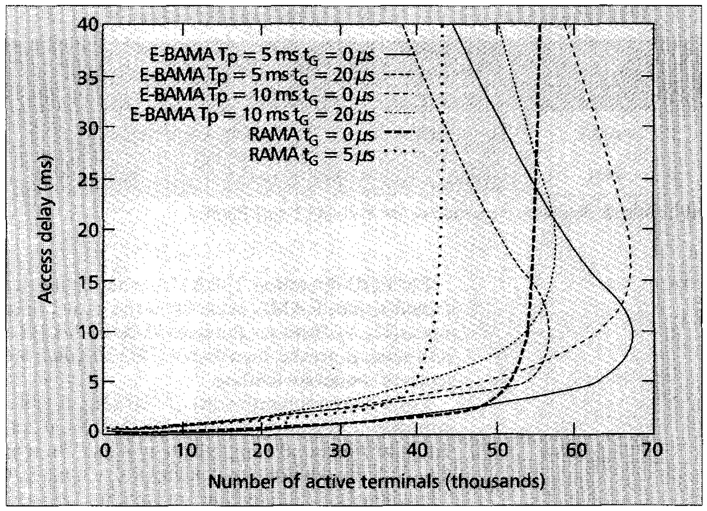
For the Aloha E-BAMA and RAMA protocols, there are two regions of operation: large bandwidth favors E-BAMA, while for small bandwidth RAMA exhibits better performance.

E-BAMA with S-Aloha verses RAMA

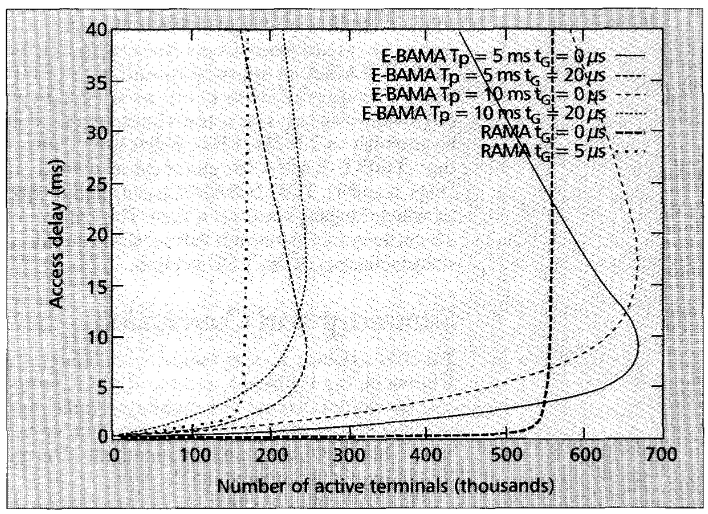
One possible way to improve the performance of E-BAMA is to use S-Aloha instead of pure Aloha. This permits use of both frequency division duplexing (FDD) and time division duplexing (TDD).



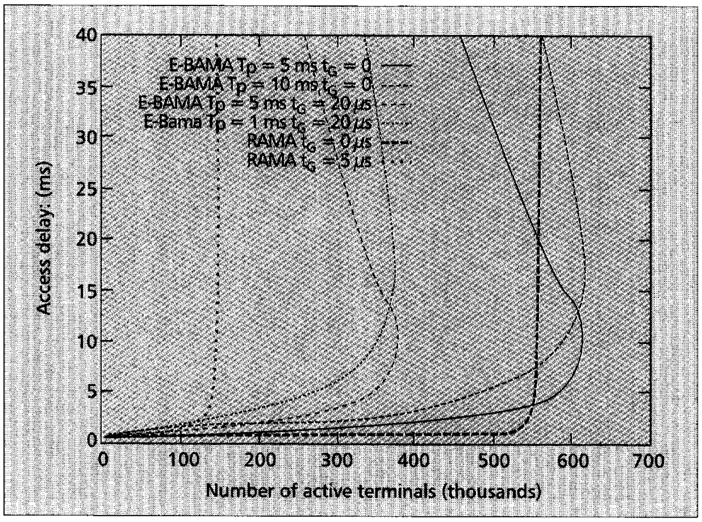
■ **Figure 4.** *RAMA versus S-Aloha E-BAMA (FDD). (BW = 200 kHz; Ac= 1 km x 1 km).*



