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Fast Retrial and Multichannel Random Access in OFDMA Wireless Networks

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***Abstract-* In telecommunications and computer-networks, a channel access method or multiple access method allows several terminals connected to the same multi-point transmission medium to transmit over it and to share its capacity. The considered promising candidates for implementing next-generation wireless communication systems are orthogonal frequency-division multiple access (OFDMA) systems. The fast retrial scheme has been proposed to improve the performance of random access in orthogonal frequency-division multiple access (OFDMA) system. Retrials are designed to follow the 1-persistent type, i.e., no exponential back-off. In our analysis we confirm that our fast retrial algorithm has the advantage of high throughput and low collision.**

***Index Terms*—Aloha, frequency reuse factor, orthogonal frequency-division multiple access (OFDMA), random access communication.**

I. INTRODUCTION

The IEEE 802.16 [1] for high-data rate fixed wireless services and the IEEE 802.20 [2] for mobile broadband wireless access service already have working groups in place for the development of B3G systems. Although code-division multiple-access (CDMA)-based systems have been developed in some research groups, it appears that orthogonal frequency-division multiplexing (OFDM) systems will play a dominant role in implementing B3G systems. IEEE 802.11a/g [3], [4] and IEEE 802.16 [1] devices are also OFDM based. The high bandwidth of OFDM comes from thousands of orthogonal subcarriers [12]. By grouping subcarriers, orthogonal frequency-division multiple access (OFDMA) systems can have many logical channels on the link layer and also exploit multiuser diversity.

Since OFDMA systems use frequency-division multiplexing, it needs to ensure an appropriate frequency reuse factor for multicell environments [9], [13]. If two neighboring cells use the same subcarrier channels, the transmission in a cell interferes with that in the other. To overcome the interference problem, the system can employ techniques like spectrum spreading [14] and multiple-receiver-based interference suppression [15]. The most widely accepted approach is to design the frequency reuse factor such that the two neighboring cells allocate subcarriers exclusively. In this paper, we design the reuse factor for random access channels in an OFDMA system. We believe that designing random access-based systems are important to be able to handle: 1) initial access; 2) bursty traffic; and 3) short packets. We briefly provide the reasons. For a long time now, random access has been a popular approach for medium access control. Local area networks (LANs) and wireless local area networks (WLANs) use carrier-sensing multiple access with collision detection (CSMA/CD) and with collision avoidance (CSMA/CA) protocols, respectively. While the CSMA type of protocol is well applied for unlicensed band systems, it is not used in cellular networks because of channel efficiencies that use a licensed band. Therefore, 2G and 3G cellular systems use a slotted Aloha type of solution for initial uplink access. To lower the collision probability, reservation protocols such as packet reservation multiple access (PRMA) have been considered [23]–[25]. While reservation-based protocols are adequate for periodic voice traffic, they are not suitable for data traffic because of the bursty nature of data traffic. Therefore, in this paper, we will consider a random access scheme that is especially tailored for wireless data networks. It is known that the random access schemes perform well for delivering short packets [8]. If many relatively long data packets are competing for random access, the collision probability goes up, resulting in low-link utilization. To solve this problem, a system like CDMA-high data rate (HDR) (or cdma2000 1x EV-DO) dedicates some uplink channels to each user by assigning a unique code [5]. This may also cause low channel utilization because data packets are not usually generated continuously. Therefore, next-generation systems are expected to support more uplink shared channels that are managed by uplink scheduling [27]. Uplink scheduling, when adopted, inevitably incurs more random access attempts because each

