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

Jo Woon Chong, *Student Member, IEEE*, Bang Chul Jung, *Student Member, IEEE*, and Dan Keun Sung, *Senior Member, IEEE*

***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). The downlink user capacity is here defined as the maximum allowable number of users served with a given data rate in a piconet. Statistical multiplexing, as noted by Walrand and Varaiya in 2000, is a method in which multiple users with intermittent transmissions efficiently share a link. The adoption of a statistical multiplexing concept enables the HFH-OFDMA system to accommodate many more users than the conventional FH-OFDMA system can. 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 the FCC UWB emission limit (power-limited). We analyze the downlink user capacity of the proposed HFH-OFDMA system in both single-piconet and multipiconet environments. In the single-piconet environment, the proposed HFH-OFDMA system which operates in 3.168–3.696-GHz band accommodates 256 users with a data rate of 532.5 kb/s in an OFDM-based UWB indoor RAN, while the proposed HFH-OFDMA system in the multipiconet environment, under the same conditions of the single-piconet environment, accommodates 110 users with a data rate of 532.5 kb/s.**

***Index Terms*—Downlink, frequency-hopping orthogonal frequency-division multiple-access (FH-OFDMA), indoor, MUI, multiple access, orthogonal frequency-division multiplexing (OFDM), orthogonal frequency-division multiple access (OFDMA), radio access network (RAN), statistical multiplexing, user capacity, ultra-wideband (UWB).**

I. Introduction

RECENTLY, ultra-wideband (UWB) technology, which operates in an overlayed bandwidth of 3.1–10.6 GHz, has been considered as a promising technology for accommodating various short-range 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. 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) [2], [3], and UWB technologies for low data rates in WPANs have also been proposed in IEEE 802.15 TG 4a [4]. The UWB technologies proposed in IEEE 802.15 TG 3a mainly aimed for efficiently supporting a small number of users requiring high data rates ranging from 110 to 480 Mb/s, while the IEEE 802.15 TG 4a committee discusses how to accommodate a large number of users requiring low data rates of several kilobits per second (kb/s) with an extremely low user channel activity of $10^{-4} \sim 10^{-5}$. However, this IEEE 802.15.4a-based technology may not be appropriate for supporting a large number of users requiring data rates of several tens to several hundreds of kb/s for indoor radio access networks (RANs), for example, in stations, airports, and department stores.

Orthogonal frequency-division multiplexing (OFDM) is one of the promising technologies for high-rate data transmission over frequency-selective fading channels. OFDM-based UWB technologies have been studied in [5]. OFDM technologies can easily overcome intersymbol-interference (ISI) in dense multipath environments such as UWB indoor environments [6]. An OFDM-based UWB technology, called a multiband orthogonal frequency-division multiplexing (MB-OFDM) physical technology was proposed by the Multi-band OFDM Alliance (MBOA) [2] in IEEE 802.15.3 TG 3a, and it has been discussed as a promising standard technology for high-rate WPAN.

MB-OFDM is a multiplexing and transmission scheme that allocates all of the subcarriers in the subband to a single user and it supports high data rate. However, it has difficulty in supporting a medium rate from several tens to several hundreds of kb/s. In this paper, we propose an efficient multiple-access scheme to support data rates of tens to several hundreds of kb/s for OFDM-based UWB indoor radio access networks (RANs). A number of multiple-access schemes for OFDM including OFDMA and FH-OFDMA have been proposed [6]. Among them, the frequency-hopping orthogonal frequency-division multiple-access (FH-OFDMA) technique yields a frequency diversity gain in frequency-selective fading channels like UWB indoor channels. In this conventional FH-OFDMA, subcarriers are exclusively allocated based on given hopping patterns (HPs).

In this paper, we propose a statistical multiplexing-based hybrid frequency-hopping (HFH)-OFDMA to increase the downlink user capacity of OFDM-based indoor UWB RANs. The downlink user capacity is defined as the maximum allowable number of users served with a given data rate in a piconet.

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The authors are with the Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea (e-mail: jwchong@cnr.kaist.ac.kr; jw9607@gmail.com; bcjung@cnr.kaist.ac.kr; dksung@ee.kaist.ac.kr).

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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 [1] is a method in which multiple users with intermittent transmissions efficiently share a link. Statistical multiplexing schemes do not have to control user data transmission, while scheduling-based schemes in cellular systems do. Moreover, the statistical multiplexing schemes 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 the proposed statistical multiplexing-based HFH-OFDMA system for OFDM-based UWB indoor RANs is described. The user capacity of the HFH-OFDMA system is analyzed in single-piconet and multipiconet environments. The performance of the proposed HFH-OFDMA system for OFDM-based UWB indoor RANs is evaluated through simulation in Section III. Finally, conclusions are presented in Section IV.

II. Statistical Multiplexing-Based HFM-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 whether the number of data users (N_u) exceeds the number of total available channels (N_a) in a piconet. The HFH-OFDMA system operates identically with the conventional FH-OFDMA system if $N_u \leq N_a$. Since each subcarrier is not allocated to different users at the same time in the conventional FH-OFDMA, no subcarrier collisions occur, as shown 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 the users may 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, whether it is busy or idle, of users with the subcarrier collision. This is possible 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 is done in a nonsubcarrier collision situation. This is because subcarrier collisions of inactive users do not affect the symbol values 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 of the colliding symbols are the same, as shown in User #3 and User #5 of the $(n+2)T_S$th slot in Fig. 1(b), then the HFH-OFDMA system controls the symbol power of the colliding subcarrier to be below −41.25 dBm/MHz, because this UWB emission limit is strictly regulated by the FCC [7], and it is called a synergy. If all of the colliding symbols are not the same, as shown in User #5 and User #N of the $(n+4)T_S$th slot in Fig. 1(b), then the HFH-OFDMA system controls the subcarriers to be off at that interval because the addition of different symbol values may yield an ambiguous symbol value at the receiver, and this is called a perforation. This symbol power control scheme which is based on synergy and perforation reduces the performance degradation when subcarrier collisions occur [8].

