CERIAS Tech Report 2004-100

Mobile-Assisted Data Forwarding for Wireless Networks

by X Wu, G Chan, B Mukherjee, B Bhargava

Center for Education and Research
Information Assurance and Security
Purdue University, West Lafayette, IN 47907-2086

MADF: Mobile-Assisted Data Forwarding for Wireless Data Networks

Xiaoxin Wu, S.-H. Gary Chan, Biswanath Mukherjee, Bharat Bhargava

Abstract: **In a cellular network, if there are too many data users in a cell, data may suffer long delay, and system's quality-of-service (QoS) will degrade. Some traditional schemes such as dynamic channel-allocation scheme (DCA) will assign more channels to hot (or overloaded) cells through a central control system (CC), and the throughput increase will be upper bounded by the number of new channels assigned to the cell. In mobile-assisted data forwarding (MADF), we add an ad-hoc overlay to the fixed cellular infrastructure and special channels–called forwarding channels– are used to connect mobile units in a hot cell and its surrounding cold cells without going through the hot cell's base station. Thus, mobile units in a hot cell can forward data to other cold cells to achieve load balancing. Most of the forwarding-channel management work in MADF is done by mobile units themselves in order to relieve the load from the CC. The traffic increase in a certain cell will not be upper bounded by the number of forwarding channels. It can be more if the users in hot cell are significantly far away from one another, and these users can use the same forwarding channels to forward data to different cold neighboring cells without interference. We find that, in a system using MADF, under a certain delay requirement, the throughput in a certain cell or for the whole network can be greatly improved.**

Index Terms: **Wireless data networking, cellular network, multi-hop, ad-hoc network, load balancing.**

I. INTRODUCTION

Wireless data service refers to service in which a mobile host is able to access the wireless infrastructure (such as the Internet) via a wireless link [1], [2]. In a wireless data network, the existing cellular network provides the necessary wireless channels to transmit data packets. The channels may be shared between voice and data, such as the packet-reservation multiple access (PRMA) protocol [3], [4] in which data packets can be transmitted whenever silence is detected in a voice channel. On the other hand, a set of wireless channels may be set aside for data communication. This is the case in, for example, the General Packet Radio Service (GPRS) [5]. In this study, we will mainly address the throughput-delay issues for the latter case.

In a wireless data network, channels should be assigned to the mobile hosts properly in the presence of fluctuating traffic in the cells so as to meet a certain quality-of-service (QoS) requirement. This requirement can be the overall throughput (packets/second) of the system, or the delay of a packet from its generation until it is received by a base station. Many channel-assignment techniques have been proposed in the literature for unbalanced load among cells [6], [7]. Fixed channel allocation (FCA) is a simple scheme which optimizes the channel-reuse pattern based on the knowledge of the load pattern in the cells [8]. However, it cannot adapt to the fluctuating traffic in a cell. Dynamic channel allocation (DCA) remedies this problem by globally assigning the channels according to the traffic demand in each cell [9], [10]. However, it requires complex global control due to ever-changing re-use pattern. To achieve a balance in complexity and performance, channel borrowing (CB) is proposed, in which channels from a cold cell may be temporarily used by its neighboring cell of heavy load [11], [12]. However, CB has the problem of "channel locking."

A. Mobile-Assisted Data Forwarding (MADF)

We propose a novel load-balancing scheme which enjoys similar simplicity as in FCA and load balancing as in DCA. In this scheme, fixed channels are assigned to each cell according to its long-term traffic pattern. In order to handle transient fluctuation in cell traffic, some "floating" channels which are not assigned to any cells are allocated to *forward* some of the traffic away from the hot cell to its neighboring cold cells. Such a traffic fluctuation can be periodic, such as the daily movement for a mobile user between his home and office. The fluctuation can also be sudden, such as when a big event (games, exhibitions, etc.) occurs.

Since these forwarded data packets are transmitted in a different cell from where the mobile host is, this technique achieves load balancing among the cells and increases the cell/network capacity. We call the channels (which may be time slots in TDMA) which play the role of traffic forwarding as "forwarding channels" (or, correspondingly, "forwarding slots"). Note that, since data packets have to cross cell boundary, an intermediate forwarding agent is required to relay the data to the neighboring cell. A forwarding agent simply relays the data; it is not a base station since it does not have to be attached to the wired infrastructure. The agent may be a fixed repeater at the cell boundary, or a mobile host. For concreteness and ease of exposition, we will consider in our study the agents as mobile units. Such a scheme is hence called "mobile-assisted

X. Wu and B. Bhargava are with the Department of Computer Sciences, Purdue University, e-mail: wu,bb@cs.purdue.edu.

S.-H. G. Chan is with Department of Computer Science, Hong Kong University of Science and Technology, email: gchan@cs.ust.hk.

B. Mukherjee is with Department of Computer Science, University of California, Davis, email: mukherje@cs.ucdavis.edu.

The work is supported by NSF grant ANI-0219110, Motorola post-doc grant, CISCO URP; and partly supported by the Teaching Development Grants from the University Grant Council in Hong Kong (HKUST-1-G) and Sino Software Research Institute in the HKUST (SSRI01/02.EG21)

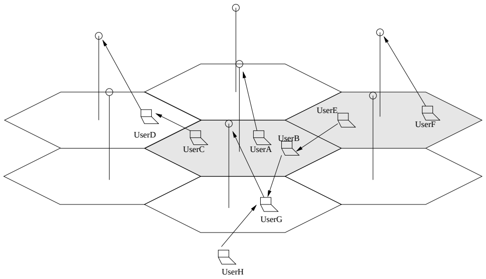

Fig. 1. A wireless data network with MADF.

data forwarding" (MADF).