mobile with pending data packets should send short channel request packets to the base station (BS). Accordingly, the effective use of random access channels is becoming important for uplink scheduling as well as initial access and short message transmission. In this paper, our contributions are threefold. First, we consider the uplink data communication in OFDMA environments and apply the random channel access for it. Second, we propose a fast retrial algorithm that is adaptive to loading condition and resolves contention. Our scheme basically uses the 1-persistent slotted Aloha and achieves fast access and high throughput for multichannel random access. Third, we find the most adequate reuse factor for random access channels in multicell OFDMA environments. Some related works are as follows. While much research has been devoted to the slotted Aloha in single-channel environments,
our work focuses on the multichannel slotted Aloha like in [16]–[18]. In [16], the multichannel slotted Aloha is analyzed for fixed bandwidth per channel or fixed total bandwidth, which is designed for multichannel satellite communication. In [17], it targets reducing the number of connections. In [18], reservation is considered.
The random access protocol has also been modified for various environments [19]–[22]. In [19], the retransmission probability is dynamically adjusted according to the transmission result in the previous slot. In [20], redundant transmissions are exploited to meet a user's deadline requirement. In [21], a random access protocol is analyzed when long-range dependent traffic is transmitted over random access channels. In [22], a cross-layer technique combined with signal processing is proposed. In CDMA systems, the random access scheme uses power control to overcome the near–far effect that basically uses a power ramping algorithm [6], [7]. Similarly, the IEEE 802.16 standard uses the power ramping for initial random access. The fundamental difference between previous work and our paper is in the objective of using random access. In future cellular networks, we expect to require both fast access and high utilization under multiple random access channel environments that will support communications for channel requests, short messages, and other signaling messages. This provides us with the main motivation to design a *simple* and *efficient* mechanism for utilizing random access channels under normal loading conditions. Our major contribution in this paper has been to extend randomness from the *time domain* to the *frequency domain*, which allows us to improve throughput and the access delay in multiple random access channel environments.

II. SYSTEM DESCRIPTION

A. Uplink Access Model

In cellular networks, downlink communication is relatively straightforward because the BS coordinates events in a centralized way. When the BS has packets to transmit over the downlink, it notifies the corresponding user and transmits them ac-cording to a scheduling scheme or the channel allocation being used.

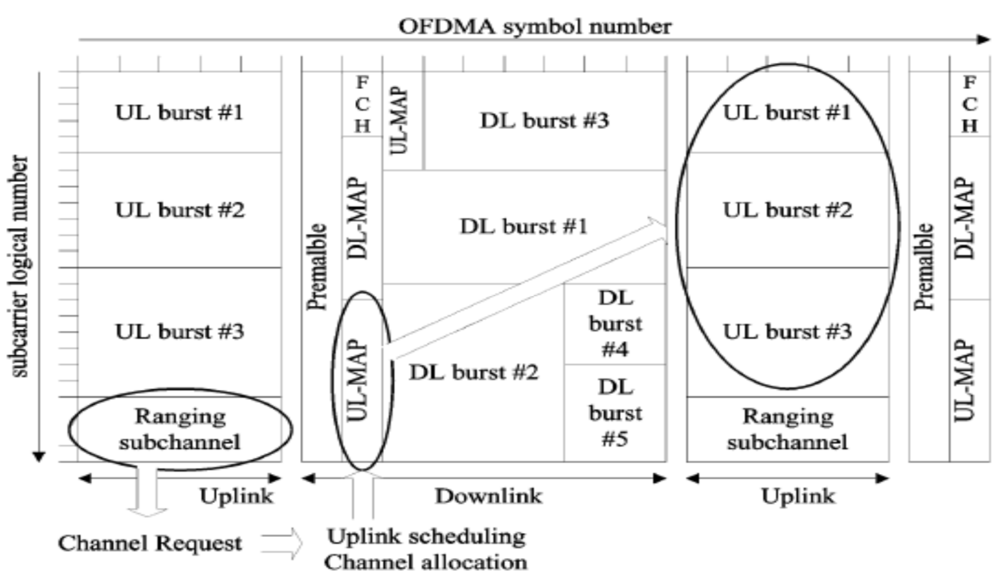

Fig. 1. Frame structure model in IEEE 802.16 TDD-OFDMA standard.

Scheduling is applicable to general data packet service over shared channels and channel allocation to voice or streaming service over dedicated channels. As new services become dominant in wireless networks, uplink transmission also needs to take advantage of shared channels. To request shared or dedicated channels, a user terminal sends control messages over contention- based common channels like in the IEEE 802.16 standard [1]. So, random access can be a good candidate for sending channel requests. Besides, as

we know, it is useful for sending
short message service, location update, initial access, etc. The difficulty with uplink transmission is that it cannot avoid contention unless a user specifically has a channel dedicated to it. The Aloha type that is widely used for random access has the drawback of having high-collision probability when the packet size is big, so it is good for short message service and channel request messages.

