Analysis of Resource Assignment for Directional Multihop Communications in mm-Wave WPANs

Meejoung Kim, Seung-Eun Hong, Yongsun Kim, and Jinkyeong Kim

This paper presents an analysis of resource assignment for multihop communications in millimeter-wave (mm-wave) wireless personal area networks. The purpose of this paper is to figure out the effect of using directional antennas and relaying devices (DEVs) in communications. The analysis is performed based on a grouping algorithm, categorization of the flows, and the relaying DEV selection policy. Three schemes are compared: direct and relaying concurrent transmission (DRCT), direct concurrent transmission (DCT), and direct nonconcurrent transmission (DNCT). Numerical results show that DRCT is better than DCT and DCT is better than DNCT for any antenna beamwidths under the proposed algorithm and policy. The results also show that using relaying DEVs increases the throughput up to 30% and that there is an optimal beamwidth that maximizes spatial reuse and depends on parameters such as the number of flows in the networks. This analysis can provide guidelines for improving the performance of mm-wave band communications with relaying DEVs.

Keywords: Directional antenna, millimeter-wave, multihop, resource assignment, IEEE 802.15.3c.

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I. Introduction

A 60-GHz band is referred to as millimeter-wave (mm-wave) because the wavelength at this band is between 1 mm and 10 mm. The Federal Communications Commission has allocated the mm-wave band between 57 GHz and 64 GHz as a flexible access common spectrum, which allows for unlicensed band utilization. With the recent advances in radio frequency integrated circuit design in mm-wave bands [1], there has been growing interest in standardization and realizing specifications for mm-wave systems. There are two standards for mm-wave wireless personal area networks (WPANs): IEEE 802.15.3c and ECMA-387. The former is based on centralized networks [2], whilst the latter is based on distributed networks [3] aiming for more than 2 Gbps as a target data rate. In addition, the standardization of IEEE 802.11ad is ongoing, which is based on centralized networks with a maximum data rate of 7 Gbps [4].

The mm-wave band has unique characteristics: high propagation loss, short wavelength, large bandwidth, and high level of interaction with atmospheric constituents. Such characteristics are associated with many properties, such as supporting a high data rate and short communication coverage. To compensate for short communication coverage of the mm-wave band, utilization of directional antennas at the physical layer is recommended. In mm-wave WPANs with directional antennas, high directivity and high path loss allow noninterfering hops to transmit concurrently over mm-wave channels.

There are various situations that require multihop in communication in the mm-wave band, which are as follows. 1) Since oxygen absorption peaks at 60 GHz, the mm-wave degrades significantly over distance. Therefore, a traffic flow transmitting over multiple short hops can achieve much higher flow throughput than that over a single long hop in an mm-wave network. 2) A transmitter and receiver pair cannot communicate directly if the distance between them is longer than the transmission range, which is owing to the short transmission range of the mm-wave band. 3) In high frequency bands, reflection is more dominant than diffraction in received power and this requires a line-of-sight (LOS) link to achieve high data rate. Therefore, a relay is needed for data transmission if moving obstacles or blockages are located within the LOS link between a transmitter and the corresponding receiver. That is, a single hop can be replaced with multiple hops for several reasons, such as to successfully communicate, achieve a high data rate, and improve performance.

Research was previously conducted on the general issues for single-hop communications [5]-[11] and multihop communications in mm-wave WPANs [12], [13]. Exclusive region (ER)-based resource management scheme and the concurrent transmissions were considered, to explore the spatial multiplexing gain in mm-wave WPANs using directional antennas in [5], [6]. Only single-hop communications were considered and the ratio of region covered by the main lobe and side lobe was used in the computation of the ER. In [7], the authors proposed a scheme that takes advantage of the large path loss in the mm-wave band. In the scheme, a single time division multiple access (TDMA) time slot can be reallocated and reused by multiple communication links simultaneously. Power controlled concurrent transmission with a directional antenna was proposed in [8]. An analytical model considering hybrid multiple access was constructed to study the throughput of the IEEE 802.15.3c mm-wave WPAN system [9]. The directional carrier sense multiple access/collision avoidance (CSMA/CA) protocol in the no acknowledgement and immediate acknowledgement modes for IEEE 802.15.3c was analyzed probabilistically under saturation environments in [10], [11]. A multihop concurrent transmission scheme was proposed to exploit the spatial capacity of the mm-wave WPAN [12]. They designed a hop selection metric to select appropriate relay hops for a traffic flow, aiming to improve the flow throughput and balance the traffic load across the network. An exhaustive search was performed to find relaying devices (DEVs) considering concurrent transmission with other flows. The communication success probability of two randomly selected DEVs in mm-wave WPANs was analyzed in [13]. In the analysis, relaying DEVs were considered in communication. On the other hand, the spatial interference statistics for a 60-GHz band was analyzed in [14]. They estimated the collision probability in mesh networks as a function of the antenna patterns and the density of simultaneously transmitting nodes.

To improve the network capacity, multiple traffic flows that do not cause harmful interference to each other can be scheduled for concurrent transmissions. In this paper, we analyze a resource assignment scheme in which multiple flows are scheduled for concurrent transmissions. Since the analysis can be applicable to any standards that support mm-wave WPANs, one specific standard, IEEE 802.15.3c, is considered in this paper. The concept of ER and the probability density function (PDF) of distance between DEVs are used for analysis. Spatial reuse owing to the use of directional antennas and multihop communications are considered. To the best of our knowledge, no prior research analyzed multihop communication in mm-wave WPANs probabilistically. Even though a multihop concurrent transmission scheme was proposed in [12], the approach used in the reference is different from ours. Hop selection metric was considered and an exhaustive search to find the appropriate relaying DEVs was performed. Analysis was not presented.

The contribution of this paper can be summarized as follows. 1) From a set of flows, concurrently transmittable flows are grouped based on the concept of ER. 2) The calculation of ER is more analytic, introducing the PDF of distance of DEVs. 3) In each group of concurrently transmittable flows, flows that need relaying DEVs are separated, and the number of such flows is derived explicitly. 4) The average number of concurrently transmittable flows and the average number of time slots used for transmissions of such flows are computed probabilistically. 5) Based on the obtained values, such performance measures as throughput are obtained in closed forms. 6) The characteristics of 802.15.3c, such as the path loss model and parameters, are used.

The remainder of the paper is organized as follows. Section II explains the system model. The grouping algorithm and an analysis of resource assignment by considering relaying DEVs are presented in section III. Section IV presents performance measures, and results of a numerical analysis are discussed in section V. Finally, section VI presents the conclusions.