We illustrate in Fig. 1 a wireless data network with MADF, in which we shade the hot cells (i.e., packets experiencing long delay and low throughput in the absence of data forwarding). User B, User D, and User G are forwarding agents. We see that it takes two hops for the packet from User C to be absorbed by a base station. On the other hand, since User E cannot find an immediate forwarding agent in its neighboring cold cell, it takes three hops for its data to be absorbed by a base station. For the users out of the coverage of this wireless network (such as User H), they can accordingly forward their packets to an agent (such as User G) in order to stay connected to the network. Note that a forwarding agent may serve multiple users at the same time. In MADF, power control may be required in order to reduce the co-channel interference of the forwarding channel. This is illustrated for the case of Users B and C, in which User C and User B may use the same forwarding channel but may be near to each other.

We note here that the forwarding channels can be "in-band," in which the channels are allocated from the cellular channel pool. On the other hand, "out-of-band" forwarding channels are special channels (e.g., Bluetooth channels [13]) not in the pool of the cellular channels. Clearly, the allocation of "in-band" channels reduces the number of available channels for the fixed infrastructure. However, their forwarding range may be further as compared to those special channels.

It is essential to keep a number of active agents for MADF function. The incentive for a mobile user to act as an agent can be that an agent can create revenue for itself through assisting other MADF users by using its own resources. In addition, liability rules can be made to enforce a user to perform as an agent. For example, a MADF user has to perform agent role for a minimum time if he wants to use this service.

In this research, we are interested in the up-link throughput and delay issues with MADF, for the single cell case and the whole network. To illustrate the improvement in throughput and delay, we consider two access techniques for the forwarding channels: Aloha and TDMA. [1] We will also compare the performance of MADF with the traditional schemes such as a DCA scheme and a microcell/macrocell scheme. In Fig. 2 we show a microcell/macrocell model. The shaded zones are the overlaid microcells. Since the distance between any two microcells is far enough compared with the microcell radio coverage, all the microcells can use the same frequency, i.e., Freq. 8.

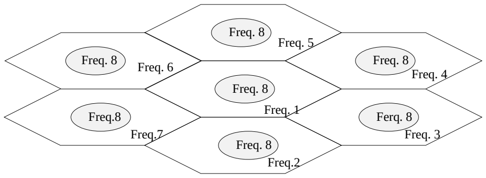

Fig. 2. A simple macrocell/microcell scheme: Frequencies 1-7 are used in each macrocell , while frequency 8 is used in the microcells overlaid in these macrocells.

B. Related Work

We briefly compare MADF to some other schemes as follows. Unlike most of the previous channel assignment techniques in which more channels are directly assigned to a cell with more traffic, MADF "forwards" traffic to the colder cells, thereby achieving load balancing. MADF differs from an access technique in which a user in the overlapping zone between two cells may use the "colder" cell to transmit its data [14] in that MADF is not restricted to those users at the cell boundary. There is also no "channel locking" problem in MADF, since channels are not "shifted" among cells. Most access techniques in wireless networks are based on a single-hop approach, by which a mobile unit is connected to the the base station by a single hop. Our scheme connects users to the fixed infrastructure via multiple hops, which increases the traffic adaptability and load-balancing capability. Our approach is different from the other multi-hop techniques such as HYPERLAN [15], [16] in that MADF is based on an existing cellular infrastructure. Another multi-hop cellular system has been proposed in [17]. While the work addresses a system in which a mobile unit connects to its base station *inside* its cell via multiple hops, MADF addresses load balancing issue by diverting traffic *away* from a host's cell.

MADF can be considered as a distributed control scheme which does not increase much load in the central control system, because data forwarding is managed by mobile units themselves once a connection is built. Since users in the cells may be mobile, the routing issues of the data packet is similar to that in an ad-hoc wireless networks which have been extensively discussed in the literature (see, for example, [18], [19]). The integration of cellular network with ad hoc network can be found in [20], [21], in which the ad hoc network is independent from the cellular network. Ad hoc channels are used to build links between cells so that voice (data) users can access to their cold neighboring cells. The in-efficiency of routing and the lack of ability to provide time-critical service is not addressed in these works. In another paper [22], it is shown that integrating with ad hoc network may not necessarily improve the cellular network performance partly due to that each network works on their own. To further improve the network

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[1] MADF may not bring as much benefit when using CDMA as access technique, since the forwarding channel and the cell channel will use the same bandwidth in such a system.

performance, in MADF, the cellular network will involve in building forwarding channel links since the cellular network at least has the knowledge that where these potential agents are located, i.e., which cells they are in. The cellular thus may guide mobile users to build links with proper agents. More details of this operation will be described later. It is shown in [23] that in a cellular-aided ad hoc network, the ad hoc network performance can be greatly improved. In fact, the routing in MADF may be much simpler given the lower number of terminals involved. The routing improvement is in the trade off of increased overhead in the cellular network. However, This overhead is trivial, given that only local information exchange among neighboring cells is needed.

C. Paper Organization

This paper is organized as follows. In Sect. II we describe in detail two system operations pertaining to the access of channels: the Aloha and TDMA operations. In Sect. III we present the analysis of the schemes and the maximum cell capacity given a certain packet delay requirement. In Sect. IV, we compare the schemes by showing some illustrative numerical results. We conclude in Sect. V.

II. SYSTEM OPERATION

We describe in this section the operations of MADF. We present two ways of accessing the channels. The simplest scheme is an Aloha system, in which both the fixed channels and forwarding channels are accessed by means of pure or slotted Aloha. Another one is a TDMA system, in which packets first contend for a slot before their transmission.

A. MADF Operation with Aloha

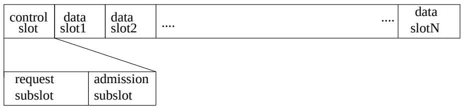
In the Aloha MADF network, we assign a data channel in each cell and a forwarding channel for the system. In pure Aloha, a mobile host in a cell starts packet transmission whenever it has a data packet using one of the channels, irrespective of other transmissions in the cell. If two or more packets are transmitting at the same time, there is a collision and all the packets cannot be delivered successfully. In this event, the collided packets back-off for a certain random delay before they are re-transmitted. In a slotted Aloha system, packets are of the same length and the time is slotted with the slot size equal to the packet transmission time. Packets can only be sent at the beginning of a slot.

