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A QoS Architecture for IDMA-based Multi-service Wireless Networks

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Abstract— **The recent investigations on interleave-division multiple-access (IDMA) have demonstrated its advantage in supporting high-data-rate and multi-rate services over wireless fading channels. This paper focuses on quality of service (QoS) guarantee in IDMA-based multi-service wireless networks. We propose a QoS architecture which addresses the key issues of QoS guarantee for multi-service in IDMA, including medium access control (MAC), admission control, power control, and rate allocation. The proposed IDMA QoS architecture avoids complex packet scheduling at the MAC layer which is however required in other existing multiple access systems. Data packets can be transmitted in IDMA without scheduling delay. Additionally, to improve the efficiency of random access, an interleave-division slotted-ALOHA (IDSA) access method is proposed for the IDMA MAC protocol. We derive the relationship between the arrival rate of access requests and the number of access interleavers allocated to an IDMA system for a given access success probability. Based on this relationship, we can adaptively adjust the number of access interleavers according to the traffic load of access requests, so as to ensure a satisfactory probability of successful access as well as low complexity of request detection at the receiver.**

I. INTRODUCTION

The increased demand for multimedia applications promotes the investigation on multiple access (MA) technologies that can support high date rates, various quality of services (QoSs) in future broadband wireless networks. Latest investigations have demonstrated the interleave-division multiple-access (IDMA) technology as a potential solution to high-data-rate/multi-rate applications over fading channels [1]–[5]. In this paper, we investigate the QoS issues in IDMA-based multi-service wireless networks. As the background of our work, here we first elaborate on the concept of IDMA.

The basic principle of IDMA is very simple [4]. The uplink information from each user to the base station (BS)[1] is first encoded using a forward error correction (FEC) code, e.g., a convolutional code. The coded signal is then interleaved using a unique interleaver before transmission. Different interleavers are used to separate the signals from different IDMA users. Compared with code-division multiple-access (CDMA), the distinguished feature of IDMA is that the spreading operation in CDMA is replaced by low rate FEC coding, which achieves increased coding gain in IDMA.

Numerical results achieved in the previous work have demonstrated the following important features of IDMA [5], comparing with the existing MA technologies.

- *Supporting high data rates*: With the existing CDMA, high data rates can be achieved by reducing spreading factor or adopting multi-code CDMA, but the former leads to reduced spreading gain against fading and interference, and the latter needs to overcome the interference among spreading sequences. In contrast, high data rate transmission can be achieved in IDMA systems by assigning the FEC codes with high coding rates.
- *Combating intra-cell interference at low computational cost*: The multiple access interference (MAI) is a major concern for both CDMA and IDMA cellular networks. The existing CDMA mitigates the MAI by multi-user detection (MUD) [3]. However, the high computational cost involved in MUD, which may increase in exponential or polynomial order of the number of users, limits its application in practical systems. In contrast to CDMA, IDMA uses the iterative chip-by-chip (CBC) detection algorithm to combat intra-cell interference. The per-user computational complexity of the CBC is independent of the number of users involved.
- *Supporting asynchronous transmission*: The orthogonal MA technologies, such as time-division multiple-access (TDMA), frequency-division multiple-access (FDMA) and orthogonal-FDMA (OFDMA), require frame synchronization to maintain orthogonality. In IDMA networks, there is no sophisticated synchronization requirement on data transmission.
- *Multi-user gain*: IDMA achieves multi-user gain in the case of each user with a rate constraint [5]. This means that given the same sum-rate, the more users in a system, the less average transmitted sum-power is required.

In the following sections, we focus on the QoS issues and solutions in IDMA-based multi-service networks. A QoS architecture is proposed for supporting various services with different QoS requirements in IDMA. Based on the QoS architecture, we design a medium access control (MAC) protocol which adopts an interleave-division slotted-ALOHA (IDSA) access method to provide efficient random access

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[1] IDMA can be applied to either cellular mobile networks or wireless local access networks. In this paper, we only consider IDMA cellular networks.

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for users. The challenging problem of packet scheduling in the MAC protocols for other existing MA systems does not exist in the proposed IDMA MAC protocol. Unlike the slot-by-slot scheduling in TDMA/CDMA systems [6], [7] or the packet-by-packet scheduling in CDMA systems [8], [9], the IDMA MAC protocol supports multi-user/rate simultaneous transmission without scheduling delay for data packets.