II. System Model

In this section, IEEE 802.15.3c MAC is briefly explained and the path loss model for IEEE 802.15.3c is investigated.

1. Overview of IEEE 802.15.3c MAC

The fundamental topology of the IEEE 802.15.3c standard is a piconet, consisting of a piconet coordinator (PNC) and several slave DEVs within its transmission range. The channel

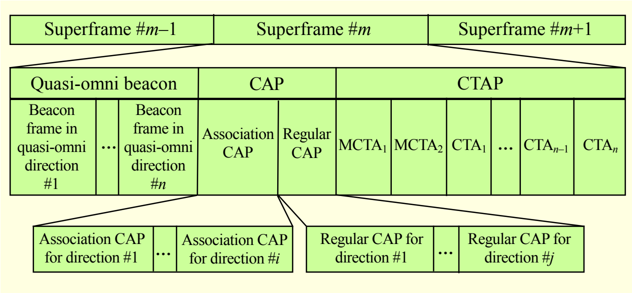

Fig. 1. Superframe structure of IEEE 802.15.3c.

time in the piconet is based on a time-slotted superframe that consists of three major components: a beacon, the contention access period (CAP), and the channel time allocation period (CTAP). The CAP is divided into association CAP and regular CAP, while CTAP is composed of the channel time allocations (CTAs) and management CTAs (MCTAs). The medium access mechanism in the CAP is CSMA/CA whilst in the CTAP is TDMA. The association CAP is only used by DEVs to send association request commands to the PNC, while the regular CAP can be used for data exchanges among DEVs and reservation of the CTAs in CTAP between DEVs and the PNC. DEVs require channel access times to the PNC during the MCTA period. CTAs are used for commands, isochronous data, and asynchronous data and have guaranteed start times and durations that allow for power saving and guaranteed QoS. The superframe structure of IEEE 802.15.3c is presented in Fig. 1.

This paper focuses on the analysis of spatial reuse in the CTAP, which is a reservation period. A single channel and the use of relaying DEVs are considered. Each DEV is equipped with a directional antenna. The beamwidths of these antennas are assumed to be identical. The antennas of all source-DEV-destination-DEV (S-D) pairs are directed toward their peers by beamforming, and the antenna direction is fixed during communication between a pair. A DEV cannot transmit and receive simultaneously.

2. Path Loss Model of IEEE 802.15.3c

For directional antennas, there are two models: the flattop model that neglects the side lobe effect and the cone plus circle model in 2D (or the cone plus sphere model in 3D) that considers the side lobe effect. Since the realistic antenna pattern is complex and does not result in a fundamental change of the capacity [15], in this paper, the cone plus circle model is employed assuming that all DEVs lie in the same plane. Then, the antenna gains with the main lobe and side lobe effects are defined by

$$G_{\mathrm{m}} = 2\pi\eta/\theta \quad \text{and} \quad G_{\mathrm{s}} = 2\pi(1-\eta)/(2\pi-\theta), \qquad (1)$$

where η and θ, $0 < \theta \le 2\pi$, are the antenna radiation efficiency and the main lobe beamwidth, respectively.

Let $G_{\mathrm{T}}(i)$, $G_{\mathrm{R}}(i)$ ([dBi]), and $r_{i,j}$ be the antenna gains for the transmitter and receiver of frame i, and the distance between the transmitter of frame i and the receiver of frame j, respectively. The average received signal power of frame i is then given by

$$P_{\mathrm{R}}(i)[\mathrm{dBm}] = G_{\mathrm{T}}(i) + G_{\mathrm{R}}(i) + P_{\mathrm{T}}(i) - PL(r_{i,i}), \qquad (2)$$

where $P_{\mathrm{T}}(i)$ and $PL(r_{i,i})$ are the transmission power and path loss of frame i, respectively. The path loss model for IEEE 802.15.3c is given by

$$PL(r_{i,i})[\mathrm{dB}] = \underbrace{PL_0}_{\substack{\text{Free space path loss at}\\ \text{reference distance}}} + \underbrace{10n\log_{10}(r_{i,i}/r_0)}_{\substack{\text{Path loss exponent}\\ \text{at relative distance } r_{i,i}}} + X_\sigma, \qquad (3)$$

where r_0 and X_σ are the reference distance of 1 m and the lognormal shadowing with a mean of zero, respectively. The path loss exponent n for mm-wave-based measurements is 2.0 for LOS and 2.5 for non-LOS [16]. If shadow fading is ignored, the PL in the 60-GHz band is computed as

$$PL[\mathrm{dB}] = 10\log_{10}\{(4\pi/\lambda)^2 r^n\}, \qquad (4)$$

where λ is the wavelength of the signal given by $\lambda = c/f$. The speed of light is represented by c, and f is the frequency of the signal, which is 60 GHz in this case.

If several frames can be transmitted simultaneously, the achievable data rate of frame i is given by

$$R_i = \kappa_1 W \log_2\left\{\frac{\kappa G_{\mathrm{T}}(i) G_{\mathrm{R}}(i) P_{\mathrm{T}}(i) r_{i,i}^{-n}}{N_0 W + \sum_{i\ne j} I_{i,j}} + 1\right\}, \qquad (5)$$

where κ_1, N_0, and W are coefficients related to the efficiency of the transceiver design, the one-sided spectral density of the white Gaussian noise, and the channel bandwidth, respectively. Constant κ is proportional to $10\log_{10}(\lambda/4\pi)^2 = -68.074$ dB. The interference power of frame i caused by frame j is $I_{i,j}$, which is given by

$$I_{i,j}[\mathrm{dB}] = \kappa + G_{\mathrm{T}}(j) + G_{\mathrm{R}}(i) + P_{\mathrm{T}}(j) - 10n\log_{10} r_{j,i}. \qquad (6)$$

As shown in (6), the interference varies according to the location, antenna gains, and the transmission power of an interferer. In addition, it is noted that the data rates of frames for concurrent transmissions may change according to the interference.

