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Smart Random Channel Access in OFDM Systems by Joint Signal Processing and Packet Scheduling

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Abstract :

OFDM techniques can be exploited to assist random access contention resolution, which can greatly improve random access efficiency. A cross-layer design method is proposed, where the OFDM-based physical-layer (PHY) signal processing and the MAC-layer packet scheduling are jointly designed and optimized. By this method, contentions can be completely resolved. Not only network throughput can be enhanced, but also more stringent QoS requirement may be supported. With the new cross-layer design method, PHY-layer signal detection can be assisted by the MAC-layer smart scheduling, whereas the latter can also be enhanced by the former. The proposed method represents an innovative approach to improve the performance of random access OFDM wireless networks.

Key words:
OFDM, random access, packet scheduling, contention resolution, cross-layer design

1 Introduction

Data communication systems employ random access to achieve high performance. Many random access protocols are proposed to reduce contention based on statistical traffic models, e.g., slotted ALOHA, CSMA, reservation-based protocols, etc. [1] [2] [3]. However, contentions cannot be completely resolved in these traditional protocols.

In order to further enhance content resolution performance, some more recent approaches are to apply signal processing techniques to deal with collisions [4] [5] where the collided signals are separated if certain conditions can be satisfied. However, those algorithms may be computationally too complex, and may suffer from ill-conditioned channels. And more importantly, QoS can not be guaranteed because collided packets with various priorities have to be resolved together with same priority, which means the loss of priority in fact.

The wide applications of OFDM in packet radios, especially the future 4G cellular systems, make it an important task to investigate how OFDM can benefit both the PHY-layer multi-path mitigation and MAC-layer multi-access.

Though OFDM has been shown effective for simplifying data transmission in multi-path fading environment [6], there is little research in how to utilize OFDM in random access contention resolution, although random access protocols are widely exploited in the above mentioned systems.

In practical OFDM systems, each user may be assigned a deterministic portion of the channel access, either in time slots (e.g., HiperLAN/2) or in sub-carriers (e.g., IEEE802.16 WMAN). The assignment procedure, however, is generally carried out via random access. For example, reservation-based TDMA, a variation of ALOHA protocol, is used in HiperLAN/2 [6]. This scheme is desirable for stream traffics such as voice and video because it can guarantee the required QoS, or packet priority. However, this structure is not efficient enough to accommodate multiple user access with various data rates. As a result, in highly dynamic wireless networks, random access is preferred.

In OFDM random access systems, traditional ALOHA or CSMA protocols are usually directly applied for MAC-

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layer channel access. The property of OFDM signals is not applied for contention resolution. In contrast, we propose in this paper a new method to resolve random access contentions in OFDM random access systems.

We follow the idea of using advanced signal processing techniques to resolve packet collisions [5]. However, considering that collided signal separation in general case is a hard problem [7], and can be solved only in some special cases, such as receiver diversity with satisfactory channel condition, we do not try to separate unknown collided data packets within the PHY-layer only. Instead, we utilize the channel access scheduling to first avoid most data packet collisions, which greatly simplifies the signal separation problem. This is one of the major differences between our method and others.

In other words, the special property of OFDM transmission is utilized to separate collided packets with signal processing techniques implemented in the PHY-layer. When assisted by the packet scheduling capability of the MAC-layer, the difficult signal separation problem becomes much easer, more robust and computationally efficient. On the other hand, the MAC-layer protocol can also take advantage of the information obtained from the PHY-layer. During signal separation, multi-user detection principles [8] are applied to obtain the necessary information to assist MAC-layer scheduling from all the channel access requests. In addition, the scheduling procedure mitigates many practical problems involved with multi-user detection, such as multi-path, near-far, etc.

Note that we do not mean that CDMA is required, but the method is applied to OFDM system with or without spreading. With this approach, OFDM symbols can be distributed to multiple users even without data packet collisions. Furthermore, it is also convenient to guarantee QoS for each user.

The new approach is a joint PHY-layer and MAC-layer design method, where the PHY-layer uses the MAC layer information to performance packet detection and separation, whereas the MAC-layer utilizes the information from the PHY-layer to schedule data packet transmissions. In contrast, traditionally, the random access and scheduling are performed in the MAC-layer with the assumption of a transparent PHY-layer. When packets collide, they are simply retransmitted. Therefore, in case of access contentions, their performance degrades. In our approach, the collision resolution is performed in the PHY-layer, assisted by the MAC-layer. Hence it can be considered as an advantage of wireless channels that the collided signals may be separated, which can be exploited with joint layer designs.