The remainder of this paper is organized as follows. The proposed QoS architecture is described in Section II, which is followed by a comparison between our QoS architecture and those of other MA technologies in Section III. A performance analysis of the IDSA access method is provided in Section IV. Finally, we conclude our paper in Section V.

II. QOS ARCHITECTURE FOR IDMA NETWORKS

The objective of MAC protocols in MA systems is to provide efficient, fair and QoS guaranteed medium access for different users. The characteristics of the MA technologies deployed at the physical layer need to be concerned in MAC protocols designs. In IDMA networks, multi-service (multi-rate and multi-Qos) can be supported more flexibly than other existing MA technologies. First, due to multi-user in IDMA separated by interleavers, the traffic from different users can be transmitted simultaneously. Complex transmission scheduling among users is accordingly not necessary and stringent delay or delay jitter requirements can be satisfied easily. Second, multi-rate transmission can be achieved in IDMA by using variable coding rate of FEC codes. Third, transmission reliability in IDMA is guaranteed via dynamic power control. The transmitted power of each IDMA user is optimized before data transmission in order to reduce both intra-cell and inter-cell interference. Based on the above considerations, a novel MAC protocol is required by IDMA-based multi-service wireless networks. In the following, we outline the QoS architecture on which our proposed MAC protocol is implemented.

Fig. 1 presents the QoS architecture for an IDMA-based network at its user terminal and BS unit. In general, a user can support multiple connections. The application traffic is first classified in terms of service types in the *traffic classifier* module. IDMA can support the following service types:

- Constant bit rate (CBR) service. It is provided a fixed amount of bandwidth[2] throughout the connection. It is suitable for such applications as circuit emulation, constant-bit-rate voice and video communications.
- Variable bit rate (VBR) service. It is provided guaranteed average bandwidth and allowed to use up to a pre-negotiated maximum bandwidth if it is available. It is suitable for both real-time streaming audio or video traffic and non-real-time interactive applications.
- Available bit rate (ABR) service. It is given no guaranteed bandwidth and delay performance, but it is allowed to use whatever bandwidth available after all CBR and VBR connections are served.

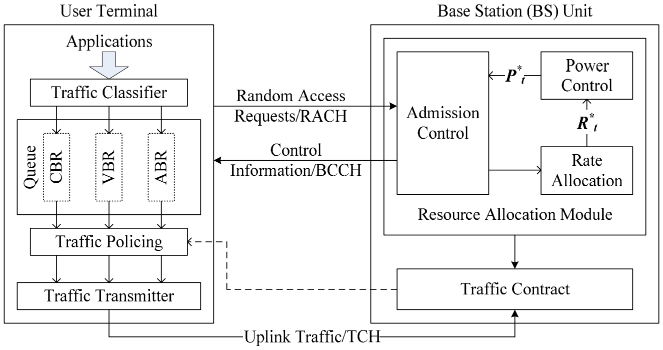

Fig. 1. QoS architecture for IDMA systems.

For each connection set-up, a user first sends an access request to the BS. The access request includes the necessary information such as the characteristics of the traffic and the required QoS. At the BS, the received access requests are processed in the *resource allocation* module comprising *admission control*, *power control* and *rate allocation*. The rate allocation module decides the transmission rate (bandwidth) that can be assigned to the users. The power control module optimizes the transmitted power of each user. Based on the results of power control and rate allocation, the admission control module makes the decision of whether to accept or reject a user's access request. The final results of resource allocation include the decision of admission control, the transmitted power and data rate allocated to each user. For those users whose access requests are accepted, their negotiated QoS is stored in a *traffic contract*. The traffic contract and the results of resource allocation are broadcast with other control information to the users through the downlink broadcast control channel (BCCH). At the user terminal, the *traffic policing* module enforces the compliance of the arriving traffic to the negotiated traffic contract. Once a request is accepted, the *traffic transmitter* retrieves the data packets from the classified *queues* and transmit with the allocated data rate and power.