Let R_i^* be the average data rate of frame i during M slots when only one frame transmits at a time. Then, it is given by $R_i^* = \kappa_1 W \log_2\{\kappa G_{\mathrm{T}}(i) G_{\mathrm{R}}(i) P_{\mathrm{T}}(i) r_{i,i}^{-n}/N_0 W + 1\}/M$. To achieve a higher performance with concurrent transmission than with M serial transmissions of a frame, the mutual interference of each frame must be less than the background noise, that is, $I_{j,i} \le N_0 W$, for all j, $j \ne i$, which is shown in Appendix A. Combining this condition with (6), the following relation is obtained:

$$r_{i,j} \ge \left\{ \frac{\kappa G_\mathrm{T}(i) G_\mathrm{R}(j) P_\mathrm{T}(i)}{N_0 W} \right\}^{1/n}, \quad \text{for all } j. \tag{7}$$

III. Grouping Algorithm and Analysis of Scheduling via Relaying Devices

1. Exclusive Region

For successful transmissions, a transmitter-receiver (Tx-Rx) pair must be capable of communication that is either interference free or has limited interference. Thus, the concept of an ER was introduced in [5], and it is defined as follows: each frame, consisting of a Tx-Rx pair, has an ER around the receiver. We define the radius of ER as follows.

Definition 1. The *ER radius* around the receiver of a flow is the minimal distance between the receiver and the transmitters of all the other flows engaging in simultaneous transmissions in such a way that the transmissions of the other flows do not cause any interference with the receiver.

According to this definition, four different ER radii are depending on the locations and antenna directions of the transmitters of other flows. Figure 2 describes the locations and antenna directions of a receiver (R) candidate and an interferer (I) candidate and shows the radii and shapes of the ER. The transmitters of all the other flows engaging in simultaneous transmissions must be located outside the ER. The detailed explanation of Fig. 2 can be found in [11].

If the path loss model of the IEEE 802.15.3c standard is used, (7) with equality can be considered as a radius of ER. Then, assuming all DEVs have the same transmission power P_T, the

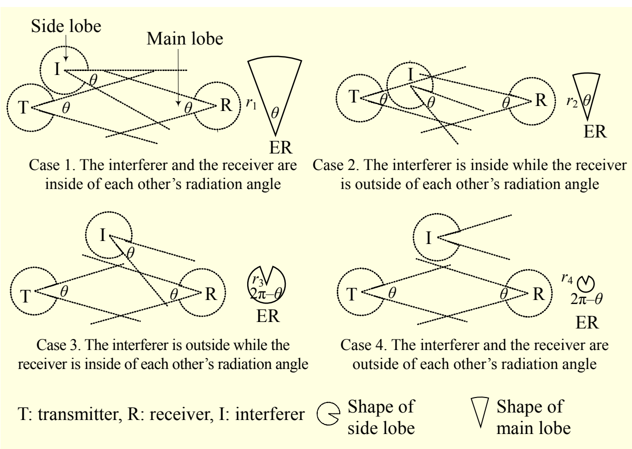

Fig. 2. Four different ER radii for directional antenna pairs.

radius for each case shown in Fig. 2 can be written as (unit: m):

$$r_1 = \left(\frac{\kappa G_\mathrm{TM} G_\mathrm{RM} P_\mathrm{T}}{N_0 W} \right)^{1/n}, \quad r_2 = \left(\frac{\kappa G_\mathrm{TS} G_\mathrm{RM} P_\mathrm{T}}{N_0 W} \right)^{1/n},$$

$$r_3 = \left(\frac{\kappa G_\mathrm{TM} G_\mathrm{RS} P_\mathrm{T}}{N_0 W} \right)^{1/n}, \quad r_4 = \left(\frac{\kappa G_\mathrm{TS} G_\mathrm{RS} P_\mathrm{T}}{N_0 W} \right)^{1/n}. \tag{8}$$

where $G_\mathrm{TM}(G_\mathrm{RM})$ and $G_\mathrm{TS}(G_\mathrm{RS})$ are the antenna gains of the main lobe and side lobe, respectively, of all transmitters (receivers).

2. Grouping Algorithm

It is assumed that a piconet is an $L\times L$ square room and that $2N$ DEVs (N distinct S-D pairs with N flows) are randomly distributed in a piconet. We distinguish an S-D pair and a Tx-Rx pair. If a source DEV and a destination DEV can communicate directly, the S-D pair can be a Tx-Rx pair. However, if a source DEV and a destination DEV cannot communicate directly, relaying DEVs between the S-D pair can be Tx-Rx pairs. Channel degradation can occur due to several factors, such as co-channel interference, blockages, and moving obstacles. In this paper, however, those factors are not considered. It is assumed that the channel condition between DEVs is not changed at all over the superframes.

Since each DEV is equipped with a directional antenna, the channel can be spatially reused. That is, N flows can be grouped in such a way that the flows in a group can be transmitted concurrently in the same CTA block. Once a DEV is scheduled to use a CTA block, it uses the same CTA block in the subsequent superframes, as long as it has frames to send and/or does not request CTA blocks to be changed.

It is known that the PDF of the distance between two DEVs, $f(x)$, is given as follows [17]:

$$f(x) = \begin{cases} f_1(x) = \dfrac{2x}{L^2}\left(\dfrac{x^2}{L^2} - 4\dfrac{x}{L} + \pi \right), & \text{if } 0 \le x \le L, \\ f_2(x) = \dfrac{2x}{L^2} \left\{ \begin{array}{l} 4\sqrt{\dfrac{x^2}{L^2} - 1} - \left(\dfrac{x^2}{L^2} + 2 - \pi \right) \\ -4\tan^{-1}\sqrt{\dfrac{x^2}{L^2} - 1} \end{array} \right\}, & \text{if } L < x \le \sqrt{2}L. \end{cases} \tag{9}$$

Let P_ER be the probability of ER for a receiver, which is the proportion of ER to the area of an $L\times L$ room. The derivation of P_ER can be found in Appendix B.

Based on P_ER, an algorithm is proposed to group the concurrently transmittable flows. Since the algorithm is recursive, initially, N_1 is set to N. The algorithm is as follows:

Algorithm. Grouping concurrently transmittable flows.

1. Select a flow from N_1 flows.

2. Construct a group G_1, which consists of the selected flow and the flows whose transmissions influence the receiver of the selected flow. Then, the average number of elements in G_1, $E(G_1)$, is given by $E(G_1)=\lceil E(K_{\text{ER}}^{N_1})+1\rceil$. Here, $E(K_{\text{ER}}^{N_1})$ is the expected number of interferers for the receiver of the selected flow when N_1 frames exist, which is given by $E(K_{\text{ER}}^{N_1})=(N_1-1)P_{\text{ER}}$. Note that the transmissions of flows in G_1 may influence other flows that are not in G_1. The average number of such influenced flows is $E(G_1)\cdot P_{\text{ER}}$.

3. Let N_2 be the number of flows that are not affected by the transmission of flows in G_1. Then, by step 2, it is given by $N_2=\lceil \{N_1-E(G_1)\}-E(G_1)\cdot P_{\text{ER}}\rceil$.

