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Multichannel Outage-aware MAC Protocols for Wireless Networks

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***Abstract*—Channel outage is a concept to reflect channel fading and interference into an efficient design of medium access control (MAC) protocols. Since each user may experience different fading and interference (i.e., channel outage) over distinct channels, throughput may vary depending on channel selection of users. In this paper, we propose two types of multichannel outage-aware MAC protocols to improve throughput: 1) frequency-domain backoff MAC protocols with outage-aware refined channel sets using distributed channel selection, and 2) time-domain backoff MAC protocols with a lowest-outage increasing heuristic using centralised channel allocation to find optimal user sets. Simulation results show the impacts of the proposed MAC protocols on throughput under multichannel outage environments with respect to various user numbers.**

***Index Terms*—Multichannel MAC protocols, channel outage, frequency-domain backoff, time-domain backoff**

I. Introduction

Current wireless standards support multiple non-overlapping channels for wireless communication; IEEE 802.11a [1] and IEEE 802.15.3 [2] provide 12 and 13 non-overlapping channels, respectively. Simultaneous usage of the multiple non-overlapping channels can improve channel capacity in which packets can be transmitted simultaneously over the distinct channels. However, conventional medium access control (MAC) protocols that are designed for a single channel cannot fully utilise the available multiple channels.

In order to improve throughput by accessing multiple non-overlapping channels, several multichannel MAC protocols have been proposed [3], [4], [5], [6], [7], [8]. There are CSMA-type and Aloha-type multichannel MAC protocols. The CSMA-type protocols [3], [4] are designed for wireless local area networks (WLANs) or ad hoc networks that use unlicensed bands. On the other hand, mainly due to channel efficiency, the Aloha-type protocols [5], [6], [7], [8] are applied for uplink access in cellular networks that use licensed bands. In this paper, we consider the Aloha-type protocols for uplinks in multichannel wireless networks that can handle initial access, bursty traffic, and short packets.

Channel outage is a concept to reflect channel *fading* and *interference* into an efficient design of medium access control (MAC) protocols. Since channel fading and interference (i.e., channel outage) may cause impairment of wireless signal, the performance of wireless communications may be degraded [9]. Under multichannel environments, channel outage becomes more crucial for system performance. Since each user may experience different channel outage on distinct channels due to various channel fading and interference, throughput may vary depending on channel selection of users. Thus, proper channel selection over the channels can improve throughput. However, the existing multichannel MAC protocols do not take into account channel outage effects when selecting a channel.

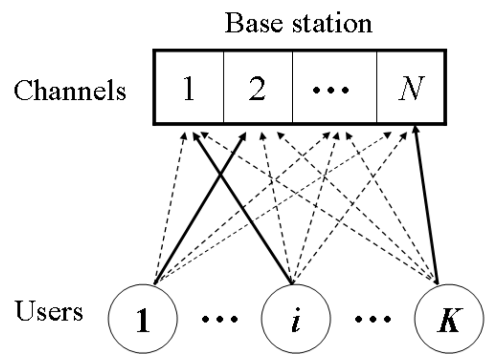


Fig. 1. The multichannel uplink system with N channels and K users. The solid lines indicate selected channels and the dotted lines are available channels.

In this paper, we propose multichannel outage-aware MAC protocols in terms of frequency-domain backoff and time-domain backoff schemes. The frequency-domain backoff MAC protocols use outage-aware refined channel sets for distributed channel selection based on the fast retrial random access [5]. On the other hand, the time-domain backoff MAC protocols adopt a lowest-outage increasing heuristic for centralised channel allocation to find optimal user sets with slotted Aloha and persistence slotted Aloha. The impacts of the proposed MAC protocols on throughput are investigated under the multichannel outage environments with respect to various user numbers.

II. System Model

In this section, we present the system model when multichannels are available with various channel outage probabilities.