A mobile host which is willing to forward data packets first sends a message to the base station of its cell (we refer the cell where the agent is as the“agent” cell) indicating its availability as a forwarding agent to others. Each base stations monitor the cell traffic load by collecting the delay reports from its users. The traffic information is sent to its neighboring cells so that a cell with a heavy load knows if there exists any cold neighboring cell.

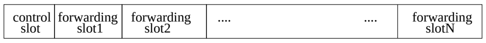
On the other hand, a host in a cell keeps on monitoring its packet delay in the data channel. At the meantime, the host builds its local connectivity by exchanging “hello” [24] messages with its neighbors who are within the coverage of the forwarding channel. If the packet delay in the hot cell exceeds a certain threshold, the host would send its base station a message asking for MADF service. The base station of this hot cell checks its neighboring cells to determine which cell (i.e., which cold cell) the data should be forwarded to. Generally a neighboring cell with the lowest traffic will be selected. Another selection factor is the availability of the agents. Once a destination cold cell is determined, the hot cell asks for the information of the agents in that cold cell. The information includes the agents’ IDs and positions. With the help of GPS technology [25], it is possible for the cellular network to know the precise position for each mobile host. In case GPS is not available, by the cellular position technology, the base station at least knows which section of a cell a mobile host resides in. With the knowledge of precise positions or sections of each mobile host, the base station of the hot cell can select proper agents for its MADF users. More than one agent will be selected, since the connectivity between the mobile host and the best agent selected by the base station may actually do not exist (e.g., due to the complex radio propagation environment). Mobile host determine which agent to be used referring to its local connectivity. Redundant agents may also be useful for routing robustness. When an agent in MADF suddenly cannot function well because it switches off or makes a large move, the host can forward data to another agent while it sends a report of the routing failure to the base station. Compared to the normal ad hoc routing protocols, the routing in MADF is simpler and more efficient since it excludes the complicated routing discovery procedures for most ad hoc routing protocols.

In order to reduce co-channel interference, a mobile host can reach only those agents in its neighboring cells. A host using a forwarding channel would continuously monitor the delay of its packets in that channel; if the delay is too high, the host would stop forwarding packets to that agent and sends a message to its base station. The base station makes the decision to forward data to another cold cell, or stop using MADF. The user may also stop using MADF when traffic in its own cell returns to a low value. A user may also choose to split its traffic between its local channel and forwarding channel so as to achieve the lowest (average) packet delay (According to our analysis, there exits an optimum traffic splitting.). However, it is not realistic to always use optimum splitting in a real network. For operation simplicity, threshold values for the traffic or delay in a cell are set for different systems, at which a mobile host will start or stop using MADF. More details on how these threshold values are determined and how much traffic should be diverted to the neighboring cold cell are shown in Section IV.

We use end-to-end acknowledgment in the Aloha system. A data packet is acknowledged only if it successfully reaches its own or the agent’s base station. In the case of forwarded packets, the acknowledgment (ACK) is first transmitted to the agent, which in turn relays this ACK to the user. The user can transmit a new packet if it receives the ACK; otherwise, it schedules a retransmission after a certain random timeout.



a) A normal frame



b) A forwarding frame

Fig. 3. The structure of the TDMA frame assigned to a cell (the normal frame) and to the forwarding channel.

B. MADF Operation in TDMA

We propose our TDMA system as follows. There is one RF channel assigned to each cell. The time on the RF channel (data channel) is divided into equal-sized frames, with each of the frame subdivided into a number of $N+1$ time slots. For each frame, the first slot is used as a control slot, which is further divided into two sub-slots: *request* subslot and *assignment* subslot, while the other slots are data slots (see Fig. 3 (a)). Data is transmitted as packets and the transmission time is equal to the slot length. Note that the reverse channels for acknowledgment in both RF channel and forwarding channel are not shown in Fig. 3.

A host wanting to transmit packets first has to wait for the *request* subslot of the next frame; then, it sends a slot-request signal to contend for the free data slots in this frame. We consider using slotted Aloha in the *request* subslot and if there is a collision, the hosts have to re-send the slot-request signal after a random number of frames. If the slot-request signal is sent successfully, the user listens to the *assignment* subslot to find out which data slot is to be used. Note that, because of the finite number of data slots, a user may not be assigned a slot in the frame even though it successfully sends a slot-request. In this case the slot-request will be queued for the next frame until this user is assigned a free data slot. In other words, the user need not send any new slot-requests during the queuing time of the slot-request. If a user has multiple packets to transmit, once it is assigned a data slot, it will use the same data slot until all its packets are transmitted. Since there is no collision in the data slot, all packets can be transmitted successfully in the slot.

When applying MADF to the TDMA system, an RF channel is reserved specially for data forwarding. The channel is divided into frames and each is also divided into $N+1$ slots, with the same size as that in data channel. When the load in a cell reaches a threshold value, the base station informs some of its users to use MADF. If the precise position for each mobile user is well known, the base station can assign a proper slot for each forwarding link as it may know exactly which slots in the forwarding channel are used and where they are used (e.g., by GPS). The slot is selected if there is no co-channel interference to both MADF users and their agents. However, this increases the computing complexity and involves in large amount of information exchanged among cells. To simplify the system, we assign N of slots as the data slots called "forwarding slots" (see Fig. 3 (b)) and the first slot as the control slot, as that in data channel. When using MADF in a hot cell, the base station selects the agents for its mobile users, but it doesn't select the forwarding slots. The user sends its connecting request to its agent, indicating which slots are free (i.e., without co-channel interference) around it by listening to the forwarding channel. Agent sends back a reply telling the user which forwarding slot to be used based on the free forwarding slots detected by both the user and the agent. In case there are no free slots, agent may ask user to stop using MADF, or randomly pick a slot. It may happen that when an agent receives a packets, it cannot find a free slot in its "agent" cell immediately. In this case, the agent will buffer the forwarded packet until it contends successfully for a free slot in its own cell. In TDMA, redundant agents are even more important for quick routing repair since a lot of applications are connection-oriented with a high QoS requirement.