2 Problem Formulation

2.1 Wireless Network Structure

Wireless network has a central controller and multiple unknown mobile users as shown in Fig.1. The central controller can be simply a mobile user, i.e., any mobile user can become the central controller. The required task of the central controller is to schedule random access, although it can also be used to relay data packets from one user to another.

Two structures are shown in Fig.1. The structure in Fig.1 (a) is similar to an infrastructure based system with base stations or access points, e.g., wireless LAN, where all users communicate with the central controller only. In this case, the central controller takes that job of base stations or access points [9] which relays all transmitted data between mobile users.

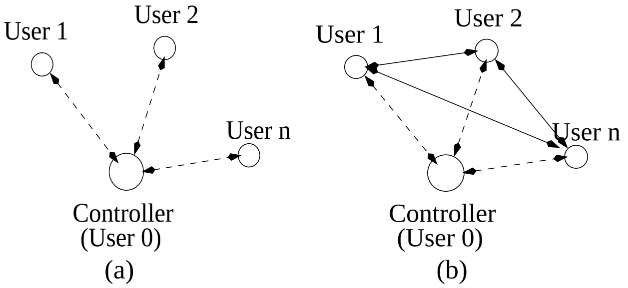
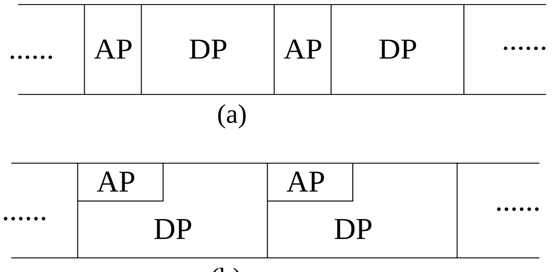


Fig. 1: Wireless network structures.

Another network structure is in Fig.1 (b), where peer-to-peer communication is supported, i.e., each user can communicate directly with all other users. In order to assist random access, one of the users, the user 0 as shown, behaves as a central controller to determine the access priority or slot synchronization. An example is the ad hoc wireless network structure specified in the Bluetooth Specifications [10]. This structure does not require complex and thus expensive central controllers. It is also robust against the system crush caused by the failure of central controllers. In addition, it is more ready to support ad hoc networks with dynamic multi-hop routing [2].

Since the number of mobile users may be known or unknown, random access schemes are required. Slot synchronization can be maintained by the central controller in slotted mode. In the unslotted mode, the central controller monitors transmission. Since the users may be unknown to the central controller, packet collision may happen. Therefore the objective of this paper is to schedule transmission so as to avoid data packet collisions in sloted or unslotted systems. In order to simplify the problem, we assume that the central controller for unslotted mode can successfully detect when the channel is free. However, we do not need such an assumption for slotted mode.



(a)

(b)

Fig.2. Packet flow in OFDM wireless networks.

Each AP or DP may spread across multiple OFDM symbols. The data flow in the proposed system consists of *access request packets* (AP) and *data packets* (DP), as shown in Fig. 10. The APs are used for the users to request channel access from the central controller and for the central controller to assign the access priority. The DPs are the information that mobile users transmit to others. Each AP or DP contains multiple OFDM symbols. Fig.2 (a) shows AP and DP with different OFDM symbols. i.e., AP and DP use different and entire OFDM symbols. In Fig.2 (b) some OFDM symbols are shared by both AP and DP at the same time. Some sub-carriers are used by AP, whereas others are used by DP. Because DPs in wireless system are usually long [9], if the APs are much shorter, then system throughput may not be severely degraded by the overhead of the AP.

When the central controller senses that the channel is free, it broadcasts to all users a beacon asking for access request. Then every active user who holds data packets for transmission sends an AP to the central controller. In OFDM systems, the APs can be transmitted with independent OFDM symbols, or with several sub-carriers of the OFDM symbols. Clearly, collision happens if there is more than one active user. From the received possibly collided signals, the central controller detects all the active users and assigns them the access priority, i.e., informs them to transmit DPs. Therefore, the selected users can transmit DPs *without* collision. This procedure is repeated whenever there are some users hold data packets for transmission. In OFDMA systems such as WMAN, the central controller can also arrange the occupation of sub-carriers for each user.