Suppose N (orthogonal) channels are available for uplink access to a base station in a wireless network where there are K users as shown in Fig. 1. Note that multiple packets transmitted over the multiple channels can be simultaneously received when the base station is equipped with multiple antennas. Let $\mathcal{K} = \{1, 2, ..., K\}$ denote the index set for all the users and $\mathcal{N} = \{1, 2, ..., N\}$ denote the index set of all the multiple channels. Denote by $p_{n,i}$ the transmission probability of user $i \in \mathcal{K}$ over channel $n \in \mathcal{N}$ in a slot time. Let $\mathcal{M}_n$ denote the set of users who access channel $n \in \mathcal{N}$. To take into account fading and interference, we assume that each user experiences different channel outage according to each channel condition. Let $q_{n,i}$ denote the channel outage probability of user $i \in \mathcal{K}$ when accessing channel $n \in \mathcal{N}$ and $\mathcal{Q} = (q_{n,i})_{N \times K}$ denote the set of all the channel outage probabilities of all the users. Each user may experience transmission failure with a certain probability (i.e., $q_{n,i}$, $n \in \mathcal{N}$ and $i \in \mathcal{K}$) depending on fading and interference.

A. Slotted Aloha

The slotted Aloha has been adopted by existing systems such as second-generation (2G) and third-generation (3G) systems for random access because of its simplicity in implementation. The slotted Aloha transmits packets in discrete timeslots with specified beginning and ending times [9]. As the random access strategy of the slotted Aloha, each user selects its transmission probability randomly and transmits a packet if the selected transmission probability is less than the maximum transmission probability p^{max} which is fixed and the same value among users.

B. Persistence slotted Aloha

In order to resolve contention in accessing a channel in slotted Aloha, persistence slotted Aloha uses an update algorithm as a persistence-probability-based scheme. The update algorithm is described as follows: Each user has own persistence probability $p_{n,i}(t)$ at slot time t in which the maximum persistence probability p^{max} is assigned at $t = 0$. When the user experiences a collision, the own persistence probability is reduced by a factor β ($0 < \beta < 1$). The number of retransmission due to the collision, denoted by α, is limited up to the maximum retransmission number m. If α reaches m, no reduced factor is applied for the update procedure. After the successful transmission, the persistence probability is set to p^{max}. Otherwise, the user uses the same persistence probability (i.e., idle case). This update procedure can be written as

$$p_{n,i}(t+1) = \min\{p^{max}, p_{n,i}(t)I_{z=0}+p^{max}I_{z=1}+p_{n,i}(t)\beta I_{z=2}\}, \tag{1}$$

where I_z denotes the indication function of which value is 1 if the event z occurs; otherwise it is 0. The events of $z = 0$, $z = 1$, and $z = 2$ are the events of idle, successful transmission, and collision, respectively.

III. The proposed outage-aware MAC protocols

This section presents two types of multichannel outage-aware MAC protocols: frequency-domain backoff schemes with distributed channel selection, and time-domain backoff schemes with centralised channel allocation.

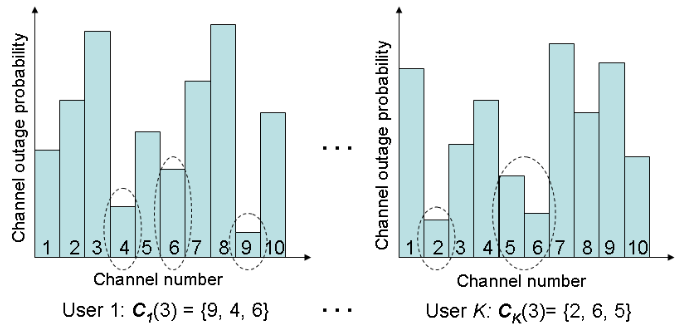


Fig. 2. The refined channel sets of K users for random channel selection with 10 total available channels ($N = 10$) and 3 lowest-outage channels ($h = 3$). The dotted ellipses indicate the selected channels for the refined channel sets.

A. The outage-aware frequency-domain backoff

The outage-aware frequency-domain backoff (OFB) MAC protocols use outage-aware refined channel sets for random access. In order to resolve transmission failure due to collision or outage effects, the protocols adopt the fast retrial algorithm using the slotted Aloha and the persistence slotted Aloha.

1) The outage-aware refined channel sets: Conventionally, existing multichannel MAC protocols such as in [5] and [8] use a random channel selection among all channels (i.e., N channels) and take into no account of various channel outage probabilities for the channel selection. In the proposed channel selection procedure, we consider a refined channel set for random selection to increase throughput. The refined channel set is now defined.