■ **Figure 5.** *RAMA versus S-Aloha E-BAMA (TDD). (BW = 200 kHz; Ac= 1 km x 1 km).*



■ **Figure 6.** *RAMA versus S-Aloha E-BAMA (TDD). (BW = 2 MHz; Ac= 1 km x 1 km).*



■ **Figure 7.** *RAMA versus S-Aloha E-BAMA (FDD). (BW = 2 MHz; Ac= 1 km x 1 km).*

Small bandwidth	Moderate bandwidth	Large bandwidth	Very large bandwidth
RAMA	TDD E-BAMA best	FDD E-BAMA best	
Best	S-Aloha best		Aloha best

■ **Table 3.** *Regions of operation for E-BAMA and RAMA.*

For FDD operation, E-BAMA achieves greater capacity than RAMA even when the guard time is zero (Fig. 4). However, the access delay of E-BAMA is, in general, greater than that of E-BAMA over the range of moderate loading.

For a channel bandwidth of 200 kHz, further improvement is possible with TDD E-BAMA if the guard interval is sufficiently small. In this case, TDD E-BAMA outperforms FDD E-BAMA even when the guard interval is around 20μs. In comparison to RAMA, the maximum capacity of TDD E-BAMA exceeds that of RAMA (Fig. 5).

TDD E-BAMA performance degrades faster then FDD E-BAMA as the guard interval increases, due to two guard intervals per slot required in the TDD E-BAMA as opposed to one in the FDD case. The degradation is not as severe as in RAMA, however. For a ten-times increase in bandwidth to 2 MHz, FDD E-BAMA is better than TDD E-BAMA for guard interval of 20 μs (Figs. 6 and 7). TDD E-BAMA is only slightly better when the guard interval is zero. This is because it is not necessary to transmit the user ID on the downstream channel of the TDD version.

Summary and Conclusion

In this article, a performance comparison between the E-BAMA and the RAMA protocols for random access in a mobile wireless environment is presented. RAMA was first introduced in [4], while E-BAMA is a new protocol based on the BAMA protocol discussed in [1].

E-BAMA operates on either a pure Aloha or S-Aloha channel in the upstream direction, while information is transmitted downstream in a first-come-first-serve fashion. For the Aloha version of E-BAMA, we observe that for small bandwidths RAMA performs better, while for large bandwidths E-BAMA outperforms RAMA.

For S-Aloha E-BAMA, either TDD or FDD can be used. For a fixed guard, there are three regions of operation in which either Aloha FDD E-BAMA, S-Aloha FDD E-BAMA, or TDD E-BAMA provides the best performance (Table 3).

When bandwidth is very scarce and the access delay is critical, RAMA is preferred because of its high throughput. For moderate bandwidth, a slight increase in capacity at the expense of delay results by switching to S-Aloha E-BAMA. When the bandwidth becomes very large, the time required by the guard interval exceeds the increased capacity benefits of S-Aloha over Aloha. It then becomes beneficial to use Aloha instead of S-Aloha.

We conclude that when the ratio of the propagation delay to the transmission time becomes large enough, unslotted random access protocols yield improved performance over their slotted counterparts. This result is applicable to metropolitan and wide-area wireless networks.

Acknowledgements

The authors wish to thank Louay M.A. Jalloul for providing information on OOK and M-FSK and acknowledge helpful discussions with Chih-Lin I.

