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Assuring Communications by Balancing Cell Load in Cellular Network*

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SUMMARY In a fixed-channel-allocation (FCA) cellular network, a fixed number of channels are assigned to each cell. However, under this scheme, the channel usage may not be efficient because of the variability in the offered traffic. Different approaches such as channel borrowing (CB) and dynamic channel allocation (DCA) have been proposed to accommodate variable traffic. Our work expands on the CB scheme and proposes a new channel-allocation scheme—called mobile-assisted connection-admission (MACA) algorithm—to achieve load balancing in a cellular network, so as to assure network communication. In this scheme, some special channels are used to directly connect mobile units from different cells; thus, a mobile unit, which is unable to connect to its own base station because it is in a heavily-loaded "hot" cell, may be able to get connected to its neighboring lightly-loaded cold cell's base station through a two-hop link. Research results show that MACA can greatly improve the performance of a cellular network by reducing blocking probabilities.

key words: *cellular network, integrated network, multi-hop, channel allocation, ad hoc network*

1. Introduction

Traditionally, a set of wireless channels are assigned to a cell in a fixed manner (i.e., the so-called fixed-channel-allocation scheme) at system deployment [1], [2]. In this way, the channel-reuse pattern can be optimized for a static traffic load, and the management of channel assignment to a mobile unit is simplified. However, such a scheme may not be able to efficiently accommodate fluctuating traffic in a cell; i.e., when the traffic increases, the call-blocking probability may increase to an undesirable level.

To mitigate this shortcoming, global channel-allocation schemes have been proposed, in which the pool of channels can be dynamically assigned to a cell depending on its current traffic demand [3], [4]. However, such schemes generally require complex global control. Additionally, efficient DCA depends on estimating co-channel interference. This is not easy especially for the uplink. To compromise between a completely fixed-channel-allocation scheme and a completely dynamic- channel-allocation scheme, our work proposes an approach in which some "dynamic" channels can be set aside from a fixed-allocation network so that a cell with a high traffic (i.e., a "hot" cell) can use channels from its neighboring "cold" cell (i.e., a cell with low traffic). Part of the traffic in the hot cell is diverted to its cold neighboring cell(s). This scheme, just like dynamic schemes, virtually assigns more channels to a hot cell in order to accommodate more traffic in the hot cell.

We illustrate our new channel-allocation scheme in Fig. 1. Effectively, we are adding an ad-hoc overlay network on a fixed-infrastructure cellular network. Channels assigned to this ad-hoc network, which are called ad-hoc channels here, can be used to help the fixed-infrastructure to achieve load balancing. In contrast, the channels in the fixed-infrastructure cellular network are called RF channels. We call this scheme mobile-assisted connection-admission (MACA) algorithm because of the mobile features of the ad-hoc network.

In Fig. 1, the hot cells are shaded. The channels drawn in solid lines are the RF channels and the channels drawn in dashed lines are the ad-hoc channels. Users D, G, and B are refered to as agents, because they act as intermediate units to help connect a mobile user from a hot cell to a cold cell's base station. MACA normally contains two hops, but it can also contain more than two hops (as from User E to User B to User G to User G's base station), which we call multi-hop MACA.

The scheme is similar to the channel-borrowing (CB) scheme [5], [6], in which, when a cell does not have enough channels, it will "borrow" one or more channel from its neighboring cells temporarily. Although simple, CB has some problems such as "channel locking" because it changes the pre-designed frequency-reuse pattern. In MACA, there is no such a problem. MACA can also be used for intracell relaying, in which a mobile unit at a weak cellular signal point forwards its data to an agent nearby instead of simply increasing the power. The agent is in the same cell but with a better signal quality. The agent then relays the data to the base station. This is helpful in increasing system capacity in a CDMA cellular network. In the core network, the control overhead in MACA is among the base stations in the neighboring cells involved in MACA application. In the radio network, mobile units will also be

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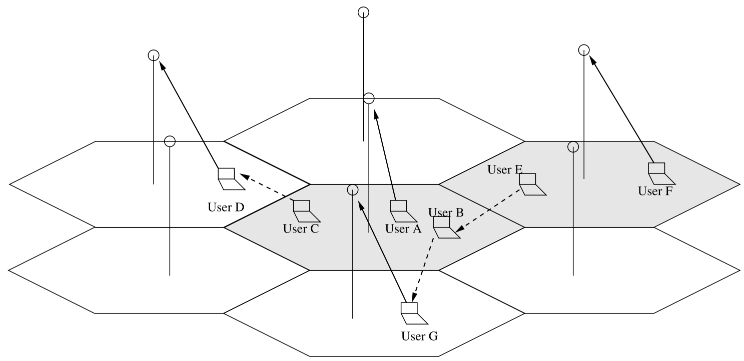


Fig. 1 A cellular network with MACA.

involved in MACA setup and link maintenance. This requires additional control signaling in both the ad hoc channel and the cellular channel. More details for operation can be found in Sect. 2. In CB, control overhead is generated by channel re-allocation, channel release, channel pool maintenance, transmision power estimation, synchronization, and channel locking. Since channel reuse pattern is affected, a higher level control is needed in the core network.