A. MAC Protocol

For simplicity, we assume that the uplink and the downlink of each cell are separated by frequency division duplex (FDD) mode. Fig. 2 presents the timing diagram and frame structure of the IDMA MAC protocol. The uplink physical channel (shown at the bottom of Fig. 2) is partitioned into a random access channel (RACH) and a traffic channel (TCH) separated by interleavers. Access requests are sent to the BS through the RACH, carrying the following information required by the resource allocation module:

- the adopted coding scheme,
- the affordable maximum transmitted power,
- the type of service,
- the QoS requirements on bit error rate, bandwidth, etc..

The randomly generated access requests can be transmitted by the slotted-ALOHA. Dividing the RACH into small time slots, referred to as *request slots*, with a fixed length equal to the transmission time of an access request, each user sends his

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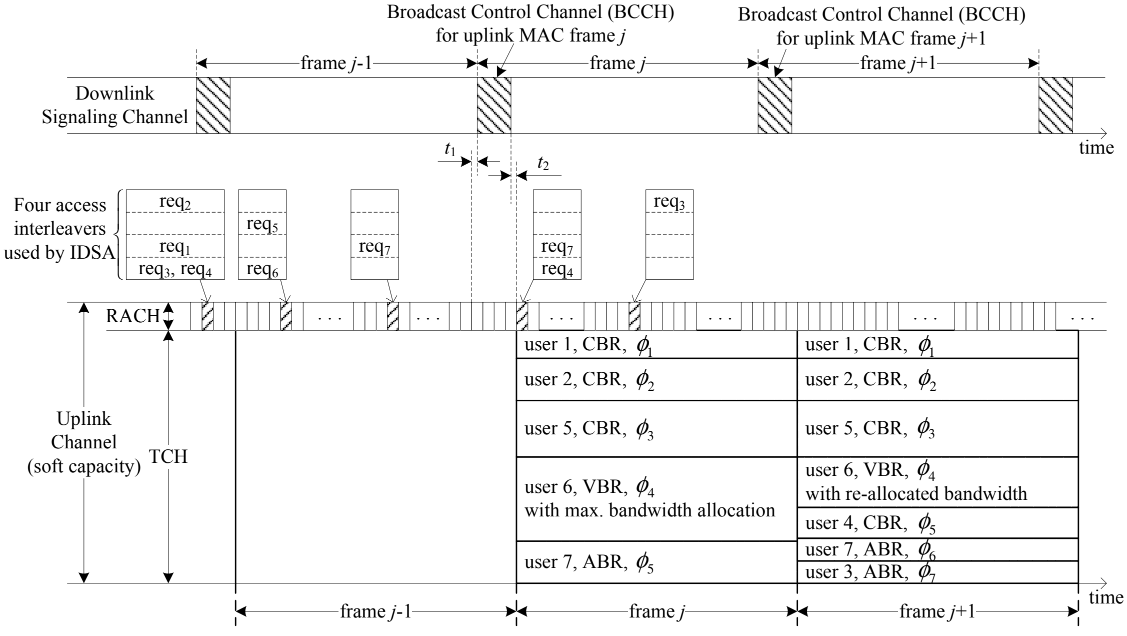
[2] IDMA link capacity is measured by the maximum transmitted data rate over the link. Hereafter, we designate the bandwidth in IDMA systems as the transmission data rate.



t_1 : the propagation delay of access requests from the user side to the BS plus the processing delay for access requests at the BS/AP.
t_2 : the propagation delay of responses from the BS to the user side plus the processing delay for responses at the user side.
req$_k$: access request of user k, k = 1, 2, 3, ...
ϕ_k : payload interleaver.

Fig. 2. The timing diagram and frame structure of the IDMA MAC protocol.

access request at the beginning of a request slot with properly optimized transmitted power. However, the collision-prone transmission with the slotted-ALOHA leads to low efficiency in the RACH. In order to improve the throughput of the RACH, our solution is that each user sends his access request by using a unique interleaver. We refer to such kind of interleavers as *access interleavers*. They are predefined by the network and broadcast to the users. With this method, multiple access requests with different access interleavers can be transmitted in the same request slot without collision, accordingly higher efficiency can be achieved than the slotted-ALOHA as will be shown later. We refer to such an enhanced slotted-ALOHA as *interleave-division slotted-ALOHA* (IDSA).

