Opportunistic Access with Random Subchannel Backoff (OARSB) for OFDMA Uplink

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***Abstract*— A distributed medium access control (MAC) algorithm for uplink OFDMA networks under the IEEE 802.16 framework is proposed and analyzed in this work. We present a simple yet efficient algorithm to enhance the system throughput by integrating opportunistic medium access and collision resolution through random subchannel backoff. Consequently, the resulting algorithm is called the opportunistic access with random subchannel backoff (OARSB) scheme. OARSB not only achieves distributed coordination among users but also reduces the amount of information exchange between the base station and users. The throughput and delay performance analysis of OARSB is conducted using a Markov chain model. The superior performance of OARSB over an existing scheme is demonstrated by analysis as well as computer simulation.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is a physical-layer technology adopted by the IEEE 802.16e standard [1] to support broadband wireless access. One of the main characteristics of OFDMA is that it allows multiple users to transmit simultaneously on orthogonal subcarriers in both downlink and uplink transmissions. In the downlink direction, which is a point-to-multipoint communication, the base station (BS) allocates the channel to users through scheduling. On the other hand, in the uplink direction, the multiple access nature demands not only communications between users and the BS but also coordination among independent users.

Coordination among users in OFDMA uplink may be done in two different ways, *i.e.* a centralized scheme or a distributed scheme. An arbitrator takes full charge of channel allocation by scheduling users in the centralized approach. In contrast, in the distributed scheme users share subchannels in a random access fashion, which is then assisted by a collision-avoidance mechanism. In particular, users operate and coordinate themselves according to short feedback messages (*e.g.,* ACK or NACK) received from the BS indicating the status (*e.g.,* success or collision) of previous requests. The main advantage of a distributed scheme is its simplicity since little information exchange is required between BS and users. For this reason, distributed channel allocation is appealing for uplink OFDMA, and it has been adopted by the 802.16e standard as an option for the uplink bandwidth request [1].

Distributed access in OFDMA networks has been studied in previous work, *e.g.* [2]–[4]. In the scheme proposed by Wang *et al.* in [2], each user determines the quality of its subchannels by a common set of centrally-optimized thresholds and sends requests of transmission in a way that allows better subchannels to "win" more likely during the contention period. If two or more request messages collide, the corresponding subchannel is not used. An opportunistic multichannel Aloha was proposed by Bai and Zhang in [3], where each user contend for a set of its subchannels that is above a certain threshold and, if the request message collides, the collided subchannels are not used. In other words, collision resolution was not considered. Choi *et al.* [4] proposed a fast retrial method where collided users, rather than procrastinate for a random time, switch immediately to a random frequency band so that collision may be resolved in the frequency domain. However, opportunistic allocation was not studied in [4].

Being motivated by [4], we consider a frequency-domain collision resolution mechanism but in the context of opportunistic access in this work. A simple yet efficient algorithm is proposed to enhance the system throughput by integrating opportunistic medium access and collision resolution through random subchannel backoff. Consequently, it is called the opportunistic access with random subchannel backoff (OARSB) scheme. The proposed OARSB scheme is a purely distributed uplink scheme with no common thresholds employed. By leveraging the multiuser diversity and resolving collisions efficiently, OARSB not only achieves distributed coordination among users but also reduces the amount of information exchange between the base station and users.

II. System Model

The frame structure of a time-division duplex (TDD)-OFDMA scheme defined in IEEE 802.16e [1] is depicted in Fig. 1, which shows the time-frequency resource planning for both uplink and downlink communications. In the uplink section, a ranging subchannel is reserved for the purpose of either synchronization between users and the BS (*i.e.,* ranging) or requests of sending uplink data from users to the BS (*i.e.,* the uplink bandwidth request).

The uplink bandwidth request is of our main interest in this work. It may be done in two different ways: polling-based (centralized) or contention-based (distributed). In the polling scheme, the BS polls each user alternately for its intent to transmit, which is suitable for the rtPS service [5]. In the contention scheme, users contend for the transmission

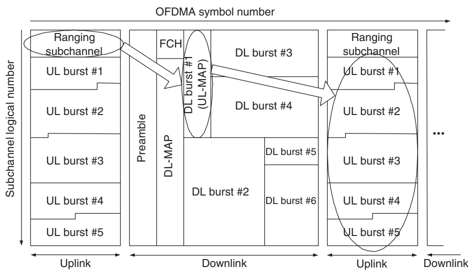

Fig. 1. TDD-OFDMA frame structure in IEEE 802.16e [1].

opportunity via random access, which is suitable for the nrtPS service [5]. Regardless of the scheme adopted, the bandwidth request process is completed in the uplink section, and results are broadcasted to users through the UL-MAP messages in the downlink. Then, users will use the uplink subchannels according to the assignment information in UL-MAP as shown in Fig. 1.

