MADF: A Novel Approach to Add an Ad-Hoc Overlay on a Fixed Cellular Infrastructure

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Abstract—**In a cellular system, if there are too many data users in a cell, which we refer to as a hot cell, data may suffer large delay, and system's quality of service (QoS) may degrade. A dynamic channel-allocation scheme assigns more channels to those hot cells under centralized control (CC). 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 users in a hot and its surrounding cold cells without going through the hot cell's base station. The forwarding-channel management in MADF is done by mobile units themselves to relieve the load on the CC. We find that, using MADF, under a certain delay requirement, the system performance can be greatly improved.**

I. Introduction

Wireless data service is gaining increasing popularity recently [1]. In such a system, mobile terminals (typically computers) in a cell are able to access the fixed wired infrastructure such as the Internet via wireless channels. Since the traffic in a cell may fluctuate quite widely, the wireless channels should be assigned to the cells in a way so as to accommodate the fluctuating traffic to meet a certain QoS requirement (such as bounded packet delay).

Traditionally, a set of wireless channels is assigned to a cell in a fixed manner (i.e., the so-called fixed channel-allocation scheme) at system deployment [2], [3], [4]. In this way, the channel-reuse pattern can be optimized and the management of channel assignment to a mobile terminal is simplified. However, such a scheme cannot accommodate fluctuating traffic in a cell: when the traffic increases, the packet delay may increase to an undesirable level.

To mitigate such a 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 [5], [6], [7], [8]. However, such schemes generally requires complex and centralized control. To compromise between a completely fixed channel allocation and a completely dynamic channel allocation, we propose 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 borrow channels from its neighboring "cold" cells (i.e., a cell with low traffic) [9]. This scheme, just like dynamic schemes, assigns more channels to a hot cell so as to accommodate more traffic in the hot cell. Thus, the channel-reuse pattern has to be adjusted continuously for fluctuating traffic. The resulting channel-assignment pattern, however, may be sub-optimal due to the difficulty in global coordination for optimal channel reuse.

We propose in this study that, instead of assigning more channels to a hot cell, some of the traffic is *diverted away* from the hot cell and "forwarded" to its neighboring cold cells, if one or more such cold neighbors exists, thereby achieving load balancing among the cells and increasing the system capacity. Such a scheme is called "mobile-assisted data forwarding" (MADF). This scheme is similar to an assignment technique in which a user in an overlapping zone between two cells can use the cell with less traffic to transmit its data [10]; however, this latter technique is useful for users only at the boundary of two cells.

In data forwarding, the pool of wireless channels is divided into fixed channels (which leads to simple channel management) and forwarding channels. The number of forwarding channels is generally small, and hence the cost of setting aside such a channel is low. A mobile terminal in a hot cell may use the forwarding channels to transmit its data to a cold neighboring cell. Since the data has to cross a cell boundary, an intermediate forwarding agent in the cold cell is required to relay the data to that cell. Note that 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. In reality, it may be a repeater placed around the boundary of a cell. It may also be another mobile terminal itself, in which case, since the user in the hot cell and/or the agent may be mobile, the routing of the data packet may be similar to that in an ad hoc wireless networks. We will not discuss this routing problems in this study, but remark that ad hoc network has been studied widely in the literature (see, for example, [11], [12]), and the routing in our system may be much simpler given the expected much smaller number of terminals involved.

Note that a forwarding agent may serve multiple users

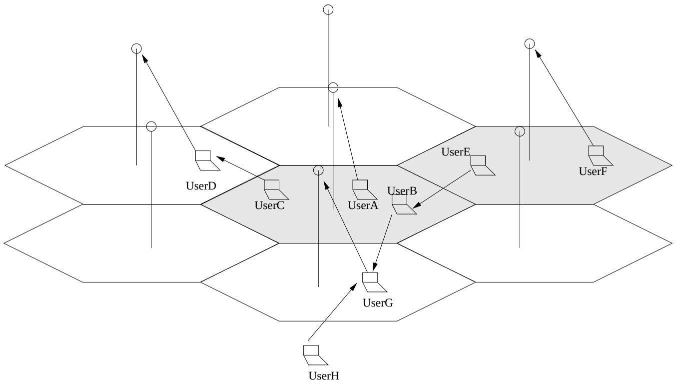

Fig. 1. A wireless data network with data forwarding (MADF).

at the same time, and data may hop through more than one forwarding agent before it is received by a base station. For the sake of simplicity in our discussion, the forwarding agent is assumed to be a mobile terminal in the remainder of this study. We illustrate in Fig. 1 a system with data forwarding, in which the hot cells are shaded. User D, User G, and User B are forwarding agents. We see that it takes two hops for the data from User C to be absorbed by a base station. As 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. A the user out of the coverage of this wireless network, but not far away, such as User H, can also have its data absorbed by taking User G as the forwarding agent.