The collision probability (P_C) in the HFH-OFDMA system is expressed as [9]

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

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 comprises one data channel, respectively. Hence, N_a is equal to $(1-\rho)N_{\text{sub}}/k$.

The perforation probability (P_{P}) and the synergy probability (P_S) are expressed as

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

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

where π_i is the probability of modulation symbol $i \in \{0, 1, \ldots, s-1\}$ and s is equal to 2 for QPSK modulation [9].

The proposed HFH-OFDMA system does not cause unnecessary subcarrier collisions for $N_u \leq N_a$. However, for $N_u > N_a$, the HFH-OFDMA system accommodates more users than the number of total available channels at the sacrifice of some perforations by using statistical multiplexing.

B. Downlink User Capacity of HFH-OFDMA: Single-Piconet Environment

In the analysis of the downlink user capacity for conventional OFDMA systems, it is assumed that all of the available subcarriers are dedicatedly allocated to multiple users. In this case, the downlink user capacity is equal to the number of total available channels. However, the channel activity of data services is generally low (e.g., 0.1–0.2), and each subcarrier may be used during a small portion of time. Hence, the conventional OFDMA systems may waste resources and limit the user capacity when the channel activity is low. On the other hand, the downlink user capacity of the conventional OFDMA systems is also limited by power, although there are available subcarriers in a piconet. This case mainly occurs when most users are located at a rather far distance or when the transmit power is strictly, such as the UWB transmit power, which is strictly regulated by the FCC.

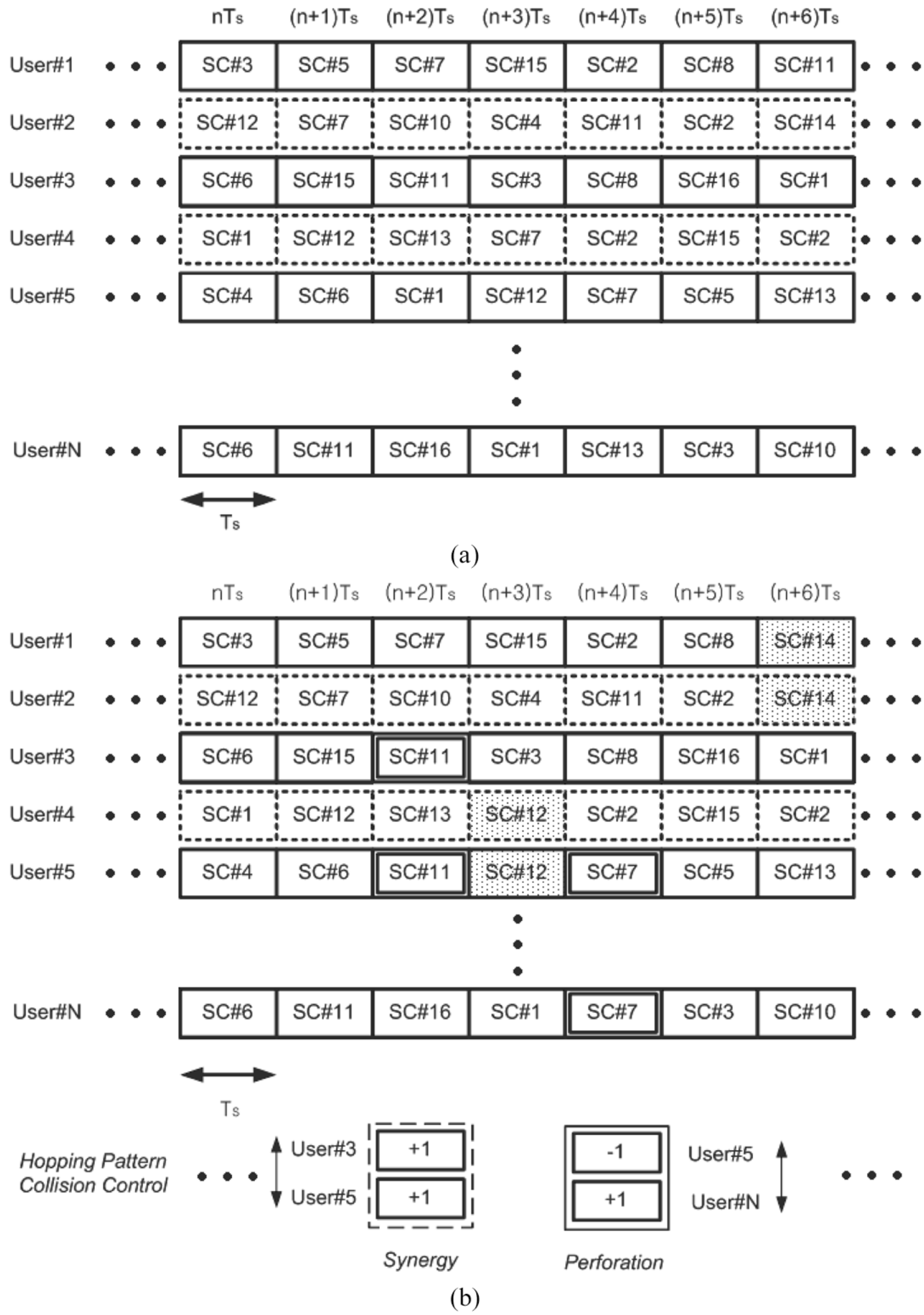


Fig. 1. Operational example of HFH-OFDMA. The HFH-OFDMA system operates identically with the conventional FH-OFDMA system for $N_u \leq N_a$. The HFH-OFDMA system allows subcarrier collisions and controls the symbol power based on both the user activity and the symbol value for $N_u > N_a$. (a) HFH-OFDMA $(N_u \leq N_a)$. (b) HFH-OFDMA $(N_u > N_a)$.

We analyze the downlink user capacity of the proposed HFH-OFDMA in two cases: a power-limited case and a resource-limited case. The downlink user capacity of the proposed HFH-OFDMA system is limited by the smaller of the user capacities for the two cases above, i.e., in the power-limited situation, the HFH-OFDMA system cannot accommodate new users due to a lack of transmit power although the number of available subcarriers is sufficient. On the other hand, in the resource-limited situation, the system cannot accommodate new users due to a lack of subcarriers, although the transmit power is sufficient. In this section, the downlink user capacity in a single-piconet environment is analyzed.