We consider the contention-based uplink channel allocation in this work, which is a distributed scheme by nature. The medium access is performed on ranging subchannels. The available subchannels are divided into logical subgroups that correspond one-to-one to the remaining uplink data subchannels. Thus, a user who plans to use a particular data subchannel will contend for its usage on the corresponding ranging subchannels. Note that a subchannel (SC) is a clustering of serveral adjacent subcarriers [6].

III. Proposed OARSB Scheme

The distributed uplink channel allocation for OFDMA may be performed using the slotted Aloha scheme [3] due to the slotted structure of OFDMA. A collision resolution policy may also be incorporated to regulate the packet retransmission as well as enhance the throughput. Thanks to the multiband structure of OFDMA, a fast collision resolution scheme can be performed in the frequency domain as well [4]. That is, collided packets "backoff" to *random* subchannels in the immediate next time slot instead of waiting for a certain number of time slots for retransmission. Since the waiting time is greatly reduced, this method is also called "fast retrials" [4]. We call it the opportunistic access with random subchannel backoff (OARSB) scheme in this work. Due to fading in a wireless environment, backoff to a subchannel in deep fade is not desirable. In other words, subchannel gains of each user should be taken into account in the backoff decision. Hence, the proposed OARSB not only resolves the collision in the frequency domain but also exploits multiuser diversity, since subchannel gains tend to vary from one user to the other.

The proposed OARSB algorithm can be described in detail as follows. Suppose that we have K contending users and a total of M uplink data subchannels. Each user is allowed to request (contend) L subchannels, where $L \leq M$. With knowledge of its own channel (but no others), each user can rank its subchannels in the descending order of channel gains and request for its best L subchannels initially (See Fig. 2(a)

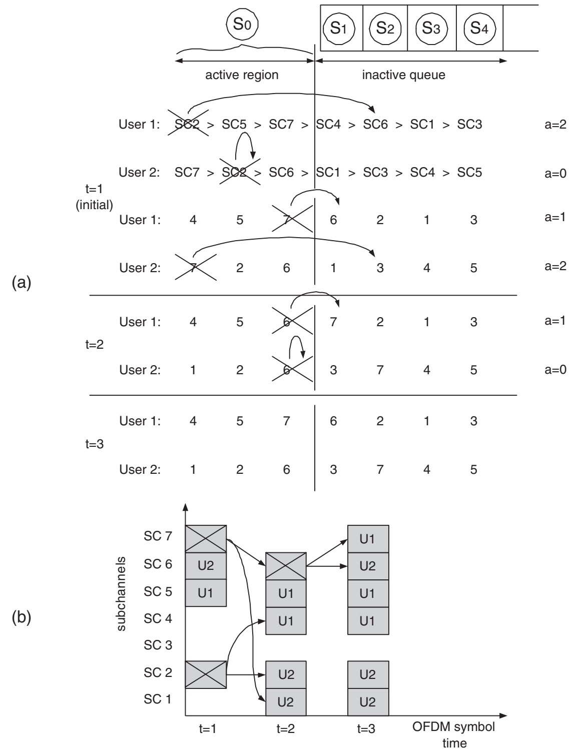

Fig. 2. An example of the proposed OARSB scheme.

for the case of $K = 2$, $M = 7$ and $L = 3$). The subchannels currently in request are called active, while the rest are inactive and queued. Thus, each user has L subchannels in the active region and $M - L$ subchannels in the inactive queue during the negotiation. The active region is denoted by S_0 while each position in the inactive queue is represented by S_i, $i = 1, \ldots, M - L$, as shown in Fig. 2(a).