Since TDMA is a connection-oriented network, it is always true that grouping the channels (slots) by a larger number to serve more users has better performance. When using MADF with TDMA, traffic in the hot cell is not intentionally split into different kinds of slots, e.g., data slots and forwarding slots, as is done in the Aloha MADF. Any new user in a hot cell will be randomly assigned a data slot or told to use a forwarding slot. The maximum number of the forwarding slots to be used in this hot cell is calculated by the base station according to the lowest QoS requirement (the average delay) and the traffic in the neighboring cells. When no data slots are available, and the number of the forwarding slots used in the hot cell doesn't reach the maximum number, the base station will inform the new user through the down-link channel to use a forwarding slot. It should be noticed that the base stations only decide how many forwarding slots should be used in MADF, while they don't decide which forwarding slots should be used. The forwarding slots are picked by mobile agents. Thus, for a mobile user using MADF, it may access any of the forwarding slots in the forwarding frame.

III. System analysis

In this section we analyze the MADF system using either Aloha or TDMA as the channel-access mechanism. The performance of interest is the packet delay, maximum throughput of a cell and maximum throughput of the system. We first consider the case in which the local traffic in the "agent" cell (the agent traffic) is low and hence can be ignored; therefore the throughput we obtain is the maximum achievable throughput. In a TDMA system, we also consider the case when the load in neighboring cells around a hot cell is not very low. All packets are of the same packet length and the same packet transmission time.

A. Analysis for Aloha and Slotted Aloha

We focus on an arbitrary cell and consider that there is one Aloha channel assigned to this cell and one extra Aloha channel is used as a forwarding channel. We assume that there are many users sharing an agent, and there are many forwarding agents in the agent cells (i.e., infinite population case).

We first consider the pure Aloha case and recall some important equations. Define λ as the throughput of the system, which is the average number of successfully transmitted packets per packet transmission time. We assume that the injection process of newly-arriving and back-logged packets into the cell is Poisson with rate G packets/(packet transmission time). It is well known that

$$\lambda = Ge^{-2G}. \quad (1)$$

Let E be the average number of retransmission attempts for each packet. Clearly, E is given by

$$E = G/\lambda - 1 = e^{2G} - 1. \quad (2)$$

Define τ as the packet transmission time. We assume that the retransmission timeout, defined as the delay from the time we know the packet is not delivered (i.e., the absence of an ACK after a round-trip delay) to the start of the next transmission, to be uniformly distributed between 0 and $k-1$ times of the packet transmission time. The maximum timeout is hence $(k-1)$ times the packet transmission time, which is $(k-1)\tau$. By noting that each retransmission takes a total time of $(1 + R + (k-1)/2) \times \tau$, the average delay, $\overline{d}$, is then clearly given by the sum of the packet transmission time and round-trip time for the ACK, i.e.,

$$\overline{D} = \tau[1 + R + E(1 + R + \frac{k-1}{2})]. \quad (3)$$

Note that, in general, since a cell's radius is only a few miles, compared with the packet processing time, $R\tau$ is very small and in Eqn. (3), R is negligible.

We now consider the delay in the MADF operation. We consider that there are many forwarding agents used by the hosts in the hot cell, so that the traffic in the agent cell may also be modeled as an Aloha system with infinite population. $\overline{D}_u$, the delay that takes users to transmit data to their own base station, can be calculated directly. To find the delay in the forwarding channel, i.e., $\overline{D}_f$, we show in Fig. 4 the end-to-end protocol operation with an intermediate agent B. A is the sender while C is the base station in the agent cell. The data packets first have to be transmitted successfully to agent B, which in turn forwards the packets to base station C using Aloha. In Fig.4, the processing time of ACK is ignored because it is normally very small. D is the end-to-end delay for the packet, which clearly consists of two Aloha system delays in tandem, i.e., $D = D_1 + D_2$, where D_1 and D_2 are the delay from sender A to agent B (the first hop), and from agent B to base station C (the second hop), respectively; and D_1, D_2 can be calculated by Eqn. (3).

For analysis simplicity, we assume that there is no local traffic in "agent" cells (The scenario that there is low traffic in these "agent" cells can also be analyzed with justifications.). The throughput in the forwarding channel from the hot cell then has to be equal to that of the agent cell. Therefore, the average delay for each hop in the forwarding channel is the same; therefore in an n-hop MADF, the delay over the whole channel is simply the delay over a single link multiplied by n. Thus, $\overline{D}_f$ can be calculated.

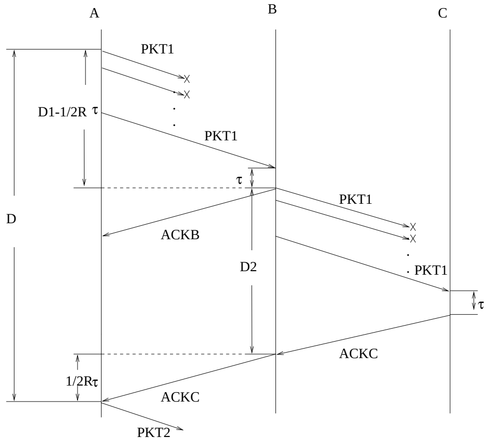


Fig. 4. A two-hop end-to-end protocol. "x" shows a failure of the transmission because of collision.