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

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

where

$[E_b/N_0]_{\rm req}$	required E_b/N_0 for a specific data rate;
$[E_b/N_0]^S_{\rm rcvd}$	received E_b/N_0 at the piconet boundary;
$\overline{v}$	mean user channel activity;
ΔE	additional required energy to compensate for the subcarrier collisions.

The received E_b/N_0 is expressed as

$$\left[\frac{E_b}{N_0}\right]^S_{\rm rcvd} = \frac{\left[\frac{S}{N_0}\right]^S_{\rm rcvd}}{R^{\rm FEC}\cdot\mu\cdot I} \quad (5)$$

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

The received signal-to-noise ratio (SNR) can be expressed as

$$\left[\frac{S}{N_0}\right]^S_{\rm rcvd} = \frac{P_T\cdot r^{-\alpha}\cdot X_0}{N_0\cdot L_1} \quad (6)$$

where

α	path-loss exponent;
r	distance from the PNC to the piconet boundary;
L_1	path loss at 1 m;
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 (6) into the S/N_0 value of (5) yields

$$\left[\frac{E_b}{N_0}\right]^S_{\rm rcvd} = \frac{P_T\cdot r^{-\alpha}}{R^{\rm FEC}\cdot\mu\cdot N_0\cdot L_1\cdot I}. \quad (7)$$

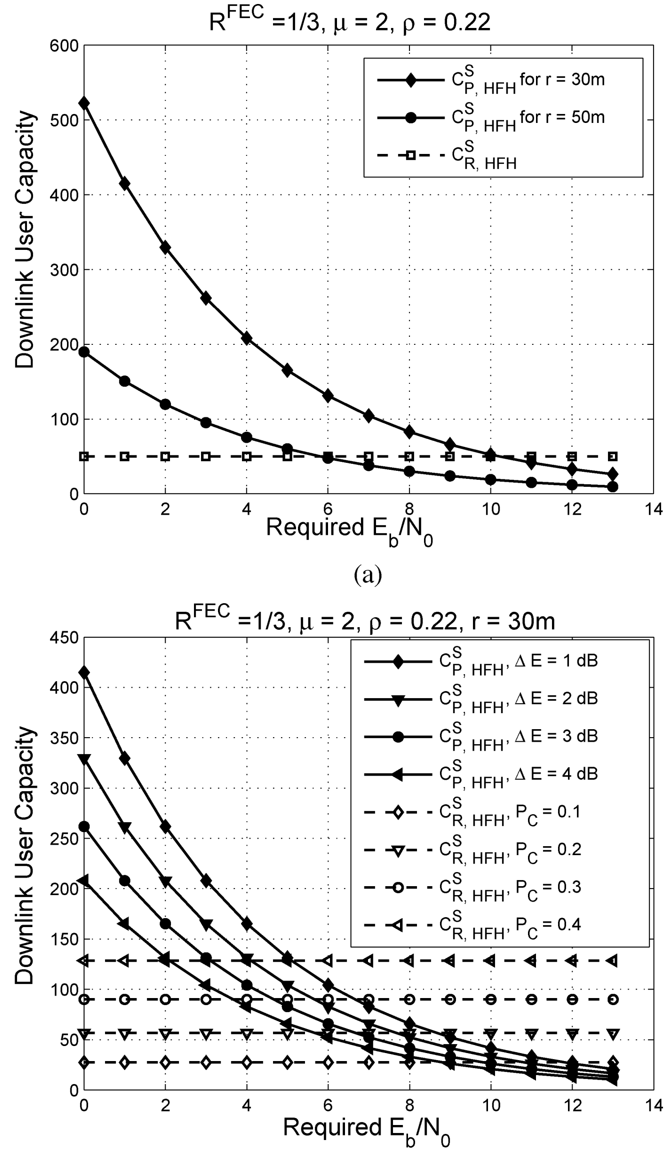
Substituting (7) into the $[E_b/N_0]^S_{\rm rcvd}$ value of (4) yields

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

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

The downlink user capacity in the resource-limited case ($C^S_{\rm R,HFH}$) can be derived from (1) and written as

$$C^S_{\rm R,HFH} = \begin{cases} \dfrac{(1-\rho)N_{\rm sub}}{k}, & \text{if } N_u \le N_a \\[2ex] 1+\dfrac{\log(1-P_C)}{\log\left(1-\dfrac{\overline{v}}{\frac{(1-\rho)N_{\rm sub}}{k}}\right)}, & \text{if } N_u > N_a \end{cases}. \quad (9)$$



(a) (b)

Fig. 2. Downlink user capacity of HFH-OFDMA in the single-piconet environment. The downlink user capacity is limited by the transmit power if the required E_b/N_0 is high or r is large (i.e., a power-limited situation). On the other hand, the downlink user capacity is limited by the resource if the required E_b/N_0 is low or r is small (i.e., a resource-limited situation). (a) Downlink user capacity $(N_u \le N_a)$. (b) Downlink user capacity $(N_u > N_a)$.