Once an access request is accepted by the network, another unique interleaver, not from the set of access interleavers, is assigned to the connection for data transmission in the uplink TCH. Multi-user/connection simultaneous transmission can be supported by interleaver separation. We refer to the interleavers for data transmission in the TCH as *payload interleavers*. The payload interleaver assigned to a user/conneciton is sent to the user through the downlink BCCH.

At the BS, successfully received access requests are processed in the resource allocation module. The response to each access request is returned to the user through the downlink BCCH before the next immediate uplink MAC frame. A user may not receive his response due to the following reasons: timeout for his response, his access request corrupted by channel errors in transmission, or his access request collided with others' using the same access interleaver in the same request slot. To enhance the reliability in the RACH, the failed access request can be retransmitted using another randomly selected access interleaver based on the truncated binary exponential backoff algorithm [10]. For example, in Fig. 2, the requests req$_3$ and req$_4$ for user 3 and 4 collide due to using the same interleaver in the same slot. They are retransmitted respectively, with a random number of backoff slots.

The uplink TCH is divided into MAC frames with a fixed length which depends on the characteristics of fading channels. For example, the duration of the frame can be chosen such that during which the channel condition is more or less constant. The admitted users can transmit their data simultaneously in the TCH at the beginning of the next immediate uplink MAC frame, as shown in Fig. 2.

B. Power Control and Rate Allocation

The objective of power control is to guarantee efficient transmission for IDMA users as well as minimize the total transmitted power in a cell, so as to further reduce the interference to the adjacent cells. Each IDMA user who wants to transmit information in the network needs to acquire his transmitted power, which is optimized to guarantee not only his QoS, but the QoS of other admitted users in both the local cell and the adjacent cells. Therefore, once a new user is admitted, the transmitted power levels of all on-going users in the local cell are re-allocated for performance improvement.

As shown in Fig. 3, the inputs to the power control module include the maximum tolerable interference in the adjacent cells and the following information of both the new and the admitted users in the local cell:

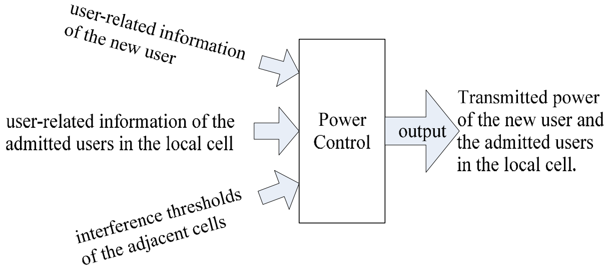


Fig. 3. Input and output of power control.

- the adopted coding scheme,
- the expected data rate,
- the estimated uplink channel condition.

The power control algorithms for CBR traffic have been studied in [11]. There is no rate allocation for CBR users since the CBR service requires fixed bandwidth allocation. However, rate re-allocation will be involved to improve the QoS performance for VBR and ABR users. For example, for a new user with VBR service, his requested average bandwidth R_{avg}^{VBR} is first used in power control. If the calculated transmitted power $\boldsymbol{P}_t^*$ for all users in the local cell (local users) just satisfies the criteria of admission control, this new VBR user is admitted with his average bandwidth allocation R_{avg}^{VBR}. Alternatively, if $\boldsymbol{P}_t^*$ for all local users satisfies the criteria of admission control, *and* the maximum link capacity is not reached, the data rate for this new VBR user can be re-allocated. In such cases, the *rate allocation* module increases the data rate for this new user by an increment δ. The resultant data rate $R_t^{*VBR} = R_{avg}^{VBR}+\delta$ is used in power re-allocation for this new VBR user and all other local users. The re-allocated power levels for all local users are verified by admission control again. This process continues in an iterative manner, until no more link capacity is available in the local cell or the maximum bandwidth allocation for this user is reached. The final data rate allocated to this new VBR user is $R_t^{*VBR} = R_{avg}^{VBR} + n\delta \le R_{max}^{VBR}$. Here n is the number of iterations in rate allocation, R_{max}^{VBR} is the maximum bandwidth required by the VBR user. On the other hand, if the results of power control cannot match the criteria of admission control even when the new VBR user is allocated with the average bandwidth R_{avg}^{VBR}, his access request is rejected.