B. Ranging

OFDMA systems use a ranging technique to adjust the uplink timing offset of a symbol. The IEEE 802.16-OFDMA uses CDMA-based ranging and defines three types of ranging: *initial ranging*, *periodic ranging*, and *bandwidth request ranging* [1]. Initial ranging uses power ramping to search for the appropriate power level, which increases transmission power step by step. When a terminal enters the network, it synchronizes the uplink offset by the initial ranging and then adjusts it periodically (periodic ranging) by using ranging. The bandwidth request also
exploits ranging that plays a role in random access. So, the ranging follows random access procedures. Given a code set, a user terminal randomly selects a code and transmits a ranging request. The BS then broadcasts the ranging response that includes information about OFDM symbols and subchannels. When a collision occurs, the terminal waits for some time and then retries. In the IEEE 802.16 standard, an exponential backoff algorithm is used to resolve collisions.

C. Channel Structure

Fig. 1 shows the frame structure defined in the IEEE 802.16 time-division duplex (TDD)-OFDMA standard. The uplink interval consists of data sub channels and ranging (or random access) subchannels. When a terminal has packets to send, it sends a channel request message to the BS. If the BS receives the request successfully, it broadcasts the assignment result through the uplink map in the next frame. Then, the terminal transmits the packets over the allocated channel(s). The procedures are the same for the dedicated channel request. To reduce the number
of random access trials, the IEEE 802.16 standard also defines a polling scheme. To serve various random access needs, future cellular networks are expected to provide multiple channels for random access. The ranging is also a kind of random access. In CDMA-based ranging, the number of codes corresponds to that of random access channels. As the number of codes grows, the conventional exponential backoff algorithm may no longer be adequate for collision resolution. This motivates us to propose a fast retrial algorithm that becomes more powerful as the number of random access channels increases.

III. COLLISION RESOLUTION

Existing systems such as second-generation (2G) and third generation (3G) cellular systems have adopted the slotted Aloha for random access. Its appeal is in large part its simplicity of implementation. We will, therefore, also assume that the random access strategy being used is the slotted Aloha. Hence, we assume that a packet that arrives during time slot is transmitted at time slot , and the terminal learns whether or not access is successful immediately at the end of each slot. Our work does not consider the capture effect [28], [29].

A. Fast Retrial Algorithm

Since the OFDMA system has multiple random access channels in the frequency domain,2 we propose a *fast retrial algorithm* that exploits the nature of multiple channels for resolving contention. When a random access fails, which is mainly caused by collision, a user terminal retries the access by random channel selection instead of conventional random backoff time. If the utilization is not very high, this scheme can be highly efficient because the probability of experiencing consecutively collisions will be low. In a conventional random access scheme for a single channel, the collision is resolved by using random backoff in the time domain as shown in Fig. 2(a). In contrast, in the multichannel environment, we resolve the collision at time by hopping in the frequency domain at time , as shown in Fig. 2(b). Hence, we refer to this approach as a fast retrial scheme. Our algorithm runs in the same manner as the 1-persistent scheme in the time domain, except that in the multichannel system, our approach spreads randomness over the frequency domain. We call this type of arrival a frequency-domain backoff or fast retrial. Through this approach, we can obtain high throughput and low access delay even under increased collision probability.

