Statistical Muliplexing Based Hybrid FH-OFDMA System for OFDM-Based UWB Indoor Radio Access Networks

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***Abstract*— We propose a statistical multiplexing based hybrid frequency hopping orthogonal frequency division multiple access (HFH-OFDMA) system to increase the downlink user capacity of orthogonal frequency division multiplexing (OFDM) based ultra-wideband (UWB) indoor radio access networks (RANs). Downlink user capacity is defined as the maximum allowable number of users served with a given data rate in a piconet. The HFH-OFDMA system accommodates more users than the conventional FH-OFDMA system by using statistical multiplexing. In OFDM based UWB indoor RANs, the downlink user capacity of the HFH-OFDMA system is limited by either the total number of available subcarriers in a piconet (resource limited) or FCC UWB emission limit (power limited). Simulation results show that the proposed HFH-OFDMA system which operates in 3.168 GHz $\sim$ 3.696 GHz band accommodates 256 users with a data rate of 532.5 kb/s in OFDM based UWB indoor RANs.**

I. Introduction

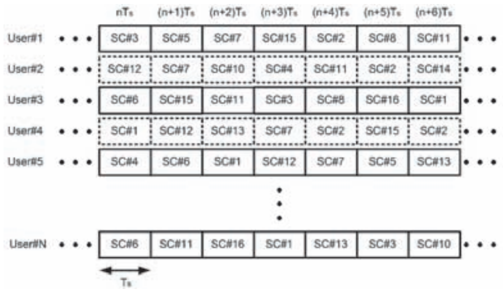
Nowadays, Ultra-wideband (UWB) technology which operates in an overlayed bandwidth, 3.1 GHz $\sim$ 10.6 GHz, has been considered as a promising technology for accommodating diverse data services. In addition to its enormous bandwidth, UWB technology has advantages, such as low cost and low power consumption. Hence, this UWB technology has been discussed as a candidate standard technology in mobile communication committees. For instance, IEEE 802.15 Task Group (TG) 3a was organized to standardize the UWB technology for supporting high data rates in wireless personal area networks (WPANs) [1], [2] and UWB technologies for low data rates in WPANs have also been proposed in IEEE 802.15 TG 4a [3]. The UWB technologies proposed in IEEE 802.15 TG 3a mainly aim for efficiently supporting a small number of users requiring high data rates ranging from 110 Mb/s to 480 Mb/s. The IEEE 802.15 TG 4a committee discuss how to accommodate a large number of users requiring low data rates of several kb/s with an extremely low user channel activity of $10^{-4} \sim 10^{-5}$. However, this technology is not appropriate for supporting a large number of users with data rates of several tens of kb/s to several hundreds of kb/s for indoor radio access networks (RANs) in stations, airports, and department stores.

Orthogonal frequency division multiplexing (OFDM) is one of promising technologies for high-rate data transmission over frequency selective fading channels. OFDM based UWB technologies have been studied in [4]. OFDM technologies can easily overcome inter-symbol-interference (ISI) in dense multipath environments such as UWB indoor environments, compared with time hopping (TH) UWB technology or direct sequence (DS) UWB technology. Moreover, OFDM based UWB technology can easily avoid interference from/to the bandwidth of existing communication systems by setting the interfering subcarriers to be off [5]. As a result, an OFDM based UWB technology, a Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) physical technology by Multi-band OFDM Alliance (MBOA) [1], was proposed in IEEE 802.15.3 TG 3a and has been discussed as a promising standard technology for high-rate WPAN.

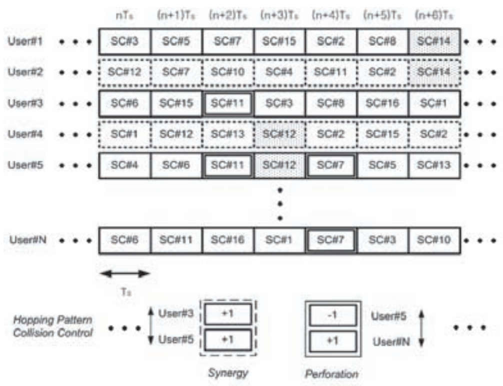
A number of multiple access schemes for OFDM including OFDMA and FH-OFDMA have been proposed [5]. Among them, the frequency hopping orthogonal frequency division multiple access (FH-OFDMA) technique has a frequency diversity gain in frequency selective fading channels like UWB indoor channel.

