

Possibility of Directional Communication in mmWave WPANs

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Abstract—In this paper, the communication success probability of two randomly selected devices is analysed in mmWave Wireless Personal Area Networks (WPANs). Devices are equipped with a directional antenna and randomly distributed in a piconet. The antenna direction of each device is randomly chosen and fixed during the communication. The communication of the selected pair can be performed either directly or via relaying devices. In the analysis, the probability density function of the distance for devices is used and transmission through both of the mainlobe and sidelobe is considered. Numerical results show that there is an optimal beamwidth that enables efficient spatial reuse and maximizes the successful communication probability of a pair of devices. The optimal value varies depending on the parameters such as the number of devices. It also can be derived that the communication of a pair of devices is difficult, when the directions of antennas of devices are fixed. The results obtained in this paper will provide a criterion for practical design of mmWave network system and implementing appliances using high data rate.

Keywords—mmWave, WPAN, directional antenna, exclusive region, relaying device

I. INTRODUCTION

Millimeter-wave (mmWave) communication has drawn considerable attention because it provides a wide bandwidth for high speed data transmission. There are two standards for mmWave WPANs, IEEE 802.15.3c and ECMA-387. The former is based on centralized networks [1] whilst the latter is based on distributed networks [2] aiming for more than 2Gbps as a target data rate. Standardization of IEEE 802.11ad is now ongoing. It is based on centralized networks with a 7Gbps target data rate [3].

The mmWave band has many of its salient properties such as supporting a high data rate as well as problems such as short communication coverage, which dues to high path losses. In order to compensate for these drawbacks of the mmWave band, utilization of directional antennas at the physical (PHY) layer and transmission over multiple short hops can be considered.

Research has been conducted in using directional antennas [4-5] and relaying devices (DEVs) [6-9] in mmWave band communication. In [6-7], the authors considered relaying to the connectivity and the quality of the 60 GHz radio links by modelling three indoor scenarios. The effects of relaying the DEVs' position, the obstacle density on the improvement of the average received signal level, and the robustness of the 60 GHz connectivity were investigated. A hop selection metric

for the piconet coordinator (PNC) to select appropriate relay hops for a flow was designed to improve flow throughput and balance the traffic load across the network in [8]. In [9, 10], directional CSMA/CA was analysed by a Markov chain model, in which the features of IEEE 802.15.3c and the effects of using directional antennas are incorporated.

In this paper, the possibility of communication of two randomly selected DEVs, one a transmitter and the other a receiver, is considered. Since the transmission range in mmWave band is short, there may be pairs that cannot communicate each other, even though the relaying DEVs are allowed to communicate when the direction of antenna for each DEV is fixed. The fixed antenna direction for a DEV is more general situation than the beamforming is done in mmWave communication. Under this situation, the communication success probability of a pair of DEVs is analysed based on the probability density function used in [10].

Section II introduces the directional antenna model and the concept of exclusive region (ER). Section III analyzes the communication success probability. Section IV presents numerical results. Section V concludes the paper.

II. SYSTEM MODEL

In this paper, the IEEE 802.15.3c network configuration is considered. The fundamental topology of IEEE 802.15.3c is a piconet, consisting of a PNC and several slave DEVs within its transmission range. The channel time in the piconet is based on the time-slotted superframe. The structure of a superframe for IEEE 802.15.3c can be found in [1].

The two models for directional antennas are: the flat-top model that neglects the sidelobe effect and the cone plus circle in 2D model or the cone plus sphere in 3D model that considers the sidelobe effect. Since the realistic antenna pattern is complex and does not result in a fundamental change of the capacity [11], the cone plus circle model in 2D is employed in this paper. All DEVs are assumed to lie in the same plane. The antenna gains with the mainlobe and sidelobe effects for PA are defined by $G_m = 2\pi\eta/\theta$ and $G_s = 2\pi(1-\eta)/(2\pi-\theta)$, respectively, where η and θ , $0 < \theta \leq 2\pi$, are the antenna radiation efficiency and the mainlobe beamwidth, respectively.