2.2 OFDM Transmitter and Receiver

The baseband OFDM transmitter and receiver are shown in Fig.3 and Fig.4 respectively. To simplify the system, we assume the signal of the user j is transmitted and received at the moment.

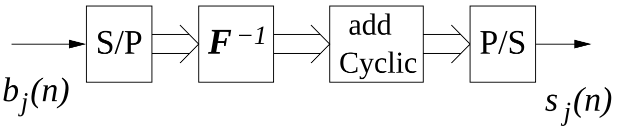


Fig.3 Baseband OFDM transmitter.

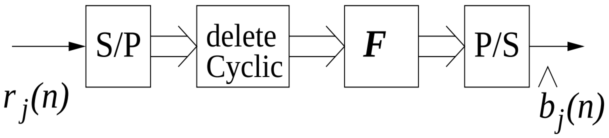


Fig.4 Baseband OFDM receiver.

Suppose the transmitted symbol is $b_j(n)$. The symbol vector $\mathbf{b}_j(n) = [b_j(nN-1), \cdots, b_j(nN-N)]^T$ is first inverse-FFT transformed to obtain

$$\mathbf{u}_j(n) = \mathbf{F}^{-1}\mathbf{b}_j(n) \tag{1}$$

where $\mathbf{F}$ is the discrete Fourier transformation matrix whose $(m,n)^{th}$ element is $e^{j2\pi mn}$ for $0 \le m \le N-1$ and $0 \le n \le N-1$. Then we add cyclic redundancy to the vector $\mathbf{u}_j(n)$ to obtain

$$\tilde{\mathrm{u}}_j(n) = \begin{bmatrix} \mathrm{u}_j(n) \\ u_j(n,0) \\ \vdots \\ u_j(n, L_c-1) \end{bmatrix} \overset{\Delta}{=} \begin{bmatrix} s_j(n(N+L_c)-1) \\ \vdots \\ s_j(n(N+L_c)-N-L_c) \end{bmatrix} \tag{2}$$

where $u_j(n,i)$, $i = 0, \cdots, L_c - 1$ is the $(i+1)$ th entry in the vector $\mathbf{u}_j(n)$ in (1). Then the transmitted signal $s_j(n)$ is simply the elements in the vector $\tilde{\mathbf{u}}_j(n)$.

For the receiver, the received noiseless sample $r_j(n)$ is

$$r_j(n) = \sum_{l=0}^{L_h-1} h_j(l) s_j(n-l-d_j), \tag{3}$$

where the FIR channel of the user j is with length L_h and coefficients $h_j(l)$. Note that $L_h - 1 \le L_c$. Without loss of generality, we can omit the delay d_j, i.e., the mobile users can be synchronized according to the central controller, which is usually the case widely applied in practice. Then we construct the received sample vector as

$$\mathbf{r}_j(n) = \begin{bmatrix} r_j(n(N+L_c)-1) \\ \vdots \\ r_j(n(N+L_c)-N) \end{bmatrix} \tag{4}$$

After the Fourier transformation, we obtain

$$\mathbf{x}_j(n) \overset{\Delta}{=} \begin{bmatrix} x_j(nN-1) \\ \vdots \\ x_j(nN-N) \end{bmatrix} = \mathbf{F}\,\mathbf{r}_j(n) = \mathbf{\Lambda}_j \mathbf{b}_j(n), \tag{5}$$

where

$$\mathbf{\Lambda}_j = \begin{bmatrix} H_j(0) & & \\ & \ddots & \\ & & H_j(N-1) \end{bmatrix}. \tag{6}$$

Then the transmitted symbols can be estimated from (5) by

$$\hat{\mathbf{b}}_j(n) = \mathbf{\Lambda}_j^{-1}\mathbf{x}_j(n), \tag{7}$$

where for simplification we assume that the diagonal matrix $\mathbf{\Lambda}_j$ is non-singular and is known.

As long as the signals from different users are synchronized, the receiver receives signal

$$\mathbf{r}(n) = \sum_{j=1}^{J} \mathbf{r}_j(n) + \mathbf{v}(n) \tag{8}$$

from which OFDM demodulation gives

$$\mathbf{x}(n) = \mathbf{F}\sum_{j=1}^{J} \mathbf{r}_j(n) = \sum_{j=1}^{J} \mathbf{\Lambda}_j \mathbf{b}_j(n) + \mathbf{F}\mathbf{v}(n). \tag{9}$$

Obviously, the receiver cannot detect each $\mathbf{b}_j(n)$ from the mixture $\mathbf{x}(n)$ any more through (7). This is called packet collision. Traditionally, such collision causes the data packet be discarded, and a retransmission be requested. We propose a new way to avoid this problem.