In this paper, we propose a statistical multiplexing based hybrid frequency hopping (HFH)-OFDMA to increase the downlink user capacity of OFDM-based UWB RANs. The downlink user capacity is defined as the maximum allowable number of users served with a given data rate in a piconet. The HFH-OFDMA system operates identically with the conventional FH-OFDMA system if the number of users, N_u is smaller than the number of total available data channels, N_a. The HFH-OFDMA system accommodates more users than N_a for $N_u > N_a$ by using statistical multiplexing. Statistical multiplexing is a method that users occupy a given channel only when they send data. Statistical multiplexing schemes do not have to control user data transmission as a scheduling-based scheme in cellular systems does. Moreover, they do not have to wait for a longer time for communications like the carrier sense multiple access collision avoidance (CSMA-CA) schemes of WLAN when tens or hundreds of users exist.

This paper is organized as follows: In Section II, the operation of statistical multiplexing based HFH-OFDMA system for OFDM based UWB RANs is explained. Moreover, the user capacity of the HFH-OFDMA system is analyzed. The performance of the proposed HFH-OFDMA system for OFDM based UWB RANs is evaluated through simulation in Section



(a) HFH-OFDMA ($N_u \leq N_a$)



(b) HFH-OFDMA ($N_u > N_a$)

Fig. 1. Operation Example of HFH-OFDMA

III. Finally, conclusions are presented in Section IV.

II. Statistical Multiplexing based Hybrid Frequency Hopping OFDMA for OFDM-Based UWB Indoor RANs

A. Operation of HFH-OFDMA

Fig. 1 shows the operation of the proposed HFH-OFDMA system. The HFH-OFDMA system checks the number of data users (N_u) and compares it with the number of total available channels in a piconet (N_a). The HFH-OFDMA system operates identically with the conventional FH-OFDMA system if $N_u \leq N_a$. Since the same subcarrier is not allocated to different users at the same time in the conventional FH-OFDMA, no subcarrier collision occurs as in Fig. 1(a).

Subcarrier collisions may occur in the HFH-OFDMA system for $N_u > N_a$. These subcarrier collisions may cause performance degradation. However, some of users can be inactive although their allocated subcarriers are the same, if the user activity is low. Hence, the HFH-OFDMA system considers this situation and controls the symbol power based on both the user activity and the symbol value for $N_u > N_a$.

If a subcarrier collision occurs, the HFH-OFDMA system checks the channel activity of users with the subcarrier collision. This is feasible in downlink since a piconet coordinator (PNC) knows each user's activity and symbol value before transmission. If all users with subcarrier collisions are inactive or if only one of all users with subcarrier collisions is active (trivial hits), as shown in the shaded blocks of Fig. 1(b), the HFH-OFDMA system does not take any action for the collision as done in a non-subcarrier collision situation. This is because subcarrier collisions of inactive users do not affect the behaviors of active users at all.

The HFH-OFDMA system starts to control symbol power when more than two users with the same subcarrier collision are active. The HFH-OFDMA system checks the symbol values of the corresponding active users. If all the colliding symbols are the same, as shown in user #3 and user #5 of (n+2)T_S slot in Fig. 1(b), the HFH-OFDMA system controls the symbol power of colliding subcarrier to be below -41.25 dBm/MHz, and it is called a synergy. This is because of a UWB emission limit of -41.25 dBm/MHz which is regulated by FCC [6]. If all the colliding symbols are not the same, as shown in user #5 and user #N of (n+6)T_S slot in Fig. 1(b), the HFH-OFDMA system controls the subcarriers to be off at that interval, and it is called a perforation. This is because the addition of different symbol values may yield an ambiguous symbol value at the receiver. This symbol power control scheme which is based on synergy and perforation reduces performance degradation when subcarrier collisions occur [7].

