A Two-dimension Opportunistic CSMA/CA Protocol for OFDMA-based In-home PLC Networks

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Abstract—Multi-channel systems can benefit from multi-user diversity by assigning channels to users with best channel conditions in different time instants. In this paper, a two-dimension opportunistic scheme for OFDMA-based in-home PLC systems with random access is presented in order to exploit multi-user diversity over different subchannels and different time slots. The proposed scheme adjusts the backoff time for each user based on the knowledge of instantaneous channel information in both frequency and time domains, and thus assigns users with better channel quality higher priority to access the channel. Moreover, users are scheduled to transmit over their favorable subchannels in order to further improve the system throughput. The analysis shows that the collision probability of the proposed scheme is considerably reduced. Additionally, simulation results demonstrate that the proposed scheme has the advantage of high saturated throughput even in the case where the number of users highly exceeds that of subchannels.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the most popular modulation schemes in both wireless [1], [2] and wired communication systems [3], [4] mainly because of its superior performance in presence of inter-symbol interference (ISI) and its high spectral efficiency. As an integration of OFDM and frequency division multiple access (FDMA) technique, orthogonal frequency division multiple access (OFDMA) attracts huge interest for multiple access schemes since it avoids the relatively large guard bands in conventional FDMA, and also inherits the advantages of OFDM. In such schemes, the whole frequency spectrum is divided into multiple narrowband subchannels, and multiple access is realized by providing each user with a set of available subchannels [5].

By employing OFDM and other techniques, the physical (PHY) layer of power line communication (PLC) systems can achieve up to 150 Mbps information rate [3], which makes PLC networks more appropriate to convey home multimedia applications and data services. In addition, PLC systems take advantage of the existing alternating current (AC) power wires as transmission medium. Consequently, PLC becomes increasingly viewed as a promising solution for in-home communications [6]. In [3], the medium access control (MAC) layer of PLC is designed to support both time division multiple access (TDMA) and collision sense multiple access/collision avoidance (CSMA/CA) services, where the latter is mainly applied to best-effort applications. The uplink random data services are considered in this paper, which are not delay sensitive. Accordingly, we focus on the CSMA/CA scheme.

Based on OFDM technique, CSMA/CA allows each station (STA) in an in-home PLC network to maintain its own backoff counter and contend with other STAs to access the available subchannels, thus enables simultaneous multi-user transmissions by providing each STA with a set of subchannels. Besides, OFDMA systems are especially robust against narrowband disturbances and impulsive noise, which are encountered in the PLC networks, and therefore OFDMA offers a suitable multiple access solution for PLC networks. However, the PLC line grids are not favorable medium for communications because they are susceptible to attenuation, noise and interference inherently, which makes it very challenging to achieve efficient transmissions to satisfy quality-of-service (QoS) requirements. Hence, the system capacity is expected to be maximized by benefiting from multi-user diversity across subchannels and in time slots due to the fact that different channels at different time instants experience different channel conditions.

Recently, great attention has been devoted to the opportunistic scheduling in a centralized or distributed manner for OFDMA-based multi-user systems with random access [7]–[12] by fully exploiting the multi-user diversity. The basic idea of multi-user diversity is to take advantage of random channel variations among different users. In order to attain the maximum throughput of uplink transmissions in OFDMA & slotted-Aloha wireless networks, [7] has proposed a fast retrial scheme in which collided users retry with another random subchannel immediately, rather than executing the conventional exponential backoff procedure. In this way, collisions may be solved in frequency domain. However, backoff to an unfavorable subchannel upon collision may adversely affect the system performance. An opportunistic Aloha for the uplink transmissions in OFDMA wireless networks is presented in [8]. Therein, a set of subchannels is allocated to a contending user under the condition that its obtained subchannel gains derived from the instantaneous channel state information (CSI) are greater than the corresponding threshold. If a collision occurs, the collided subchannel set is not utilized by the contending users. This work gives the subchannel assignment solution from the opportunistic viewpoint, but collision resolution is not taken into account.