Another similar scheme is proposed in [7], in which users in the overlapping zone of cells will pick the channels from the cell with the least traffic. This doesn't cause the channel-locking problem. However, the problem with this approach is that only a limited number of users in the overlapping zone can use the scheme. Our scheme overcomes all of these limitations.

In MACA, if ad-hoc channels are the RF channels reserved for the ad-hoc operation, the scheme is called in-band MACA. If ad-hoc channels are some other wireless channels such as infrared channels, the scheme is called out-of-band MACA. Out-of-band MACA is possible since ad hoc networks normally use the free Industrial-Scientific-Medical (ISM) channels. These channels have short-range radio coverage, and can not be used as the cellular channels. However, they can be used as ad hoc channels in MACA when users and agents are close enough.

To increase the channel reuse, ad-hoc channels should have lower power and can only reach a short distance compared to the normal RF channels. When MACA is needed, if a new user to a hot cell is at the edge of this cell, it can use MACA directly through an agent in a neighboring cold cell. If the new user is at the center of the hot cell or cannot reach any agent, an intra-cell handoff will be used (see Sect. 2). Generally, if enough users and agents are uniformly distributed in cells, our analysis shows that there is a good probability that a link can be built between a user and an agent even if the ad-hoc channel has a very short coverage.

The mobile feature of MACA causes some complexity in MACA link set-up and maintenance. However, in MACA, the user only needs to find any suitable agent, not a specific one. The routing technique for MACA may be similar to that for ad-hoc networks [8]–[10], but much simpler. Furthermore, the cellular network can be involved in building ad-hoc links, since the cellular network may have the knowledge where the users and the potential agents are located through the cellular positioning technology. Therefore, the cellular network can guide mobile users to build links with proper agents. The extra signaling load in the cellular network is the information exchange among neighboring cells, which is not significant. More details of this operation are in Sect. 2. It is shown in [11] that, with the help of cellular network, even the performance of a normal ad hoc network can be greatly improved.

The previous work on integration of cellular network with ad hoc network can be found in [12], [13], in which the ad hoc network is independent from the cellular network. Ad hoc channels are used to build links between cells, which enables voice (data) users to access their cold neighboring cells. The in-efficiency of routing and the lack of ability to provide time-critical service is not addressed. In another paper [14], it is shown that integrating with ad hoc network may not necessarily improve the cellular network performance. This is partly due to the fact that each network works on its own. The previous research has not worked on the system level and none of these works have addressed security issues caused by using ad hoc links.

Our study is organized as follows. In Sect. 2, we present the operation and security of the system. In Sect. 3, ad hoc link probability between any two cells is analyzed, and a two-cell analytical model is built for the system performance with MACA. In Sect. 4, we show some important results and comparisons. The study is concluded in Sect. 5.

2. System Operation and Security

2.1 System Operation

In system operation, it is assumed that the position of each mobile unit is known by the cellular network. To reduce the system operation complexity, it is assumed that only a single hop of ad hoc link will be used. Thus, in MACA, the link between a user and a base station is built up by using a hop of ad hoc link and a hop of cellular link. It is also assumed that a mobile unit is always able to exchange limited control information with its own base station through the control channel. However, in a hot cell, this control channel should be used as less as possible. Finally, it is assumed that a mobile unit can work in different bandwidths (i.e., RF bandwidth and ad-hoc bandwidth).

2.1.1 Basic MACA Operations

The following are the major operations:

1. A mobile unit (an agent) with spare resources that would like to be an agent sends a message to its base station. The base station makes an agent table to record these potential agents and their positions. An agent is removed from the table if it moves out of the cell or is no longer able to act as an agent (e.g., shortage of power).
2. A mobile unit (a user) coming to a hot cell will be informed by the base station that it has to use MACA to assure its communication to the cellular system. The user will send out a short *testing message* in an ad hoc channel† during a testing period. The *testing* message is sent repeatedly, with a random length of time between every two transmissions. This is to avoid the retransmission collision if there is another user close by also sending the *testing* message. The *testing* message can be as simple as a user's ID. The period lasts for a while to assure that most agents within the ad hoc coverage of this mobile user receive the *testing* message.
3. The user's base station decides to which neighboring cell's base station a user should be connected. The decision is made according to the user's position and information of the neighboring cells (e.g., cell load). After the testing period, the user's base station sends the message to one of its neighboring cells, telling it the user will be connected to this neighboring cell through MACA. The message includes the user's position.
4. This neighboring cell checks its agent table. An agent is picked by its position and is paged. If this agent receives the *testing* message, it will send an ACK to its base station. Otherwise, the base station has to pick another agent. After the agent is determined, the agent's base station sends a *start* message to both the agent and the user's base station. The user gets the *start* message from its base station and begins to use MACA.
5. The *start* message indicates which ad hoc channel to be used. The channel is picked according to the information such as positions of the active users and agents in the local area (including the agent's cell and all its neighboring cells) and the ad hoc channels they are using. This information is exchanged within the local area.
6. When using MACA, the user continues to send *testing* messages, but with a much lower frequency. The active agent and the potential future agents listen to the *testing* message and make the judgement whether the user is still within their radio coverage. This can help to protect the user from suffering a sudden ad hoc link break. An ad hoc link break occurs in the following situation: 1) an agent has the data to send by itself or it has data to be received from the cellular network; 2) the user is out of agent's radio coverage; 3) an agent moves out of its current cell; 4) an agent runs out of power. If the ad hoc link breaks, the agent will inform its own base station, so that a new agent that receives the *testing* message can be picked immediately. On the other hand, the base station will keep a record of MACA applications, including the positions of agents and users, and the corresponding ad hoc channels in usage. This record is used for the base station to make routing and ad hoc channel assignment decisions for new MACA users.
7. If the user needs to stop using MACA, it will send its agent a *done* message. The agent replies with an ACK and informs its base station about the finish. The user's base station is informed by the agent's base station.