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

Taking into account the power-limited and resource-limited cases, the downlink user capacity of HFH-OFDMA systems ($C^S_{\rm HFH}$) is given as

$$C^S_{\rm HFH} = \min\left\{C^S_{\rm P,HFH}, C^S_{\rm R,HFH}\right\}. \quad (10)$$

Fig. 2 shows the downlink user capacity of the HFH-OFDMA system in a single-piconet environment for various sets of r, P_C, and ΔE. ρ, $N_{\rm sub}$, $R^{\rm FEC}$, and μ are set to 0.22, 128, 1/3, and 2,

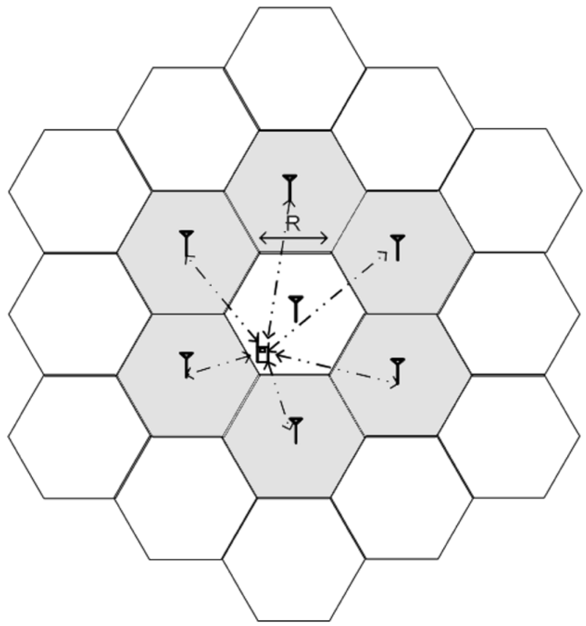


Fig. 3. Multipiconet environment. A target piconet is assumed to be closely surrounded by six neighbor piconets and the surrounding neighbor piconets interfere with the target piconet.

respectively. L_1, I, and $\overline{v}$ are set to 44.2 dB, 2.2 dB, and 0.2, respectively [2]. In particular, P_T is set to -14.0 dBm considering the FCC UWB emission limit [7]. For $N_u \le N_a$, as r increases, $C^S_{\text{P,HFH}}$ decreases, as shown in Fig. 2(a), because the path loss at the cell boundary increases. However, $C^S_{\text{R,HFH}}$ does not depend on r and remains constant. For a radius r of 30 m, C^S_{HFH} is limited by a $C^S_{\text{R,HFH}}$ value of 50 if the required E_b/N_0 is smaller than 10.2 dB. In the same case, C^S_{HFH} is limited by $C^S_{\text{P,HFH}}$, which is determined by (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. Fig. 2(b) shows that $C^S_{\text{P,HFH}}$ depends on ΔE and $C^S_{\text{R,HFH}}$ also depends on P_C. If $\overline{v}$, P_C, and ΔE are set to 0.2, 0.3, and 2 dB, respectively, then C^S_{HFH} is limited by a $C^S_{\text{R,HFH}}$ value of 89, which is derived from (9) if the required E_b/N_0 is smaller than 5.7 dB. In the same case, C^S_{HFH} is limited by $C^S_{\text{P,HFH}}$, which is determined by (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 (i.e., a power-limited situation). On the other hand, the downlink user capacity is limited by the resource if the required E_b/N_0 is low or r is small (i.e., a resource-limited situation).

C. Downlink User Capacity of HFH-OFDMA: Multipiconet Environment

Fig. 3 shows a multipiconet environment considered in the analysis. A target piconet is assumed to be closely surrounded by six neighbor piconets. Since the target piconet and the surrounding neighbor piconets operate in the same band that ranges from 3.168 to 3.696 GHz, the surrounding neighbor piconets interfere with the target piconet. This interference reduces the downlink user capacity of the HFH-OFDMA system, compared with that in the single-piconet environment without interference from neighbor piconets.

In the power-limited case, the downlink user capacity ($C^M_{\text{P,HFH}}$) of the HFH-OFDMA system in the multipiconet environment can be expressed as

$$C^M_{\text{P,HFH}} = \frac{\left[\frac{E_b}{I_0+N_0}\right]^M_{\text{rcvd}}}{\overline{v}\left(\left[\frac{E_b}{I_0+N_0}\right]_{\text{req}} \cdot \Delta E\right)} \cdot \frac{(1-\rho)N_{\text{sub}}}{k} \tag{11}$$

where I_0 denotes the interference from other PNCs. The received $E_b/(I_0+N_0)$ and the received signal-to-interference-and-noise ratio (SINR) are written, respectively, as

$$\left[\frac{E_b}{I_0+N_0}\right]^M_{\text{rcvd}} = \frac{\left[\frac{S}{(I_0+N_0)}\right]^M_{\text{rcvd}}}{R^{\text{FEC}} \cdot \mu \cdot I} \tag{12}$$

$$\left[\frac{S}{I_0+N_0}\right]^M_{\text{rcvd}} = \frac{P_T r^{-\alpha} X_0 L_1^{-1}}{\left(W \sum_{i=1}^{i_0} P_T d_i^{-\alpha} X_i L_1^{-1} + N_0\right)} \tag{13}$$

where

- d_i distance from the ith interfering PNC to the mobile station;
- n average number of users in an interfering piconet;
- i_0 number of interfering piconets considered;
- W interference loading factor;
- X_i shadowing factor from the ith interfering PNC.

The interference loading factor W is expressed as

$$W = \min\left\{1, \frac{\overline{v}kn + \rho N_{\text{sub}}}{N_{\text{sub}}}\right\}. \tag{14}$$

Both X_0 and X_i are assumed to have a median value of 1. Substituting (13) into the $[S/(I_0+N_0)]^M_{\text{rcvd}}$ value of (12) yields

$$\left[\frac{E_b}{I_0+N_0}\right]^M_{\text{rcvd}} = \frac{P_T r^{-\alpha} L_1^{-1}}{R^{\text{FEC}} \mu I \left(W \sum_{i=1}^{i_0} P_T d_i^{-\alpha} L_1^{-1} + N_0\right)}. \tag{15}$$

Substituting (15) into the $[E_b/(I_0+N_0)]^M_{\text{Rcvd}}$ value of (11) yields (16), which is shown at the bottom of the following page. The additional term in the denominator, $W \sum_{i=1}^{i_0} P_T d_i^{-\alpha} L_1^{-1}$, denotes the interference from neighbor PNCs, and it reduces $C^M_{\text{P,HFH}}$. W varies from 0 to 1. W is equal to 0 when no neighbor piconet exists, while W is equal to 1 when full interference is loaded from the neighbor piconets to the target piconet. From this fact, $[E_b/(I_0+N_0)]^M_{\text{rcvd}}$ can have a range as

$$\left[\frac{E_b}{N_0}\right]^S_{\text{rcvd}} \ge \left[\frac{E_b}{I_0+N_0}\right]^M_{\text{rcvd}} \tag{17}$$

$$\left[\frac{E_b}{I_0+N_0}\right]^M_{\text{rcvd}} \ge \frac{P_T r^{-\alpha} L_1^{-1}}{R^{\text{FEC}} \mu I \left(\sum_{i=1}^{i_0} P_T d_i^{-\alpha} L_1^{-1} + N_0\right)} \tag{18}$$