The purpose of this paper is to analyse the possibility of communication of two randomly selected DEVs. It is assumed that the antenna direction of each DEV is randomly chosen and fixed during communication. The communication of a

pair can occur either directly or via relaying DEVs. If a pair of DEVs is located outside each other's transmission range and no suitable relaying DEV exists between them, the communication of the pair cannot succeed. Since each DEV is equipped with a directional antenna, the channel can be used by several DEVs simultaneously. That is, several transmitters can transmit concurrently and the corresponding receivers may receive successfully. A transmitter-receiver pair has to be capable of interference-free (or limited) communication for successful transmission. Thus, the concept of an *Exclusive Region* (ER) was introduced in [4], which is defined as follows: each frame, consisting of a transmitter-receiver pair, has an ER around the receiver. The transmitters of all the other frames engaging in simultaneous transmission must be located outside the ER.

Fig. 1 describes the locations and antenna directions of a receiver (R) and an interferer (I) candidate and illustrates the radii of the ER. This includes four different cases: the I and R are inside each other's radiation angle (Case 1), the I is inside while the R is outside each other's radiation angle (Case 2), the I is outside while the R is inside each other's radiation angle (Case 3), and the I and R are outside each other's radiation angle (Case 4). The detailed explanation for Fig. 1 can be found in [10].

Let $\{r_i\}_{i=1}^4$ be the radii for ER. Since the computation of the ER radius can be found in the literature including [4, 9], the detail for it is omitted here. In the process of computation, the number of interferers and the advantage of concurrent transmissions are considered. In the references, the ER radius was derived as $\{\kappa G_T G_R P_T / N_0 W\}^{1/n}$. Here G_T and G_R are the antenna gains of the transmitter and receiver, respectively. N_0 is the one-sided spectral density of the white Gaussian noise and is assumed that each DEV experiences identical noise. κ is a constant proportional to $10\log_{10}(\lambda/4\pi)^2$ and W is the channel bandwidth. P_T is the transmission power and n is the path loss exponent. Then the ER radius for each case shown in Fig. 1 can be written as follows (unit: m):

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

$$r_3 = \left(\frac{\kappa G_{TS} G_{RM} P_T}{N_0 W} \right)^{1/n}, \quad \text{and} \quad r_4 = \left(\frac{\kappa G_{TS} G_{RS} P_T}{N_0 W} \right)^{1/n}, \quad (1)$$

where G_{TM} (G_{TS}) and G_{RM} (G_{RS}) are the antenna gains of the mainlobe (sidelobe) of transmitters and receivers, respectively.

III. ANALYSIS OF COMMUNICATION PROBABILITY

It is assumed that N DEVs are randomly distributed in a piconet, which is an $L \times L$ square room. Each DEV is equipped with a directional antenna and beamwidths of DEV's antenna are assumed identical. It is assumed that a DEV cannot transmit and receive simultaneously.

It is known that the probability density function of the distance between two DEVs, $f(x)$, is given as follows [12]:

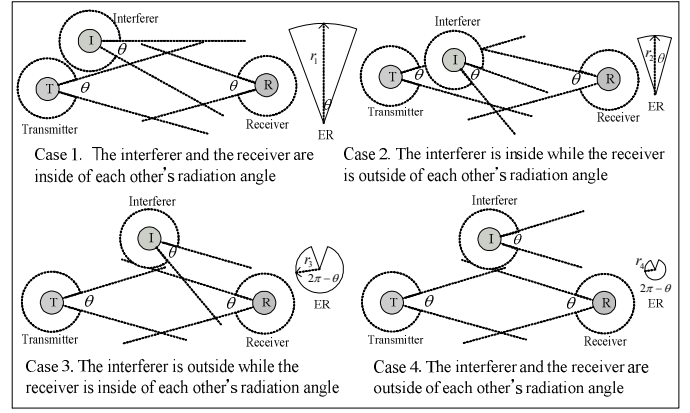


Figure 1. Four different ER radii for directional antenna pairs

$$f(x) = \begin{cases} 2 \frac{x}{L} \left(\frac{x^2}{L^2} - 4 \frac{x}{L} + \pi \right) \cdot \frac{1}{L}, & \text{if } 0 \leq x \leq L \\ 2 \frac{x}{L} \left\{ 4 \sqrt{\frac{x^2}{L^2} - 1} - \left(\frac{x^2}{L^2} + 2 - \pi \right) \right\} \cdot \frac{1}{L}, & \text{if } L < x \leq \sqrt{2}L \end{cases} \quad (2)$$