Some power control under which different users transmit at different power levels may be required in order to keep the co-channel interference of the forwarding channel to the minimum. This is illustrated in the case of Users B and C in Fig. 1, in which User C and User B may use the same forwarding channel.

In this research, we are interested in the maximum capacity of a cell using data forwarding. Since packet delay is increased, we are also interested in the cell capacity given a certain packet delay requirement. Let D be the packet delay from the time of transmission until it is acknowledged. We may want to meet a certain average packet delay requirement given by $\overline{D} \leq \hat{D}$ or a certain percentile requirement $P(D > \hat{D}) \leq \epsilon$ for some values $\hat{D}$ and ϵ. Given a wireless forwarding channel, there are many ways to use such a channel for data transmission. The simple ones are Aloha, slotted Aloha, FDMA, TDMA and CDMA schemes. We will focus on using Aloha and TDMA for data transmission.

In Section 2, we present the operation and analysis of the system, and derive the maximum cell capacity given a certain delay requirement. In Section 3, we show some illustrative numerical results and comparisons. We conclude the study in Section 4. More details can be found in [13].

II. System Operation and Analysis

A. System Operation

In a data-forwarding network, a forwarding agent that is willing to forward data first measures its local traffic in its cell (the "agent" cell). The local traffic may be measured by sending some test packets to the base station and observing the acknowledgement delay. If the traffic in the cell is lower than a certain threshold λ_A packets/sec (deduced from the packet delay obtained), the forwarding agent (mobile unit) broadcasts a "free" signal in the forwarding channel periodically, indicating its availability to relay data packets. In the forwarding process, the agent keeps monitoring the arriving traffic in the forwarding channel so that it won't accept more traffic than it can handle (by asking users to back-off).

Users in a hot cell would collect the "free" signal when the packet delay in the hot cell exceeds a certain threshold. A hot-cell user starts using an agent once such an agent is identified. (Such an agent can be chosen according to the quality of the signal received by the hot-cell user and the local traffic; these pieces of information can be included in the "free" messages.) In order to reduce co-channel interference, the user can reach only agents in its neighboring cells. A user using a forwarding channel would continuously track the delay of its packets and when the forwarding channel can no longer satisfy the delay requirement, the user would stop using the forwarding channel and try to find a new agent.

There are two traffic threshold values for users in the hot cell: 1) the traffic at which the user starts to use a forwarding channel, and 2) the load at which the user stops using the forwarding channel because the traffic in its own cell has returned to the some low value. (In [13] we will show how to obtain these threshold values in the pure Aloha case.) Alternatively, a user may choose to split its traffic between its local channel and forwarding channel so as to achieve the lowest (average) packet delay. We consider end-to-end acknowledgement in which a data packet is acknowledged only if it reaches the target base station successfully; the user retransmits the back-logged packet if it does not receive its acknowledgement after a certain timeout.

B. System Analysis

In this section, we mathematically analyze the MADF system's average packet delay using either Aloha or TDMA as the channel-access mechanism in a cell.

B.1 Aloha and Slotted Aloha

Let λ be the normalized throughput, G be the corresponding transmission rate, l be the packet length, $R \times l$ be the round-trip propagation delay, E be the average

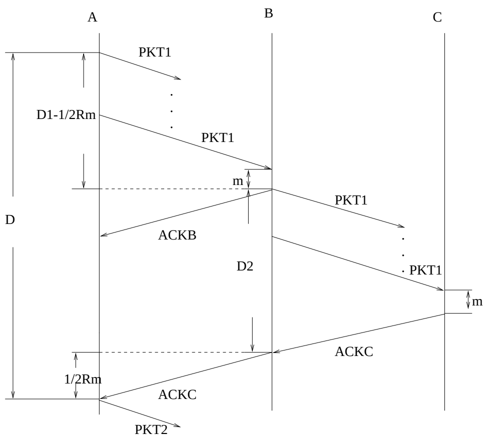

Fig. 2. A two-hop end-to-end protocol: the overall delay is the sum of the delays of each hop.