4. Select a flow from the N_2 flows randomly.

5. Construct G_2, which consists of the selected flow and the flows that influence the receiver of the selected flow. Then, the average number of elements in G_2 is given by $E(G_2)=\lceil E(K_{\text{ER}}^{N_2})+1\rceil$, just the same as step 2.

6. Repeat this procedure until $N_k<1$. Assume that $\{G_i\}_{i=1}^{k}$ is constructed.

7. Select a flow from each group G_i and construct a group C_1 with these flows. Remove the selected flow from each group G_i.

8. Repeat step 7 until all $G_i=\phi$.

9. Assume that $\{C_i\}_{i=1}^{m}$ is constructed, where $m=\max_i E(G_i)$.

Note that the flows in each C_i can be transmitted concurrently and the transmissions will be successful. In addition, a flow either belongs to one C_i or does not belong to any and $\sum_{i=1}^{m}|C_i|\le N$, where $|C_i|$ is the number of flows in C_i.

3. Separating Flows Requiring Relaying Devices

In this paper, only the S-D pairs that cannot communicate directly owing to the distance between them are assumed to use relaying DEVs. Using relaying DEVs for performance enhancement is not considered. That is, the flows requiring relaying DEVs are distinguished on the basis of the distance between S and D.

Let *TR* be the transmission range of a transmitter. Then, the radius of *TR* is given by $r_{\text{TR}}=10^{\{\kappa+G_{\text{TM}}+G_{\text{RM}}+P_{\text{T}}-P_{\text{R}}[\text{dB}]\}/10n}$. In r_{TR}, −55 dB is used for P_{R}, which is the receiver sensitivity corresponding to the base data rate of 1.65 Gbps. Since r_{TR} can be less than the maximal distance of the piconet, S-D pairs that cannot communicate directly with each other can exist. Let P_{ntx} be the probability of such S-D pairs, that is, the proportion of S-D pairs that cannot communicate directly to all S-D pairs in the piconet. There may exist pairs of DEVs that can communicate directly even though the pairs are not S-D pairs. In other words, two DEVs lie inside each other's beams and one DEV lies inside the *TR* of the other DEV. Let P_{TR} be the probability of such pairs. Then, P_{ntx} and P_{TR} are given by

$$P_{\text{ntx}}=\begin{cases}\int_{r_{\text{TR}}}^{L} f_1(x)dx+\int_{L}^{\sqrt{2}L} f_2(x)dx, & \text{if } 0\le r_{\text{TR}}\le L,\\ \int_{r_{\text{TR}}}^{\sqrt{2}L} f_2(x)dx, & \text{if } L<r_{\text{TR}}\le\sqrt{2}L,\\ 0, & \text{if } \sqrt{2}L<r_{\text{TR}},\end{cases} \tag{10}$$

and

$$P_{\text{TR}}=\begin{cases}\left(\frac{\theta}{2\pi}\right)^2\int_0^{r_{\text{TR}}} f_1(x)dx, & \text{if } 0\le r_{\text{TR}}\le L,\\ \left(\frac{\theta}{2\pi}\right)^2\left\{\int_0^{L} f_1(x)dx+\int_{L}^{r_{\text{TR}}} f_2(x)dx\right\}, & \text{if } L<r_{\text{TR}}\le\sqrt{2}L,\\ \left(\frac{\theta}{2\pi}\right)^2\left\{\int_0^{L} f_1(x)dx+\int_{L}^{\sqrt{2}L} f_2(x)dx\right\}, & \text{if } \sqrt{2}L<r_{\text{TR}},\end{cases} \tag{11}$$

respectively. Here $f_i(x)$ is the function given in (9).

For notational clarity, N_A and L_B are used for number and length specifying A and B, respectively. Additionally, d and r are used to indicate "transmit directly" and "transmit via relaying DEVs," respectively.

Let $N_{d,\max}$, $N_{d,i}$, and $N_{r,i}$ be the maximum number of flows that can communicate directly in a CTA, the number of directly transmittable S-D pairs with flows in C_i, and the number of flows in C_i that must use relaying DEVs for transmission, respectively. Then, they are given by

$$N_{d,\max}=k(1-P_{\text{ntx}}),$$

$$N_{d,i}=|C_i|\cdot(1-P_{\text{ntx}}),$$

$$N_{r,i}=|C_i|\cdot P_{\text{ntx}}. \tag{12}$$

Next, we consider the policy of selecting the relaying DEVs of a flow as follows.

(i) All S-D pairs that can communicate directly are not considered as relaying DEVs of other flows.

(ii) For a flow in C_i that needs relaying DEVs, the S-D pairs that have flows in other groups, $C_j, j\ne i$, and cannot communicate directly can be candidates for relaying DEVs for the flow.

(iii) Once a DEV is determined as a relaying DEV of a flow in a CTA, it cannot be used as a relaying DEV for another flow in the superframe.

Note that (iii) is to reduce the complexity of the policy. Suppose that (iii) is not contained in the policy, that is, a DEV can be selected as a relaying DEV in several CTAs in a superframe. Then, the probability of a DEV being selected as a relaying DEV two or more times is low because the antenna directions of all DEVs are assumed to be fixed. However, the complexity becomes high because all DEVs except S-D pairs that can communicate directly must be checked to verify whether they can be relaying DEVs of all other flows requiring relaying DEVs.

Let $n_{r,i}$ be the number of flows in C_i that can be transmitted via relaying DEVs in one of the CTAs. Then, according to (i) through (iii), $n_{r,i}$ can be found using the following steps. In the following steps, "the flows in C_i" means the flows in C_i that need relaying DEVs for transmission.

Step 1. The number of relaying DEV candidates (NRC) for the first flow in C_1 is $(2\sum_{j=2}^{m} N_{r,j} - 1)P_{\text{TR}}$.

According to (iii), once the relaying DEV for the first flows in C_1 has been chosen, the remaining NRC for the other flows is given by $(2\sum_{j=2}^{m} N_{r,j} - 3)P_{\text{TR}}$. Therefore, the NRC for the second flow in C_1 is $(2\sum_{j=2}^{m} N_{r,j} - 3)P_{\text{TR}}$. In general, the NRC for the w-th flow in C_1 is $\{2\sum_{j=2}^{m} N_{r,j} - (2w-1)\}P_{\text{TR}}$, under the condition $2\sum_{j=2}^{m} N_{r,j} - (2w-1) \geq 1$. Therefore, the NRC for the flows in C_1 is given by $\sum_{w=1}^{|N_{r,1}|} \chi_{\{2\sum_{j=2}^{m} N_{r,j} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - (2w-1)\}P_{\text{TR}}$.