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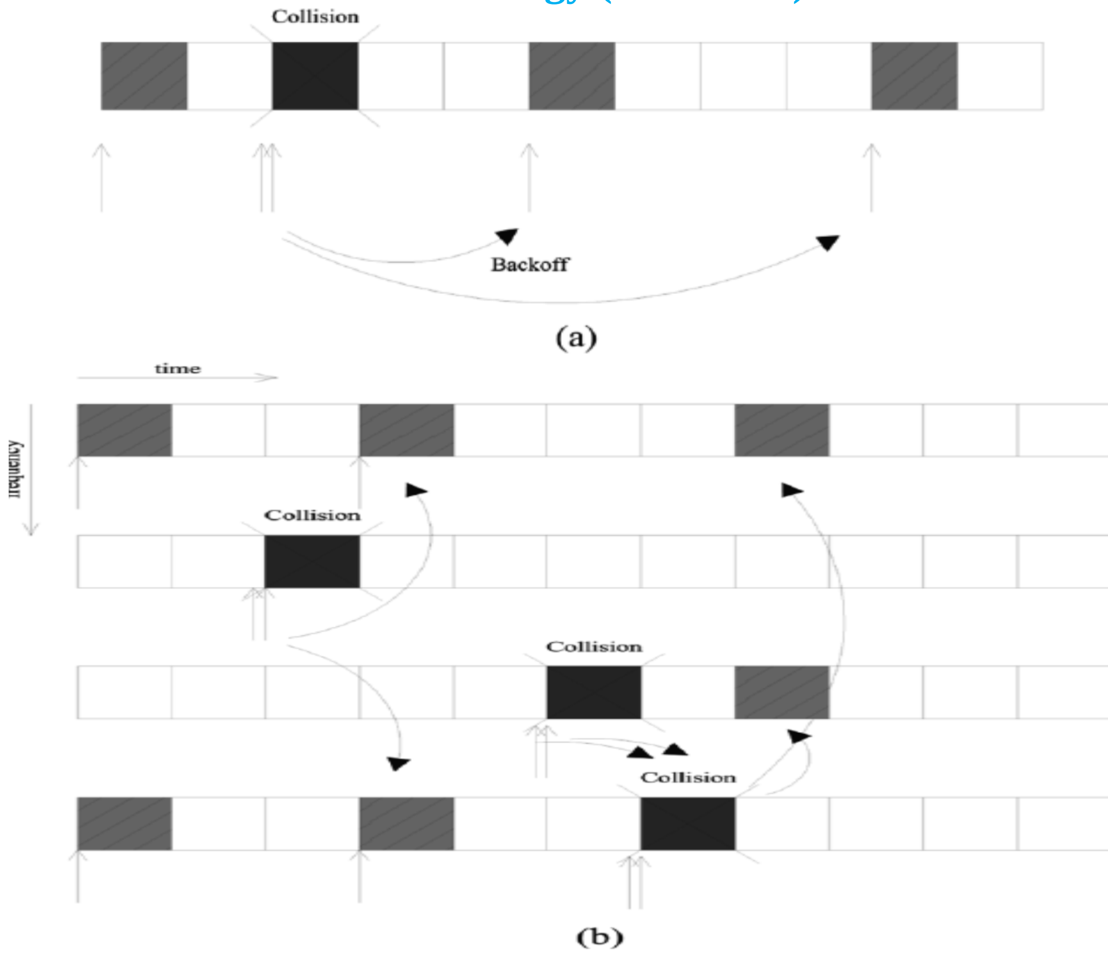

Fig. 2. Randomness in time and frequency domain: (a) Time-domain backoff in single channel. (b) Frequency-domain backoff in multiple channels.

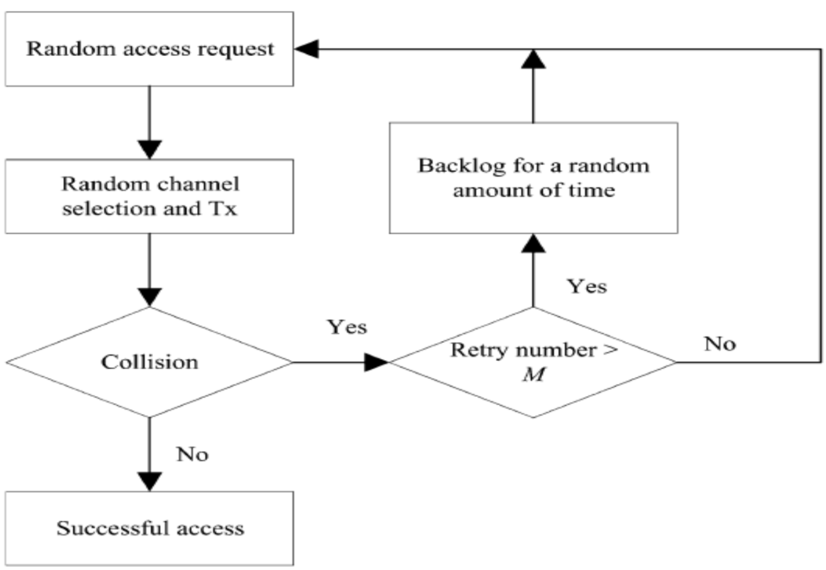

Fig. 3. Proposed fast retrial algorithm.

The fast retrial algorithm is illustrated in Fig. 3. This algorithm limits the maximum number of retrials to M. That is, if the retrial number is larger than M, it uses random backoff in the time domain, i.e., waits for a random amount of time and thengives a retrial

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like in the slotted Aloha. We call this type of arrival a time-domain backoff. Our algorithm operates well under normal loading conditions, where the combined rate of new arrivals and retransmissions is not far above the full loading. A detailed numerical investigation is provided in Section V.