number of retransmission attempts for each packet, and $k \times l$ be the maximum time that a back-off packet can wait before it is retransmitted. We list some important results for pure Aloha as follows:

$$\lambda = Ge^{-2G}, \tag{1}$$

$$\overline{D} = l[1 + R + E(1 + R + \frac{k-1}{2})], \tag{2}$$

where

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

Without loss of generality, if we assume $l = 1$, the average delay can then be written as:

$$\overline{D} = 1 + (k+1)(e^{2G} - 1)/2. \tag{3}$$

Using the end-to-end protocol as shown in Fig. 2, when there are n different cascaded Aloha channels with the same throughput in each hop and the corresponding transmission rate is G in each hop, the average delay in the whole link is:

$$\overline{D} = n[1 + (k+1)(e^{2G} - 1)/2]. \tag{4}$$

Assume now that we have a system with a MADF scheme as shown in Fig. 1. Let there be one Aloha channel in each cell and an extra Aloha channel for the forwarding channel; and users in a hot cell are using a one-hop MADF scheme to forward data to their agents. When the forwarded data is the only traffic in these agents' cell(s), i.e., the local traffic in these agents is zero, the average delay from agents to their base stations is the same as the average delay from the users to their agents. If the normalized throughput in the forwarding channel is known, the corresponding transmission rate G can be calculated by Eq. (1). Since the end-to-end protocol is used in the forwarding channel, using Eq. (4), the average packet delay for the forwarded data is:

$$\overline{D} = 2[1 + (k+1)(e^{2G} - 1)/2]. \tag{5}$$

When using a one-hop forwarding channel and when there is no background traffic in agents' cell, to get the lowest average packet delay for the system, the traffic may not be evenly split between the channel in the hot cell and the forwarding channel. In a stable system, if the throughput in the hot cell channel is λ_u and the throughput in the forwarding channel is λ_f, assuming that the attempted transmission rates for these two channels are G_u and G_f respectively, G_u and G_f can be calculated using a numerical method from the following identities:

$$\lambda_u = G_u e^{-2G_u},$$

$$\lambda_f = G_f e^{-2G_f}.$$

$\overline{D_u}$, the average packet delay in the channel of the hot cell can be found by Eq. (3) and $\overline{D_f}$, the average delay in the forwarding channel can be found by Eq. (5). The average packet delay $\overline{D}$ for this hot cell then is calculated as the weighted average of $\overline{D_u}$ and $\overline{D_f}$, which is:

$$\overline{D} = \frac{\lambda_u \overline{D_u} + \lambda_f \overline{D_f}}{\lambda_u + \lambda_f}. \tag{6}$$

Since the maximum normalized throughput in an Aloha channel is 0.18, if $\lambda_u > \lambda_f$, the system throughput has its maximum value when $\lambda_u = 0.18$.

The derivations for the slotted Aloha system with MADF are similar to those for pure Aloha.

B.2 TDMA

In a TDMA system, let each cell have one channel. Time on each channel consists of periodic nonoverlapping, and equal-sized frames, and each frame is divided into $(m+1)$ time slots, among which the first slot is used as a control slot. Each slot (except the control slot) can carry one data packet. When a new user enters the system, it will wait for the control slot and send a slot-request signal to contend for the free slots in the frame. We assume that slotted Aloha is used for accessing the control slot. If there is a collision in the control slot, the user will resend the slot-request signal after a random number of frames. If the user cannot find a free slot in the frame after it transmit a slot-request signal successfully (the information of slot assignments is included in the downlink control signal from the base station), it will keep on sending the slot-request signal in the following frames.