If $W = 0$, that is, $[E_b/(I_0+N_0)]^M_{\rm rcvd}|_{W=0} = [E_b/N_0]^S_{\rm rcvd}$, then $C^M_{\rm P,HFH}$ has the maximum value as given by

$$\left[C^M_{\rm P,HFH}\right]_{\max} = C^M_{\rm P,HFH}\big|_{W=0} = C^S_{\rm P,HFH}. \tag{19}$$

If $W = 1$, that is, the full interference from the neighbor piconet affects the target piconet, then $C^M_{\rm P,HFH}$ has the minimum value as given by

$$\begin{aligned}\left[C^M_{\rm P,HFH}\right]_{\min} &= C^M_{\rm P,HFH}\big|_{W=1} \\ &= \frac{P_T r^{-\alpha} L_1^{-1}(1-\rho) N_{\rm sub}}{R^{\rm FEC}\mu I\left(\sum_{i=1}^{i_0} P_T d_i^{-\alpha} L_1^{-1} + N_0\right)\overline{v}\left(\left[\frac{E_b}{I_0+N_0}\right]_{\rm req}\Delta E\right)k}.\end{aligned} \tag{20}$$

As mentioned, cell coverage of the indoor RAN environments, such as stations, airports, and department stores, is not as wide as that of cellular system environments. Hence, considering interference only from the closely surrounded six neighbor PNCs and neglecting the thermal noise at the receiver (N_0), (20) is approximated as

$$\left[C^M_{\rm P,HFH}\right]_{\min} \simeq \frac{q^\alpha \cdot (1-\rho)\cdot N_{\rm sub}}{6\cdot R^{\rm FEC}\cdot \mu \cdot I \cdot \overline{v}\left(\left[\frac{E_b}{I_0+N_0}\right]_{\rm req}\cdot \Delta E\right)\cdot k} \tag{21}$$

where $q = D/r$, and D denotes the distance from a target PNC to a neighbor PNC.

In the resource-limited case, the downlink user capacity $(C^M_{\rm R,HFH})$ of the HFH-OFDMA system in the multipiconet environment is identical to $C^S_{\rm R,HFH}$, since the number of subcarriers in a piconet does not change in the multipiconet environment. Hence, $C^M_{\rm R,HFH}$ is expressed as

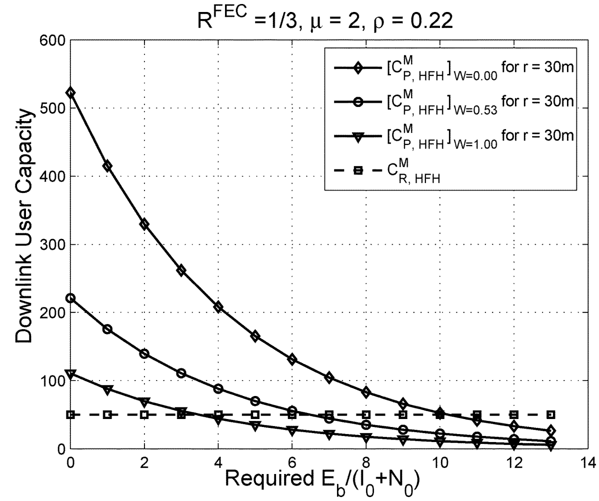
$$C^M_{\rm R,HFH} = C^S_{\rm R,HFH}. \tag{22}$$

Similar to the single-piconet environment, the downlink user capacity $(C^M_{\rm HFH})$ of the HFH-OFDMA system in the multipiconet environment is written as

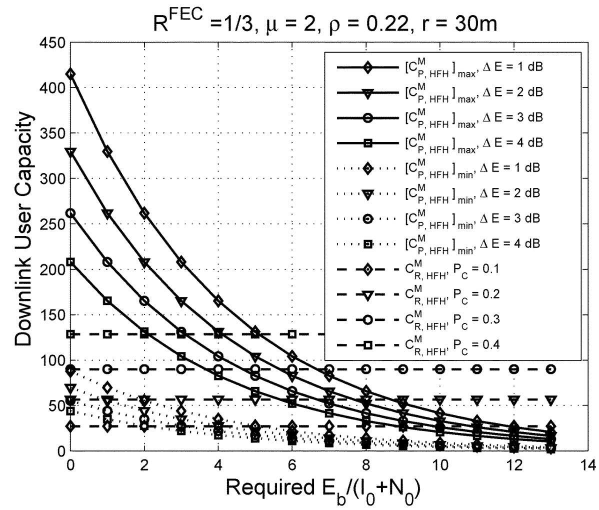
$$C^M_{\rm HFH} = min\left\{C^M_{\rm P,HFH}, C^M_{\rm R,HFH}\right\}. \tag{23}$$

Fig. 4 shows the maximum and minimum downlink user capacities of the HFH-OFDMA system in the multipiconet environment. The parameter values are the same as for the single-piconet environment. For $N_u \le N_a$, Fig. 4(a) shows a comparison of $C^M_{\rm P,HFH}$ and $C^M_{\rm R,HFH}$ for the three different cases of interference loading. $C^M_{\rm P,HFH}$ decreases although $C^M_{\rm R,HFH}$ remains constant as the interference loading factor W increases.

For $N_u > N_a$, the proposed HFH-OFDMA in the multipiconet environment allows subcarrier collisions, as shown in the single-piconet environment. Fig. 4(b) shows $C^M_{\rm P,HFH}$ and $C^M_{\rm R,HFH}$ for $N_u > N_a$ and shows a similar trend to Fig. 2(b). $C^M_{\rm P,HFH}$ also decreases as W increases. The HFH-OFDMA system in the multipiconet environment normally operates with $W = w_0$, where w_0 ranges from 0 to 1.