We now define the following notations. These notations will be used to analytically obtain the collision probability and the throughput:

N number of random access channels;
M maximum number of allowed fast retrials;
λ combined rate of new and time-domain backlogged arrivals;
λ_T total arrival rate;
T throughput;
p user collision probability (ratio of collisions to total trials);
q slot collision probability (ratio of collision slots to total slots);
Υ ratio of fast retrials to the number of collisions in the previous slot;
p_{nc} The possibility of a channel has no collision;
S scheduled transmission have been send during the i^{th} slot.

Assume that the total of the new and time-domain backlogged arrivals in a slot follows a Poisson distribution with mean λ. Then, the total arrival rate at slot i is nothing but the sum of λ and fast retrials caused by collision at slot i-1. In this case fast retrials follow a Poisson distribution i.e. arrivals in a time slot are Poisson with mean λ_T.

So, the total arrival rate at slot is given as

$$\lambda_T(i) = \lambda + p \cdot \gamma \cdot \lambda_T(i-1) \qquad (1)$$

Since the maximum number of fast retrials is bounded by M, the added arrival rate is reduced by a factor γ , which is the ratio of fast retrials at slot i to the number of collisions at slot i-1 .

We obtain γ as

$$\gamma = \frac{M}{\sum_{i=0}^{M} p^i} = \frac{S - N\,P_{nc}}{\sum_{i=0}^{M} p^i} \qquad (2)$$

In steady state, we express λ_T by omitting the slot index i as

$$\lambda_T = \frac{\lambda(1-(p\gamma)^{M+1})}{(1-p\gamma)} \qquad (3)$$

Assuming that channels are independent, we obtain the total throughput of N channels by N times the throughput of a single channel [17].

Therefore, we have

$$T = N\frac{\lambda_T}{N}\exp\left(-\frac{\lambda_T}{N}\right) = \lambda_T \exp\left(-\frac{\lambda_T}{N}\right) \qquad (4)$$

Since the user collision probability is defined as the ratio of collisions to total trials in number, we have

$$P = \frac{E[\text{collisions}]}{E[\text{success}]+E[\text{collisions}]} \qquad (5)$$

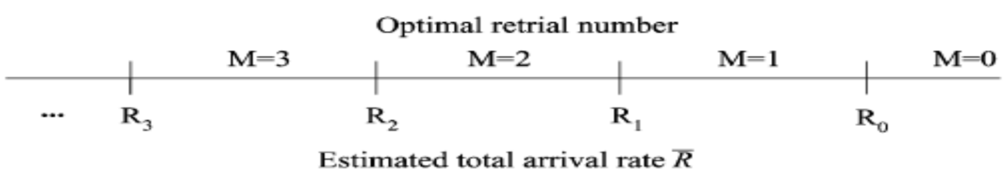

Fig. 4. Load adaptive M selection for estimated arrival rate R.

where

$$E[\text{collisions}] = \sum_{k=2}^{\infty} k \frac{(\frac{\lambda_T}{N})^k}{k!} \exp(-\frac{\lambda_T}{N})$$
$$= \frac{\lambda_T}{N}(1-\exp(-\frac{\lambda_T}{N})) \quad (6)$$

$$E[\text{success}] = \frac{\lambda_T}{N}\exp(-\frac{\lambda_T}{N}) \quad (7)$$

Therefore

$$P = 1-\exp(-\frac{\lambda_T}{N}) \quad (8)$$

Meanwhile, in a single channel, slot collision occurs when two or more users arrive at the same slot. Thus, we can represent the slot collision probability q as

$$q = 1\text{-}\ (1+\frac{\lambda_T}{N})\exp(-\frac{\lambda_T}{N}) \quad (9)$$

Unlike the conventional slotted Aloha, the throughput in (4) is a function of λ_T, which is a function of p. Therefore, we obtain p and T in a recursive manner.

From p, we can obtain the probability distribution of the access delay, i.e., the probability that m time slots are required to successfully access the channel. Therefore

$$Pr\ \{\text{access delay} = m+1\} = (1\text{-}\ p)\ p^m,\ 0 \le m \le M. \quad (10)$$

Accordingly, the probability that the access delay is smaller than or equal to M+1 is given by

$$Pr\ \{\text{access delay} \le m+1\} = (1\text{-}\ p) \sum_{m=0}^{M} p^m = 1\text{-}\ p^{M+1}.$$