Let C_i denote the order statistic set of channels of user $i \in \mathcal{K}$ in terms of the increasing channel outage probability. Let $o_{i,(t)}$ denote the channel number of user i of the tth increasing order of channel outage probability. Thus, C_i can be written as $C_i = \{o_{i,(1)}, o_{i,(2)}, ..., o_{i,(N)}\}$. Instead of random channel selection among all N channels, a base station selects a refined set with h lowest-outage channels for user i, denoted by $C_i(h)$. Then, user i selects a random channel in $C_i(h) = \{o_{i,(1)}, o_{i,(2)}, ..., o_{i,(h)}\}$.

Fig. 2 shows the refined channel sets of K users for random channel selection when $N = 10$ and $h = 3$. To illustrate, consider that User 1 has $C_1 = \{9, 4, 6, 1, 5, 10, 2, 7, 3, 8\}$ and $|C_1| = N = 10$. When $h = 3$, the refined channel set becomes $C_1(3) = \{9, 4, 6\}$.

2) The OFB with the slotted Aloha: This protocol is based on the fast retrial algorithm which uses a frequency-domain backoff scheme. It resolves contention by random channel selection instead of conventional random backoff time. This algorithm repeats the random channel selection (i.e., the frequency-domain backoff) until the retrial number reaches the maximum number of retrials, denoted by M. It then uses the slotted Aloha as a time-domain backoff for resolving contention. Note that this algorithm can be efficient if the channel utilisation is not very high.

We adopt the outage-aware refined channel sets for random channel selection with the fast retrial algorithm. After the retrial number reaches M, similar to the fast retrial algorithm,

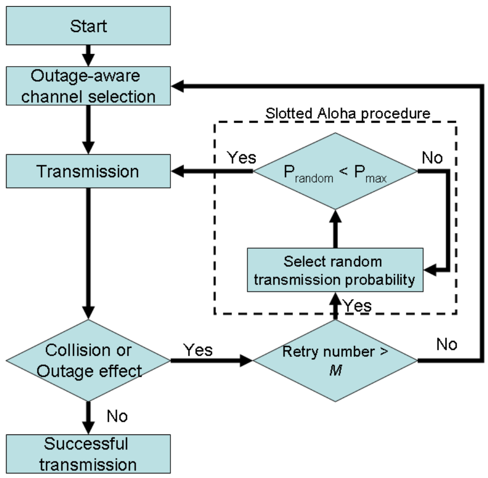


Fig. 3. The outage-aware fast retrial with the slotted Aloha

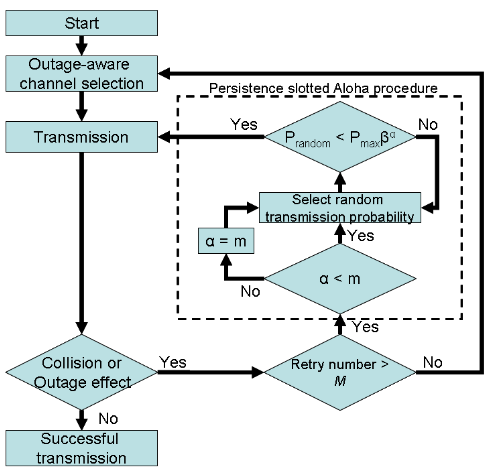


Fig. 4. The outage-aware fast retrial with the persistence slotted Aloha

the slotted Aloha is used in the 1-persistent manner to resolve contention for normal load condition. Fig. 3 shows the procedures of the OFB with the slotted Aloha.

3) The OFB with the persistence slotted Aloha: This protocol follows the same procedure of the fast retrial with the outage-aware refined channel sets for random access, but it uses persistent slotted Aloha instead of the slotted Aloha. Since the persistent slotted Aloha dynamically adjust users' transmission probabilities, it may have better performance for heavy load conditions. The procedures of the OFB with the persistence slotted Aloha are illustrated in Fig. 4.

B. The outage-aware time-domain backoff

The outage-aware time-domain backoff (OTB) MAC protocols use a centralised channel allocation scheme with the slotted Aloha and the persistence slotted Aloha.