Note that the traffic in a hot cell can be split between the local channel and the forwarding channel to achieve the minimum average packet delay. Since λ_f and λ_u are the throughput in the local channel and the forwarding channel, respectively, the average packet delay for the users in the hot cell, $\overline{D}$, is thus obtained as:

$$\overline{D} = \frac{\lambda_u \overline{D}_u + \lambda_f \overline{D}_f}{\lambda_u + \lambda_f}. \quad (4)$$

Using the above equation, the minimum value of $\overline{D}$ given a certain throughput (given by $\lambda_u + \lambda_f$) can be obtained by adjusting λ_u and λ_f. Similarly, the maximum throughput under a certain delay constraint can be obtained. In other words, the optimum amount of traffic to be diverted to the agent cell is determined.

Using MADF with slotted Aloha, the throughput is slightly changed to:

$$\lambda = Ge^{-G}. \quad (5)$$

The average delay on one hop is given by

$$\overline{D} = \tau(1 + 0.5 + R + E(1 + 0.5 + R + \frac{k-1}{2})). \quad (6)$$

The factor 0.5 in the above equation is due to the fact that each packet has to wait for an average of 0.5 packet transmission time before it is aligned with the slot boundary and can be transmitted. E is obviously given by

$$E = G/\lambda - 1 = e^{G} - 1. \quad (7)$$

Given these equations, the derivation of the performance is similar to that of pure Aloha.

B. Analysis for TDMA

In order to derive the maximum throughput for the TDMA MADF network, we assume that each user has a large number of packets to transmit continuously. We consider that the slot-request signal can always be transmitted successfully, and there is no re-transmission delay for the slot-request signal. As usual, we are interested in the system throughput and users' access delay (defined as the time from the instance of the arrival for the first packet of the data burst, until the time it is delivered to a base station).

We assume that users in a hot cell are using no more than M forwarding slots to forward the data to a neighboring cold cell. M is calculated by the average delay requirement and the load in both the hot cell and the cold cell, and $M \leq N$. For simplicity, we first assume that the local load in the cold cell is 0. We assume that each frame has length τ_f and each slot has length τ_s, where $\tau_f = (N+1)\tau_s$.

When a new user in the hot cell, say User A, starts to transmit data, it has to wait for an average time of t_1 for the control slot, i.e.,

$$t_1 = \tau_f/2. \tag{8}$$

In the control slot, User A will send the slot-request. Since there is no collision for slot-requests, the slot-request from User A will always be received successfully and the hot cell's base station will try to either assign User A a data slot or ask User A to use MADF right after it receives the slot-request. If at that time there is no slot available, User A has to wait for the following frames until it gets a free data slot or a forwarding slot. Assuming that each of the N data slots and M forwarding slots have the same slot utilization P, where P can also be considered to be the normalized throughput in each slot, the probability that User A can or cannot find a free slot (a data slot or a forwarding slot) is $1 - P^{N+M}$ or P^{N+M}, respectively. Define E the average number of frames that user A has to pass before a frame comes, during which User A can get access to a data slot or a forwarding slot after it has successfully sent the slot-request, define t_2 the corresponding time User A has to wait, then:

$$\begin{aligned} E &= \sum_{i=1}^{\infty} i(P^{N+M})^i(1-P^{N+M}) = P^{N+M}/(1-P^{N+M}) \\ &= 1/(1-P^{N+M}) - 1, \end{aligned} \tag{9}$$

and

$$t_2 = E\tau_f. \tag{10}$$

The position of the data slot or the forwarding slot that User A uses to transmit data can be at any position in the frame except at the first slots of frames, which are the control slots. Ignoring the propagation delay in the frame in which User A will successfully transmit its first data packet, define t_3 to be the average time between the beginning of this frame and the time User A's first data packet is received by either the hot cell's base station or by an agent, then:

$$t_3 = \sum_{i=2}^{N+1} i\tau_s \frac{1}{N} = \frac{(N+2)}{2}\tau_s = \frac{1}{2}\tau_f + \tau_s. \tag{11}$$

Define $\overline{D_u}$ to be the average delay that User A experiences in having its first data packet received by either the hot cell's base station or an agent after it gets data to transmit, then:

$$\overline{D_u} = t_1 + t_2 + t_3 = \tau_f/(1-P^{N+M}) + \frac{1}{2}\tau_s. \tag{12}$$

With M forwarding slots to be used and the throughput of P in each forwarding slot, a throughput of MP is forwarded to the cold neighboring cell. Since the local load in the neighboring cell is 0, as we assumed at the beginning of the analysis, with the assumption that each data slot in the cold cell is assigned with the same forwarded traffic, the utilization of each data slot in the cold cell then is MP/N. Similar to Eqn (12) with the number of available slots modified as N and the data slot utilization modified as MP/N, define $\overline{D_c}$ to be the access delay that agents take to have the forwarded packets received by the cold cell's base station, then:

$$\overline{D_c} = \tau_f/(1-(MP/N)^N) + \tau_s. \tag{13}$$

Ignoring the processing delay in the agents, the access delay for the users who use MADF, $\overline{D_f}$, is:

$$\overline{D_f} = \overline{D_u} + \overline{D_c}. \tag{14}$$

Define $\overline{D}$ the average access delay for the users in the hot cell. Since a throughput of NP is transmitted to the hot cell directly with the average delay of $\overline{D_u}$ and a throughput of MP is transmitted to the cold cell with the average delay of $\overline{D_f}$, then:

$$\overline{D} = \frac{NP\overline{D_u} + MP\overline{D_f}}{NP+MP} = \frac{N\overline{D_u} + M\overline{D_f}}{N+M}. \tag{15}$$

In such a TDMA MADF, when the local traffic in the cold cell is not 0, the access delay can also be calculated. If the slot utilization in the cold cell is P_c before the users in its neighboring hot cell forward data to it, when MADF is used, the average access delay in this cold cell is calculated by

$$\overline{D_c} = \tau_f/(1-(MP/N + P_c)^N) + \tau_s. \tag{16}$$

$\overline{D}$ can then be calculated following Eqns (14) and (15).