The collision probability (P_C) in the HFH-OFDMA system is expressed as [8]

$$P_C = \begin{cases} 0, & \textit{if } N_u \leq N_a \\ 1 - \left\{1 - \frac{\overline{v}}{(1-\rho)N_{sub}/k}\right\}^{N_u - 1}, & \textit{if } N_u > N_a, \end{cases} \tag{1}$$

where $\overline{v}$, ρ, and k are the mean channel activity, the proportion of signaling overhead for channel estimation and synchronization, and the number of subcarriers which consists of one data channel, respectively. Hence, N_a equals to $\frac{(1-\rho)N_{sub}}{k}$.

The perforation probability (P_P) and the synergy probability (P_S) are expressed as

$$P_P = \begin{cases} 0, & \textit{if } N_u \leq N_a \\ 1 - \sum_{i=0}^{s-1} \pi_i \left\{1 - \frac{(1-\pi_i)\overline{v}}{(1-\rho)N_{sub}/k}\right\}^{N_u - 1}, & \textit{if } N_u > N_a \end{cases} \tag{2}$$

$$P_S = \begin{cases} 0, & \textit{if } N_u \leq N_a \\ P_C - P_P, & \textit{if } N_u > N_a \end{cases} \tag{3}$$

where π_i is the probability of modulation symbol i $\in \{0, 1, ..., s-1\}$ and s is equal to 2 for QPSK modulation [8].

The proposed HFH-OFDMA system avoids unnecessary subcarrier collisions for $N_u \leq N_a$. For $N_u > N_a$, the HFH-OFDMA system accommodates more users than the number of total available channels by using statistical multiplexing.

B. Downlink User Capacity of HFH-OFDMA

In the analysis of user capacity for conventional OFDMA systems, it is assumed that the allocated subcarriers are dedicatedly utilized by mobile users. In this case, user capacity is equal to the number of total available channels. However, the channel activity of data service which we consider is low (e.g. $0.1 \sim 0.2$), and subcarriers may be used during a small portion of time. Hence, conventional OFDMA systems waste resource and limit the user capacity when the channel activity is low. On the other hand, user capacity of conventional OFDMA systems can be limited by power although there are available subcarriers in a piconet. This case mainly occurs when users are located in a rather far distance or transmit power is strictly limited like UWB transmit power which is regulated by FCC as -41.25 dBm/MHz in indoor environments.

We analyze the downlink user capacity of the proposed HFH-OFDMA in two cases: a power limited case and a resource limited case. Smaller downlink user capacity for the above two cases practically limits the downlink user capacity of the proposed HFH-OFDMA system. That is, in the power limited situation, the HFH-OFDMA system can not accommodate new users due to a lack of transmit power although the number of available subcarriers is sufficient. Conversely, in the resource limited situation, it can not accommodate new users due to a lack of subcarriers although the transmit power is sufficient.

To obtain the low bound user capacity ($C_{P,HFH}$) in the power-limited case, we assume that all the users are located at the piconet boundary and the activity of data channels is identical. $C_{P,HFH}$ is expressed as

$$C_{P,HFH} = \frac{\left[\frac{E_b}{N_0}\right]_{rcvd}}{\overline{v}(\left[\frac{E_b}{N_0}\right]_{req} \cdot \Delta P)} \frac{(1-\rho)N_{sub}}{k} \tag{4}$$

where

$\left[\frac{E_b}{N_0}\right]_{req}$ Required E_b/N_0 for a specific data rate

$\left[\frac{E_b}{N_0}\right]_{rcvd}$ Received E_b/N_0 at the piconet boundary

$\overline{v}$ Mean user channel activity

ΔP Additionally required energy to compensate for the subcarrier collisions

The received E_b/N_0 is expressed as

$$\left[\frac{E_b}{N_0}\right]_{rcvd} = \frac{[S/N_0]_{rcvd}}{R^{FEC} \cdot \mu \cdot I}, \tag{5}$$

where R^{FEC}, μ, and I denote the channel code rate, the modulation order, and the implementation loss, respectively.