The frequency-domain backoff collision resolution is realized in the following way. We assume that users know the feedback messages (success or collision) within one time slot. Upon collision (*i.e.,* two or more users request for the same subchannel), the collided subchannel is "backoffed" to the inactive queue in a random position S_a, which is determined by a random number, a, chosen uniformly and independently from $[0, W-1]$, where W is the backoff window size. All the subchannels in original $S_1, \cdots, S_a$ positions will be shifted one position toward the active region, and the front one will become active to substitute for this collided subchannel. For example, with $W = 3$ in Fig. 2(a), the collided SC 2 of user 1 is assigned $a = 2$ at $t = 1$ and thus backoffed to position S_2 at $t = 2$. Besides, the front one of the inactive queue, SC 4, becomes active to replace SC 2. Note that if $a = 0$, the collided subchannel will "backoff" to S_0, *i.e.,* remain active. For example, user 2's SC 2 from $t = 1$ to $t = 2$ in Fig. 2(a).

When multiple collisions happen, the same process will be performed for each collided subchannel sequentially, as seen in $t = 1$ of the example. The step-by-step backoff process is shown in Fig. 2(a) and its corresponding "subchannel

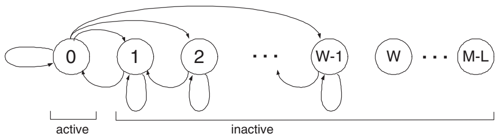

Fig. 3. The Markov chain description of the behavior of SC m of user k.

switching" is shown in Fig. 2(b). It is worthwhile to point out that one major difference between the proposed OARSB algorithm and fast retrials in [4] is that OARSB switches to *good* subchannels instead of *random* subchannels. This is realized by a frequency-domain backoff design where collided good subchannels are not discarded but retained for possible future retrials. With help of randomness, the backoff design also reduces the likelihood of re-collision.

IV. Delay and Throughput Analysis

The delay (due to collision resolution) and throughput for the proposed OARSB scheme are analyzed in this section. Understanding the delay and throughput helps in choosing proper parameters for the algorithm given the ranging period length and throughput requirements. To facilitate the analysis, we make the following three assumptions.

A1) Channel fading is independent across subchannels and users, *i.e.,* subchannel gains are i.i.d. for all users. This is achievable if the subchannel bandwidth is bigger than the coherence bandwidth, and users act independently.

A2) For a particular time t, subchannels of users are equally likely to be active, *i.e.,*

$$\begin{aligned} \tau_{k,m}(t) &= Pr\{\text{SC } m \text{ of user } k \text{ is active at time } t\} \\ &\triangleq \tau, \quad k=1,\ldots,K, m=1,\ldots,M. \end{aligned} \tag{1}$$

Furthermore, the state of activeness is independent across subchannels and users.

A3) The timeline of the ranging period is partitioned into initial ($t=1$) and backoff ($t=2,3,\ldots$) two stages. For the initial stage, we can obtain explicitly

$$\tau_{k,m}(1) \triangleq \tau_1 = L/M, \quad \text{for all } k,\ m. \tag{2}$$

For the backoff stage, we assume the probability values remain constant over time. Thus, along with assumption A2 we have

$$\tau_{k,m}(t) \triangleq \tau, \quad \text{for all } k,\ m \text{ and } t \geq 2, \tag{3}$$

where τ will be derived in Sec. IV-A.

A. Markov Chain Model

We use a Markov chain model to describe the transition dynamics of a subchannel, through which we can obtain steady state probabilities and transition probabilities that will be used in the analysis given in Secs. IV-B and IV-C.

The dynamic of a particular subchannel, m, of a particular user, k, of the proposed OARSB is depicted in Fig. 3, where state i corresponds to position S_i in Fig. 2(a). We drop "S" for notational convenience. The transitions shown in Fig. 3 have ruled out less likely transitions for the sake of analytical tractability. For example, the transition from state $W-1$ to 0 implies at least $W-1$ SCs in the active region of this user collide, which is unlikely to happen. For this reason, backward transitions only occur in adjacent states. Besides, if a subchannel falls initially in states $W,\cdots,M-L$, it will stay in the same state due to our algorithm.