Motivated by [7], Chang et al. [9] put forward a collision
resolution policy for [8], where collided good subchannels are set with random backoff time for future retrial, rather than discarded. In addition, subchannels are not randomly but opportunistically assigned to contending users. However, multiuser diversity is not considered in the contention period in this work which focuses merely on the opportunistic subchannel allocation. Furthermore, another backoff mechanism is shown in [10], in which all users estimate their channel power gains and compare them with a predefined backoff threshold. The users with greater channel gain occupy smaller numbers of backoff slots, which results in higher priority in the channel contention, and thus they are more likely to obtain their favorable subchannels. Herein, the backoff counters are initialized as different values according to users’ channel conditions, but multiuser diversity is not taken into account for the decrement of backoff counter.

Compared with the above schemes, several schemes are studied to take advantage of multiuser diversity in the contention process. In [11], a backoff mechanism that aims at minimizing collision probability in time and frequency domains for OFDMA & CSMA/CA systems is presented. This mechanism enables users to adjust their backoff time according to the number of available subchannels at the current instant, and then randomly select one subchannel for data transmission. The channel time-diversity is exploited in this paper, but a random subchannel selection after backoff period may degrade the system performance, i.e., multiuser diversity should be exploited in subchannel choice. As an extension of [11], the authors have proposed in [12] that STAs are opportunistically arranged to transmit over their favorable subchannels simultaneously. Nevertheless, the mechanism of backoff counter decrement can not guarantee that users with better channel quality achieve their favorable subchannels since backoff counters are reduced by the same value for both 'better' and 'worse' users.

In this paper, we present a two-dimension opportunistic CSMA/CA protocol for OFDMA-based in-home PLC networks. By exploiting multiuser diversity over different subchannels and within different slots, the designed scheme adjusts the backoff time for each active user according to instantaneous channel quality in frequency and time domains, and assigns each user its favorable subchannel. In this way, users with best channel quality at the current slot have higher priority to access their favorable subchannels, and thus the system throughput is enhanced.

The remainder of this paper is organized as follows: Section II presents the employed system model. In Section III, the proposed two-dimension opportunistic CSMA/CA scheme for OFDMA-based in-home PLC systems is described, and the related analysis of collision probability is given. The simulation results are shown and analyzed in section IV. Section V gives some conclusions.

II. SYSTEM MODEL

An OFDMA-based home PLC network with $D$ subcarriers and $M$ users is taken into account in this paper, where these users act as base communication devices, i.e., STAs, and connect with the central coordinator (CCo), or Home Gateway (Fig. 1). The CCo executes externally broadband communications with an internet service provider (ISP), and coordinates data transmission within the home. By utilizing OFDMA technique, multiple STAs can obtain different subchannels and communicate with the CCo simultaneously.

The uplink multipoint-to-point transmissions, i.e., from STAs to the CCo, are considered in this paper. The connection between each STA and CCo is defined as a path, and the channel transfer function of path $i$ is denoted by $H_i(f)$. We assume that each STA operates independently and has knowledge of only its own instantaneous channel conditions. When the signal is transferred on one path, noise at the CCo can be regarded as a combination of background noise and noises generated by all close-by electrical appliances connected to the power-line network, as shown in Fig. 2. $S_i(f)$ is defined as the noise power spectrum generated by the $i_{th}$ path, so the contribution of the $i_{th}$ noise resource to the CCo is $S_i(f) \times |H_i(f)|^2$. Employing the noise model in [13], it is assumed that the paths from 1 to $M$ correspond to the PLC communication paths, and the remaining paths from $M + 1$ to $M + A$ represent the noise sources. We assume that the different noise signals are uncorrelated, and the aggregated noise spectrum at the CCo is expressed as:

$$S_{CCo} = \sum_{i=1}^{A} S_i(f) \times |H_M+i(f)|^2. \tag{1}$$

Here, the noise power spectral density (PSD) varies in different time slots, so the noise spectrum at the CCo is time-varying.