We assume that each user has a large number of packets to transmit continuously. When a user gets a free slot, it will use the same slot until all the packets are transmitted. We can make a further assumption that the new user

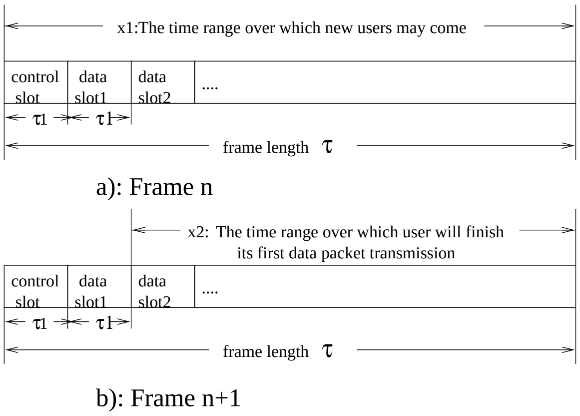

Fig. 3. Frames in TDMA.

arriving rate in the system is low enough so the slot-request signal can always be transmitted successfully. In the remainder of this analysis, we assume that there is no retransmission delay for the slot-request signal.

In a stable TDMA system (the average normalized throughput in each slot remains the same over a relatively long period of time), we assume the normalized throughput in each slot is p, which equals the utilization probability for each slot. The normalized throughput in the system with m slots then is $mp/(m+1)$. The frame length is τ and the slot length is τ_1, where $\tau = (m+1)\tau_1$. In Fig. 3(a) we show an arbitrary frame n in which a user may come to this frame during the time range x_1 and the user will wait for an average duration of $\tau/2$ until the control slot in the next frame comes, which is the first slot in frame (n+1) shown in Fig. 3 (b). This user will send the slot-request signal to the base station and following the earlier assumption, this slot-request signal can always be transmitted successfully. Since the slot-request signal is a much smaller packet compared with a normal data packet, the transmission time for a single slot-request signal is very small, much less than the length of one slot. If we ignore the signal propagation delay, we can assume that a user can get the immediate reply of a slot-request signal, so it can use any free data slot following the control slot. If the user is assigned a free slot in frame $(n+1)$, it will begin to transmit its first data packet. Since there is an equal probability for every data slot that can be assigned to this user, the average time required for the user to transmit its first packet after it gets the control slot and is assigned a free slot then is $2\tau_1 + (\tau - 2\tau_1)/2$ (see Fig. 3 (b)). If there is no free slot in that frame, the user will retransmit the slot-request signal in the control slot of the following frame. This process will be repeated until finally the user gets a free slot.

In a TDMA system with the average slot utilization of p, since there are m slots in each frame, the probability that a user cannot find a free slot is p^m. If a user has to retransmit the slot-request signal i times before it finally gets a free slot without collision in the control slot, the average number of retransmission attempts E is:

$$E = \sum_{i=1}^{\infty} i(p^m)^i(1-p^m) = p^m/(1-p^m) = 1/(1-p^m) - 1. \tag{7}$$

If we define $\overline{D}$ to be the average packet delay in a TDMA system, which is the delay measured from the instant that the first packet of a user[1] arrives until it gets delivered to the system, then $\overline{D}$ for a one-hop link is given by:

$$\overline{D} = \tau/2 + E\tau + 2\tau_1 + (\tau - 2\tau_1)/2 = \tau/(1-p^m) + \tau_1. \tag{8}$$

For a l-hop channel, the overall packet delay can be calculated as $\overline{D} = \overline{D_1} + \overline{D_2} + ..\overline{D_l}$ where $\overline{D_1}$, $\overline{D_2}$,...$\overline{D_l}$ are the average packet delay in each hop.

Through the central control system in the base station, MADF can also be used by the TDMA system. However, the users out of the system coverage cannot be served. In a TDMA system with the MADF scheme, we assign an extra channel for data forwarding. The forwarding channel is also repeated in frames with the length of τ. Each frame has $(m+1)$ slots with the length of τ_1, all the slots are data slots, and we call these slots forwarding slots. Now, we assume that n forwarding slots are used in a hot cell to forward data to the agents in a cold cell with a one-hop data forwarding. In the cold cell we assume there is no local traffic and all the m slots in this cold cell can be used to transmit the forwarded data. If the normalized throughput in each slot of the hot cell is p, the system throughput is $(m+n)p$. The forwarded throughput is np so the normalized throughput in each slot in the agents' cell is np/m. Ignoring the fact that the first slot in the forwarding frame can also transmit data, using Eq. (8), the delay for the user to transmit data either to the hot cell's base station or to an agent in the cold cell is:

$$\overline{D_u} = \tau/(1-p^{m+n}) + \tau_1. \tag{9}$$

The average delay $\overline{D_f}$, which is the delay from the user to the agent's base station, is given by:

$$\overline{D_f} = \tau/(1-p^{m+n}) + \tau_1 + \tau/(1-(np/m)^m) + \tau_1. \tag{10}$$

The average delay for the packet in the hot cell $\overline{D}$ is:

$$\overline{D} = \frac{m\overline{D_u} + n\overline{D_f}}{m+n}.$$

[1] We assume a user has a lot of packets to be transmitted at a time, and after its first packet gets a free slot successfully, the following packets will use that slot without competition in the control slot.