Let q_m be the probability that an active SC m sees no collision. By the assumption of independent subchannels and users and the fact that an active SC m sees no collision when the rest $K-1$ SC m's are all inactive, we have

$$q_m = q = (1-\tau)^{K-1}. \tag{4}$$

Let $A(t)$ represent the state at time t. Then, the transition probabilities are defined by

$$P_{i,j} = Pr[A(t+1)=j|A(t)=i],\ i,j=0,\ldots,W-1. \tag{5}$$

In the following, we will obtain all non-zero transitions in Fig. 3 in terms of q. First, we look at the self transition of state 0, which is the probability that an active SC at time t remains active at time $t+1$. This may occur in two possible cases; namely, this SC does not collide or it collides but backoffs to the active region again (*i.e.,* when $a=0$). Since a takes on value 0 with probability $1/W$, we have

$$P_{0,0} = q + (1-q)\frac{1}{W}. \tag{6}$$

The outgoing transitions from state 0 to state i correspond to the case where this SC collides and backoffs to state i (*i.e.,* when $a=i$). As a result, we have

$$P_{0,i} = (1-q)\frac{1}{W},\ i=1,\ldots,W-1. \tag{7}$$

Then, we derive the transitions for the remaining states. The self transitions of state i, $i=1,\ldots,W-1$, may occur in two possible ways: no collisions in user k's active region (of size L), or l collisions, $1\leq l\leq L$, which all backoff to positions in front of state i. By summing these two cases, we have

$$P_{i,i} = q^L + \sum_{l=1}^{L}\binom{L}{l}(1-q)^l q^{L-l}(\frac{i}{W})^l,\ i=1,\ldots,W-1. \tag{8}$$

The outgoing transition probabilities are simply one minus the self transition probabilities, *i.e.,*

$$P_{i,i-1} = 1-P_{i,i},\ i=1,\ldots,W-1. \tag{9}$$

Let $\mathbf{P}$ denote the transition matrix of this Markov chain model with $P_{i,j}$ as the (i,j) entry, and $\boldsymbol{\pi}=(\pi_0,\pi_1,\cdots,\pi_{W-1})$ be the steady-state probabilities. Then, $\boldsymbol{\pi}$ can be uniquely obtained by solving the following equations:

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P}, \quad \text{and} \quad \sum_{i=0}^{W-1}\pi_i = \frac{L+W-1}{M}. \tag{10}$$

By the definition of τ in (1), we have

$$\tau = \pi_0. \tag{11}$$

Note that τ in (11) is a function of q (because $\mathbf{P}$ is a function of q), and q in (4) is a function of τ. This nonlinear system can be solved using numerical methods and can be shown to have an unique solution set.

B. Delay Analysis

The delay is defined as the time it takes for the collision to resolve, *i.e.*

$$d \triangleq \{t_d \mid \text{collision is resolved at time } t = t_d\}. \quad (12)$$

For example, we have $d = 3$ in Fig. 2. In general, we have $d = 1, 2, \ldots, D$, where D is the maximum allowed delay, which can be viewed as the finite length of the ranging period. If the collision is not resolved at the end of the ranging period, we set $d = D$. If no initial collision occurs so that no collision resolution takes place, we have $d = 1$. For the special case of no collision resolution scheme as that given in [3], we get $d = 1$ always.

Let P_{c0} be the initial collision probability (*i.e.,* collision occurs at $t = 1$), and P_c be the collision probability for all subsequent time slots (*i.e.,* collision occurs at $t = 2, 3, \ldots$) with assumption A3. Note that the delay is equal to n if collision occurs in consecutive time slots $t = 1, \ldots, n-1$ and resolves at $t = n$. Thus, we obtain

$$Pr\{d = n\} = \begin{cases} 1 - P_{c0}, & n = 1, \\ P_{c0}P_c^{n-2}(1 - P_c), & 1 < n < D, \\ \sum_{i=D}^{\infty} P_{c0}P_c^{i-2}(1 - P_c), & n = D. \end{cases} \quad (13)$$

The expected delay can be calculated as

$$E[d] = 1 - P_{c0} + P_{c0}\big[2 + \frac{P_c(1 - P_c^{D-2})}{1 - P_c}\big]. \quad (14)$$

The value of P_{c0} can be obtained as follows. We first observe that "no initial collision" is equivalent to "all active SCs are successful at $t = 1$". An SC m is successful if one and only one SC m is active. With the independent assumption across subchannels and users, the probability of no initial collision is the number of permutations that involve no duplicate subchannels in the active region divided by the number of total possible permutations. This yields

$$P_{c0} = \begin{cases} 1 - \frac{M(M-1)\cdots(M-LK+1)}{(M(M-1)\cdots(M-L+1))^K}, & \text{if } LK \leq M, \\ 1, & \text{else,} \end{cases} \quad (15)$$

where we use the fact that, when $LK > M$, at least one SC appears in the active region more than once.