In [14]–[16], the authors have investigated and confirmed the cyclostationary nature of noises in power lines. The noise spectrum is observed to be periodic with the frequency of the power line cycle (50 or 60 Hz). Thereby, the channel signal-to-noise ratio (SNR) exhibits periodicity characteristics. Accordingly, the cyclostationary PLC channel noise is modeled in [17] using a time mask multiplied by the noise PSD, i.e., $S_i(t) = S_i \times Mask(t)$. The time mask spans in an AC cycle
period (20 milliseconds for 50 Hz), and shows how the noise PSD varies from one time slot to another during the 20 ms cycle period. By repeating the time mask over every AC power cycle, the cyclostationary channel is established. Consequently, the SNR value over path $i$ from STA$_i$ to the CCo is computed as:

$$SNR_i = \frac{|H_i|^2}{S_{CCo}}.$$  

(2)

Based on the above SNR values, the transmission rate at the PHY layer can be obtained by employing the bit-loading algorithm for OFDM-based PLC channel [18]. The bit-loading is realized on 64 subcarriers selected in 1.8 – 30 MHz, where the number is shown as an example and does not affect the performance of the proposed scheme.

It is assumed that all STAs and CCo are synchronized with the AC cycle in order to exploit the cyclostationary nature of PLC channel SNR.

### III. Two-Dimension Opportunistic CSMA/CA Protocol

In this section, we propose a two-dimension opportunistic CSMA/CA protocol for OFDMA-based PLC systems, in which a backoff scheme is designed to opportunistically employ instantaneous subchannel conditions in frequency and time domains to reduce collision probability. Moreover, subchannels are assigned to users that can achieve more gains from these subchannels. Subsequently, the analysis about collision probability is given.

#### A. Protocol Design

As noted in Section I, different channels at different instants experience different channel conditions. The objective of the proposed protocol design is to exploit multiuser diversity over different subchannels and within different time slots to improve system throughput for data services. In order to realize it, two mechanisms are incorporated into the proposed protocol: i) active STAs with favorable channel conditions in both frequency and time domains have higher priority to access the channel; ii) active STAs select their corresponding best subchannels for data transmissions.

The considered $D$ subcarriers are contiguously divided into groups of subchannels due to the fact that subcarriers which fall within the coherence bandwidth have similar responses. Each subchannel contains the same number of subcarriers, and each STA employs one subchannel, which would facilitate our design. When a data packet arrives at STA$_i$, STA$_i$ will detect the states of all subchannels for a contention interframe spacing (CIFS) period. If there is no idle subchannel, STA$_i$ will persist in monitoring the channel. On the contrary, if at least one subchannel is available, STA$_i$ initializes the contention window size, the backoff counter and the backoff decrement step, and then enters into the backoff procedure.

The contention window size of STA$_i$, $W_i$, is initialized as $W_{\text{min}}$ at its first transmission attempt, and this value is determined by the binary exponential backoff algorithm. The initial value of backoff counter, $BC_i$, is set as $W_i - 1$ or randomly chosen in the range of $[0, W_i - 1]$, which are both studied in this paper. Subsequently, the backoff counter is reduced by a backoff decrement step per backoff slot during the backoff process if there is at least one idle subchannel per backoff slot. Here, the backoff decrement step of STA$_i$ is denoted as $L_i$ ($L_i \geq 1$) and is calculated by:

$$L_i = \left\lceil \frac{\max(R_{i,k}^{t})}{\bar{R}} \right\rceil, \; k \in \{1, 2, \cdots K_{idle}\}.$$  

(3)

where $\lceil \cdot \rceil$ denotes the ceiling function, $\max(R_{i,k}^{t})$ represents the maximum data rate achieved by STA$_i$ over idle subchannel $k$ at slot $t$ ($k$ is defined as STA$_i$’s favorable subchannel in this case), $K_{idle}$ is the number of idle subchannels at $t$, and $\bar{R}$ is the average data rate over all subchannels which can be obtained by the periodic channel estimation procedure in [3]. During this procedure, each STA measures the PLC subchannels and reports the results to the CCo. Then, the CCo computes $\bar{R}$ based on the feedback using:

$$\bar{R} = \frac{\sum_{i=1}^{K} \sum_{k=1}^{K_{idle}} R_{i,k}^{t}}{M \times K}.$$  

(4)

Here, $K$ and $R_{i,k}^{t}$ are the number of total subchannels and the data rate of STA$_i$ over subchannel $k$, respectively. Finally, the CCo periodically broadcasts the result of (4) to all STAs. During STA$_i$’s backoff process, three cases may occur:

- If STA$_i$’s favorable subchannel remains idle during the backoff process, its backoff counter is reduced by $L_i$ from (3) per backoff slot until its value reaches zero.
- If STA$_i$’s favorable subchannel is occupied by another STA, and there is still at least one subchannel available, STA$_i$ will update $L_i$ based on the conditions of available subchannels according to (3), and then continue its backoff process.
- If STA$_i$ senses that the subchannels which are idle within the precedent backoff slot are all occupied by other STAs in the current backoff slot, it will interrupt the current backoff procedure. At the same time, the backoff counter is reset as $W_i$ in the case where the initialized $BC_i$ is constant or it is frozen in the case where the initialized $BC_i$ is a random value. Subsequently, STA$_i$ will monitor the channel until there is at least one subchannel idle for a duration of CIFS, reset $L_i$ according to the state of available subchannels and continue the backoff process in the same way as above.

It should be noted that collisions are resolved in both frequency and time domains by allocating different subchannels to different STAs and adjusting $L_i$ according to (3). Besides, the backoff policy always entitles the STAs with better instantaneous channel conditions to obtain higher priority in the assignment of their favorable subchannels, and thus the system throughput is improved.

When the backoff counter of STA$_i$ reaches zero, it launches the transmission to the CCo by utilizing the chosen subchannel during its backoff process. This subchannel will be freed by STA$_i$ after its transmission completes. If the CCo receives
the packet from STA\textsubscript{i} successfully, it will reply to STA\textsubscript{i} with an acknowledge message after a response interframe spacing (RIFS) period. The acknowledge messages are transmitted over some reserved subcarriers. However, if STA\textsubscript{i} could not receive the acknowledgement (ACK) from the CCo within a predefined deferred period, it will regard this transmission as disabled. In this paper, we only consider the unsuccessful transmissions caused by collisions when more than one STAs start to transmit simultaneously over the same subchannel. In the case of collisions, the collided STAs will update their corresponding contention window sizes according to the binary exponential algorithm and try to retransmit the current packet in the subsequent contention period by repeating the above process. The maximum number of transmission attempts is set as 3 for all STAs. If STA\textsubscript{i} can not receive the ACK from the CCo after 3 transmission attempts, it will drop this packet.

Fig. 3 illustrates the above protocol with an example of three STAs and two subchannels. Without loss of generality, data packets are supposed to arrive at these three STAs simultaneously. They will set their own contention window sizes and related backoff decrement steps according to (3) after a CIFS period. STA A and B finish their backoff procedures in six and three backoff slots respectively based on their actual channel conditions in frequency and time domains. Subsequently, they select the corresponding favorable subchannels, i.e. subchannel 2 for STA A and 1 for STA B, to transmit data packets.

Here, we assume that STA C’s favorable subchannel is 1. It is noted that subchannel 1 is occupied by STA B during STA C’s backoff procedure, therefore, STA C has to update its backoff decrement step. When there is no available subchannel, STA C will begin to monitor the channel until sensing at least one idle subchannel, then will restart the backoff procedure.

**B. Collision Probability Analysis**

Compared with the single channel systems, the advantages in collision probability of the OFDMA-based multichannel systems are analyzed in [11]. In this subsection, we focus on the collision probability analysis for our proposed scheme. Without loss of generality, we assume that STA A an B begin the corresponding backoff procedures at the tth and (t + \tau)tth slot, L\textsubscript{A} and L\textsubscript{B} are the backoff decrement steps for A and B respectively. The backoff counter is initialized to be the same as W − 1 for STA A and B.

When a collision occurs between STA A and B, it indicates that they transmit their own packets over the same subchannel within the same slot. That is to say, STA A and B finish their backoff procedures after n time slots simultaneously, where 1 ≤ n < W − \tau − 1, which corresponds to the following two scenarios:

1) \tau = 0: if these two STAs collide, they will have the same backoff decrement step, i.e., L\textsubscript{A} = L\textsubscript{B}. Thus, the corresponding probability \( P_1 \) is:

\[
P_1 = P(\tau = 0) \cdot P(L\textsubscript{A} = L\textsubscript{B}) = \frac{1}{W} \cdot \sum_{L\textsubscript{A}=L\textsubscript{B}=1}^{L\text{max}} P(L\textsubscript{A})P(L\textsubscript{B}),
\]

where \( L\text{max} \) is the maximum value of \( L\textsubscript{A} \) and \( L\textsubscript{B} \).