For ABR users, they are allowed to share the remaining capacity fairly after the allocation of CBR and VBR connections. The transmitted power of each ABR user is then calculated according to his allocated data rates.

C. Admission Control

The uplink capacity of IDMA-based cellular systems is interference limited due to the MAI. The MAI rises as the number of users in transmission increases. The objective of admission control is to guarantee that the QoS of the admitted users in both the local cell and the adjacent cells will not be violated by the admission of a new user. Hence, a new user is admitted conditional on that not only the transmitted power allocated to him can be afforded, but also the interference from the local cell can be tolerated by the adjacent cells.

Additionally, service differentiation is involved in the admission control. According to our admission policy, the CBR and VBR users are admitted on a call by call basis; while the ABR users are admitted on a frame by frame basis. Referring to Fig. 2, once the CBR and VBR users have been accepted, they do not need to send any more requests during their calls. On the other hand, ABR user 7 has to send requests for every uplink MAC frame. For example, in Fig. 2, once ABR user 7 is admitted and dynamically assigned payload interleaver ϕ_5 to transmit in uplink MAC frame j, he immediately sends a new access request req$_7$ for his transmission permission in uplink MAC frame $j+1$. Once this new access request is accepted, ABR user 7 is again dynamically assigned payload interleaver, say ϕ_6, to transmit in uplink MAC frame $j+1$.

Service-prioritized access to the network is also provided in the admission control. The traffic with higher priority always access the TCH first. The access priority in decreasing order is CBR, VBR and then ABR. For example, in Fig. 2, in uplink MAC frame j, three CBR users 1, 2, 5 are first allocated with their required bandwidth and transmit with payload interleavers ϕ_1, ϕ_2 and ϕ_3, and then VBR user 6 is allocated with his maximum bandwidth and transmit with payload interleaver ϕ_4, finally the rest of uplink capacity is allocated to ABR user 7 who uses payload interleaver ϕ_5. In order to admit the new CBR user 4, the bandwidth of VBR user 6 is reallocated in uplink MAC frame $j+1$. The remaining uplink capacity is shared by ABR user 7 and the new ABR user 3 fairly.

We can further improve the link capacity by prioritizing the users in the same type of service. For example, the channel conditions can be considered in admission control among multiple users with VBR or ABR services. The VBR or ABR users with good channel conditions are allowed to access first, so as to avoid link capacity degradation in both the local cell and the adjacent cells due to the admission of the users with bad channel conditions.

III. COMPARISON WITH OTHER QOS ARCHITECTURES

The differences between IDMA and other exiting MA technologies lead to the above different considerations in the QoS architecture for IDMA-based cellular systems. A comparison of QoS architectures for different MA technologies is presented in Table I.

Besides, there is another difference in power control for multi-service QoS guarantee between IDMA and CDMA. Power control is used to combat the "near-far" problem in CDMA cellular systems, by maintaining nearly equal received power of each user at the BS. With such kind of power control, when different users transmit their packets by TD-CDMA, the capacity per time slot is limited by the type of traffic with the most stringent BER requirement. An existing solution is known as BER scheduling [7], which assigns the packets with either equal or almost the same maximum BER specifications in the same slot to transmit. In contrast, power control in

TABLE I

QoS PROVISIONING IN IDMA VS. OTHER MA TECHNOLOGIES.

	TDMA/OFDMA, e.g., WiMax	CDMA, e.g., UMTS	IDMA
Allocated resource	Time slots, in TDMA WiMax; Sub-carries in OFDMA WiMax.	Codes, transmission power, time slots (for time division CDMA (TD-CDMA)).	Interleavers, transmission rate and power.
Resource scheduling policy	Frame-by-frame packet scheduling.	Packet scheduling on a code-slot basis in terms of BER requirements, e.g., BER scheduling policy for TD-CDMA [7].	Service-differentiated resource scheduling: on a call-by-call basis for CBR/VBR traffic; on a frame-by-frame basis for ABR traffic.
Supporting multi-rate connections	Through slot-by-slot scheduling.	Through slot-by-slot scheduling or packet-by-packet scheduling.	No scheduling is required.