3 Schedule Random Access via OFDM Signal Processing

3.1 Requests for Channel Access

Each user has to request for channel access in a contention manner. In TDMA systems, the request is performed in some random access control channel. In IEEE 802.11 wireless LAN or other random access networks, the request may be performed whenever the user holds data packet for transmission. To simplify the problem, we assume that each active user j transmit as AP a unique access code

$$\mathbf{c}_j = [\,c_j(1), \cdots, c_j(M)\,], \quad j = 0, \cdots, P-1, \tag{10}$$

where the code length is M, and there are at most J codes or users.

There are various ways that the code $\mathbf{c}_j$ can be transmitted within the OFDM transmission. First, they can be transmitted in one of the sub-carriers in the OFDM symbols, as shown in Fig.2 (b). Hence each AP will be across M OFDM symbols. Second, if there are more null sub-carriers, then APs can be transmitted on them. Third, the central controller may designate some slots specifically for APs, where a series of entire OFDM symbols are occupied by APs, as shown in Fig.2 (a).

To simplify the problem, we assume that in the first case, only one sub-carrier is assigned by the central controller as the access request sub-carrier, whereas in the second case the entire OFDM symbol is used.

3.2 Access Request Detection using One Sub-carrier

We consider the case where all APs are transmitted within one sub-carrier. Without loss of generality, it is assumed that the first sub-carrier is used, whereas in practice, the sub-carrier can be selected with time-hopping to overcome the possible deep fading in some carriers. Note that the central controller can determine adaptively the sub-carrier to avoid those with low SNR. We also assume a synchronized transmission. At a time instant n, there are altogether J users requesting channel access. From (5), the baseband signal received at the central controller after FFT processing is

$$\begin{aligned} x(nN-1) &= \sum_{j=0}^{J-1} A_j\, x_j(nN-1) \\ &= \sum_{j=0}^{J-1} A_j\, H_j(0)\, c_j(n) + v(nN-1) \end{aligned} \tag{11}$$

where the indication function $A_j = 1$ means active user and $A_j = 0$ means that the user j is not active. The received samples relative to all the AP code coefficients are

$$\begin{aligned} \mathbf{y}(N) &= [\,x(N-1)\ \cdots x(MN-1)]^T \\ &= \sum_{j=0}^{J-1} A_j \mathbf{H}_j(0)\,[\,c_j(1)\cdots c_j(M)]^T + \tilde{\mathbf{v}}(N) \end{aligned} \tag{12}$$

where $\tilde{\mathbf{v}}(N)^T$ is the noise vector and $\mathbf{H}_j(0)$ is the channel frequency domain coefficient matrix.

Define a $J \times M$ code matrix

$$\mathbf{C}_J = \begin{bmatrix} c_0(1) & \cdots & c_0(M) \\ \vdots & & \vdots \\ c_{J-1}(1) & \cdots & c_{J-1}(M) \end{bmatrix} \tag{13}$$

which contains all the AP codes.

Then, as long as $M \geq P$, we can find codes such that the matrix $\mathbf{C}_P$ is full rank. Therefore, there exist P vectors $\mathbf{g}_j$, $j = 0, \cdots, P-1$ such that

$$\begin{aligned} \mathrm{C}_P \mathrm{g}_j &= [0, \cdots, 0, 1, 0, \cdots, 0] \\ &\triangleq \mathbf{e}_j, \quad j = 0, \cdots, P-1. \end{aligned} \tag{14}$$

In order to detect whether a user k is active or not, we can use the vector $\mathbf{g}_k$ as a detector, whose output is

$$z_k = \mathbf{y}^T(N)\mathbf{g}_k = \tilde{\mathbf{v}}^T(N)\mathbf{g}_k \tag{15}$$

Therefore, we can find a proper threshold value θ_k such that the decisions can be made according to

$$\text{If } |z_k| < \theta_k, \text{ then user } k \text{ is not active}. \tag{16}$$

or

$$\text{If } |z_k| > \theta_k, \text{ then user } k \text{ is active}. \tag{17}$$

From the standard signal detection procedure [11], we can detect whether the user k is requesting for channel access.