Here, χ_A is the indicator function taking either value 1 if A is true or 0 if A is false. Then, $n_{r,1}$ is given by

$$n_{r,1} = \left| \left\{ w \leq N_{r,1} : \chi_{\{2\sum_{j=2}^{m} N_{r,j} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - (2w-1)\}P_{\text{TR}} \right\} \right|.$$

Step 2. The same procedure is considered for the flows in C_2. Then, the NRC for the flows in C_2 is obtained as

$$\sum_{w=1}^{|N_{r,2}|} \chi_{\{2\sum_{j=2}^{m} N_{r,j} - N_{r,\text{used},1} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - N_{r,\text{used},1} - (2w-1)\}P_{\text{TR}},$$

where $N_{r,\text{used},1}$ is the number of DEVs selected as relaying DEVs for the flows in C_1. Then, $n_{r,2}$ is given by

$$n_{r,2} = \left| \left\{ w \leq N_{r,2} : \chi_{\{2\sum_{j=2}^{m} N_{r,j} - N_{r,\text{used},1} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - N_{r,\text{used},1} - (2w-1)\}P_{\text{TR}} \right\} \right|.$$

Step 3. Repeat Step 2 as long as DEVs that can be used for relaying DEVs exist, that is, $\chi_A = 1$. Then, the NRC for the flows in C_k and $n_{r,k}$ are given by

$$\sum_{w=1}^{|N_{r,k}|} \chi_{\{2\sum_{j=2}^{m} N_{r,j} - \sum_{j=1}^{k-1} N_{r,\text{used},j} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - \sum_{j=1}^{k-1} N_{r,\text{used},j} - (2w-1)\}P_{\text{TR}}$$

and

$$n_{r,k} = \left| \left\{ w \leq N_{r,k} : \chi_{\{2\sum_{j=2}^{m} N_{r,j} - \sum_{j=1}^{k-1} N_{r,\text{used},j} - 2w \geq 1\}} \cdot \{2\sum_{j=2}^{m} N_{r,j} - \sum_{j=1}^{k-1} N_{r,\text{used},j} - (2w-1)\}P_{\text{TR}} \right\} \right|,$$

respectively, where $N_{r,\text{used},j}$ is the number of DEVs selected as relaying DEVs for the flows in C_j.

The complexities of the grouping algorithm and the relaying DEV selection policy are as follows. The required number of comparisons for the construction of G_1 is N_1-1. The number of comparisons required to figure out the flows that may influence the transmission of flows in G_i is $\sum_{i=0}^{E(G_i)-1} \{(N_i - 1) - E(G_i) - i\}$. Combining these, the complexity of the grouping algorithm is $O(N(N^2-1))$. On the other hand, the number of comparisons, $N_{r,j} \sum_{i \neq j} N_{r,j} P_{\text{TR}}$, is required for the relaying DEV selection policy, which gives $O(N^2)$. Hence, the complexity of the proposed scheme, including the grouping algorithm, is $O(N(N^2-1))$.

Let $E(N_{\text{P,CTA},i})$, $i = 1, \cdots, m$, and $E(N_{\text{P,CTA}})$ be the number of flows in C_i that can be transmitted either directly or via relaying DEVs and the average number of flows that are transmitted in a CTA, respectively. Then, they are given by

$$E(N_{\text{P,CTA},i}) = N_{d,i} + n_{r,i},$$
$$E(N_{\text{P,CTA}}) = \frac{1}{m} \sum_{i=1}^{m} E(N_{\text{P,CTA},i}). \qquad (13)$$

4. Computation of Average Length of CTA

To compute the average length of a CTA, $E(L_{\text{CTA}})$, the average transmission rate $E(R)$ for concurrent transmission must be considered. Note that the average distance between DEVs, $E(X)$, is given by

$$E(X) = \int_0^L x f_1(x)dx + \int_L^{\sqrt{2}L} x f_2(x)dx \qquad (14)$$

and the distance between an S-D pair that communicates directly is less than $\min(r_{\text{TR}}, \sqrt{2}L)$. Since the interference between concurrently transmitting flows can be ignored, $E(R)$ can be written as

$$E(R) = \kappa_1 W \log_2 \left\{ \kappa G_{\text{T}} G_{\text{R}} P_{\text{T}} E(X)^{-n} / N_0 W + 1 \right\}. \qquad (15)$$

Therefore, $E(L_{\text{CTA}})$ is given by $E(L_{\text{P}})/E(R)$, where $E(L_{\text{P}})$ is the average length of a frame in a flow. Let $E(N_{\text{CTA}})$ be the average number of CTAs in a CTAP. Then, it can be obtained as follows.

(i) Find c that satisfies $\sup_c \{cE(L_{\text{CTA}})\} \leq T_{\text{CTAP}}$, where T_{CTAP} is the time duration of CTAP.

(ii) Since $E(N_{\text{CTA}})$ cannot be larger than either c or m, set $E(N_{\text{CTA}})$ to $\min(c, m)$.

Note that the multihop scheduling is performed on a superframe basis. As the situation of DEVs can be considered identical in the beginning of a superframe, the same scheduling policy can be applied in the subsequent superframes.

IV. Performance Measures

The system throughput *Th*, average transmission delay *E*(*D*), and channel occupancy rate *Ch* are considered performance measures. Three different scheduling schemes are compared: direct and relaying concurrent transmission (DRCT), direct concurrent transmission (DCT), and direct nonconcurrent transmission (DNCT). In DRCT, flows that are transmittable either directly or via relaying DEVs are transmitted concurrently. In DCT, flows that are transmittable only directly are transmitted concurrently. In DNCT, only directly transmittable flows are transmitted and only one flow is transmitted in a CTA. In all three schemes, the PNC will not assign a CTA to a frame unless the remaining time in the CTAP is sufficient to transmit the frame completely. The transmission order is the same as the order of C_i , that is, the flows in C_i are assigned to the *i*-th CTA. For each performance measure, subscripts are used to discern the scheduling schemes.