2.1.2 MACA Handoff Operations

When a connected user enters a hot target cell, it may use MACA to keep connected with its former base station. The operation works like a queuing handoff [15], [16], yet it gives more time for the user to wait for a free channel in the target cell because through MACA, the user can be connected to its former base station even it gets out of the overlapped zone between the two cells. The performance of such a handoff can be found in [17].

To increase the ad-hoc channel reuse, when a local RF channel is released in a cell and a user in this cell is using MACA, the newly-released RF channel will be assigned to this MACA user and the ad-hoc channel and the RF channel in the neighboring cell used in MACA are released. We call this "ad-hoc channel release" (ACR). If several users in a cell are using MACA when an RF channel in this cell is released, the MACA user using the ad hoc channel with the worst quality (measured by signal power), or with the highest neighboring cell traffic (measured by the number of occupied channels) will take this RF channel and stop using MACA. ACR is also a kind of handoff since the user connects to a different base station. On the other hand, when a MACA user enters a cold target cell, it will stop using MACA and get connected to the cold cell's base station directly.

To improve the communication quality, a connected user may switch to another RF channel during the time it stays in the same cell. This is called an intra-cell handoff. In a MACA system, intra-cell handoff is used more frequently.

Intra-cell handoff can help to build a MACA link. If a new user coming to a hot cell is too far away from any agent in the neighboring cold cells, the base station of this hot cell will ask one of its current active users (probably the one close to a neighboring cold cell) to use MACA and release the local RF channel. The released channel will be

†This channel can be a predefined channel especially for ad hoc control.

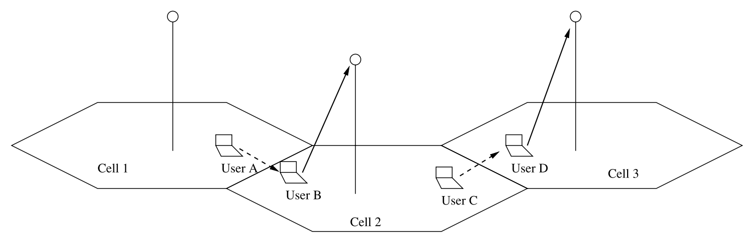


Fig. 2 Using channel switching to achieve MACA to cross cells.

assigned to this new user. Intra-cell handoff can also help a user achieve a sort of multi-hop MACA (or "crossing-cell MACA"). As shown in Fig. 2, User A comes to the hot cell (Cell 1) and channels are available in Cell 3, which is separated by another hot cell, Cell 2, from Cell 1. Intra-cell handoff is operated in Cell 2; thus, User C will use MACA and release a RF channel in Cell 2. This released channel can then be used by User A with MACA through User B as agent. The user and the free RF channel can be n cells apart, and the user is virtually able to use this free RF channel through n intra-cell handoffs and $n+1$ MACA connection. The same ad hoc channel can be re-used for crossing-cell connection if ad hoc links are far away enough. Crossing-cell MACA works like a multi-hop ad hoc connection, but it is more stable because it has multiple one-hop ad hoc links instead of one multi-hop ad hoc link. The trade off is the cellular operating load.

If there are enough ad hoc channels and mobile units, with intra-cell handoff and the crossing-cell MACA scheme, a user is able to use the RF channel in any cell. Assume a system with n cells, each cell is assigned c RF channel. With out-of-band MACA and enough ad-hoc channels, the system is equivalent to a large cell with $c \times n$ channels. The performance should be better than the global dynamic channel-allocation (DCA) scheme since DCA cannot reach a perfect frequency-reuse pattern.

Crossing-cell MACA may generate high cellular operating load, especially when a user is far away from an available RF channel. To simplify system operation and simulation, in this study, we only investigate the system with single intra-cell handoff, and we do not use multi-hop ad hoc links. MACA can be used only by a user in a hot cell adjacent to a cold cell. A handoff failure or a new call block will occur when a cellular user or a MACA user enters a hot cell with no cold neighboring cells, or no ad hoc link can be built between this hot cell and its cold neighboring cells even with intra-cell handoff. Our simulation results show that, with a number of ad hoc channels, an out-of-band MACA can catch up with DCA in performance.