Given the load in the hot cell and the agent's cell, the number of the forwarding slots to be used can be determined so that the optimum system throughput can be achieved under a delay constraint.

IV. Numerical Results and Comparison

In this section, we show the throughput improvement when users in a hot cell use MADF to forward data to a cold cell in an Aloha and a TDMA network. Matlab will be the analysis tool. We also examine the throughput improvement in the whole network when using MADF by simulating a 7 × 7-cell TDMA cellular network using a c simulator.

A. Pure Aloha with MADF

In pure Aloha, compared with the transmission time, the round-trip propagation delay is very small and can be ignored. We consider that $\tau = 1$. For re-transmission scheme, we pick the integer k as 5. We still assume one pure-Aloha channel in each cell and an extra pure-Aloha channel for MADF.

In Fig. 5, we show the maximum throughput in a pure-Aloha network with and without the one-hop MADF vs. different $\hat{D}$s. From the delay-throughput curve without MADF, we find that, when the throughput λ is less than 0.15, the average delay $\overline{D}$ increases slowly. After that, $\overline{D}$ increases much faster. When $\lambda = 0.15$, $\overline{D} = 3$. For our choice of the Aloha system's parameters, if we use $\overline{D} = 3$ as the delay constraint $\hat{D}$, the maximum throughput in a single cell with one pure-Aloha channel is 0.15. When throughput in a cell approaches this point, users in that cell have to use MADF to split the traffic. It should be noted that $\hat{D}$ can be any other value due to different QoS requirements, but the analysis will still hold. In Fig. 5, the cross point of the two curves at $\lambda = 0.08$ is the throughput threshold value at which a user should stop using MADF since, below this point, MADF cannot bring any throughput enhancement. When $\hat{D} = 3$, there is 47% throughput improvement of Aloha with MADF over the normal Aloha network.

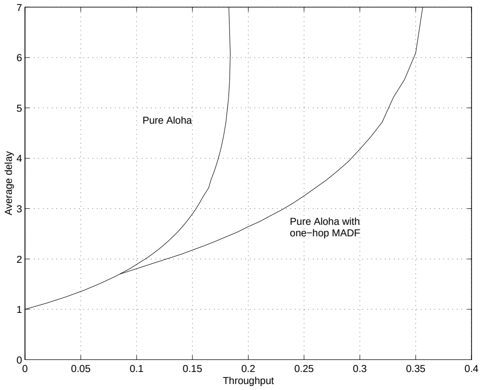


Fig. 5. Throughput in pure Aloha with and without MADF.

If the traffic in a hot cell can only be split to a cold cell through a multi-hop MADF, the average delay in the forwarding channel increases. Compared to the network with one-hop MADF, networks with multi-hop MADF have larger average delay. Under the same $\hat{D}$, the multi-hop MADF schemes achieve lower throughput increase, while if we relax the value of $\hat{D}$, we can still achieve high throughput enhancement. The throughput improvement with multi-hop MADF is shown in Fig. 6, which shows multi-hop MADF improves the delay-throughput performance and the cell with fewer hops of MADF has the larger throughput under the same $\hat{D}$. The cross points of the curves show the throughput threshold values under which a user should not use multi-hop MADF.

Now we compare the throughput improvement in a MADF network, a dynamic channel-allocation (DCA) network, and a macrocell/microcell network (Fig. 2). We consider a seven-cell cellular network (a cell in the center with six cells around) with one Aloha channel fixed assigned to each cell and one extra Aloha channel to be used as the forwarding channel, the dynamic channel or the microcell channels in these three schemes respectively. The dynamic channel can be assigned to any hot cell, but cannot be reused in the neighboring cells. We compare the maximum throughput of the center cell in these three schemes (defined as λ_C) when there is a very high load in the center cell and no load in its neighboring cells. We also compare the maximum throughput in this 7-cell network (throughput for all the seven cells and defined as λ_S) when all the cells are heavily loaded. We still consider the delay constraint $\hat{D}$ as 3. The throughput comparison with/without delay constraint is shown in Table 1. We find that, in the MADF network, the throughput in the center cell can be increased much more than the other two networks. However, the network throughput is less in the MADF network because, in the network with MADF, the overall number of channels connected directly to the fixed infrastructure is fewer than other two networks.

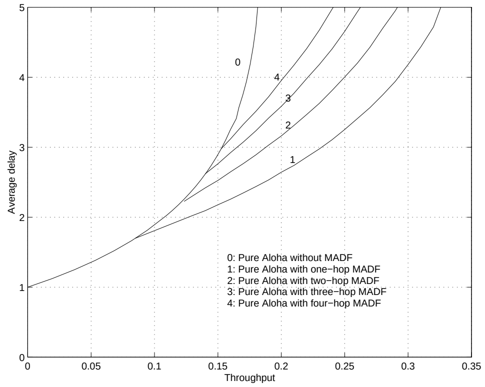


Fig. 6. Maximum throughput comparison between pure Aloha with different hops of MADF.

Table 1. Throughput comparison in the MADF, DCA and macrocell/microcell network. (First number in each entry is with delay constraint; the second number is without delay constraint.)

schemes	MADF	DCA	Macro-micro
λ_S	1.05/1.26	1.50/1.80	2.10/2.52
λ_C	0.57/1.26	0.30/0.36	0.30/0.36

B. TDMA with MADF

We consider a TDMA network with one fixed RF channel in each cell and an extra RF channel used as forwarding channel. We assume the slot length to be 1.