Since the ER radius can be larger than the maximal distance of the room, let $r_{e,i}$ be the value of $\min(r_i, \sqrt{2}L)$. The cases of ERs shown in Fig. 1 are not mutually exclusive and the cases are independent, the probability of ER for a receiver, which is the proportion of ER to the area of an $L \times L$ room, is obtained, as follows:

$$P_{ER_i} = \left[\left(\frac{\theta}{2\pi} \right)^2 \int_0^{r_{e,i}} f(x) dx + \left(\frac{\theta}{2\pi} \right) \left(1 - \frac{\theta}{2\pi} \right) \sum_{i=2}^3 \int_0^{r_{e,i}} f(x) dx \right. \\ \left. + \left(1 - \frac{\theta}{2\pi} \right)^2 \int_0^{r_{e,i}} f(x) dx \right] \\ - \left[\left(\frac{\theta}{2\pi} \right)^3 \left(1 - \frac{\theta}{2\pi} \right) \left\{ \prod_{i=1,2} \int_0^{r_{e,i}} f(x) dx + \prod_{i=1,3} \int_0^{r_{e,i}} f(x) dx \right\} \right. \\ \left. + \left(\frac{\theta}{2\pi} \right)^2 \left(1 - \frac{\theta}{2\pi} \right)^2 \left\{ \prod_{i=1,4} \int_0^{r_{e,i}} f(x) dx + \prod_{i=2,3} \int_0^{r_{e,i}} f(x) dx \right\} \right. \\ \left. + \left(\frac{\theta}{2\pi} \right) \left(1 - \frac{\theta}{2\pi} \right)^3 \left\{ \prod_{i=2,4} \int_0^{r_{e,i}} f(x) dx + \prod_{i=3,4} \int_0^{r_{e,i}} f(x) dx \right\} \right] \\ + \left[\left(\frac{\theta}{2\pi} \right)^4 \left(1 - \frac{\theta}{2\pi} \right)^2 \prod_{i=1,2,3} \int_0^{r_{e,i}} f(x) dx \right. \\ \left. + \left(\frac{\theta}{2\pi} \right)^3 \left(1 - \frac{\theta}{2\pi} \right)^3 \left\{ \prod_{i=1,2,4} \int_0^{r_{e,i}} f(x) dx + \prod_{i=1,3,4} \int_0^{r_{e,i}} f(x) dx \right\} \right. \\ \left. + \left(\frac{\theta}{2\pi} \right)^2 \left(1 - \frac{\theta}{2\pi} \right)^4 \prod_{i=2,3,4} \int_0^{r_{e,i}} f(x) dx \right. \\ \left. - \left(\frac{\theta}{2\pi} \right)^4 \left(1 - \frac{\theta}{2\pi} \right)^4 \prod_{i=1}^4 \int_0^{r_{e,i}} f(x) dx \right] \quad (3)$$

Eq. (3) is obtained from the formula $P(\bigcup_{i=1}^n A_i) = \sum_{i=1}^n P(A_i) - \sum_{i_1 < i_2} P(A_{i_1} \cap A_{i_2}) + \dots + (-1)^k \sum_{i_1 < \dots < i_k} P(\bigcap_{j=1}^k A_{i_j})$, where A_i is the event of Case i in Fig. 1.