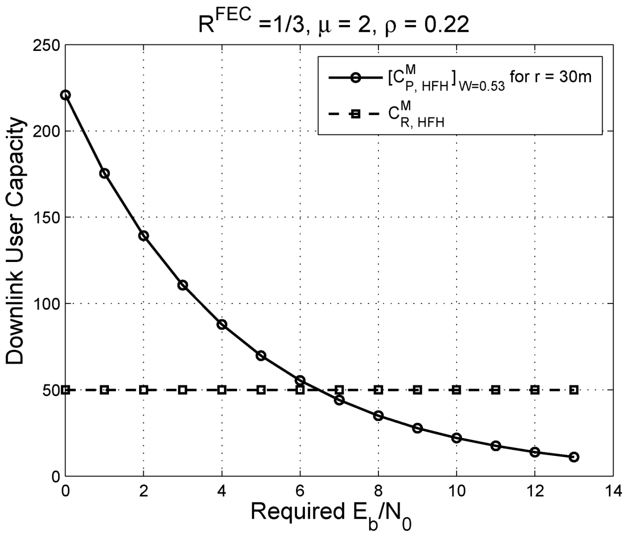
(a)



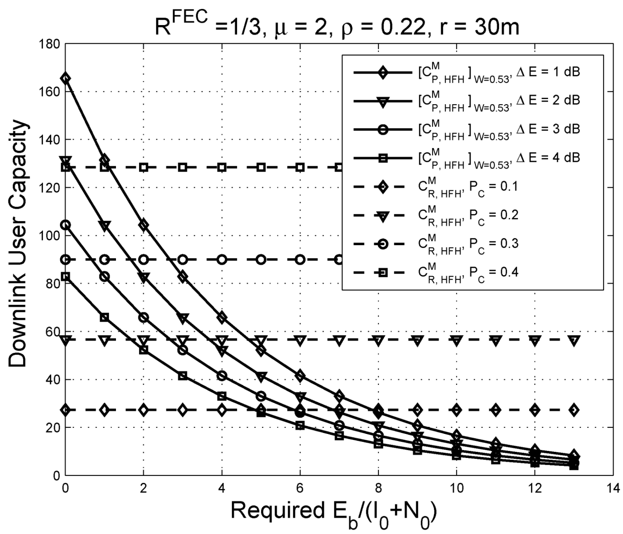
(b)

Fig. 4. Maximum and minimum downlink user capacities of the HFH-OFDMA system in the multipiconet environment. $C^M_{\rm P,HFH}$ decreases although $C^M_{\rm R,HFH}$ remains constant as the interference loading factor W increases. (a) Downlink user capacity $(N_u \le N_a)$. (b) Downlink user capacity $(N_u > N_a)$.

$$C^M_{\rm P,HFH} = \frac{P_T r^{-\alpha} L_1^{-1}(1-\rho) N_{\rm sub}}{R^{\rm FEC}\mu I\left(W\sum_{i=1}^{i_0} P_T d_i^{-\alpha} L_1^{-1} + N_0\right)\overline{v}\left(\left[\frac{E_b}{I_0+N_0}\right]_{\rm req}\Delta E\right)k} \tag{16}$$



(a)



(b)

Fig. 5. Downlink user capacity of the HFH-OFDMA system in the multipiconet case ($W = 0.53$). This value of 0.53 is derived in the case when the average number of users in an interfering piconet is 100 under the assumption that $\overline{v}$, k, ρ, and $N_{\rm sub}$ are set to 0.2, 2, 0.22, and 128, respectively. (a) Downlink user capacity ($N_u \leq N_a$). (b) Downlink user capacity ($N_u > N_a$).

Fig. 5 shows the downlink user capacity of the HFH-OFDMA system in the multipiconet environment when the interference loading factor W is set to 0.53. This value of W is derived in the case when the average number of users in an interfering piconet is 100, that is, n is equal to 100, under the assumption that $\overline{v}$, k, ρ, and $N_{\rm sub}$ are set to 0.2, 2, 0.22, and 128, respectively. For $N_u \leq N_a$, $C^M_{\rm HFH}$ is limited by a $C^M_{\rm R,HFH}$ value of 50, as shown in Fig. 5(a) if the required $E_b/(I_0+N_0)$ is smaller than 6.3 dB. In the same case, $C^M_{\rm HFH}$ is limited by $C^M_{\rm P,HFH}$ if the required $E_b/(I_0+N_0)$ is larger than 6.3 dB.

For $N_u > N_a$, if we assume that $\overline{v}$, P_C, and ΔP are set to 0.2, 0.3, and 2.0 dB, respectively, $C^M_{\rm HFH}$ is limited by a $C^M_{\rm R,HFH}$ value of 90, which is derived from (22) if the required $E_b/(I_0+N_0)$ is smaller than 1.9 dB. In the same case, $C^M_{\rm HFH}$ is limited by $C^M_{\rm P,HFH}$ which is determined by (16) if the required $E_b/(I_0+N_0)$ is larger than 1.9 dB.

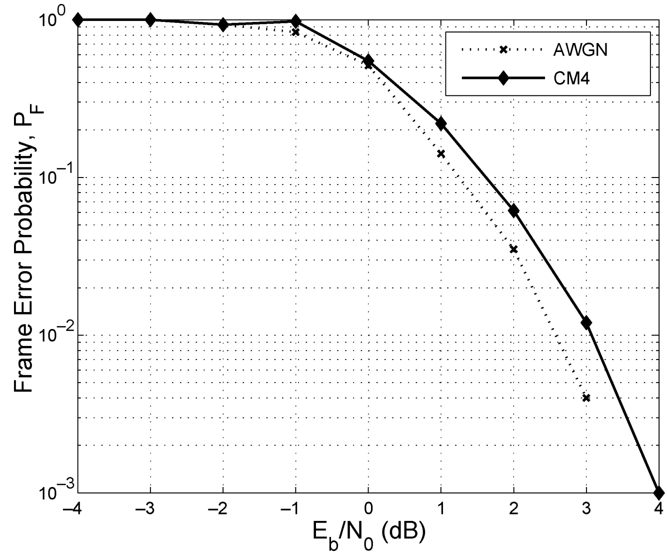


Fig. 6. FER performance of HFH-OFDMA ($N_u \leq N_a$). To achieve an FER requirement of 0.01 in the UWB indoor RANs (CM4), the proposed HFH-OFDMA requires an E_b/N_0 value of 3.18 dB when $N_u \leq N_a$.