We first use our analytical model to explore the performance of TDMA with the frame made up by different number of slots. We compare the channel utilization (the percentage of time that a channel transmits data) in these different TDMA schemes since, for the same RF channel, higher channel utilization means higher throughput. It is shown in Fig. 7 that, in the TDMA network, when the number of slots in each frame increases, the maximum channel utilization increases because more of the channel is used as data slots, and the delay decreases at the high channel utilization but increases at low channel utilization. Compared with slotted Aloha, with a looser delay constraint, TDMA can achieve higher channel utilization. Specifically, TDMA can achieve a channel utilization larger than 0.36 while slotted Aloha cannot. Note that there is a minimum delay for both TDMA and slotted Aloha even when channel utilization is close to 0 because packets have to wait for the slots.

In Figs. 8 and 9, we explore the performance improvement when using MADF in a TDMA network with frame size of 6 slots. When users in a hot cell use one-hop MADF to forward data to one of its cold neighboring cells whose the local load is 0, with different number of the forwarding slots used in MADF, the throughput improvement in this hot cell is shown in Fig. 8. The crossover points between the curve without MADF and the curves with MADF in the figure show the throughput threshold values over which MADF can help to improve the network performance. At relatively large delay, i.e., when delay is larger than 10 in Fig. 8, throughput increases when the number of used forwarding slots increases. At a delay value of 15, there is an approximately 20%, 38% and 57% of throughput improvement over a normal TDMA cell by using MADF in TDMA with 1, 2, and 3 forwarding slots. This delay can also be used as the threshold value beyond which MADF should not be used, since the average delay will increase rapidly.

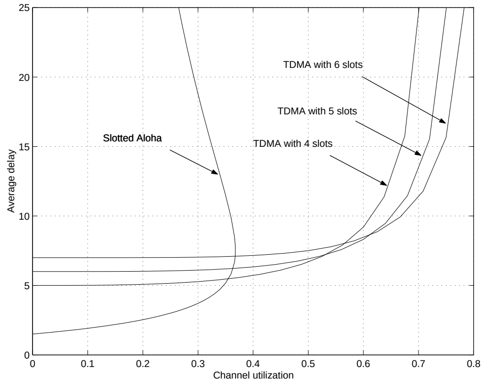


Fig. 7. Delay vs. throughput comparison between slotted Aloha and TDMA with different numbers of slots in a frame.

In Fig. 9, we show the throughput improvement for a TDMA cell using MADF when there is different local load P_c in its agent's cell. Three forwarding slots are used. When there is a light load ($P_c = 0.3$) in the agent's cell, the throughput improvement is very close to that when there is no load in the agent's cell. When there is a moderate load ($P_c = 0.5$) in the agent's cell, less throughput improvement can be achieved.

Finally, we use simulation to examine the performance of MADF in a 7×7-cell two-dimensional cellular network (Fig. 10). A network with a larger size has the similar simulation results. For this simulation, there are 30 channels in each cell, and the cluster size for frequency reuse is 4, i.e., the channel with the same frequency cannot be used in two neighboring cells. (The cells with the same letter in Fig. 10 use the same channels.) We examine the performance of both "in-band" and "out-of-band" MADF schemes. In an "in-band" MADF scheme, we reserve 2 channels in each cell as forwarding channels. Since the cluster size for frequency reuse is 4, globally we have 8 different forwarding channels. We set the constraint that a forwarding channel cannot be reused in the same cell. In an "out-of-band" MADF scheme, we also set the total number of the forwarding channels as 8. We consider the throughput in each cell and the average access delay for the new arrivals to the network. We assume the network to be a homogeneous network and new user arrival in each cell is a Poisson process. It will take a certain amount of time for the user to transmit all the data when it is assigned a channel, and this time is negatively exponentially distributed with the mean of 1 minute and an upper bound of 3 minutes. We define the throughput in a channel to be 1 if the utilization for this channel is 1.

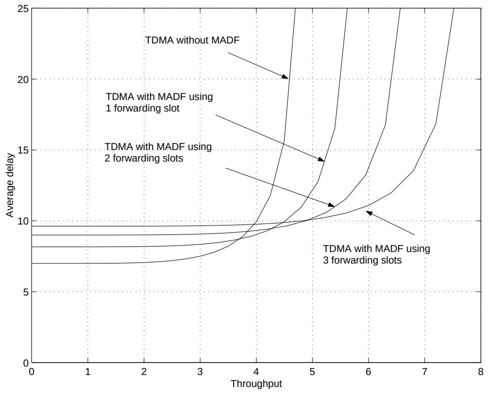


Fig. 8. Delay-throughput comparison between a TDMA cell without MADF and with MADF using different number of forwarding slots.

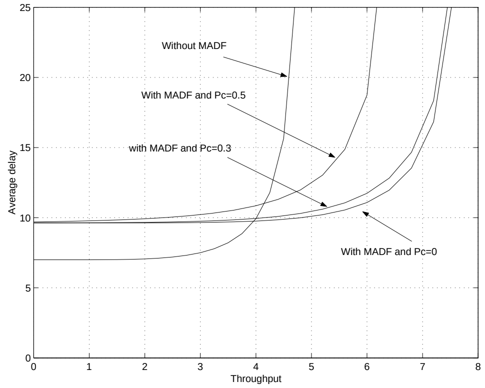


Fig. 9. Delay-throughput comparison in a TDMA cell with MADF when agent's cell has different loads.

Figure 11 shows the throughput-delay results in the cellular network with an "in-band" MADF scheme, with an "out-of-band" MADF scheme, and without MADF. With the same cell throughput, the scheme with "out-of-band" MADF has the least delay. When the cell throughput is

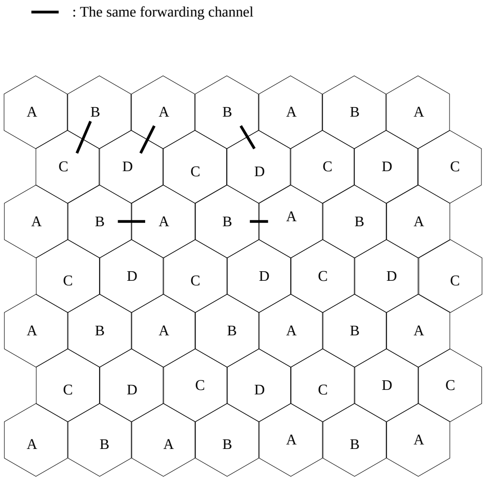


Fig. 10. A 7 × 7-cell TDMA network model.