2.2 System Security

Ad hoc networks are particularly vulnerable to attacks. This is due to its features of open medium, dynamic changing topology, cooperative algorithm, lack of centralized monitoring and management point, and the lack of a clear line of defense. Security in ad hoc networks also suffers from the slow information distribution, i.e., mobile units may not be informed about an attack even after the attack has been discovered for a certain time. General security solutions for ad hoc networks can be found in [18], [19].

Security problem is less serious in MACA than that in a normal ad hoc network since most operations are handled by base stations, and only one-hop ad hoc links are used. Additionally, only cellular users with a cellular ID can participate in the MACA application, and the cellular infrastructure may work as a trusted center and a central security monitoring point. Whenever there is an attack, it is easy to detect the attacker (most probably a compromised agent).

MACA achieves security by secret key assignments and intrusion detection through base stations. To keep the privacy of the communication, the data from a user should be encrypted by a session key. The agent does not know the session key so it can not read the content of the user's data. However, there exists a key between the user and the agent. The header of the packet (including the user identity) should be encrypted by this key. The agent uses the same key to decrypt the header to check if it receives the data from the right user. A packet sequence number is also included in the header to avoid the attack of a malicious node, since a malicious node may buffer a user's packet and re-send it. In this case, the agent drops the repeated packet.

These keys are assigned during the MACA link set up. The key to encrypt the data between a user and the cellular network can be assigned following the same procedure as that for a cellular user. The key to encrypt the user header is generated by the agent's base station. This key is forwarded to the agent and the user's base station, and user gets the key from its base station.

With these key assignments, only few attacks may threaten MACA security. One of possible attacks by a compromised agent is the Byzantine attack. The agent drops the data from its user and claims that it can not receive the data. In MACA, intrusion detection on this attack is simple. The base station can keep a record for each agent, and when the packet dropping rate for an agent is over a threshold value, this agent is assured to behave maliciously, and will be given warnings or be punished. This threshold value depends on the rate of errors caused by the unstable radio environment.

Another possible attack is jamming the ad hoc channel. This can be avoided by performing an intra-cell handoff. The base station can ask an active user far away from the jammer to release the RF channel and use MACA.

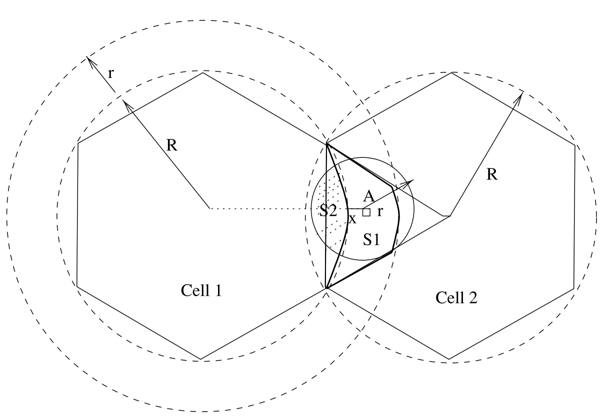
3. System Analysis

In this section, we first analyze the probability that an ad hoc link can be established between neighboring cells. Then, we use a two-dimensional Markov-chain model to analyze the system performance (i.e., new-call blocking probability) with MACA in a simple network model which has only two cells. This two-cell model can be used to approximate a linear cellular network such as a highway cellular network.

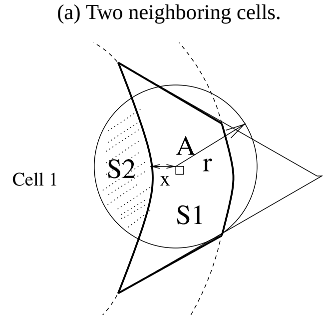
3.1 Ad-Hoc Channel Link Probability

Assume the mobile units are uniformly distributed in two cells as shown in Fig. 3. The radius (i.e., coverage) of an RF channel is R and that of an ad-hoc channel is r. Cell 1 is a cold cell with RF channel available and Cell 2 is a hot cell with no more free RF channels.

User A (Fig. 3) in Cell 2 will use MACA and it needs to find an agent in Cell 1. Since there is no free channel in Cell 2, it can be approximated that all the mobile units in the overlapping zone of the two cells are using or will use channels from Cell 1, thus the overlapping zone is considered a part of Cell 1. In Fig. 3(a), Cell 2 is equally divided into six sectors†, and we assume that only users in the sector adjacent to Cell 1 (the triangle in Cell 2) but not in the overlapping zone will search for agents in Cell 1. Users in other sectors will try to find agents in other neighboring cells. Considering the ad hoc channel coverage of r, only the users in the area S_1 within the thick lines can use an ad-hoc channel to reach any agent in Cell 1.



(a) Two neighboring cells.



(b) Zoom in of overlap area.

Fig. 3 Analytical model for a successful link probability.

Assume that user A is x away from the edge of Cell 1, where $0 < x < r$. With point A as center, we draw a circle with radius r. The shaded zone S_2 is the area in which, if an agent exists, a link between an agent and user A can be built through an ad-hoc channel. With the uniform-distribution assumption and a finite number of N_a agents in Cell 1, the probability $P(x)$ that at least one agent is present in the area S_2, can be found, which is:

$$P(x) = 1 - \left(1 - \frac{A_{S_2(x)}}{A_{cell_1}}\right)^{N_a}. \tag{1}$$

A_{cell_1} is the area of Cell 1, and $A_{S_2}(x)$ is the area of S_2 depended on x.