2) \tau ≥ 1: if STA A and B collide, \( L\textsubscript{A} \) and \( L\textsubscript{B} \) should satisfy the following conditions:

\[
\begin{align*}
L\textsubscript{A} &< L\textsubscript{B} \\
(W - 1) - (n + \tau)L\textsubscript{A} &\leq 0 \\
(W - 1) - nL\textsubscript{B} &\leq 0 \\
(W - 1) - (n + \tau - 1)L\textsubscript{A} &> 0 \\
(W - 1) - (n - 1)L\textsubscript{B} &> 0
\end{align*}
\]

Deriving from (6), we can obtain:

\[
\left\{ \begin{array}{l}
\frac{W-1}{n+\tau} \leq L\textsubscript{A} < \frac{W-1}{n} \\
\frac{W-1}{n} \leq L\textsubscript{B} < \frac{W-1}{n-1} 
\end{array} \right.
\]

When \( L\textsubscript{A} \) is given, all \( L\textsubscript{B} \) satisfying \( L\textsubscript{A} < L\textsubscript{B} \) can be achieved. Then, for each pair of \((L\textsubscript{A}, L\textsubscript{B})\), we can obtain the corresponding \( n \) and \( \tau \) according to (7). In all cases, we find that only one pair of \( n \) and \( \tau \) corresponds to one pair of \((L\textsubscript{A}, L\textsubscript{B})\). In addition, \( \tau \) follows the uniform distribution in \([0, W - 1]\). Therefore, the probability of an event satisfying (7) is \( P(L\textsubscript{A})P(L\textsubscript{B})/W \). In this way, the probability of all events satisfying (7), \( P_2 \), is derived by accumulating all probabilities:

\[
P_2 = P(\tau \geq 1) \cdot P\left( \frac{W - 1}{n + \tau} \leq L\textsubscript{A} < \frac{W - 1}{n + \tau - 1} \right) \cap \left( \frac{W - 1}{n} \leq L\textsubscript{B} < \frac{W - 1}{n - 1} \right) = \frac{1}{W} \sum_{L\text{A}=1}^{L\text{max}-1} \sum_{L\text{B}=L\text{A}+1}^{L\text{max}} P(L\textsubscript{A})P(L\textsubscript{B}).
\]

Furthermore, the probability that two STAs select the same subchannel is equal to \( 1/K \), so the collision probability in the above two scenarios is:

\[
P_{col} = \frac{1}{K} \cdot (P_1 + P_2).
\]
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measurement in [19], the noise model in Section II and Eq. (3), the probability distribution of backoff decrement step is:

\[ P(L) = \begin{cases} 
0.446, & \text{if } L = 1 \\
0.469, & \text{if } L = 2 \\
0.083, & \text{if } L = 3 \\
0.002, & \text{if } L = 4 
\end{cases} \] (10)

In Table I, all values of \((L_A, L_B, n, \tau)\) satisfying (7) are listed. Consequently, we obtained \(P_{col} = 0.00544\) which corresponds to the collision probability of any two users over the same subchannel in the case of \(K = 4\) and \(W = 32\) according to (9). Accordingly, the collision probability in the case of \(K = M = 4\) and \(W = 32\) is 0.033, which is far smaller than the collision probability, about 0.12, obtained in [11] when \(K = M = 5\) and \(W_{min} = 32\).

The collision probability in the scenario where the backoff counter is initialized as constant is analyzed above. As for the scenario of random \(BC_i\) in the range of \([0, W - 1]\), the collision probability is lower than the results obtained from (9) since a random selection mechanism is more favorable to reduce the collision probability.

### IV. Simulation Results and Analysis

The performance of the proposed two-dimension opportunistic CSMA/CA protocol for OFDMA-based systems is evaluated through computer simulations in this section. We consider the scenario of saturated throughput, i.e., all STAs have infinite packets to transmit, which is a key performance of data services.

The simulations are executed in 100 AC power cycles (2s). For the simulation parameters, the duration of CIFS, RIFS and backoff slot are set as 35.84, 26 and 35.84 µs, respectively according to [3]; the minimum contention window size, \(W_{min}\), as 32; the data packet size as 1000 bytes. At the PHY layer, the channel transfer functions are obtained by the measurement in [19]. The selected subcarriers as mentioned in Section II are contiguously grouped into 2, 4 and 8 subchannels respectively. The number of STAs is increased from 1 to 14, and each scenario is simulated for 100 times in order to obtain an average value.