1) The outage-aware heuristic for channel allocation: The conventional time-domain backoff MAC protocols consider that users are allocated to specific channels for packet transmission. Unlike the frequency-domain backoff MAC protocols, users keep the allocated channels. Thus, aggregated channel throughput strongly depends on the sets of users who access distinct channels. Under multichannel outage environments, the sets of users also affect the channel throughput because users may experience different channel outage probabilities. Hence, finding the optimal sets of users for channel access becomes crucial in order to maximise the channel throughput. This problem can be interpreted as a multiple knapsack problem [10] or a binpacking problem with a fixed size of bins [11]. Since these problems are NP-hard (i.e., the optimal channel allocation needs exhaustive searching to maximise all the channel throughput), efficient heuristic algorithms are needed.

We propose a lowest-outage increasing heuristic to find the optimal sets of users with respect to the increasing order of outage probabilities. This heuristic cannot guarantee the maximum aggregated channel throughput, but it can be implemented with reduced complexity obtaining an acceptable aggregated channel throughput. The channel allocation problem of this heuristic can be written as

$$
\begin{aligned}
\text{maximise} \quad & \sum_{n\in\mathcal{N}}\sum_{i\in\mathcal{K}}(1-q_{n,i})x_{n,i} \\
\text{subject to} \quad & \sum_{i\in\mathcal{K}} x_{n,i} \le \lceil \frac{K}{N} \rceil, \quad n\in\mathcal{N}, \\
& \sum_{n\in\mathcal{N}} x_{n,i} = 1, \qquad i\in\mathcal{K}, \\
& x_{n,i} = 0 \text{ or } 1, \qquad i\in\mathcal{K}, n\in\mathcal{N}
\end{aligned} \tag{2}
$$

where $\lceil a \rceil$ denotes the smallest integer number greater than a and $x_{n,i}$ denotes the indication function as

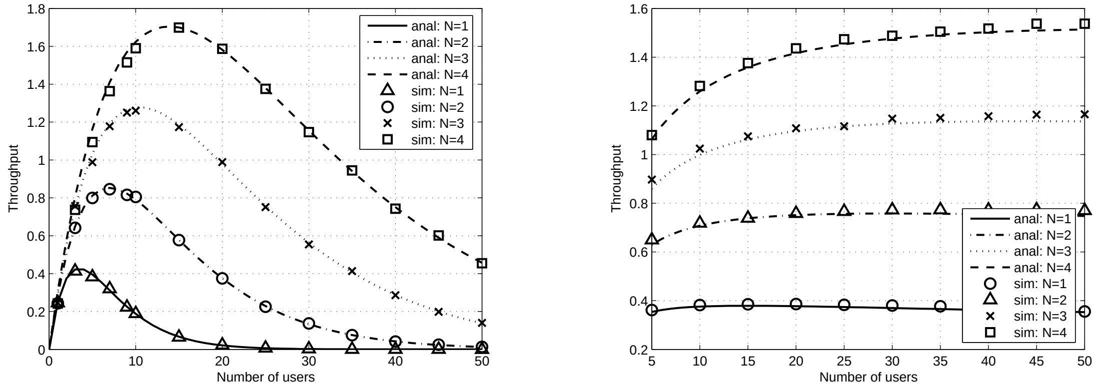
$$
x_{n,i} = \begin{cases} 1 & \text{if user } i \text{ is assigned to channel } n; \\ 0 & \text{otherwise.} \end{cases} \tag{3}
$$

The lowest-outage increasing heuristic is described as follows: First, by using the channel outage matrix, $\mathcal{Q}$, the sequence of users for the channel allocation procedure is obtained in a increasing order of the channel outage probabilities. Then, following the sequence, each user is allocated to the channel which gives the lowest channel outage probability. If the number of users in a channel is greater than the ideal number of users (i.e., $|\mathcal{M}_n| > \lceil \frac{K}{N} \rceil$), the users who have lower sequential priorities in the channel are redistributed to a channel that gives the next lowest channel outage probability. The procedures are repeated until all users are allocated and the ideal number of users in each channel is satisfied. The time complexity of the heuristic is $O(KN) + O(K)$.