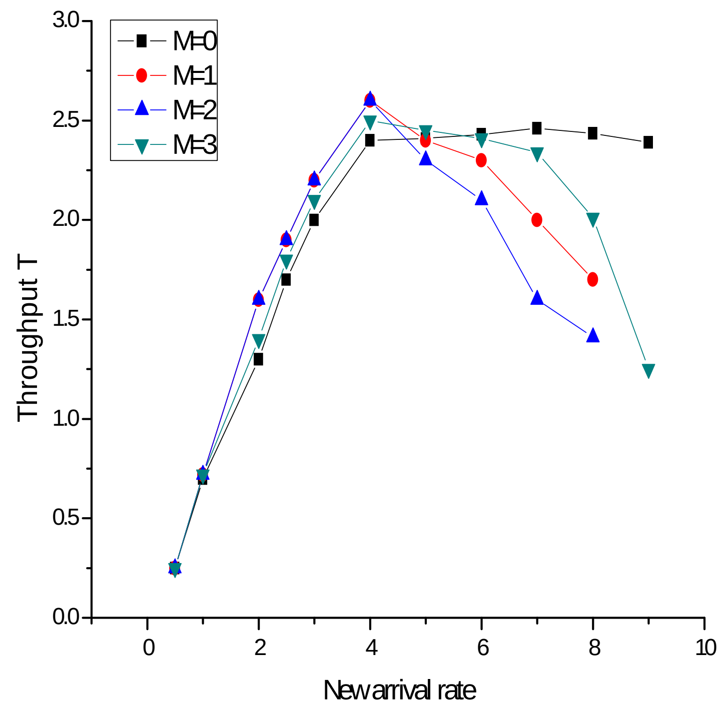

Fig. 5. Throughput versus new arrival rate (N = 7)

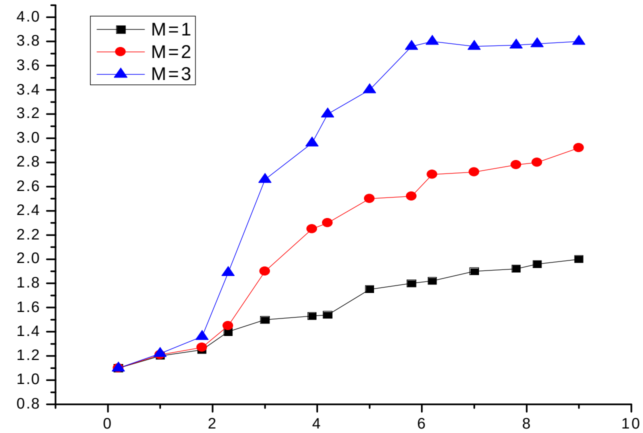

Fig. 6. λ_T / λ versus new arrival rate (N = 7).

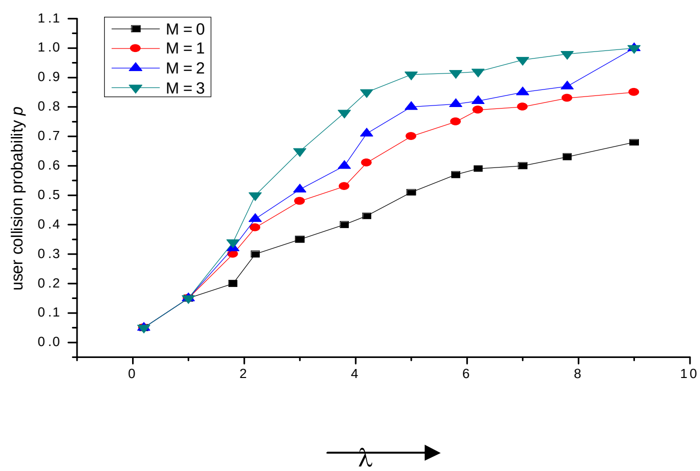

Fig. 7. User collision probability versus new arrival rate (N = 7)