Assume N_u users are in Cell 2. Define $A_{S_1}(x)$ to be the area within S_1 with the outside edge x away from the edge of Cell 1. The cumulative probability function that a user is located in the area S_1 and x away from the edge of Cell 1, which we refer to as $F(x)$, is:

$$F(x) = 1 - \left(1 - \frac{A_{S_1}(x)}{A_{cell_2}}\right)^{N_u}, \tag{2}$$

where A_{cell_2} is the area of Cell 2 and $A_{S_1}(x)$ is the area of S_1 depended on x.

$A_{S_1}(x)$, $A_{S_2}(x)$, A_{Cell_1}, A_{Cell_2} can be calculated in terms of R, r, and x. Thus, $F(x)$ can be found. From $F(x)$, we can find the corresponding density function $f(x)$. Since the probability that a user who is x units away from the boundary of Cell 1 can find an agent in Cell 1 only depends on x, the link probability that a user in the area S_1 can reach an agent in Cell 1 through an ad-hoc channel with a radius of r is:

$$p_{link} = \int_0^r P(x) f(x) dx. \tag{3}$$

This probability can be calculated numerically although a simple explicit formula cannot be found.

The probability that there exist n such links between two neighboring cells, if the number of links is much smaller than the total number of agents and the total number of users in the two cells, is approximately p_{link}^n. If a cell is surrounded by six other cells, the probability that a cell can build a link with any of its six neighboring cells P_{Link} is:

$$P_{Link} = 1 - (1 - p_{link})^6. \tag{4}$$

3.2 Blocking Probability in a Two-Cell Model

Assume two cells, Cell 1 and Cell 2, next to each other with c_R channels in each cell and c_a ad-hoc channels between the two cells. With MACA, a single cell can accommodate as many as $c_R + c_a$ users. It is also assumed that the ad hoc channel coverage is large enough so that through MACA

†A sector is the triangle connecting the central point and two consective edge points of a hexigon.

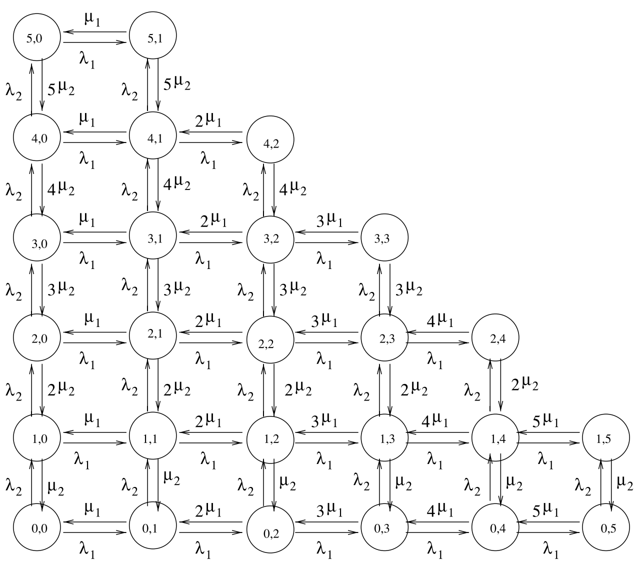


Fig. 4 State-transition diagram for MACA in a 2-cell model with $C_R = 3$ RF channels and $c_a = 2$ ad-hoc channels.

and intra-cell handoff, a user can always get connected to its neighboring cells. The call arrival in each cell follows a Poisson distribution and the call duration time is negative exponentially distributed. Here we don't consider handoff. A call is blocked in one cell when 1) there is no free channel in both cells or 2) there is no free channel in the call's arrival cell and there is no free ad-hoc channel. Assume the arrival rates in Cell 1 and Cell 2 are λ_1 and λ_2, and the average call-holding times in Cell 1 and Cell 2 are $1/\mu_1$ and $1/\mu_2$, respectively. Figure 4 shows the state-transition diagram with $c_R = 3$ in each cell and $c_a = 2$. State (i, j) is the state that there are i active users in Cell 2 and j active users in Cell 1. From the state-transition diagram, we can find the state probabilities ($p(i, j)$), from which we can find the blocking probability in each cell. The blocking probability in Cell 1 (P_{b1}) and the blocking probability in Cell 2 (P_{b2}) are as follows:

$$p_{b1} = \sum_{i=0}^{c_R - c_a} p(i, c_R + c_a) + \sum_{i=c_R-c_a+1}^{c_R+c_a} p(i, c_R + c_a + 1 - i). \tag{5}$$

$$p_{b2} = \sum_{j=0}^{c_R - c_a} p(c_R + c_a, j) + \sum_{j=c_R-c_r+1}^{c_R+c_a} p(c_R + c_a + 1 - j, j). \tag{6}$$

4. Important Results

In this section, we evaluate the MACA system using our analytical model and a simulation model. ρ is referred to as the load in each cell, and $\rho = \lambda/c\mu$, where c is the total number of RF channels in each cell, while λ and μ are the arrival rate and departure rate in each cell, respectively, i.e., all cells are equally loaded in our examples here.