The performance measures for the DRCT scheme are given as follows:

$$Th_{\text{DRCT}} = \frac{\{E(N_{\text{CTA}})E(N_{\text{P,CTA}}) + E(C^{\text{c}}_{\text{sch}})\}E(L_{\text{P}})}{T_{SF\_\max} - (T_{\text{beacon}} + 2T_{\text{guard}} + T_{\text{CAP}} + T_{\text{MCTA}})}, \quad (16)$$

$$E_{\text{DRCT}}(D) = \frac{1}{N}\left[E_{\text{s,DRCT}}(D) + E_{\text{ns,DRCT}}(D)\right]. \quad (17)$$

The descriptions and values of the parameters in (16) can be found in Table 1. The values in the table are based on the IEEE 802.15.3c standard. $E(C^{\text{c}}_{\text{sch}})$ is the average number of flows that do not belong to any of the $\{C_i\}_{i=1}^m$ but are scheduled to use the remaining time of the CTAP. Here, superscript c in $C^{\text{c}}_{\text{sch}}$ implies the complement. $E_{\text{s,DRCT}}(D)$ is the average transmission delay for the scheduled flows, which includes the waiting time as well as the transmission time. $E_{\text{ns,DRCT}}(D)$ is the average delay for the unscheduled flows, which is equal to the waiting time. Then, $E_{\text{s,DRCT}}(D)$ and $E_{\text{ns,DRCT}}(D)$ are respectively given by

$$E_{\text{s,DRCT}}(D) = \frac{1}{2}E(N_{\text{CTA}})\{E(N_{\text{CTA}})+1\}E(L_{\text{CTA}})E(N_{\text{P,CTA}}) + \left\{E(N_{\text{CTA}})E(L_{\text{CTA}}) + |E(C^{\text{c}}_{\text{sch}})|E(L_{\text{CTA}})\right\} \quad (18)$$

and

$$E_{\text{ns,DRCT}}(D) = \left\{T_{SF\_\max} - (T_{\text{beacon}} + 2T_{\text{guard}} + T_{\text{CAP}} + T_{\text{MCTA}})\right\} \cdot \left\{N - E(N_{\text{CTA}})E(N_{\text{P,CTA}}) - E(C^{\text{c}}_{\text{sch}})\right\}. \quad (19)$$

The channel occupancy rate is defined as the ratio of the CTAP used to the total usable CTAP, which is given by

$$Ch_{\text{DRCT}} = \frac{E(N_{\text{CTA}})E(L_{\text{CTA}})}{T_{SF\_\max} - (T_{\text{beacon}} + 2T_{\text{guard}} + T_{\text{CAP}} + T_{\text{MCTA}})}. \quad (20)$$

The only difference between DCT and DRCT is that $N_{d,i}$ is used for $E(N_{\text{P,CTA},i})$ instead of $N_{d,i} + n_{r,i}$ in (13). Since DNCT transmits only one directly transmittable flow in a CTA, $E(N_{\text{P,CTA}}) = 1$ and $E(N_{\text{CTA}}) = c$ are used for DNCT.

Table 1. Descriptions and values of used parameters.

Time duration	Value	Parameter	Value
$T_{SF\_\max}$ (superframe)	65.535 ms	n (path loss exponent)	2
T_{beacon} (beacon)	0.05 ms	P_{T} (transmission power)	10 mW
T_{guard} (guard)	$1.6{\cdot}10^{-4}$ ms	P_{R} (receive power)	–55 dB
T_{CAP} (CAP)	0.5 ms	κ	–68.074 dB
t_{slot} (slot)	6.5 µs	W (channel bandwidth)	1,728 MHz
T_{MCTA} (MCTA)	$N{\cdot}t_{\text{slot}}$	N_0 (Gaussian noise)	–91.9 dB

V. Numerical Results

This section presents the numerical results, obtained using Matlab (version 7.7) for 100 consecutive superframes. The set of parameters is based on the IEEE 802.15.3c standard, as shown in Table 1. The value N_0 in the table is the average noise. L is set to 10 m and η is set to 1. Three cases are considered: [Case A] $\theta = 60°$, $E(L_{\text{p}})=8\times10^7$ bits, [Case B] $\theta = 90°$, $E(L_{\text{p}}) = 8\times10^7$ bits, and [Case C] $\theta = 90°$, $E(L_{\text{p}}) = 5\times10^7$ bits.

On the basis of the analysis, the following statements can be made: (a) The number of concurrently transmittable flows varies with θ and *N*; (b) If the CTAP is not fully used, a longer $E(L_{\text{P}})$ will lead to better throughput; (c) An optimal beamwidth exists, and it depends on $E(L_{\text{P}})$ and *N*; (d) All the performance measures indicate that DRCT is the best among the three schemes and that DCT is better than DNCT. The following figures demonstrate the validity of these statements. In the following figures, up to 100 flows are assumed to be deployed in the piconet. Even though a 100-flow deployment is not realistic from a practical standpoint, the tendency of the performance limit can be explored from the figures. The analysis is verified by simulation. The analytical and simulation results are slightly different and the size of the difference depends on θ, N, and $E(L_{\text{P}})$. One of the reasons for the difference seems to be the use of the ceil function in the

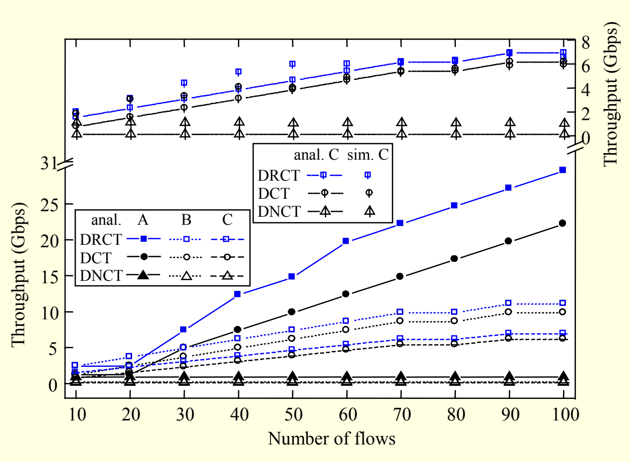

Fig. 3. Comparison of throughputs for three cases.

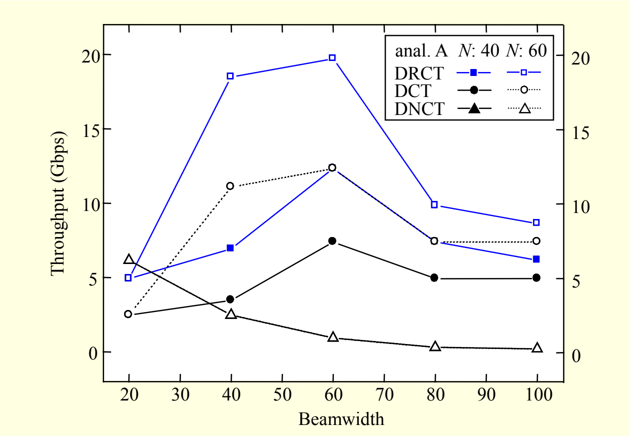

Fig. 4. Comparison of throughputs for different values of N in case A.