IDMA has no such constraints. The QoS for different types of simultaneously transmitted traffic can be guaranteed under dynamic power and rate allocations among the IDMA users, without compromising the capacity performance.

IV. INTERLEAVERS MANAGEMENT

One issue of the IDMA MAC protocol is the possible collision among access requests transmitted in RACH by IDSA. An alternative solution is to allocate a large number of access interleavers to the IDMA system so as to reduce the collision probability among access requests. However, such a method involves a high computational cost of detecting the access requests at the BS. To solve this problem, we propose a strategy that adaptively allocates the available interleavers in the network to the transmissions of either access requests or traffic. Let Π be the set of N interleavers available in an IDMA system. Let Π_c denote a set of M, $M < N$, interleavers which are randomly selected from Π by the network and exclusively used as access interleavers. Thus, the subset of $N - M$ interleavers from $\Pi - \Pi_c$ can be used as payload interleavers. Here we analyze the optimal number of access interleavers M for an IDMA system.

For the proposed IDSA access method, collision happens in the cases that more than one user sends their access requests using the same access interleaver in the same request slot. The collided requests are retransmitted after a random backoff time by the truncated binary exponential backoff algorithm.

Let X be the length of the request slot. Consider a reference request packet is transmitted at time t_0, the beginning of request slot $[t_0, t_0 + X)$. This request packet will not be collided only if other request packets arriving in the previous request slot $[t_0 - X, t_0)$ choose the access interleavers different from the one used by the reference request. For the reference request that randomly selects an access interleaver from Π_c, the probability of choosing access interleaver j is given by

$$p_j = 1/M.$$

Let K denote the maximum number of backoff slots (request slots) for retransmission of collided access requests. Under the assumption of $K \to \infty$, the arrivals of the total access requests in one slot, including both the new and the retransmitted requests, can be approximated by a Poisson process. Then, the probability that n access requests arrive within $[t_0 - X, t_0)$ is given by [10]

$$p(n) = \frac{G^n e^{-G}}{n!}, \tag{1}$$

where G denotes the average number of the arriving access requests per slot, including both the new and the retransmitted requests.

The probability that the n requests arriving within $[t_0 - X, t_0)$ do not choose access interleaver j is,

$$(1 - \frac{1}{M})^n. \tag{2}$$

Thus, given n requests arriving in the previous slot, the probability that the reference access request is successfully transmitted using interleaver j in $[t_0, t_0 + X)$ is given by

$$p_j(1 - \frac{1}{M})^n p(n) = \frac{1}{M}(1 - \frac{1}{M})^n p(n). \tag{3}$$

The probability of successful transmission for an access request using any access interleaver, denoted P_s, is obtained by,

$$\begin{aligned} P_s &= \sum_{n=0}^{\infty} M \cdot \frac{1}{M} \cdot (1 - \frac{1}{M})^n \cdot p(n) \\ &= \sum_{n=0}^{\infty} p(n)(1 - \frac{1}{M})^n . \end{aligned} \tag{4}$$

Substituting Eq. (1) into Eq. (4), we have,

$$\begin{aligned} P_s &= \sum_{n=0}^{\infty} \frac{G^n e^{-G}}{n!}(1 - \frac{1}{M})^n \\ &= e^{-G} \sum_{n=0}^{\infty} \frac{[G(1 - 1/M)]^n}{n!} \\ &= e^{-G/M}. \end{aligned} \tag{5}$$

The average retransmission times per request is given by

$$\frac{1}{P_s} - 1 = \frac{1 - P_s}{P_s}.$$

Let S denote the number of successfully transmitted access requests in one request slot, that is the throughput of the access method. For the IDSA, it is calculated by

$$S = GP_s = Ge^{-G/M}, \tag{6}$$

Now we consider the case of finite backoff time. It is assumed that the number of backoff slots for retransmission of a collided request is uniformly distributed between 1 and K. Thus, the average number of backoff slots for an access