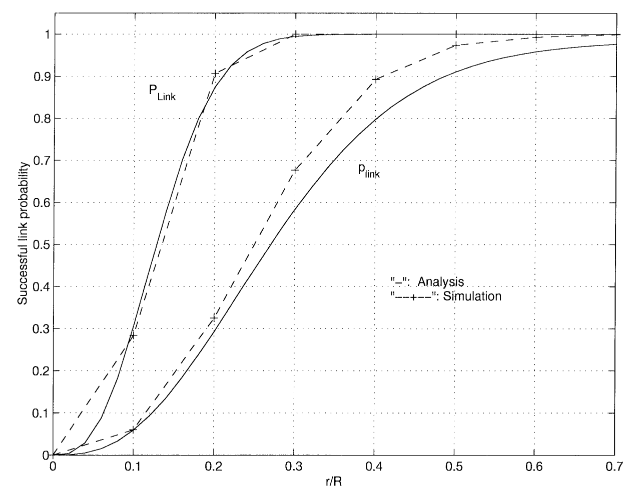


Fig. 5 Successful link probability between two cells.

4.1 Numerical Results for Analytical Models

Figure 5 shows the successful link probability calculated by Eq. (3) and Eq. (4) versus ad-hoc channel coverage. Here 30 mobile units are uniformly distributed in each cell. The corresponding simulation results are also shown. It is found that, for a cell surrounded by six neighboring cells, even if the radius of the ad-hoc channel r is very small compared with the radius of the RF channel R, the probability that a link can be established between a mobile unit in this cell and a mobile unit in one of its neighboring cells through the ad-hoc channel is still very large. This is due to the relatively large number of mobile units in each cell. The link probability in our analysis is smaller than the one obtained from the simulation especially when the ratio of r/R is large. This is because to simplify the analysis, we make the assumption that a user in a cell sector can only get connected to an agent in the cell adjacent to this sector, while in the simulation, there is no such constraint.

Figure 6 shows the performance of MACA compared to that of the DCA and the FCA schemes in a two-cell model. 30 channels are assigned in each cell. Two channels from each cell are used for ad-hoc channels for the in-band MACA. Thus, there are 4 ad-hoc channels. The out-of-band MACA also has 4 ad-hoc channels. In DCA, 60 channels are used by the users from both of the cells. It is found that the performance of out-of-band MACA is always better than that of FCA while the performance of in-band MACA is better than that of FCA only at light load. This is because at the high load, there is a large probability of MACA application. It may happen that a user cannot use the free RF channel in its neighboring cell through an agent because all the ad hoc channels are used up. Thus, under high load circumstances, the performance improvement brought by MACA cannot compensate for the degradation of performance caused by reduction of the number of RF channels. Figure 7 shows that, when the number of ad-hoc channels is

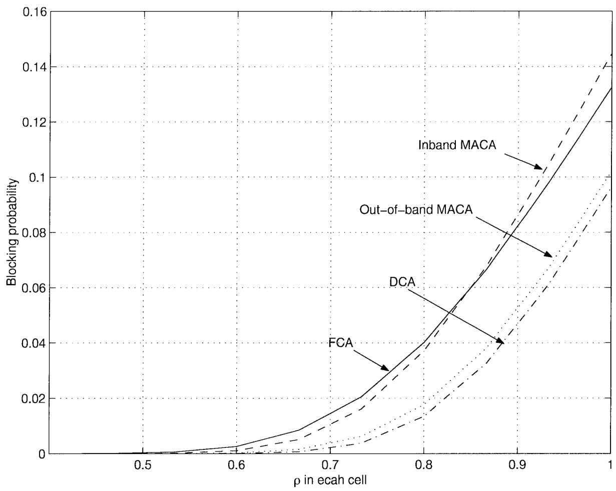


Fig. 6 Blocking probability comparison in a two-cell model.

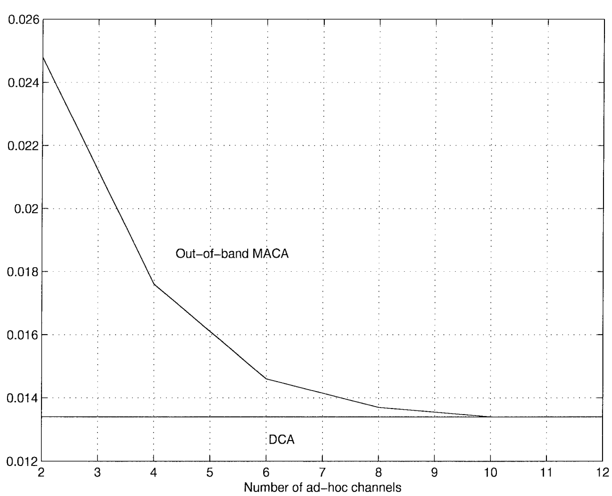


Fig. 7 Blocking probability for DCA and out-of-band MACA with different numbers of ad-hoc channels for $\rho = 0.8$.