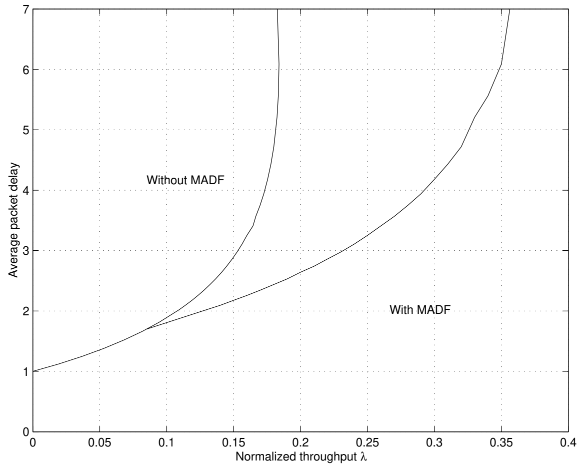

Fig. 4. Maximum λ with MADF.

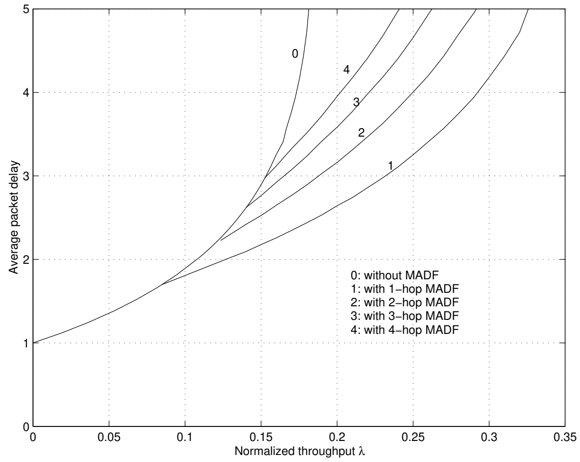

Fig. 5. Maximum throughput comparison between systems with different hops of forwarding channel.

III. Numerical Results and Comparison

We show some numerical results using the MADF scheme with the Aloha and the TDMA systems.

A. Aloha

We use the same cellular system as described in Section 2. Each cell has one Aloha channel and there is an extra Aloha channel reserved for forwarding operation. Using this model, we will examine the throughput, delay and operation of the system with MADF.

In Fig. 4, we show the maximum throughput with and without the one-hop MADF scheme vs. different delay constraints $\hat{D}$. Here we assume the local throughput in the agents is 0. The cross point of the two curves at $\lambda = 0.08$ in Fig. 4 is the value at which a user should stop using the forwarding channel since, below this point, MADF cannot bring any throughput enhancement.

When a multi-hop forwarding channel is used, the average delay in the forwarding channel increases. Compared with the system with one-hop MADF, the system with multi-hop MADF has larger average delay. Under the same delay requirement $\hat{D}$, the multi-hop MADF scheme achieves lower throughput increase, while if we loosen up on the $\hat{D}$ constraint, we can still achieve high throughput enhancement (Fig. 5).

In the power-control described earlier, we set the coverage radius of a forwarding channel to be half that of a standard cell, assume users are uniformly distributed in each cell, and 20% of users can reach the agents in the same neighboring cell. Our research indicates that, with MADF, a 25% increase of throughput can be achieved.