3.3 Access Requests Detection Using More Sub-carriers

In some cases, access request packets can be scheduled by the central controller to be transmitted using one or several entire OFDM symbols. In this case, each user j independently OFDM modulate the code $\mathbf{C}_j$ and then transmit it to the central controller. Since OFDM symbols can be synchronized by the central controller, the baseband signal obtained by the central controller is

$$\mathbf{y}(n) = \sum_{j=0}^{J-1} \mathbf{x}_j(n) + \mathbf{w}(n) = \sum_{j=0}^{J-1} \mathbf{H}_j \mathbf{b}_j(n) + \mathbf{w}(n), \tag{18}$$

where $\mathbf{b}_j(n)$ contains $c_j(l)$ as coefficients.

3.4 Channel Access Algorithm

Since the OFDM system allow multiple users to transmit at the same time with different sub-carriers within each OFDM symbol, the access request can be performed at any time. However, for synchronization reason, the access request period begins when the central controller broadcasts an initialization beacon to all users. Each active user j transmits the code $\mathbf{C}_j$, with one or more predetermined sub-carriers in the OFDM symbol. The central controller then detects the active users by the techniques described in sub-chapter 3.2.2. After the detections, the central controller can then schedule the data packet transmission and broadcast the channel access information to all users. This procedure is illustrated in Fig. 10. When all the active users are processed, it broadcasts a new beacon to initialize another access request period.

Because contentions are known before data packet transmission, the central controller can schedule transmission according to their priorities or QoS. Users with higher priorities can be asked to transmit earlier. Hence QoS become feasible in random access OFDM systems.

As a result, packet collision during the access request period can be completely resolved by signal processing. Data packets can be transmitted without collision through scheduling. Therefore, system performance will not be affected by collisions. As long as the request packet size is much smaller than the data packet size, the system can achieve high throughput and low delay.

To summarize, the proposed method for scheduling random access of OFDM networks includes an algorithm for detecting active users and a protocol for scheduling the access request packets and data packets. We first give the detection algorithm which utilizes the information of access request packets and the multi-user detection principles.

The method is robust thanks to the application of OFDM. The detection is performed without the negative effect of multi-path channels since sub-carriers with high noise can be avoided. Most importantly, the codes can be orthogonal to each other, i.e., $\mathbf{c}_i \mathbf{c}_j^T = \delta_{ij}$. The orthogonality can be preserved for detection; hence multiple access interference can be completely eliminated from the decision metrics.

The computational complexity is as low as $O(PM)$ for P users and average $O(M)$ for each user. This algorithm is robust against the near-far problem because it utilizes the multi-user detection principles, i.e., the signals from all other active users are completely canceled from z_j except the desired ones.

4 Simulations

In this section we use simulations to study the performance of the proposed method, and especially, the impact of the access request detection error on the system performance. The detection error depends only on the received signal to noise ratio (SNR). Since SNR is practically available, we can choose the optimal decision threshold 6_k. In this case, the decision error rate (DER) can be optimal.

The measurement is the decision error rate (DER) which is defined as

$$\mathrm{DER} = \frac{\text{total number of wrong decisions}}{\text{total number of decisions}} \qquad (19)$$

Throughput is a measure of the amount of work performed by a system over a period of time. Therefore, we define the throughput as the average number of data symbols successfully transmitted in a symbol interval.

The measurement is the throughput which is defined as

$$\text{Throughput} = \frac{\text{total successful data slots}}{\text{total data slots}} \qquad (20)$$

Similar to the throughput definition, we also define and analyze the packet delay (including data packet transmission time) of the data packets during a transmission period when data packets are contending for transmission. Let the transmission period.

We first investigate the performance of the access request separation. The measurement is the decision error rate (DER) which is defined as eq. (19). Second, we compare the new protocol with the ALOHA-based access reserve protocols in terms of throughput and delay.

We use $M = 50$, $N = 10$, $J = 5$ and Poisson distribution for the number of data packets. The length of the data packet is 2000, which is approximately that of the WLAN standard [9]. The length of access request packet is over-estimated to be 100 to accommodate the possible delays and synchronizations. We performed 100 runs of the algorithms to obtain the average DER, throughput and delay. During each run, we examined 5000 data packet slots. Channels as well as transmission delay were generated randomly for each user during each run. When data packets collided, they requested transmission again during the next transmission period, whereas in ALOHA collided data packets were backed-off an exponential delay before trying retransmission.