The received signal-to-noise ratio can be expressed as

$$\left[\frac{S}{N_0}\right]_{rcvd} = \frac{P_T \cdot r^{-\alpha} \cdot X_0}{N_0 \cdot L_1}, \tag{6}$$

where

α Path-loss exponent

r Distance from PNC to the piconet boundary

L_1 Path loss at 1m

N_0 Thermal noise at the receiver

P_T Transmit power per subcarrier

X_0 Shadowing factor from the PNC

X_0 is assumed to have a median value of 1. Substituting Eqn. (6) into S/N_0 of Eqn. (5) yields

$$\left[\frac{E_b}{N_0}\right]_{rcvd} = \frac{P_T \cdot r^{-\alpha}}{R^{FEC} \cdot \mu \cdot N_0 \cdot L_1 \cdot I}. \tag{7}$$

Substituting Eqn. (7) into $[E_b/N_0]_{rcvd}$ of Eqn. (4) yields

$$C_{P,HFH} = \frac{P_T \cdot r^{-\alpha} \cdot (1-\rho) \cdot N_{sub}}{R^{FEC} \cdot \mu \cdot N_0 \cdot L_1 \cdot \ I \cdot \overline{v}(\left[\frac{E_b}{N_0}\right]_{req} \cdot \Delta P) \cdot k} \tag{8}$$

For $N_u \le N_a$, ΔP is equal to 0 since no collision exists. However, for $N_u > N_a$, ΔP is greater than 0 and its value is determined by the channel coder which compensates for subcarrier collisions.

The downlink user capacity in the resource limited case ($C_{R,HFH}$) can be derived from from Eqn. (1) and expressed as

$$C_{R,HFH} = \begin{cases} \frac{(1-\rho)N_{sub}}{k}, & if\ N_u \le N_a \\ 1 + \frac{log(1-P_C)}{log(1-\frac{\overline{v}}{(1-\rho)N_{sub}/k})}, & if\ N_u > N_a \end{cases} \tag{9}$$

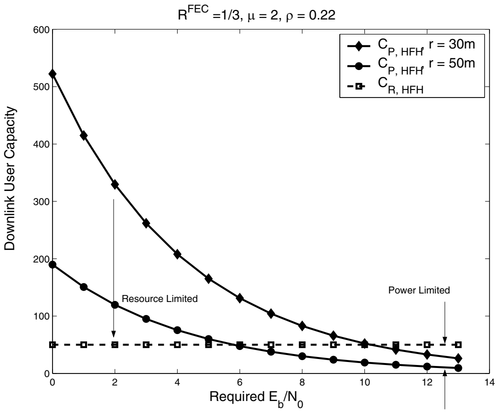
For $N_u \le N_a$, $C_{R,HFH}$ is determined by N_{sub}, ρ, and k. However, for $N_u > N_a$, $C_{R,HFH}$ is determined by not only N_a, ρ, and k but also channel activity $\overline{v}$ and collision probability P_C.

Taking into account the power limited and resource limited cases, the downlink user capacity of HFH-OFDMA systems (C_{HFH}) is expressed as

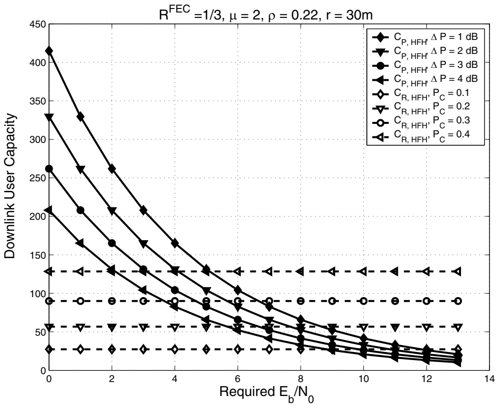
$$C_{HFH} = min\{C_{P,HFH}, C_{R,HFH}\} \tag{10}$$