III. Performance Evaluation

We consider an additive white Gaussian noise (AWGN) channel and the CM4, a UWB indoor channel that is one of the IEEE 802.15 TG 3a UWB indoor channel models [10]. 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 nonline-of-sight (NLOS) UWB indoor environment.

OFDMA parameter values are set 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 inverse fast Fourier transform (IFFT)/fast Fourier transform (FFT): 242.42 ns;
- cyclic prefix: 60.61 ns;
- 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 two groups and that two subcarriers from each group are allocated to a user at a time. Therefore, each group consists of 50 subcarriers and each user transmits data following two HPs, which are independently allocated by two groups. In this case, $N_{\rm sub}$, ρ, and k are set to 128, 0.22, and 2, respectively. Hence, the number of available channels (N_a) is 50, which is given by the relation of $N_a = (1-\rho)N_{\rm sub}/k$. Convolutional coding with a code rate 1/3 and quaternay phase-shift keying (QPSK) modulation are used. Each bit is assumed to be repeated eight 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 eight repeated bits. A frame consists of 1200 coded bits.

Fig. 6 shows the frame-error-rate (FER) curve of the proposed HFH-OFDMA system for $N_u \leq N_a$. To achieve an FER re-

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

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 ($\left[\frac{E_b}{N_0}\right]^S_{rcvd} = P_R - P_N - I$)	3.2 dB
Required E_b/N_0 ($\left[\frac{E_b}{N_0}\right]_{req} + \Delta M_{dB}$)	(3.18+ΔM) dB

quirement 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 in the CM4 channel is close to that in the AWGN channel. This is because the MRC scheme in the CM4 frequency-selective fading channel yields similar performance to that in the AWGN channel [11]. 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, 30 m (L_2) [10]. The link budget shows that $[E_b/N_0]^S_{\text{rcvd}}$ and $[E_b/N_0]_{\text{req}}$ are 3.2 dB and $(3.18 + \Delta M)$ dB, respectively. ΔM is a margin which is used to compensate for the variation in propagation loss.

Fig. 7(a) shows the FER performance of the 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. 7(b) shows the additional required energy (ΔE) to satisfy an FER requirement of 0.01 as the HP collision probability increases. For an HP collision probability of 40%, ΔE is 2.6 dB. ΔE depends on the applied channel coding scheme. Hence, we can reduce ΔE by applying a much stronger channel coding scheme (for example, a Turbo coder with a code rate of 1/3) to the HFH-OFDMA system.

Table II shows the downlink user capacity of the proposed HFH-OFDMA system for varying the required E_b/N_0 values and the mean user channel activity $\overline{v}$ in the single-piconet environmet. Table II is derived from (8), (9), and Fig. 2. If the required E_b/N_0 value and $\overline{v}$ are set to 3.18 dB and 0.1, respectively, then C_{HFH} is limited by a $C_{\text{R,HFH}}$ value of 256, as shown in Table II, i.e., 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 set to 3.18 dB and 0.1, respectively. For a required E_b/N_0 value of 4.7 dB, if $\overline{v}$ is 0.4, then C_{HFH} is fixed to 50, as shown in Table II, although $C_{\text{P,HFH}}$ is less than 50. We need to select the operation mode yielding larger downlink user capacity between the noncollision mode ($N_u \leq N_a$) and the collision mode ($N_u > N_a$) when $N_u > N_a$, in the HFH-OFDMA.

Table III shows the downlink user capacity of the proposed HFH-OFDMA system for varying the required $E_b/(I_0 + N_0)$ values and the mean user channel activity $\overline{v}$ in the multipiconet

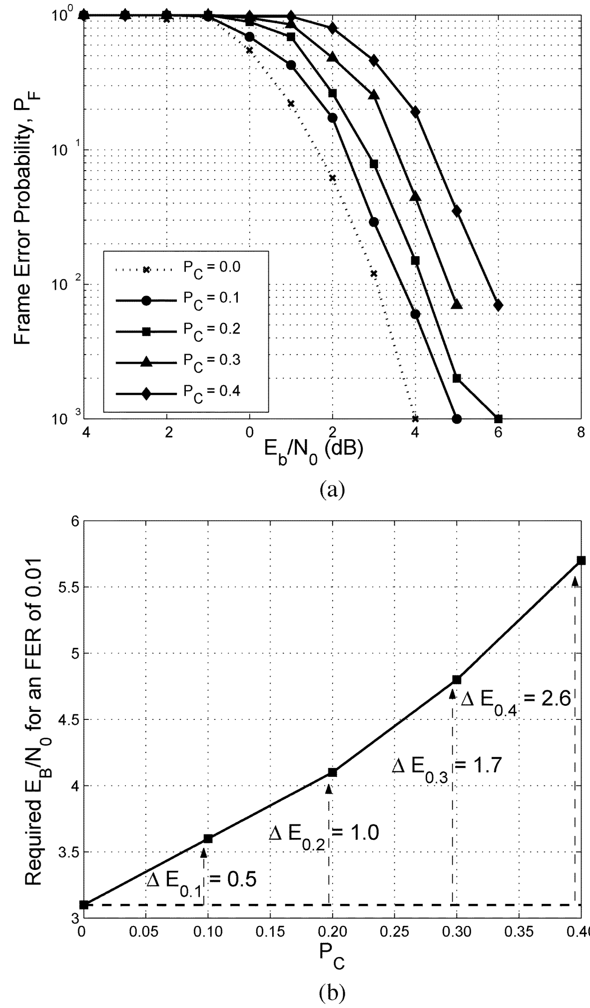


Fig. 7. FER performance of HFH-OFDMA ($N_u > N_a$). As the HP collision probability (P_C) increases, the HFH-OFDMA system needs additional required energy (ΔE) to satisfy an FER requirement of 0.01. (a) FER curve. (b) Required E_b/N_0 and ΔE for an FER of 0.01.