First, we study the DER as a function of SNR, where the offered traffic load 1. DER as a function of SNR is shown in Fig. 5, which shows that detection error rate can be sufficiently small. The throughput performance is shown in Fig.6, where we compared the new protocol with slotted ALOHA. It is clearly seen that the new protocol can achieve much higher throughput than ALOHA. The average delay packet delay performance is shown Fig. 7, where we compared new protocol with the slotted ALOHA. Note that for ALOHA we obtained results with the best exponential back-off parameter. It is clearly seen that the new method has better packet delay than the ALOHA.

5 Conclusions

New joint layer design method to improve the performance of random channel access in OFDM systems is proposed. To take advantage of the special property of OFDM signals, physical layer signal processing technique and MAC layer scheduling protocol are used to completely resolve contentions. Besides high throughput, it has another advantage, i.e., supporting QoS scheduling, which will be investigated in the future.

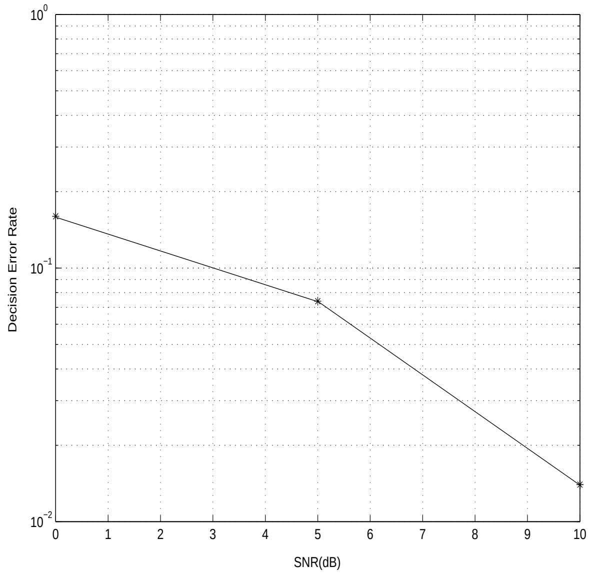


Fig.5 Performance of the access request detection algorithm.

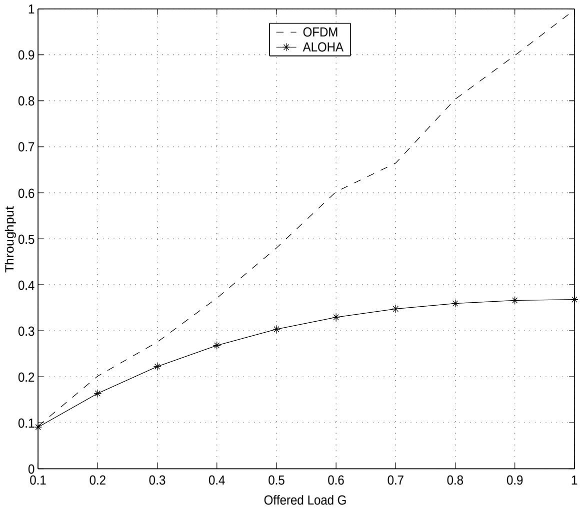


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Fig.6 Performance of the random access protocol in terms of throughput.

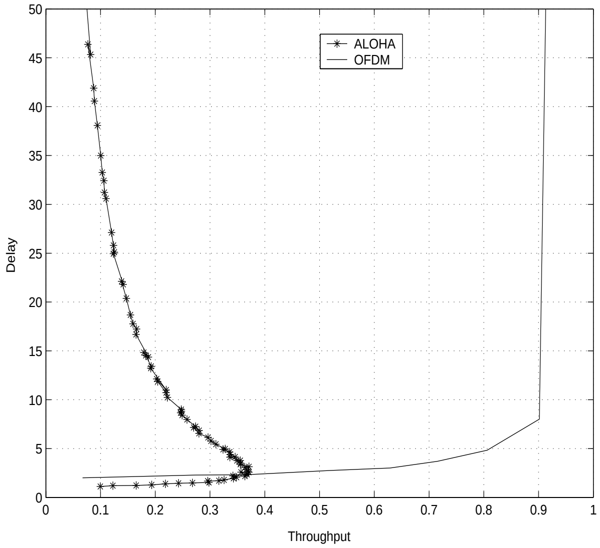

Fig.7 Performance of the random access protocol in terms of delay.

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