Fig. 2 shows the downlink user capacity of HFH-OFDMA systems versus the required E_b/N_0, for various sets of r, P_C, and ΔP. ρ, N_{sub}, R^{FEC}, and μ are set to 0.22, 128, 1/3, and 2. L_1, I and $\overline{v}$ are set to 44.2 dB, 2.2 dB, and 0.2 [1]. Especially, P_T is set to -14.0 dBm considering FCC UWB emission limit [6]. For $N_u \le N_a$, as r increases, $C_{P,HFH}$ decreases as shown in Fig. 2(a) since path loss at the cell boundary increases. However, $C_{R,HFH}$ does not depend on the r and remains constant. For a radius r of 30m, C_{HFH} is limited by ($C_{R,HFH}$) of 50 if the required E_b/N_0 is smaller than 10.2 dB. In the same case, C_{HFH} is limited by $C_{P,HFH}$ which is determined by the Eqn. (4) if the required E_b/N_0 is larger than 10.2 dB.

For $N_u > N_a$, the proposed HFH-OFDMA allows subcarrier collisions. Hence, $C_{P,HFH}$ and $C_{R,HFH}$ additionally depends on the ΔP and P_C, respectively, as shown in Fig. 2(b). If we assume that $\overline{v}$, P_C, and ΔP to compensate for P_C are equal to 0.2, 0.3, and 2 dB, respectively, C_{HFH} is limited by $C_{R,HFH}$ of 89 which is derived from Eqn. (9) if the required E_b/N_0 is smaller than 5.7 dB. In the same case,



(a) Downlink User Capacity $(N_u \leq N_a)$



(b) Downlink User Capacity $(N_u > N_a)$

Fig. 2. Downlink User Capacity of HFH-OFDMA

C_{HFH} is limited by $C_{P,HFH}$ which is determined by Eqn. (4) if the required E_b/N_0 is larger than 5.7 dB.

The analysis results show that the downlink user capacity is limited by the transmit power if the required E_b/N_0 is high or r is large (power limited situation). On the contrary, user capacity is limited by the resource if the required E_b/N_0 is low or r is small (resource limited situation).

III. Performance Evaluation

We consider an additive white gaussian noise (AWGN) channel and a UWB indoor channel, CM4 which is one of IEEE 802.15 TG 3a UWB indoor channel models [9]. The channel characteristic of CM4 is similar to that of indoor RAN environments, such as stations, airports, and department stores since CM4 is measured in an extremely NLOS UWB indoor environment.

OFDM parameter values are as follows:

- Channel Bandwidth : 528 MHz
- Subcarrier Bandwidth : 4.125 MHz
- Number of Total Subcarriers : 128
- Number of Data Subcarriers : 100
- Symbol Interval : 312.5 ns
- Switching Interval for IFFT/FFT : 242.42 ns
- Cyclic Prefix : 60.61 ns

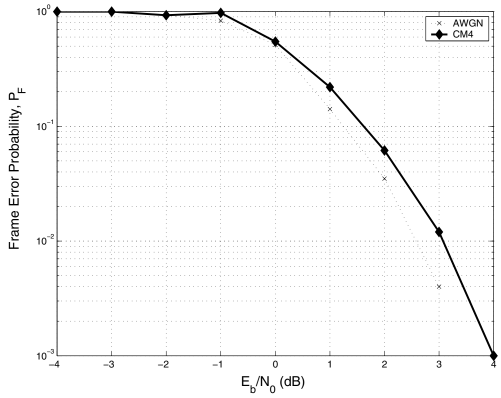


Fig. 3. FER Performance of HFH-OFDMA $(N_u \leq N_a)$

- Guard Interval : 9.47 ns

These parameters are set considering indoor UWB RAN environments like stations, airports, and department stores.