The value of P_c may be approximated with assumptions A2–A3. Note that the probability of no collision, $1 - P_c$, is equal to the probability that all active SCs see no collision. Let us first consider a particular user k. The probability that an active SC of user k sees no collision is $(1-\tau)^{K-1}$, *i.e.,* when none of the remaining $K - 1$ same SC's is active. This probability applies to user k's all L active SCs. Then, we examine another user $k' \neq k$. Its active SC sees no collision with probability $(1-\tau)^{K-2}$, *i.e.,* with one less interfering user. This yields

$$P_c = 1 - \big[(1-\tau)(1-\tau)^2 \cdots (1-\tau)^{K-1}\big]^L. \quad (16)$$

Note that replacing τ by τ_1 in (16) gives an approximation to the exact P_{c0} in (15). Finally, substituting (15) and (16) in (14) yields the analytical delay result.

C. Throughput Analysis

The throughput T is defined as the total information rate (in bits/sec) supported by all successful subchannels at the end of collision resolution, *i.e.,* at $t = d$. We are interested in finding the average number of successful subchannels, $E[N]$, and the average supportable information rate of each successful subchannel, $E[R]$. Then, with these two, the average throughput is given by [3]: $E[T] = E[N] \cdot E[R]$.

The average number of successful subchannels, $E[N]$, can be derived as follows. We define

$$\rho_m(t) = Pr[\text{SC } m \text{ is successful at time } t] = \rho(t). \quad (17)$$

This leads to $E[N] = M \cdot E[\rho(d)]$, where the expectation is taken over d based on (13). To obtain $\rho(d)$, we observe that the OARSB scheme relies on the interaction between users to resolve collision effectively. In other words, all K SC m's should be considered jointly. Besides, the OARSB scheme operates sequentially to create inter-dependence between times $t+1$ and t in terms of an SC being successful or not. As a result, $\rho(t+1)$ and $\rho(t)$ are dependent. In light of these two observations, we resort to a Markov chain that jointly considers K users and traces all the history up to $t = d$ (such as steps shown in Fig. 2(a)). For a particular SC m, this Markov chain has three possible states: successful (denoted by state S); unsuccessful when no SC m is active (denoted by state U_0); and unsuccessful when two or more SC m's are active (denoted by state U_2).

The transition probability $Q_{i,j}$ is defined as

$$Q_{i,j} = Pr[B(t+1) = j|B(t) = i], \; i, j = S, U_2, U_0, \quad (18)$$

where $B(t)$ represents the state at time t. We can derive all $Q_{i,j}$ by scrutinizing the interaction between subchannels of all K users. First, we examine state S. Since an active subchannel will become inactive only upon collision, a successful subchannel can either remain successful (S) or collide with others (U_2). Thus, $Q_{S,U_0} = 0$. To obtain Q_{S,U_2}, we use the fact that the transition from S to U_2 takes place when at least one of the $K - 1$ inactive SC m's become active, *i.e.,* from state 1 to 0 in Fig. 3. This leads to

$$Q_{S,U_2} = \frac{Pr[B(t+1) = U_2 \text{ and } B(t) = S]}{Pr[B(t) = S]} = \frac{\sum_{j=1}^{K-1} K\tau\binom{K-1}{j}\pi_1^j(1-\tau-\pi_1)^{K-1-j}\big[1 - P_{1,1}^j\big]}{K\tau(1-\tau)^{K-1}}.$$

Since the sum of transition probabilities of a state is equal to one, we have $Q_{S,S} = 1 - Q_{S,U_2}$. The same analysis applies to states U_0 and U_2. The results are however omitted here due to space. Interested readers are referred to [7].

Let $\mathbf{Q}$ be the transition probability matrix, *i.e.,*

$$\mathbf{Q} = \begin{bmatrix} Q_{S,S} & Q_{S,U_2} & Q_{S,U_0} \\ Q_{U_2,S} & Q_{U_2,U_2} & Q_{U_2,U_0} \\ Q_{U_0,S} & Q_{U_0,U_2} & Q_{U_0,U_0} \end{bmatrix}.$$

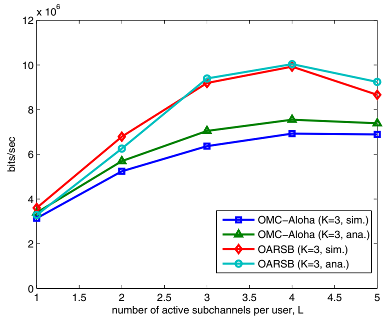

Fig. 4. Throughput vs. the number of active subchannels per user, L, for OARSB and the scheme proposed in [3], with $K = 3$, $M = 15$ and $W = 3$.