Let $E(K_{\text{interf}}^N)$ be the expected number of interferers of a tagged receiver when N DEVs exist. Then it is given by:

$$E(K_{\text{interf}}^N) = (N-2)P_{ER}. \quad (4)$$

Since the reception occurs through both the mainlobe and sidelobe of DEVs according to the antenna model considered in this paper, the transmission range can be distinguished depending on the antenna directions of the transmitter and receiver, which are four different areas. Let TR_m and TR_s be the average transmission ranges through the mainlobe and sidelobe, respectively. Then they are given by

$$TR_m = 10^{[\kappa + G_{TM} + \{G_{RM}(\theta/2\pi) + G_{RS}(1-\theta/2\pi)\} + P_T - P_R - PL_0(\text{dB})]/10n}, \quad (5)$$

$$\text{and } TR_s = 10^{[\kappa + G_{TS} + \{G_{RM}(\theta/2\pi) + G_{RS}(1-\theta/2\pi)\} + P_T - P_R - PL_0(\text{dB})]/10n}, \quad (6)$$

respectively. Let $P_{TR_{ms}}$ and P_{rs} be the probability of transmission range consisting of the mainlobe and sidelobe sides of the transmitter's antenna and the probability that the transmitters that may cause interference to a receiver are not transmitting, respectively. Then, they are given by

$$P_{TR_{ms}} = \frac{\theta}{2\pi} \int_0^{TR_m} f(x)dx + \left(1 - \frac{\theta}{2\pi}\right) \int_0^{TR_s} f(x)dx, \quad (7)$$

$$\text{and } P_{rs} = (1 - p_t)^{E(K_{\text{interf}}^N)}, \quad (8)$$

respectively, where p_t is the transmission probability of a DEV. The average transmission ranges given by Eq. (5)-(6) are used in Eq. (7) instead of the average of all four different areas. Note that a DEV lying in the portion of Eq. (7) may receive for this antenna model. If Eq. (7) is not satisfied, the transmission cannot succeed. Define $P_{nTR_{ms}}$ as

$$P_{nTR_{ms}} = 1 - P_{TR_{ms}}. \quad (9)$$

Since this paper focuses on the transmission success probability of a randomly selected pair of DEVs and the use of relaying DEVs is allowed in the communication of the pair, several ways can be considered for communication success as follows:

- (i) The pair can communicate directly and the transmission succeeds.
- (ii) The pair cannot communicate directly but the transmission succeeds via relaying DEVs. Since the direction of an antenna for each DEV is assumed to be fixed, maximally $N-2$ DEVs can be used as the relaying DEVs.

Let P_{suc} , $P_{suc,i}$, and R_j be the transmission success probability of the selected pair's communication, the transmission success probability of the selected pair's communication via i , $i \geq 1$, relaying DEVs, and the j th relaying DEV, respectively. Then, for (i), the transmission success probability is given by $P_{TR_{ms}} P_{rs}$. For (ii), the closed form of $P_{suc,i}$ can be found as follows: For $i=1$, R_1 and the receiver have to lie in either the mainlobe or the sidelobe of the transmitter's antenna and R_1 's antenna, respectively. The probability of each is $P_{TR_{ms}}$. The receiver has to be located outside of the mainlobe and the sidelobe of the transmitter's antenna. The probability for this is $P_{nTR_{ms}}$. Moreover, each transmission has to succeed, which is with probability P_{rs} .

Combining these, $P_{suc,1}$ is obtained as $P_{TR_{ms}}^2 P_{rs}^2 P_{nTR_{ms}}$. For $i=2$, R_1 , R_2 , and the receiver have to lie in either the mainlobe or the sidelobe of the transmitter's antenna, R_1 's antenna, and R_2 's antenna, respectively. The probability of each is $P_{TR_{ms}}$. R_2 and the receiver has to be located outside of the mainlobe and the sidelobe of the transmitter's antenna, and the receiver has to be located outside of the mainlobe and the sidelobe of the R_1 's antenna. The probability of each is $P_{nTR_{ms}}$. Moreover, each transmission has to succeed with probability P_{rs} . Therefore, $P_{suc,2}$ is obtained as $P_{TR_{ms}}^3 P_{rs}^3 P_{nTR_{ms}}^{1+2}$. Similarly, $P_{suc,i}$ is obtained as $P_{TR_{ms}}^{i+1} P_{rs}^{i+1} P_{nTR_{ms}}^{1+2+\dots+i}$. Therefore, P_{suc} is given by

$$P_{suc} = \sum_{i=1}^{N-1} P_{TR_{ms}}^i P_{rs}^i P_{nTR_{ms}}^{i(i-1)/2}. \quad (10)$$