We assume that 100 subcarriers are divided into 2 groups and 2 subcarriers from each group are allocated to a user at a time. Therefore, a group consists of 50 subcarriers and each user transmits data following 2 hopping patterns (HPs) which are independently allocated by two groups. In this case, N_{sub}, ρ, and k are equal to 128, 0.22, and 2. Hence, the number of available channels (N_a) is 50 which is given by the relation of $N_a = \frac{(1-\rho)N_{sub}}{k}$. Convolutional coding (code rate 1/3) and QPSK modulation are used. Each bit is repeated 8 times. Hence, the data rate of each user is 532.5 kb/s. At the receiver, a soft Viterbi decoder decodes the encoded symbols and the maximum ratio combining (MRC) scheme combines 8 repeated bits. A frame consists of 1200 coded bits.

Fig. 3 shows the frame error rate (FER) curve of the proposed HFH-OFDMA system for $N_u \leq N_a$. To achieve an FER requirement of 0.01 in the UWB indoor RANs (CM4), the proposed HFH-OFDMA requires an E_b/N_0 value of 3.18 dB. The FER curve of CM4 is close to that of AWGN. This is because the MRC scheme in the CM4 frequency selective fading channel yields similar performance to that in an AWGN channel [10]. For $N_u \leq N_a$, the link budget of the proposed HFH-OFDMA system is calculated in Table I. We consider a path loss exponent α of 2 in calculating the path loss at the cell boundary, 30m (L_2) [9]. The link budget shows that $\left[\frac{E_b}{N_0}\right]_{rcvd}$ and $\left[\frac{E_b}{N_0}\right]_{req}$ are 3.2 dB and (3.18 + ΔM) dB, respectively. ΔM is a margin which is intended to compensate for the variation in propagation loss.

Fig. 4(a) shows the FER performance of HFH-OFDMA system for $N_u > N_a$. As the HP collision probability (P_C) increases, the FER performance of the HFH-OFDMA system becomes worse. Fig. 4(b) shows the additionally required energy (ΔP) to satisfy an FER requirement of 0.01 as the HP collision probability increases. For an HP collision probability of 40 %, ΔP is 2.6 dB. ΔP depends on the applied channel coding scheme. Hence, we can reduce ΔP by applying a much stronger channel coding scheme (e.g. Turbo code of 1/3) to the HFH-OFDMA system.

TABLE I

CALCULATION OF LINK BUDGET OF HFH-OFDMA SYSTEMS AT THE PICONET BOUNDARY OF 30M ($N_u \leq N_a$)

Parameter	Value
Aggregated Information Rate (R_B)	26.6 Mb/s
Transmit Power (P_T)	-14.0 dBm
Path Loss at 1 meter (L_1)	44.2 dB
Path Loss at the cell boundary of 30m (L_2)	29.5 dB
Receiver Power ($P_R = P_T - L_1 - L_2$)	-87.7 dBm
Receiver Noise Figure at the Antenna Terminal (NF)	6.6 dB
Average Receiver Noise Power per Bit ($P_N = -174 + NF + 10 \times \log R_B$)	-93.2 dBm
Implementation Loss (I)	2.3 dB
Received E_b/N_0 ($\left[\frac{E_b}{N_0}\right]_{rcvd} = P_R - P_N - I$)	3.2 dB
Required E_b/N_0 ($\left[\frac{E_b}{N_0}\right]_{req} + \Delta M_{dB}$)	(3.18+ΔM) dB