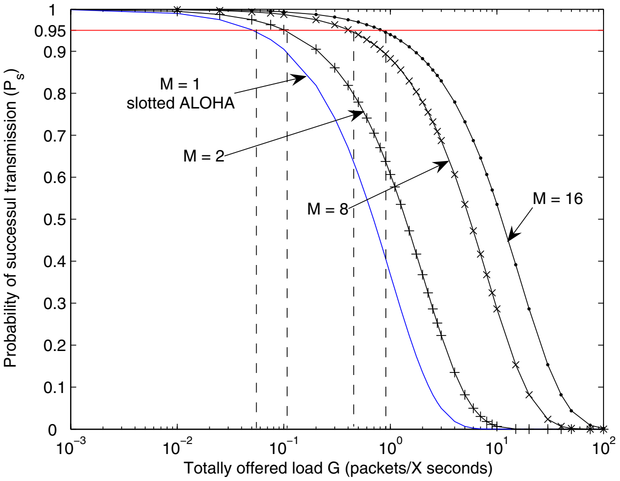


Fig. 4. The probability of successful transmission of an access request.

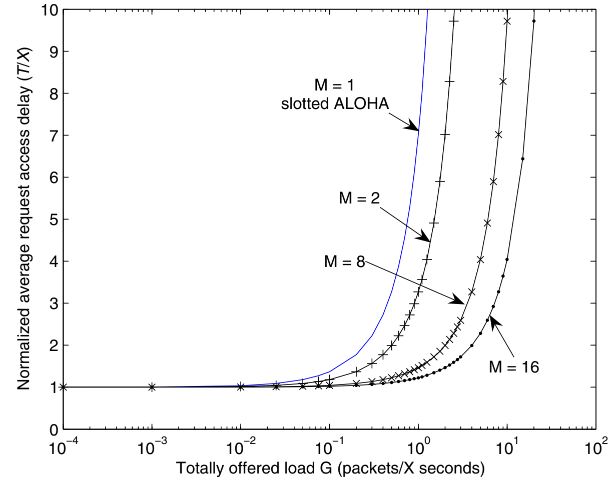


Fig. 5. Average access delay for $K = 4$.

request, denoted by B, is $B = (1+K)/2$. Finally, the average request access delay, denoted by T, can be derived as,

$$\begin{aligned} T &= X \cdot \left[1 + \frac{t_{prop}}{X} + \frac{1-Ps}{Ps}(1 + B + \frac{t_{prop}}{X})\right] \\ &= X \cdot \underbrace{\left[1 + \frac{t_{prop}}{X} + (e^{G/M} - 1)(1 + B + \frac{t_{prop}}{X})\right]}_{\text{average transmissions per request packet}} \quad (7) \end{aligned}$$

where t_{prop} is the propagation delay of an access request.

We present in Fig. 4 the probabilities of successful transmission of requests, P_s, achieved by the IDSA method in the cases of $M = 1, 2, 8, 16$. The normalized average request access delay (T/X) of the IDSA method in the case of $t_{prop} = 0.0$ and $K = 4$ is plotted in Fig. 5.

Fig. 4 provides the relationship between P_s and the values of G and M. For example, if the system requires $P_s \geq 0.95$, for $G \leq 0.055$ request packets per slot, it is enough to allocate only one access interleaver to the IDMA system, that is $M = 1$. In such a case, the IDSA is equivalent to the traditional slotted-ALOHA. When the value of G increases to 0.9 request packets per slot, at least 16 access interleavers should be allocated to the IDMA system in order to guarantee 95% successful transmission probability for access requests. The results demonstrate that we can adaptively adjust the number of access interleavers M in terms of the intensity of the arriving access requests. One advantage of this approach is that we can control the proportion of capacity allocated to RACH. Besides, compared with the means that a large number of access interleavers is allocated to access requests for a high P_s, our approach requires lower computational cost to detect multiple access requests at BS.

V. CONCLUSION

We have addressed the major QoS issues in IDMA-based multi-service wireless networks. The contribution of this paper is that the proposed MAC protocol is significantly simple when compared with those for the other existing TDMA or CDMA systems. The QoS in terms of delay, which is guaranteed by complex packet scheduling in the traditional multiple access networks, can be guaranteed by the IDMA MAC protocol without scheduling policy. With the IDMA MAC protocol, once a connection is admitted to the network, its data packets can be transmitted immediately in the next uplink MAC frame, thus no scheduling delay will be introduced. Besides, the bandwidth allocation among multiple services can be guaranteed based on service prioritized access.

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