We explain the proposed heuristic using a simple example. Consider 5 users and 3 channels (i.e., $K = 5$ and $N = 3$) in the example network. Assume that each user has various channel outage probabilities over the channels as follows

$$
\mathcal{Q} = \begin{pmatrix} 0.3 & 0.7 & 0.2 \\ 0.4 & 0.1 & 0.2 \\ 0.7 & 0.4 & 0.3 \\ 0.3 & 0.1 & 0.2 \\ 0.5 & 0.2 & 0.4 \end{pmatrix}. \tag{4}
$$

The sequence of users for channel allocation is $\{2, 4, 1, 5, 3\}$ in the increasing order of channel outage probabilities from $\mathcal{Q}$.



(a) The slotted Aloha

(b) The persistence slotted Aloha

Fig. 5. Throughput curves of the slotted Aloha and the persistence slotted Aloha with different number of channels when users are equally distributed over total channels and there is no channel outage.

The lowest-outage increasing heuristic first allocates all the users based on the sequence as $\mathcal{M}_1 = \{\phi\}$, $\mathcal{M}_2 = \{2,4,5\}$, and $\mathcal{M}_3 = \{1,3\}$. Then, by using the redistribution of user 5 because the number of users in Channel 2 is greater than the ideal number of users, $\lceil \frac{K}{N} \rceil = 2$, the channel allocation is obtained as $\mathcal{M}_1 = \{5\}$, $\mathcal{M}_2 = \{2,4\}$, and $\mathcal{M}_3 = \{1,3\}$.

2) The OTB with the Aloha-type MAC: We apply the outage-aware heuristic for channel allocation to the Aloha-type MAC protocols: The slotted Aloha and the persistence slotted Aloha. Unlike the OFB protocols, the OTB protocols have no frequency hopping in order to resolve collisions. When users are allocated to specific channels, each user keeps its own channel to access a base station. Thus, these protocols need sophisticated channel allocation operated by a base station as a centralised procedure.

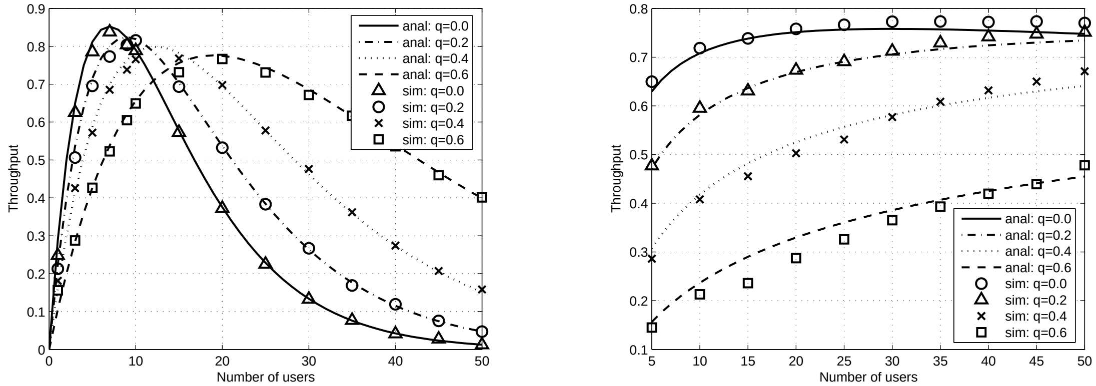
IV. Simulation Results

This section presents the impacts of various channel numbers and channel outage probabilities on throughput of the slotted Aloha and the persistence slotted Aloha. In addition, the proposed outage-aware MAC protocols are compared in terms of throughput under the multichannel outage environments. In our simulation, we assume that each user can transmit a packet to a base station in a single hop and always has a packet for transmission (i.e., the saturated condition). We also assume that the size of a slot is long enough to transmit a packet. Our simulation parameters are listed as follows: $p^{max} = 0.25$, $\beta = 0.5$, and $m = 7$ for the packet transmission, $M = 5$ for the fast retrial scheme, and $h = 3$ for the outage-aware refined channel sets. Each simulation result is an average of 20 runs in which each run has 5000 time slots.