References

[1] Z. Haas, and C-L. I, "On Handoffs in Packetized Wireless Systems," Proc. Globecom 93, pp. 1808-14, Houston, TX., Nov. 28-Dec. 2, 1993.
[2] N. Abramson, "The Aloha System—Another Alternative for Computer Communications," AFIPS Conference Proc., Fall Joint Computer Conf., vol. 37, pp. 281-85, 1970.
[3] L. Kleinrock, Queuing Systems Volume 2: Computer Communications, (New York: John Wiley and Sons, 1976), pp. 360-71.
[4] N. Amitay, "Resource Auction Multiple Access (RAMA): Efficient Method for Fast Resource Assignment in Decentralized Wireless PCS," *Electron. Lett.*, vol. 28, no. 8, April 9, 1992, pp. 799-801.
[5] N. Amitay, "Distributed Switching and Control with Fast Resource Assignment/Handoff for Personal Communications Systems," submitted to *IEEE Journal of Sel. Area Comm.*
[6] N. Amitay, and S. Nanda, "Speech Multiplexing in Wireless PCS Employing Resource Auction Multiple Access (RAMA)," *Electron. Lett.*, vol. 28, no. 25, pp. 2294-95, Dec. 3, 1992.
[7] E. Lee, and D. Messerschmitt, Digital Communication, (Boston: Kluwer Academic Pub., 1988).
[8] G.P. Pollini, Capacity of an IEEE 802.6 based Cellular Packet Switch, Proc. ICC 93, Geneva, Switzerland, pp. 1264-68, May 23-26 1993.
[9] R. Thomas, H. Gilbert, and G. Mazziotto, Influence of the Moving of the Mobile Stations on the Performance of a Radio Mobile Cellular Network, Proc. 3rd Nordic Seminar, Paper 9.4, Copenhagen, Denmark, September 1988.
[10] K.S. Meier-Hellstern, E. Alonso, and D. O'Neil, The Use of SS7 and GSM to Support High Density Personal Communications, Proc. ICC 92, Chicago, IL, Paper 356.2, June 15-18, 1992.

Biographies

Gregory P. Pollini [S] received a B.S. in electrical engineering from Rutgers University and an M.S. in electrical engineering in 1992, and he is currently a Ph.D. student at Rutgers. His research at Rutgers WINLAB covers several topics related to wireless network control and packet reservation multiple access. In 1993 he was an independent consultant at AT&T Bell Laboratories, Holmdel, New Jersey in the communication systems laboratory, during which time work on this article was completed. He is a member of Tau Beta Pi and Eta Kappa Nu.

ZYGMUNT J. HAAS [SM '90] received his B.Sc. in electrical engineering from Technion/Israel in 1979 and M.Sc. in electrical engineering from Tel-Aviv University/Israel in 1985, both summa cum laude. From 1979 until 1985 he worked for the Government of Israel. In 1988, he earned his Ph.D. from Stanford University researching fast packet-switched networks and subsequently joined AT&T Bell Laboratories in Holmdel New Jersey, where he is now a member of technical staff. He is an author of numerous technical papers and holds several patents in the field of mobile networks, wireless communication, high-speed networking, and optical switching.

Appendix
The Upstream Access Delay of E-BAMA

The upstream control channel in E-BAMA can be almost any type of random access channel. This article considers the (pure) Aloha and S-Aloha protocols. This appendix derives the access delay in terms of the average beacon period (time between retries).

The relation for the access delay of S-Aloha is given by Kleinrock [6], assuming that the access delay is the total time between the transmission of the first packet and the reception of the acknowledgement for the last (first successful) packet. We have defined the access delay to be the time between the transmission of the first packet and the transmission of the successful packet excluding the actual transmission time of the final packet itself. Thus the access delay is:

$$W = \frac{1-q}{q_t}\left[R+1+\frac{K-1}{2}\right] \ [slots], \qquad \text{(A1)}$$

where

- q = probability that the first transmission succeeds.
- q_t = probability that a retry succeeds.
- R = the number of slots after any try which cannot be used for a retry.
- K = the number of slots to choose between with equal probability.

When K gets large, q and q_t can be approximated by $q = q_t = e^{-G}$ [6]. This approximation becomes increasingly good as the slot size decreases.

Now, we must choose K and R so that the average beacon period is T_p. Thus they must satisfy

$$K = 2\left[\frac{T_b}{T_{slot}} - R\right] - 1, \qquad \text{(A2)}$$

which, when substituted into Eq. (A.1), gives

$$W = (e^G - 1)\frac{T_b}{T_{slot}} \ [slots]. \qquad \text{(A3)}$$

Note that the variables K and R drop out completely and are replaced by the single variable T_b. This expression neglects the vacation interval of 1/2 *slot*. Including the vacation time and expressing the results in seconds by multiplying W by T_{slot} gives the access time as:

$$t_{acc}(S-Aloha) = (e^G - 1)T_b + \frac{T_{slot}}{2} \ [sec]. \qquad \text{(A4)}$$

This is Eq. (12). Neglecting the vacation time and using the characteristic equation of pure Aloha similarly yields

$$t_{acc}(Aloha) = (e^{2G} - 1)T_b \ [\text{sec}]. \qquad \text{(A5)}$$

When bandwidth is very scarce and the access delay is critical, RAMA is preferred because of its high throughput.