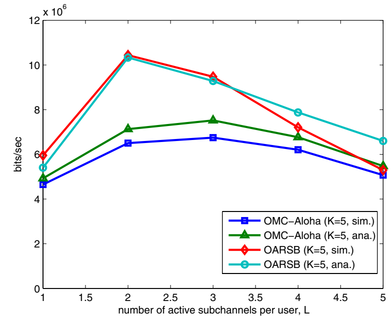

Fig. 5. Throughput vs. the number of active subchannels per user, L, for OARSB and the scheme proposed in [3], with $K = 5$, $M = 15$ and $W = 3$.

Then, $\rho(d)$ can be obtained as the first element of $\boldsymbol{\alpha}\mathbf{Q}^{d-1}$, where $\boldsymbol{\alpha} = (\alpha_S, \alpha_{U_2}, \alpha_{U_0})$ is the initial state probability vector with $\alpha_S = K\tau_1(1-\tau_1)^{K-1}$, $\alpha_{U_0} = (1-\tau_1)^K$, and $\alpha_{U_2} = 1 - \alpha_S - \alpha_{U_0}$. Note that the scheme in [3] is a special case of the proposed OARSB with $\rho(1) = K\tau_1(1-\tau_1)^{K-1}$ and $E[N] = M \cdot \rho(1)$.

Now, we are ready derive $E[R]$ to complete the throughput analysis. The average rate of each successful subchannel is the average rate of all potentially successful subchannels, *i.e.,* the best $L+W-1$ subchannels of each user (Fig. 3). Furthermore, the SNR of the i-th best subchannel follows the probability distribution function (pdf) of the i-th largest exponential order statistics for the Rayleigh fading channel. With a discrete adaptive modulation scheme and given pdfs, the average rate of i-th best subchannel, r_i, can be easily obtained. Thus, we have $E[R] = \frac{1}{L+W-1}\sum_{i=1}^{L+W-1} r_i$.

V. Simulation Results

Computer simulation is performed in this section to demonstrate the performance of the proposed OARSB scheme and verify the analysis given in Sec. IV numerically. An OFDMA system is implemented with parameters specified in [8]. We choose an FFT size of 512, which is divided into 16 subchannels, each of which has 32 subcarriers. One subchannel is dedicated for the ranging purpose; thus, we have $M = 15$ data subchannels for contention. The Rayleigh fading channel is adopted in the simulation and its parameters are chosen such that the assumption A1 in Sec. IV is met. We assume $\text{BER} = 10^{-3}$ and $\text{SNR} = 16$ dB.

The throughput performance of the proposed OARSB scheme is shown in Figs. 4 and 5 for $K = 3$ and 5, respectively, with the OMC-Aloha scheme [3] as the performance benchmark. Both schemes allow an equal number of requested (active) subchannels, L, from each user for fair comparison. $W = 3$ is considered for the OARSB scheme. We see that the adoption of subchannel backoff scheme in OARSB for collision resolution greatly improves the throughput. Besides, the best throughput is achieved at around $L = M/K$ or $M/K - 1$, the best compromise between channel utilization and subchannel collision. Furthermore, the analytical and simulation results agree well. This confirms the use of steady-state approximation in (11) and independence assumptions of A1–A3 in the analytical derivation.

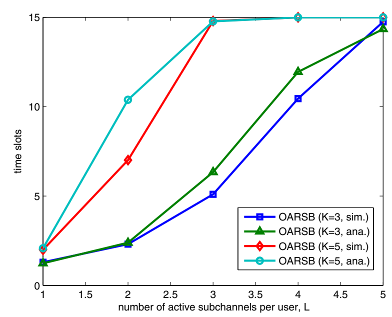

Fig. 6. The collision resolution delay vs. the number of active subchannels per user, L, with $M = 15$, $K = 3$ or 5, and $W = 3$.

The collision resolution delay for OARSB is shown in Fig. 6. Generally, bigger L or bigger K will incur bigger delay, due to more contending subchannels or users in place. Note that we set the maximum allowable delay (*i.e.,* the ranging period length), D, to 15. Thus, in cases where the collision tends to persist after the ranging period (typically for $L > M/K$), the delay is $D = 15$.

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