Throughput curves of the slotted Aloha and the persistence slotted Aloha with different number of channels are shown in Fig. 5 when users are equally distributed over total channels and there is no channel outage. The throughput of the protocols increase proportionally with the channel numbers because the number of users who access a channel is reduced resulting in low collision probability. Since the slotted Aloha uses the fixed transmission probability, the throughput significantly decreases with more users as shown in Fig. 5(a). On the other hand, the persistence slotted Aloha has no throughput degradation according to the increasing user numbers in which it dynamically adjusts its transmission based on the update algorithm as shown in Fig. 5(b).

Fig. 6 shows the throughput curves of the slotted Aloha and the persistence slotted Aloha with various channel outage probabilities when $N = 2$ and users are equally distributed over the channels. We assume that each user experiences the same channel outage probability over all channels. Fig. 6(a) shows that when the channel outage is high, the slotted Aloha achieves better throughput with more users. Since the high channel outage leads to eliminate more transmitted packets, this causes lower packet collision with higher throughput. However, the maximum achievable throughput is reduced according to the increasing channel outages. On the other hand, the throughput of persistence slotted Aloha decreases proportionally with the channel outage as shown in Fig. 6(b) in which the increased transmission failure causes lower persistence transmission probability resulting in longer delay in the update algorithm.

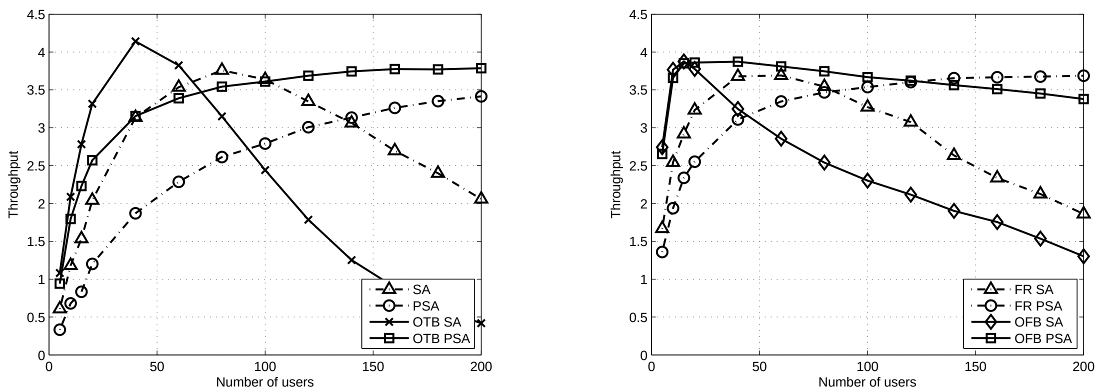
Throughput comparisons of the proposed outage-aware MAC protocols with the conventional MAC protocols are shown in Fig. 7 in terms of the time-domain backoff and frequency-domain backoff schemes when $N = 10$. We assume that each user has different channel probabilities over distinct channels. Fig. 7(a) shows the throughput curves of the time-domain backoff MAC protocols in which each user keeps its allocated channel for transmission. The dashed lines indicate the results of the conventional MAC protocols such as the slotted Aloha (SA) and the persistence slotted Aloha (PSA) over the multiple channels. These MAC protocols use the random channel allocation with even distribution of users over the channels. Since the slotted Aloha uses the fixed transmission probability, the slotted Aloha outperforms the persistence



(a) The slotted Aloha

(b) The persistence slotted Aloha

Fig. 6. Throughput curves of the slotted Aloha and the persistence slotted Aloha with various channel outage probabilities when $N = 2$ and users are equally distributed over the channels.



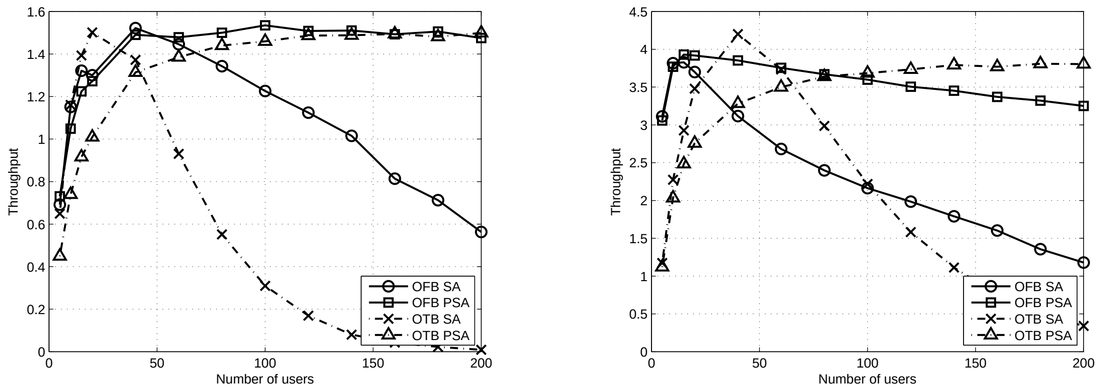
(a) The time-domain backoff MAC protocols