Now we compare the throughput improvement in the system with MADF, dynamic channel allocation (DCA) and macrocell/microcell ([13]) architecture. We consider a seven-cell cellular system with one Aloha channel in each cell and one extra channel to be used as forwarding channel, dynamic channel, or microcell channel in these three schemes. The radius of a microcell is half of that of the overlaying macrocell, and there is only one microcell in the middle each macrocell, thus the microcells in the neighboring macrocells can use the same channel. Under the delay constraint $\hat{D} = 3$, the maximum throughput for the system λ_S and the maximum throughput with/without delay constraint for the central cell λ_C are compared in Table I. We find that, in the system with MADF, the throughput in a cell can be increased much more than the other two schemes. However, the system throughput (throughput for all the seven cells) is marginally less in the system with MADF.

schemes	MADF	DCA	Macro-Micro
λ_{system}	1.05/1.26	1.20/1.44	1.33/1.54
λ_{cell}	0.57/1.26	0.30/0.36	0.19/0.22

TABLE I

Maximum throughput comparison of MADF, DCA and Macrocell-Microcell with/without delay constraint

B. TDMA

If the TDMA system uses MADF scheme to forward data with one of the forwarding slots (see Section 3) and there is no local traffic for the agent, the throughput improvement for a delay constraint is shown in Fig. 6. In this example MADF can help to improve the system throughput when delay requirement is larger than 7.7 (see crossover point in Fig. 6).

Now, we use simulation to examine the performance of MADF in a 7×7-cell two-dimensional cellular network. We assume that there are 30 channels in each cell, and the cluster size for frequency reuse is 4, i.e.,

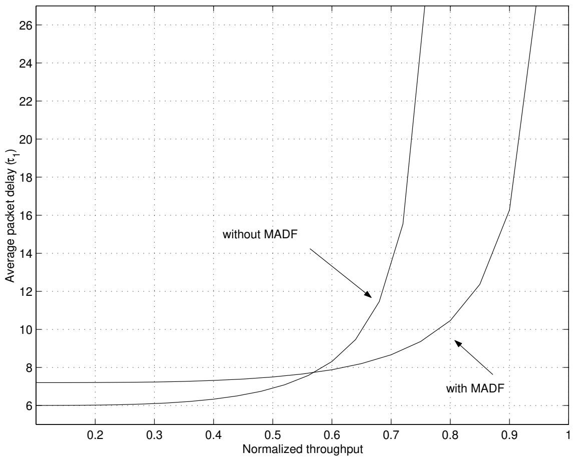

Fig. 6. Delay-throughput comparison between TDMA systems with and without MADF.

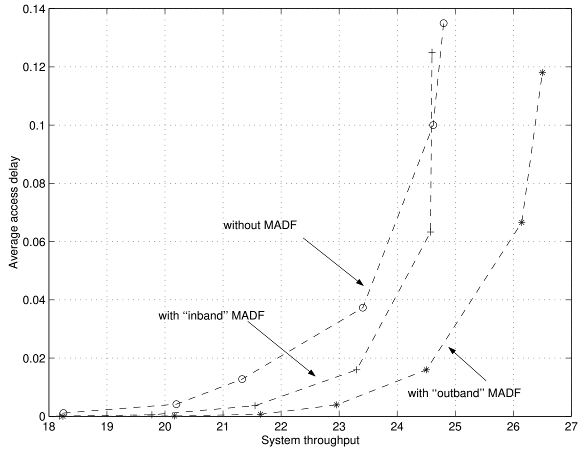

Fig. 7. Delay-throughput comparison in a 7×7-cell network model.

the channel with the same frequency cannot be used in two neighboring cells. We examine the performance of both "inband" and "outband" MADF scheme. In an "inband" MADF scheme, some ordinary channels in a cell are reserved as forwarding channels. In our simulation, we reserve 2 channels in each cell for 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 "outband" MADF scheme, extra channels are used for forwarding channels, and here we also set the total number of the forwarding channels as 8. We consider the overall throughput in the network and the average access delay for the new arrivals to the system. Fig. 7 shows the throughput-delay results in the cellular network with an "inband" MADF scheme, with an "outband" MAFDF scheme, and without MADF. With the same system throughput, the scheme with "outband" MADF has the least delay. When the system throughput is low (below the cross point in the figure), the scheme with "inband" MADF has the less delay than the scheme without MADF. When the system throughput is high, the delay in the system with "inband" MADF is the highest.

IV. Conclusion

We proposed and evaluated the performance characteristics of a new data forwarding scheme (MADF) in a wireless network. Using MADF, part of the traffic in a hot cell is forwarded to cold cells by special forwarding channels between mobile users. We first used an Aloha system to examine the MADF scheme. We found that, under a certain delay requirement, the throughput in one cell can be greatly improved. We then used MADF in a TDMA system and the results show that, in TDMA systems, the throughput can also be improved significantly.

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