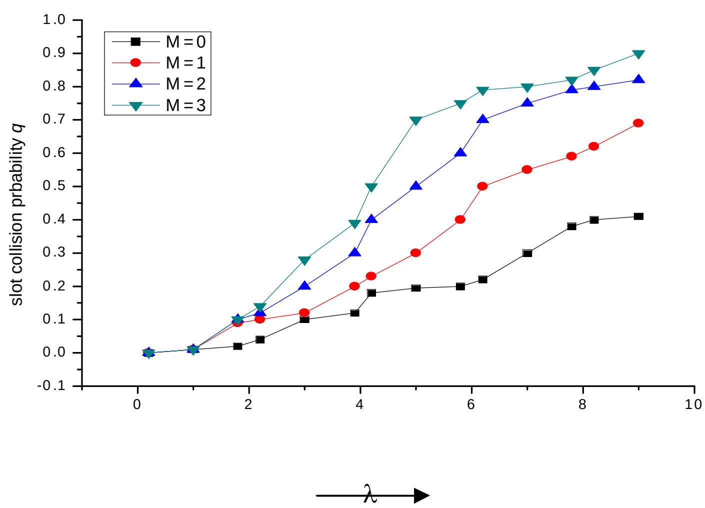

Fig. 8. Slot collision probability versus new arrival rate (N = 7)

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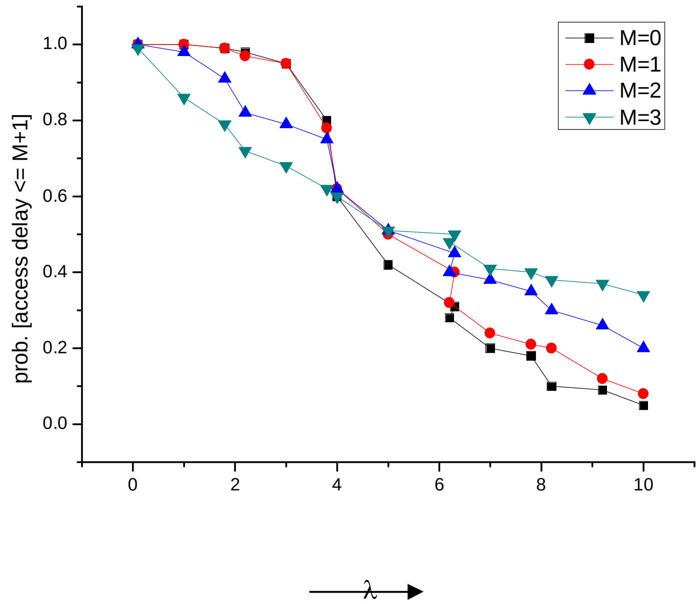

Fig. 9. Prob. [access delay ≤ M + 1] versus new arrival rate (N = 7)

B. Load Adaptivity

For a given N, there exist appropriate operating ranges for λ and M. It is intuitively obvious that if M goes high, the average offered load for a given time interval also increases due to the increased fast retrials.

IV. NUMERICAL RESULTS

A cell has seven channels, and this implies that of seven is the total arrival rate that achieves maximum throughput in the slotted Aloha. We assume that users are distributed uniformly in each cell without mobility. Users in wireless communications experience different channel conditions according to path loss and fading in reality. However, as we focus on the access failure due to the collision only, we assume that the BS receives a random access perfectly if there is no collision. Fig. 5 shows the throughput curve as a function of λ. The case of M=0 corresponds to conventional slotted Aloha. When we increase M, more retrials contribute to the total arrival rate. So, the maximum throughput is obtained at a lower arrival rate. Fig. 6 shows the ratio of λ_T to λ as a function of λ. The higher the value of M, the higher is this ratio because of more retrials. Figs. 7 and 8 show the user collision probability and the slot collision probability, respectively. Although both collision probabilities increase with an increase in M, the throughput performance becomes better under the normal load. Fig. 5 shows the throughput increase with respect to at the light load. This implies that the fast retrial algorithm performs very well in spite of the increased collision probability shown in Fig. 7.

Fig. 9 plots the probability of access delay smaller than slots according to λ. In the conventional Aloha type, each access can be exponentially backlogged over future slots, so the access delay cannot be guaranteed. However, in the fast retrial algorithm, most access trials succeed within slots under a stable loading. Thus, the gap grows as increases, since the number of retrials also increases.

V. CONCLUSION

Several of research has been committed to the study of random access methods such as the slotted Aloha. In satellite communications data is transmitted over random access channels, it is important to lower the collision probability to achieve high throughput at full load for a single channel. In the design of random access schemes fast access becomes especially important. In particular, this is true for multichannel environments like OFDMA systems. In this paper, we developed a fast access algorithm that handles retrials in a system with multiple random access channels. This algorithm retransmits 1-persistently within the allowed maximum number of retrials based on the estimated total arrival rate. The algorithm is derived to take advantage of the structural property of OFDMA systems where multiple channels are available. Thus, instead of retransmissions occurring in time, they occur over a different frequency. Our algorithm operates very well under the stable load condition. For a heavy load, our scheme can work like a conventional competitive scheme.