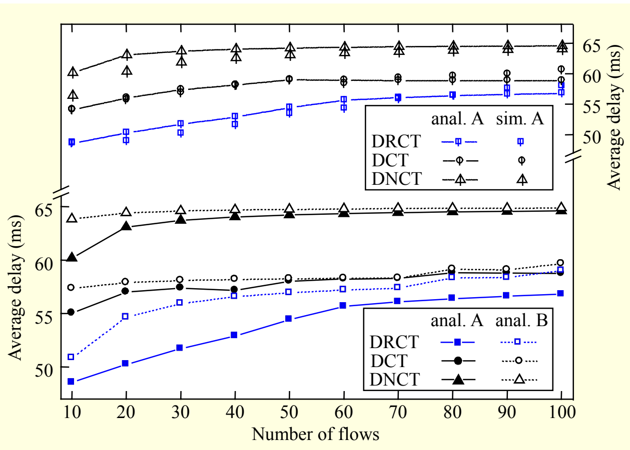

Fig. 5. Comparison of average delays for two cases.

grouping algorithm. In the figures, "anal." and "sim." stand for the analytical and simulation results, respectively. For example,

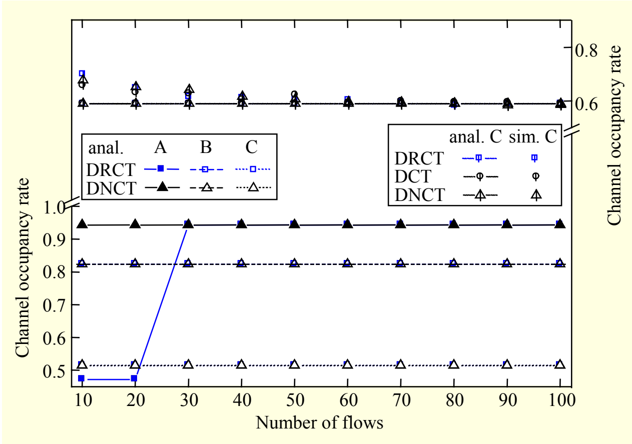

Fig. 6. Comparison of channel occupancy rates for three cases.

"anal. A" reflects the analytical result for case A.

Figure 3 compares the throughput for the three cases. The throughput satisfies the relations

$$Th_{\text{DNCT}} < Th_{\text{DCT}} < Th_{\text{DRCT}}, \quad \text{for any case,}$$

$$Th_{\text{C}} < Th_{\text{B}} < Th_{\text{A}}, \quad \text{for any scheme.} \qquad (21)$$

This can be explained by statements (a) and (b). The obtained throughput in this figure can be compared with that in [12] (Fig. 4). Multihop concurrent transmission, single hop concurrent transmission, and single hop transmission in [12] correspond to DRCT, DCT, and DNCT, respectively, in our schemes. The throughput obtained in [12] differs from that obtained in using our schemes, while the tendencies of the plots are similar. This difference may come from the following two factors: First, different parameter values and piconet size are used. Second, this paper is based on mathematical analysis, whereas a specific hop selection metric was used and an exhaustive search for relaying DEVs was performed in [12]. Figure 4 compares the throughput for case A with two values of N, 40 and 60. It displays the variation of throughput with θ and shows the existence of an optimal θ. For a fixed value of θ, the number of concurrently transmittable flows increases with N, which increases the throughput for DRCT and DCT. Th_{DNCT} decreases as θ increases, which seems obvious since the transmission range becomes short as θ increases. Figure 5 compares $E(D)$ for two cases. The average delays satisfy the following relations:

$$E_{\text{DRCT}}(D) < E_{\text{DCT}}(D) < E_{\text{DNCT}}(D), \quad \text{for any case,}$$

$$E_{\text{A}}(D) < E_{\text{B}}(D), \quad \text{for any scheme.} \qquad (22)$$

Equation (22) represents the results from concurrent transmission.

Figure 6 compares the channel occupancy rate for the three cases. The channel occupancy rates satisfy the following relations:

$$Ch_{\mathrm{DRCT}} = Ch_{\mathrm{DCT}} < Ch_{\mathrm{DNCT}}, \quad \text{for any case.} \tag{23}$$

It shows that statement (b) is true. By comparing $|Ch_{\mathrm{DRCT}} - Ch_{\mathrm{DNCT}}|$ and $|Th_{\mathrm{DRCT}} - Th_{\mathrm{DNCT}}|$, it can be derived that using a directional antenna and relaying DEVs significantly improves the performance.

From the numerical results, we can conclude that the use of relaying DEVs allows for more efficient use of a channel and enhances the performance significantly when each DEV is equipped with a directional antenna.

VI. Conclusion

In this paper, resource assignment for multihop communications is analyzed in mm-wave WPANs. The analysis is performed on the basis of the exclusive region, a grouping algorithm, categorization of the flows, and the probability density function of the distance between DEVs. Numerical results show that schemes with concurrent transmission are always better than those with nonconcurrent transmission, and there is an optimal beamwidth that maximizes the performance. In addition, the use of relaying DEVs allows for more efficient use of a channel and enhances the performance significantly when each DEV is equipped with a directional antenna. The results provide guidelines for evaluating the performance of mm-wave band communications when relaying DEVs are used.

The analysis will be extended to more practical environments, such as a three-dimensional cubic piconet. More realistic situations will be considered, removing the restrictions imposed in this paper. For example, the use of identical transmission power and the restriction of considering only a direct LOS path can be removed in the analysis. Furthermore, the wireless interconnections may change during the frame transmission process due to the co-channel interference, existence of obstacles, and mobility of DEVs. Therefore, such factors must be considered in the analysis in future work. In addition, a similar analysis can be carried out for the analysis of directional CSMA/CA.

Appendix A. Derivation of the sufficient condition for concurrent transmission.

If the total interference from other frames is less than the total background noise, that is, $\sum_{j\neq i} I_{j,i} \leq (M-1)N_0 W$ in (5), the following relation holds:

$$\log_2\left\{\frac{\Gamma}{N_0 W + \sum_{j\neq i} I_{j,i}} + 1\right\} \geq \frac{1}{M}\log_2\left\{\frac{\Gamma}{N_0 W} + 1\right\}, \tag{A.1}$$

where $\Gamma = \kappa G_{\mathrm{T}}(i) G_{\mathrm{R}}(i) P_{\mathrm{T}}(i) r_{i,i}^{-n}$. This gives $R_i \geq R_i^*$.