(b) The frequency-domain backoff MAC protocols

Fig. 7. Throughput curves of the proposed outage-aware MAC protocols compared with the conventional MAC protocols in terms of the time-domain backoff and frequency-domain backoff schemes when $N = 10$.

slotted Aloha when the number of users is small (e.g., around 140 users when $N = 10$). Note that the number of users for the slotted Aloha to dominate the persistence slotted Aloha increases according to the channel numbers. On the other hand, the outage-aware time-domain backoff MAC protocols with the slotted Aloha (OTB SA) and that with the persistence slotted Aloha (OTB PSA) improve throughput significantly. The OTB PSA obtains better performance than the conventional PSA with all user numbers. The OTB SA achieves the highest throughput until the user number reaches around 70. However, the throughput of the OTB SA dramatically decreases when the user number becomes large because of the fixed transmission probability and the outage-aware channel allocation. Fig. 7(b) shows the throughput curves of the frequency-domain backoff MAC protocols. Since the frequency-domain backoff MAC protocols resolves the transmission failure by hopping channels up to the limited retry number, they achieve much higher throughput than the time-domain backoff MAC protocols when the number of users becomes small. The dashed lines indicate the results of the fast retrial with the slotted Aloha (FR SA) and that with the persistence slotted Aloha (FR PSA). Because of the outage-aware refined channel sets for random access, the outage-aware frequency-domain backoff with the slotted Aloha (OFB SA) and that with the persistence slotted Aloha (OFB PSA) achieve higher throughput than FR SA and FR PSA when user number becomes small. However, when the number of users increase, the OFB SA degrades throughput significantly because of the nature of the slotted Aloha and the outage-aware refined channel sets.

Fig. 8 shows the throughput curves of the proposed outage-aware MAC protocols with different channel numbers. When the number of channels is small (e.g., $N = 4$) as shown in Fig. 8(a), the OTB SA outperforms the others with small user numbers because the centralised channel allocation improves throughput, but it has significant throughput degradation as the user number increases in which the outage-aware channel allocation causes more collision. The OFB PSA dominates the others with large user numbers with the advantage of



(a) $N = 4$ (b) $N = 10$

Fig. 8. Throughput curves of the proposed outage-aware MAC protocols with small channel number and large channel number.

outage-aware frequency hopping. On the other hand, when the number of channel becomes large (e.g., $N = 10$), the OFB PSA achieves the best throughput with small user numbers. This is because the frequency-domain backoff scheme has more advantages with more channels and less users. However, with large user numbers, the OFB PSA becomes less efficient than the OTB PSA in which hopping channels causes more transmission failure with more users.

V. Conclusion

We have proposed the multichannel MAC protocols by taking into account the channel outage effects to reflect channel fading and interference. The outage-aware frequency-domain backoff MAC protocols have been developed based on the distributed channel selection with the refined outage-aware channel set for random access. On the other hand, the outage-aware time-domain backoff MAC protocols have been designed using the centralised channel allocation. Since the channel allocation problem under the multichannel outage environments is NP-hard, the lowest-outage increasing heuristic has been used for the channel allocation. Simulation results showed that the throughput proportionally increases with the channel number. Similar to the conventional time-domain backoff MAC protocols, the outage-aware time-domain backoff with the slotted Aloha outperforms that with the persistence slotted Aloha only if the number of users is sufficiently small. On the other hand, the outage-aware frequency-domain backoff with the persistence slotted Aloha outperforms that with the slotted Aloha for any number of users. This results from that the frequency hopping within the refined outage-aware channel set obtains better throughput for smaller number of users and more channels.

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