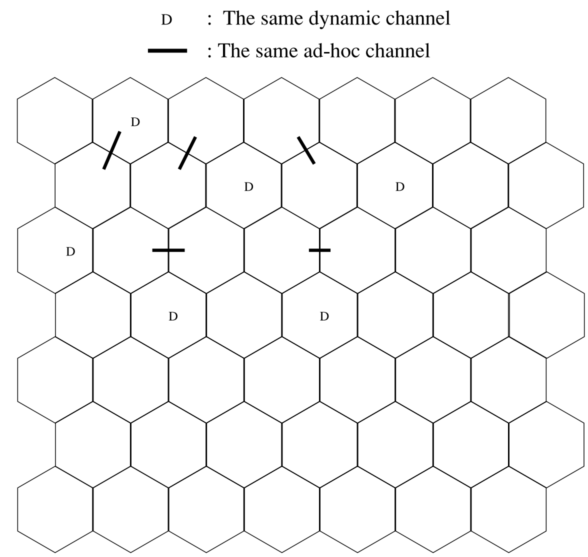


Fig. 8 Dynamic channel and ad-hoc channel reuse example in a 7×7 cellular network model.

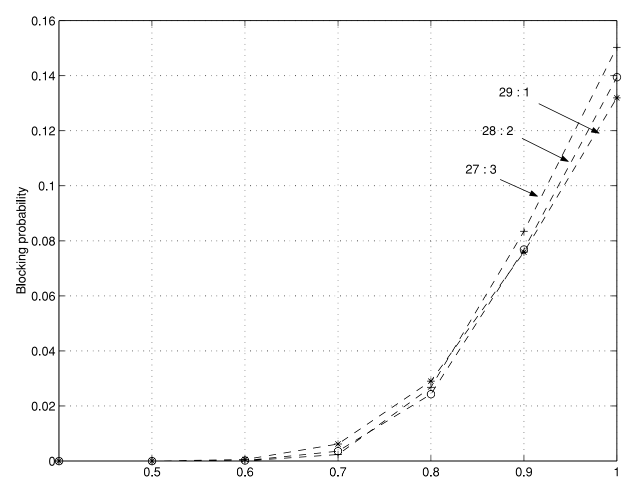


Fig. 9 Blocking probabilities for in-band MACA with different number of ad-hoc channels (1, 2, 3).

large enough, the performance of out-of-band MACA will eventually matches that of DCA in the two-cell model.

4.2 Simulation Results in a 7×7 Cellular Network Model

A two-dimensional model is more realistic for a cellular network in an urban area. However, developing an analytical model for a two-dimensional cellular network with MACA is difficult, so we resort to simulation results.

Here, a 7×7 cellular system is examined. Each cell has Poisson call arrivals with the same arrival rate λ. The call-holding time is negative exponentially distributed with mean $1/\mu$. It is assumed that there are 120 different channels in the entire network and the cluster size for frequency reuse is set to be 4, i.e., the channel with the same frequency cannot be reused in two neighboring cells. For FCA, there are 30 channels in each cell. For DCA, the same channel can not be used in two adjacent cells. For the in-band MACA scheme, if from one cell, n channels are used for ad-hoc channels, then there are $4 \times n$ ad-hoc channels in the system. We assume that with the intra-cell handoff, a user can always use MACA to get connected to its cold neighboring cell if there is an ad hoc channel available. In simulation, the radio coverage for an ad hoc channel is limited by the constraint that the same ad-hoc channel cannot be reused in the same cell. Figure 8 shows our simulation model and the channel reuse for ad-hoc channels and dynamic channels. Approximately 5 million arrivals to the 7×7 cellular network are simulated. The call blocking probability is the total number of blocked calls divided by the total number of call arrivals in the entire system during the simulation run.

Figure 9 shows the performance of three in-band MACA schemes with different numbers of ad-hoc channels (1, 2, and 3 per cell). It shows that more ad-hoc channels will lead to a little better performance at a low load and a

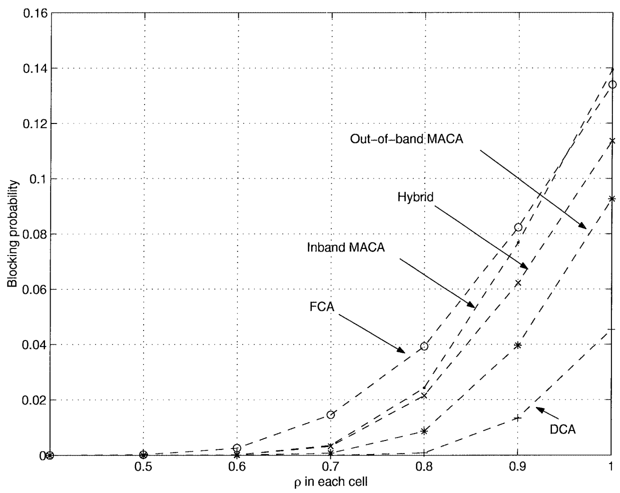


Fig. 10 Blocking probabilities for different schemes.