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Numerical results demonstrate that our algorithm achieves high throughput and low access delay compared to conventional slotted Aloha. Moreover, the operating points can be easily controlled by varying the parameters of our algorithm. This policy is also important from the point of view of initial access because user terminals are expected to use random access channels initially without having detailed channel information about the cell.

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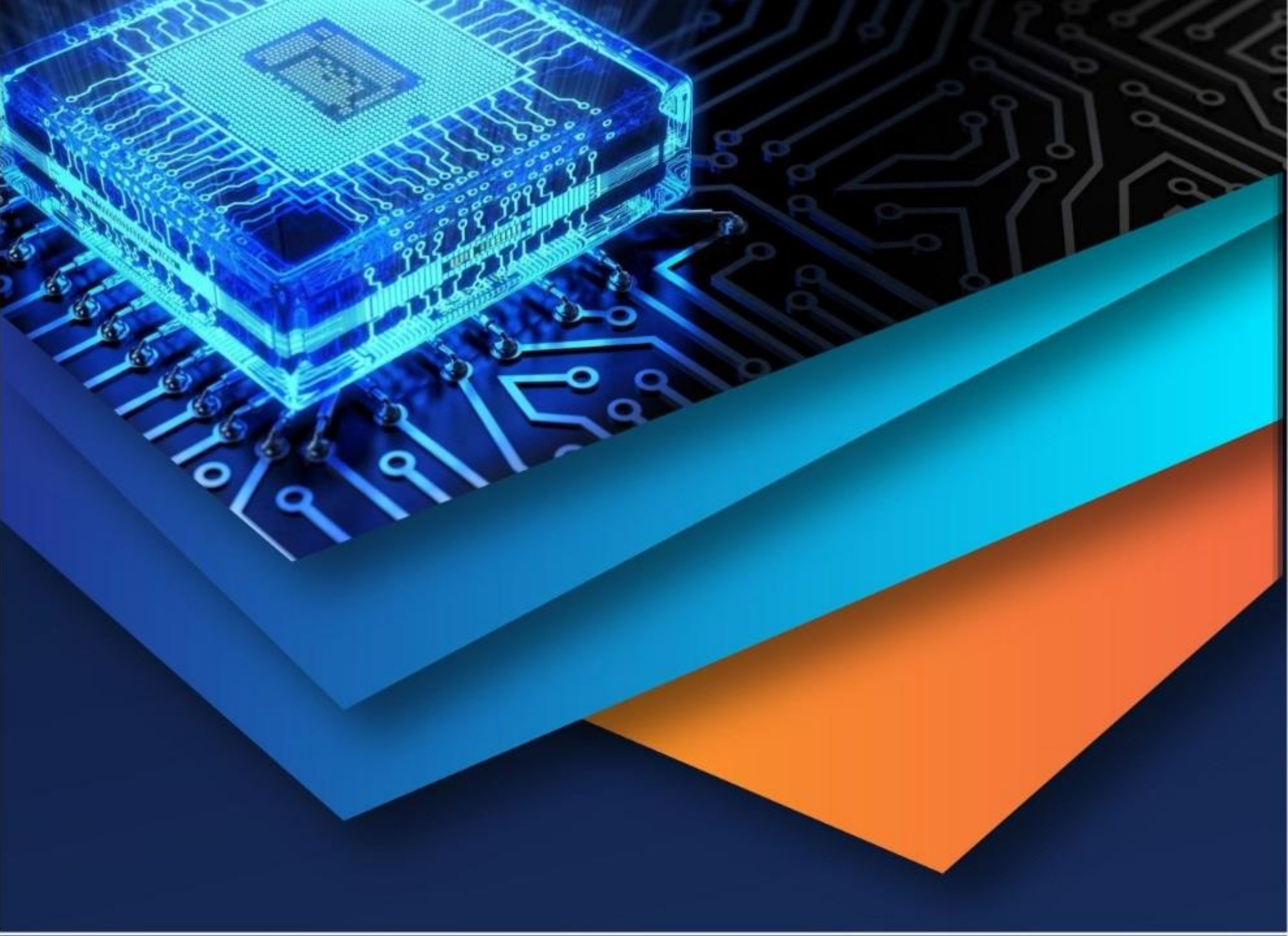

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