The simulations for the proposed scheme are designed in two main scenarios regarding the initialized value of backoff counter: i) constant \(BC_i\) and ii) random \(BC_i\) in the range of \([0, W - 1]\), and the saturated throughput of our proposed scheme is compared with that of [12].

![Fig. 4. Average saturated throughput of the scheme in [12] and the proposed scheme, respectively.](image)

![Fig. 5. Average saturated throughput and fairness index of the scheme in [12].](image)

**A. Constant \(BC_i\)**

As shown in Fig. 4, when the number of STAs is less than that of subchannels, i.e., \(M < K\), the saturated system throughput is augmented with the increasing number of \(M\) for each case of \(K\) in both schemes. Whereas for a given \(M\), the throughput is decreased with the rising \(K\) since the available subchannels are not fully employed. For example, in the case of \(M = 2\), the saturated throughput of \(K = 4\) is higher than that of \(K = 8\). On the other hand, when \(M \geq K\), the saturated throughput is dramatically lowered with the increase of \(M\) for each \(K\) in the scheme of [12] because the random \(BC_i\) of this scheme cannot guarantee the STAs to obtain their favorable

<table>
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**TABLE I**

VALUES OF \((L_A, L_B, n, \tau)\) FOR ALL COLLISION POSSIBILITIES
subchannels. In contrast to it, the system throughput of our proposed scheme keeps around a value when increasing $M$ for each $K$ because the multiuser diversity is exploited in both backoff and subchannel allocation processes. Moreover, the greater $M$ is, the more gain the proposed scheme can achieve from the multiuser diversity. Besides, the throughput remains to 2.8 Mbps as $K = 4$ and $M \geq 11$ because the proposed system could not obtain more gain from the multiuser diversity with a considerably great $M$.

B. Random $BC_i$

When increasing the number of STAs, the results of saturated throughput of the scheme in [12], the proposed scheme with $BC_i = 31$ and with random $BC_i$ in the range of $[0,31]$ in the case of $K = 4$ are compared in Fig. 5(a). We notice that when $M \geq K$, the saturated throughput of our proposed scheme with random initial $BC_i$ decreases apparently compared with the scheme with constant initial $BC_i$ when increasing $M$ because STAs with best channel quality can not always be assigned the appropriate subchannels in such a mechanism. For example, a STA with $L = 1$ obtains a subchannel when its backoff counter is initialized as 3, which indicates that this STA which is not favorable for the current subchannel has higher priority to access the channel because of the small $BC_i$. It can be seen that the saturated throughput of the proposed scheme with random $BC_i$ is greater than that of the scheme in [12] especially when $M > 4$ since the proposed design of $L_i$ contributes to the reduction of collision probability.

C. Fairness among STAs

Here, Jain’s fairness index [20] is utilized to measure long-term fairness among STAs:

\[
\text{fairness index} = \left( \frac{\sum_{i=1}^{M} r_i}{M \cdot \sum_{i=1}^{M} r_i^2} \right)^2.
\]

where $r_i$ is the throughput of STA$_i$ during the simulation round. The more this fairness index approaches to 1, the fairer the scheme is.

In Fig. 5(b), it is noted that the saturated throughput of our proposed scheme with constant initial $BC_i$ is increased by sacrificing fairness among STAs, i.e., STAs with lower channel quality could hardly succeed in the channel contention. However, the proposed scheme with random initial $BC_i$ can improve the system throughput on maintaining the long-term fairness among users.

V. CONCLUSIONS

In order to exploit multiuser diversity over different subchannels and within different time instants to improve system throughput, a two-dimension opportunistic scheme for OFDMA & CSMA/CA in-home PLC systems is proposed in this paper. The proposed scheme enables the dynamic reduction of the backoff counter according to the instantaneous channel information in both frequency and time domains, and assigns users their favorable subchannels for transmissions. Analyses and numerical results indicate that the proposed scheme with constant initial $BC_i$ can apparently improve the system throughput, but at the price of user fairness, while the scheme with random initial $BC_i$ achieves a tradeoff between system throughput and fairness.

REFERENCES