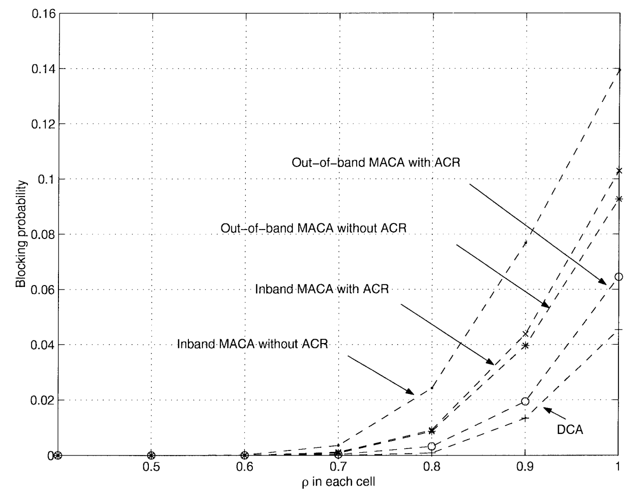


Fig. 11 Performance improvement with ACR.

worse performance at a high load, although the differences are not very significant. The reason, again, is that at a high load, the performance improvement due to using MACA is overwhelmed by the performance degradation caused by reduction of the number of RF channels. It appears that the in-band MACA with 28 fixed channels in each cell and 8 ad-hoc channels in the system is a good compromise, since it has relatively decent blocking probability at both a high load and a low load when compared to other two schemes.

Figure 10 shows the overall blocking probability comparison among different schemes. For the in-band MACA, we set aside 8 ad-hoc channels in the system and use 28 RF channels in each cell. For out-of-band MACA, we use 8 ad-hoc channels. The number of RF channels in each cell is still 30. We also consider a hybrid channel-allocation scheme, in which each cell has 28 fixed channels and 8 channels are used as global dynamic channels. The simulation results show that, at a light load, in-band MACA has better performance than FCA, but at a heavy load, the performance of in-band MACA is worse. The reason has been explained before. Out-of-band MACA has much better performance than FCA, in-band MACA, and the hybrid scheme. DCA still has the best performance. Although not shown here, our simulations of the 7×7 network model show that, with MACA, the cells at the corners or at the edges of the network layout have larger blocking probabilities since they have fewer neighboring cells to use MACA with, while in DCA, these cells have smaller blocking probabilities since they have less co-channel interference.

Figure 11 shows the improvement when using ACR for both in-band MACA and out-of-band MACA. ACR greatly reduces the blocking probabilities in both in-band and out-of-band MACA, since it improves channel efficiency. ACR also reduces the probability that a call is blocked due to the unavailability of ad hoc channels, since ACR stops using MACA and releases ad hoc channels whenever there are local RF channels available. This is verified by the fact that the blocking probability in in-band MACA with ACR is close to that in out-of-band MACA without ACR and even at a high load, the blocking probability for in-band MACA with ACR is lower than that in FCA (refer to Fig. 10).

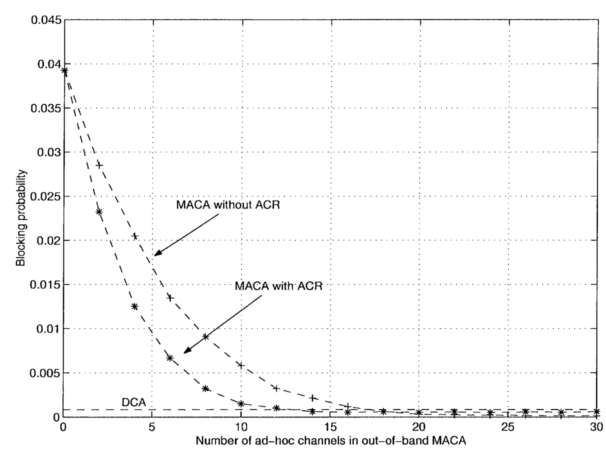


Fig. 12 Blocking probability for out-of-band MACA with different numbers of ad-hoc channels for $\rho = 0.8$.

Figure 12 shows the performance of out-of-band MACA when the number of ad-hoc channels changes. It is found that, to achieve the same performance, MACA scheme with ACR needs fewer ad-hoc channels than the MACA scheme without ACR. This figure shows that, when the number of ad-hoc channels becomes large, the performance of MACA approaches the performance of DCA. If the number of ad-hoc channels is large enough, the performance of both the MACA with and without ACR is better than DCA.

5. Conclusion

In this study, we proposed a new channel-allocation scheme, called MACA, in which special channels are deployed between cells to achieve load balancing, to assure cellular communications. We examined the performance of MACA with a 2-cell analytical model and a 7×7-cell simulation model. We find that MACA can greatly improve the performance over FCA. In some case, the performance of MACA is comparable to DCA but with simpler operations.

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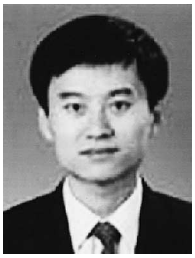

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