Appendix B. Derivation of P_{ER}.

Since the ERs for the cases shown in Fig. 2 are not mutually exclusive and the cases are independent, P_{ER} is obtained as follows:

$$\begin{aligned}
P_{\mathrm{ER}} = &\left[\begin{array}{l}\left(\frac{\theta}{2\pi}\right)^2 \int_0^{r_{e,1}} f(x)dx + \left(\frac{\theta}{2\pi}\right)\left(1-\frac{\theta}{2\pi}\right)\sum_{i=2}^{3}\int_0^{r_{e,i}} f(x)dx \\ +\left(1-\frac{\theta}{2\pi}\right)^2 \int_0^{r_{e,4}} f(x)dx\end{array}\right] \\
&-\left[\begin{array}{l}\left(\frac{\theta}{2\pi}\right)^3\left(1-\frac{\theta}{2\pi}\right)\left\{\prod_{i=1,2}\int_0^{r_{e,i}} f(x)dx + \prod_{i=1,3}\int_0^{r_{e,i}} f(x)dx\right\} \\ +\left(\frac{\theta}{2\pi}\right)^2\left(1-\frac{\theta}{2\pi}\right)^2\left\{\prod_{i=1,4}\int_0^{r_{e,i}} f(x)dx + \prod_{i=2,3}\int_0^{r_{e,i}} f(x)dx\right\} \\ +\left(\frac{\theta}{2\pi}\right)\left(1-\frac{\theta}{2\pi}\right)^3\left\{\prod_{i=2,4}\int_0^{r_{e,i}} f(x)dx + \prod_{i=3,4}\int_0^{r_{e,i}} f(x)dx\right\}\end{array}\right] \\
&+\left[\begin{array}{l}\left(\frac{\theta}{2\pi}\right)^4\left(1-\frac{\theta}{2\pi}\right)^2\prod_{i=1,2,3}\int_0^{r_{e,i}} f(x)dx \\ +\left(\frac{\theta}{2\pi}\right)^3\left(1-\frac{\theta}{2\pi}\right)^3\left\{\prod_{i=1,2,4}\int_0^{r_{e,i}} f(x)dx + \prod_{i=1,3,4}\int_0^{r_{e,i}} f(x)dx\right\} \\ +\left(\frac{\theta}{2\pi}\right)^2\left(1-\frac{\theta}{2\pi}\right)^4\prod_{i=2,3,4}\int_0^{r_{e,i}} f(x)dx\end{array}\right] \\
&-\left(\frac{\theta}{2\pi}\right)^4\left(1-\frac{\theta}{2\pi}\right)^4\prod_{i=1}^{4}\int_0^{r_{e,i}} f(x)dx,
\end{aligned} \tag{A.2}$$

where $r_{e,i} = \min(r_i, \sqrt{2}L)$.

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References

[1] K. Jung et al., "Multi-Gbps 60GHz Wireless Transceiver Design for Mobile Applications," poster, BWRC Summer Retreat, June 2009.

[2] IEEE 802, Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs): Amendment 2: Millimeter-Wave Based Alternative Physical Layer Extension, June 2009.

[3] ECMA International, "Standard ECMA-387: High Rate 60 GHz PHY, MAC and HDMI PALs," 2nd ed., Dec. 2008.

[4] IEEE P802.11ad/D7.0, Part 11: Wireless LAN Medium Access Control 5 (MAC) and Physical Layer (PHY) Specifications–Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band, Apr. 2012.

[5] L.X. Cai et al., "REX: A Randomized EXclusive Region Based Scheduling Scheme for mmWave WPANs with Directional Antenna," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, 2010, pp. 113-121.

[6] L.X. Cai et al., "Spatial Multiplexing Capacity Analysis of mmWave WPANs with Directional Antennae," *Proc. GLOBECOM*, 2007, pp. 4744-4748.

[7] C. Sum et al. "Virtual Time-Slot Allocation Scheme for Throughput Enhancement in a Millimeter-Wave Multi-Gbps WPAN System," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, Oct. 2009, pp. 1379-1389.

[8] Y. Kim et al., "Power Controlled Concurrent Transmissions in mmWave WPANs," *IEICE Trans. Commun.* vol. E93-B, no. 10, 2010, pp. 2808-2811.

[9] C.W. Pyo and H. Harada, "Throughput Analysis and Improvement of Hybrid Multiple Access in IEEE 802.15.3c mm-Wave WPAN," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, Oct. 2009, pp. 1414-1424.

[10] M. Kim, Y. Kim, and W. Lee, "Saturation Performance Analysis of Directional CSMA/CA in mmWave WPANs," *Wireless Commun. Mobile Comput.*, published online in Wiley Online Library, DOI: 10.1002/wcm.1174.

[11] M. Kim, Y.S. Kim, and W. Lee, "Performance Analysis of Directional CSMA/CA for IEEE 802.15.3c under Saturation Environments," *ETRI J.*, vol. 34, no. 1, Feb. 2012, pp. 24-34.

[12] J. Qiao, L.X. Cai, and X. Shen, "Multi-hop Concurrent Transmission in Millimeter Wave WPANs with Directional Antenna," *Proc. IEEE ICC*, 2010, pp. 1-5.

[13] M. Kim, S.-E. Hong, and J. Kim, "Analysis of Directional Communication via Relaying Devices in mmWave WPANs," *IEEE Commun. Lett.*, vol. 16, no.5, Mar. 2012, pp. 342-345.

[14] S. Singh, R. Mudumbai, and U. Madhow, "Interference Analysis for Highly Directional 60-GHz Mesh Networks: The Case for Rethinking Medium Access Control," *IEEE/ACM Trans. Netw.*, vol. 19, no. 5, Oct. 2011, pp1513-1527.

[15] S. Yi, Y. Pei, and S. Kalyanaraman, "On the Capacity Improvement of Ad Hoc Wireless Networks Using Directional Antennas" *Proc. MobiHoc*, 2003, pp. 108-116.

[16] A. Seyedi, "TG3c Selection Criteria," doc. IEEE 802.15-05-0493-23-003c, Jan. 2007.

[17] Wolfram MathWorld, "Square Line Picking," Jan. 2005. Available: http://mathworld. wolfram.com/SquareLinePicking. Html

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