TABLE II

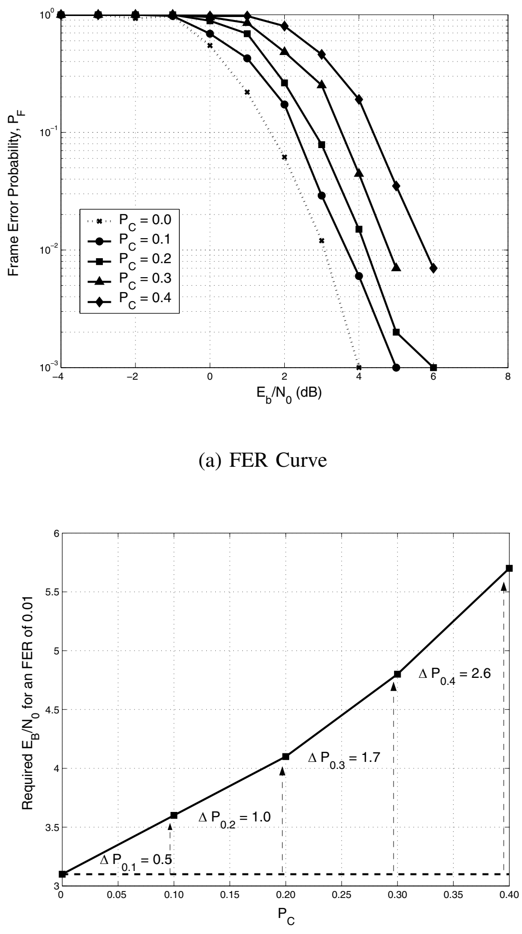
DOWNLINK USER CAPACITY OF THE HYBRID FH-OFDMA SYSTEM AND THE CONVENTIONAL FH-OFDMA SYSTEM

$R^{FEC} = 1/3, \quad \mu = 2, \quad \rho = 0.22, r = 30m,$
$P_C = 0.4, \quad [E_b/N_0]_{req} = 3.18dB, \quad \Delta P = 2.6dB$

$\overline{v}$	Hybrid FH-OFDMA	Conventional FH-OFDMA
0.1	256.2	50.0
0.2	128.5	50.0
0.3	85.9	50.0
0.4	64.6	50.0

$R^{FEC} = 1/3, \quad \mu = 2, \quad \rho = 0.22$, r = 30m,
$P_C = 0.4, \quad [E_b/N_0]_{req} = 6.18dB, \quad \Delta P = 2.6dB$

$\overline{v}$	Hybrid FH-OFDMA	Conventional FH-OFDMA
0.1	138.3	50.0
0.2	69.2	50.0
0.3	50.0	50.0
0.4	50.0	50.0



(a) FER Curve

(b) Required E_b/N_0 and ΔP

Fig. 4. FER Performance of HFH-OFDMA ($N_u > N_a$)

Table II shows the downlink user capacity of the proposed HFH-OFDMA system for varying the required E_b/N_0 and the mean user channel activity $\overline{v}$. Table II is derived from Eqn. (8), Eqn. (9), and Fig. 2. If the required E_b/N_0 value and $\overline{v}$ are equal to 3.18 dB and 0.1, respectively, C_{HFH} is limited by $C_{R,HFH}$ of 256 as in Table II. That is, the HFH-OFDMA system can accommodate 256 users with 525.2 kb/s in UWB indoor RANs if the required E_b/N_0 value and $\overline{v}$ are equal to 3.18 dB and 0.1. For a required E_b/N_0 value of 6.2 dB, if $\overline{v}$ is 0.3 or higher, C_{HFH} is fixed to 50 as in Table II although $C_{P,HFH}$ which limits C_{HFH} is less than 50. This is possible by implementing the algorithm, which selects the operation mode yielding larger downlink user capacity among non-collision mode ($N_u \leq N_a$) and collision mode ($N_u > N_a$) when $N_u > N_a$, in the HFH-OFDMA. In summary, the HFH-OFDMA system can accommodate more users than conventional FH-OFDMA system in OFDM based UWB indoor RANs.

IV. CONCLUSION

In this paper, we proposed a statistical multiplexing based HFH-OFDMA system for OFDM-based UWB RANs and analyzed the performance in terms of downlink user capacity. The analysis results show that the downlink user capacity of the HFH-OFDMA system is limited by either the total number of available subcarriers in a picocell (resource limited) or FCC UWB emission limit, -41.25 dBm/MHz (power limited). The proposed HFH-OFDMA system avoids unnecessary subcarrier collisions when the number of users is small. Moreover, the proposed HFH-OFDMA can accommodate more users than conventional FH-OFDMA through statistical multiplexing when the number of users is large.

ACKNOWLEDGMENT

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