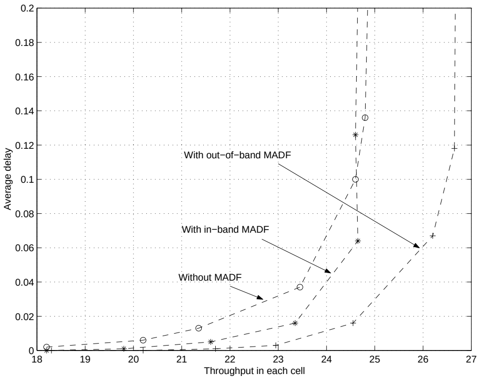


Fig. 11. Delay-throughput comparison in a 7 × 7-cell TDMA network model.

low (below the crosspoint in the figure), the scheme with "in-band" MADF has the less delay than the scheme without MADF. When the cell throughput is high, the delay in the system with "in-band" MADF is the highest. The "in-band" MADF can thus improve system performance before the network is overloaded while for the "out-of-band" MADF, it can always bring much better network performance. As a result not shown here, a cell closer to the center of the network has a lower delay, since it has more neighboring cells to forward data to. On the other hand, the cells at the corner have the worst delays.

V. CONCLUSION

We have proposed and evaluated the performance characteristics of a new data forwarding scheme (MADF) in wireless networks. Unlike the traditional cellular network resource allocation schemes, in which more radio resource is allocated to the cells with heavy traffic, MADF tries to forward part of the traffic in hot cells to cold cells, in order to achieve load balancing and enhance system performance. A number of channels called forwarding channels are used to forward data between cells. A mobile unit in a hot cell will use the forwarding channel to forward data to a mobile unit named agent in a cold cell, and the agent will relay the forwarded data to its own base station. With the analytical models and the simulation model we built for MADF, we have following important results:

- In an Aloha network, when a cell has one cold neighboring cell, using MADF under a certain delay constraint, the throughput in this cell can be improved as much as 47%. The throughput improvement is significant and superior to that in other schemes especially when there are more than one cold neighboring cells. Throughput can also be improved by multi-hop MADF.
- In a TDMA network, MADF can not only improve the throughput in a single cell, but can also improve the network throughput. An "out-of-band" MADF can make large network throughput enhancement over the traditional FCA scheme. An "in-band" MADF can also improve the network performance at relatively low throughput.

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Xiaoxin Wu received his B. E. degree from Beijing University of Posts and Telecommunications in 1990 and the Ph.D degree from University of California, Davis in 2001. After that he joined Arraycomm Inc. as a protocol research engineer. Since 2002, he has been working as a postdoctoral researcher in Department of Computer Science, Purdue University. His major research interests include routing, security, quality of service (QoS), and resource allocation in ad hoc network, cellular network, and integrated wireless networks. He served as technical program committee member for VTC2003 in symposium of Integrated Heterogeneous Wireless Networks.

S.-H. Gary Chan (S’89-M’98) received the MSE and PhD degrees in electrical engineering from Stanford University, Stanford, CA, in 1994 and 1999, respectively, with a minor in business administration. He obtained his B.S.E. degree (highest honor) in electrical engineering from Princeton University, Princeton, NJ, in 1993, with certificates in Engineering Physics, Applied and Computational Mathematics, and Engineering Management Systems. He is currently an Assistant Professor with the Department of Computer Science, The Hong Kong University of Science and Technology, Hong Kong, and an Adjunct Researcher with the Microsoft Research Asia in Beijing. He was a Visiting Assistant Professor in networking at the Department of Computer Science, University of California, Davis, from September 1998 to June 1999. His research interest includes multimedia networking, peer-to-peer multicast networks, high-speed and wireless communications networks, and Internet technologies and protocols.

Biswanath Mukherjee (S’82–M’87) received the B.Tech. (Hons) degree from Indian Institute of Technology, Kharagpur (India) in 1980 and the Ph.D. degree from University of Washington, Seattle, in June 1987. In July 1987, he joined the University of California, Davis, where he has been Professor of Computer Science since July 1995, and served as Chairman of Computer Science during September 1997 to June 2000. He is co-winner of paper awards presented at the 1991 and the 1994 National Computer Security Conferences. He serves or has served on the editorial boards of the IEEE/ACM Transactions on Networking, IEEE Network, ACM/Baltzer Wireless Information Networks (WINET), Journal of High-Speed Networks, Photonic Network Communications, and Optical Network Magazine. He also served as Editor-at-Large for optical networking and communications for the IEEE Communications Society. He served as the Technical Program Chair of the IEEE INFOCOM ’96 conference. He is author of the textbook ”Optical Communication Networks” published by McGraw-Hill in 1997. His research interests include lightwave networks, network security, and wireless networks. His e-mail address is: mukherje@cs.ucdavis.edu.

Bharat Bhargava received his B.E. degree from Indiana Institute of Science and M.S. and Ph.D. degrees in EE from Purdue University. He is a professor of computer sciences at Purdue University. His research involves host authentication and key management, secure routing and dealing with malicious hosts, adaptability to attacks, and experimental studies. Related research is in formalizing evidence, trust, and fraud. Professor Bhargava is a Fellow of the Institute of Electrical and Electronics Engineers and of the Institute of Electronics and Telecommunication Engineers. He has been awarded the charter Gold Core Member distinction by the IEEE Computer Society for his distinguished service. In 1999 he received IEEE Technical Achievement award for a major impact of his decade long contributions to foundations of adaptability in communication and distributed systems.