TABLE II
DOWNLINK USER CAPACITY OF THE HYBRID FH-OFDMA SYSTEM AND THE CONVENTIONAL FH-OFDMA SYSTEM IN THE SINGLE-PICONET ENVIRONMENT

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

$\overline{v}$	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,
$P_C = 0.4, \quad [E_b/N_0]_{req} = 4.7dB, \quad \Delta E = 2.6dB$

$\overline{v}$	Hybrid FH-OFDMA	Conventional FH-OFDMA
0.1	195.64	50.0
0.2	97.82	50.0
0.3	65.21	50.0
0.4	50.0	50.0

environment. Table III is derived from (16), (22), and Fig. 5. If the required $E_b/(I_0 + N_0)$ value and $\overline{v}$ are set to 3.18 dB and 0.1, respectively, then C^M_{HFH} is limited by a $C^M_{\text{P,HFH}}$ value of

TABLE III
DOWNLINK USER CAPACITY OF THE HYBRID FH-OFDMA SYSTEM AND THE CONVENTIONAL FH-OFDMA SYSTEM IN THE MULTIPICONET ENVIRONMENT

$R^{FEC} = 1/3, \quad \mu = 2, \quad \rho = 0.22, \quad r = 30m, \quad W = 0.53$

$P_C = 0.4, \quad [E_b/(I_0 + N_0)]_{req} = 3.18dB, \quad \Delta E = 2.6dB$

$\overline{v}$	Hybrid FH-OFDMA	Conventional FH-OFDMA
0.1	110.50	50.0
0.2	55.25	50.0
0.3	50	50.0
0.4	50	50.0

$R^{FEC} = 1/3, \quad \mu = 2, \quad \rho = 0.22, \quad r = 30m, \quad W = 0.53$

$P_C = 0.4, \quad [E_b/(I_0 + N_0)]_{req} = 4.7dB, \quad \Delta E = 2.6dB$

$\overline{v}$	Hybrid FH-OFDMA	Conventional FH-OFDMA
0.1	78.02	50.0
0.2	50.0	50.0
0.3	50.0	50.0
0.4	50.0	50.0

110, as shown in Table III. That is, the HFH-OFDMA system can accommodate 110 users with 525.2 kb/s in UWB indoor RANs if the required $E_b/(I_0 + N_0)$ value and $\overline{v}$ are set to 3.18 dB and 0.1, respectively. For a required $E_b/(I_0 + N_0)$ value of 4.7 dB, if $\overline{v}$ is 0.2 or higher, then C^M_{HFH} is fixed to 50, as shown in Table III although $C^M_{\text{P,HFH}}$ is less than 50. In summary, the HFH-OFDMA system in both single-piconet and multipiconet environments can accommodate more users than the conventional FH-OFDMA system in OFDM-based UWB indoor RANs.

IV. CONCLUSION

In this paper, we proposed a statistical multiplexing-based HFH-OFDMA system as a multiple-access scheme for OFDM-based UWB indoor RANs and analyzed the performance in terms of the downlink user capacity in single-piconet and multipiconet environments. 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 piconet (resource-limited) or an FCC UWB emission limit of −41.25 dBm/MHz (power-limited). The proposed HFH-OFDMA system does not cause unnecessary subcarrier collisions when the number of users is small. Moreover, the proposed HFH-OFDMA can accommodate more users than the conventional FH-OFDMA through statistical multiplexing when the number of users is large.

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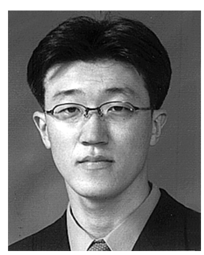
Jo Woon Chong (S'02) received the B.S. and M.S. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2002 and 2004, respectively, and is currently working toward the Ph.D. degree at KAIST.

Since 2003, he has been a Teaching and Research Assistant with the Department of Electrical Engineering and Computer Science, KAIST. His research interests include ultra-wideband (UWB) communication systems, OFDM systems, multiple-access technologies for wireless personal area networks (WPANs) and wireless local area networks (WLANs), and *ad-hoc* networks.



Bang Chul Jung (S'02) received the B.S. degree in electronics engineering from Ajou University, Suwon, Korea, in 2002, the M.S. degree in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2004, and is currently working toward the Ph.D. degree at KAIST.

Since 2003, he has been a Teaching and Research Assistant with the Department of Electrical Engineering and Computer Science, KAIST. His research interests include orthogonal code-hopping systems for packet data transmission, OFDM systems, radio resource management, wireless scheduling algorithms, link- and system-level simulations for third- and fourth–generation wireless communication systems, adaptive modulation and coding, and multiple-input multiple-output systems.

Dan Keun Sung (S'80–M'86–SM'00) received the B.S. degree in electronics engineering from Seoul National University, Seoul, Korea, in 1975, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin, in 1982 and 1986, respectively.

In 1986, he joined the faculty of the Korea Advanced Institute of Science and Technology (KAIST), Daejon, Korea, where he is currently a Professor with the Department of Electrical Engineering and Computer Science. He was Director of the Satellite Technology Research Center (SaTReC) of KAIST from 1996 to 1999. He is also the Division Editor of the *Journal of Communications and Networks*. His research interests include mobile communication systems and networks, high-speed networks, next-generation IP-based networks, traffic control in wireless and wireline networks, signaling networks, intelligent networks, performance and reliability of communication systems, and microsatellites.

Dr. Sung is a member of the National Academy of Engineering of Korea. He is the Editor of the *IEEE Communication Magazine*. He was the recipient of the National Order of Merits, Dongbaek Medal in 1992, the Research Achievement Award in 1997, the MoMuc Paper Award in 1997, the Academic Excellent Award in 2000, the Best Paper Award at APCC2000, and This Month's Scientist Award by MOST and KOSEF in 2004.