The maximum value of P_{suc} can be found by differentiating Eq. (10). However, since Eq. (10) is a function of three variables, p_t , θ , and N , differentiation of Eq. (10) is very complicated. Instead of differentiating it, therefore, the maximum values of P_{suc} is obtained numerically in the following section.

IV. NUMERICAL RESULTS

This section presents the numerical results using Matlab 7.7. The set of parameters is based on the IEEE 802.15.3c standard, as follows: $n=2$, $P_T=10$ mW, $P_R=-55$ dB, $\kappa=-68.074$ dB, $W=1728$ MHz, and $N_0=-80.665$ dB, which is the average noise. L is set to 10 m. Each figure presents P_{suc} for $\eta=1$. Three values of p_t (0.01, 0.1, 0) are considered. It shows that P_{suc} is maximum at $p_t=0$, which is more or less obvious.

Fig. 2 compares P_{suc} for varying θ and p_t . As the number of DEVs and θ increase, the number of DEVs in transmission range may increase. These DEVs can act as either interferers or relaying DEVs. For instance, P_{suc} decreases as N and θ increase for $p_t=0.01$ and 0.1. The decrement of P_{suc} is larger for larger p_t and N . It is obvious since P_{suc} becomes smaller if p_t becomes larger. In these cases, the DEVs act as interferers. While P_{suc} slightly increases as N increases and increases as θ increases when $p_t=0$. This implies that the DEVs act as relaying DEVs when $p_t=0$.

Fig. 3 compare P_{suc} for varying N and p_t . It shows that there is an optimal beamwidth that maximizes P_{suc} and it depends on N and p_t for fixed beamwidth. For fixed θ , P_{suc} decreases and the optimal beamwidth tends to decrease as N increases. When $p_t=0$, P_{suc} steadily increases as N increases. This comes from the reason explained in Fig. 2.

From the numerical results, it can be derived that it is difficult for a pair of DEVs to communicate when the antenna direction of each DEV is fixed.

V. CONCLUSIONS

In this paper, the communication possibility of a randomly selected pair of two DEVs is considered in the mmWave band. This is analysed using the probability density function of distance of DEVs and the concept of exclusive region under IEEE 802.15.3c. It is showing that there is an optimal beamwidth which enables the resource spatially used so as to maximize the communication success probability of a pair of DEVs for fixed number of devices.

This analysis will be extended to include the required time for communication success and eliminate the restrictions imposed in this work, such as fixed antenna direction.

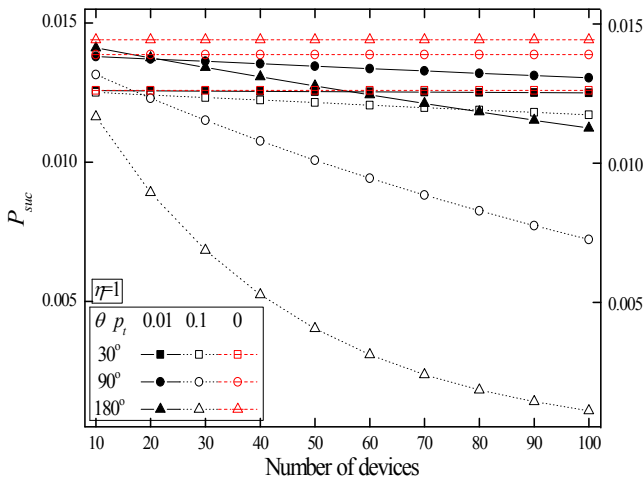


Figure 2. Transmission success probabilities for varying θ and p_t .

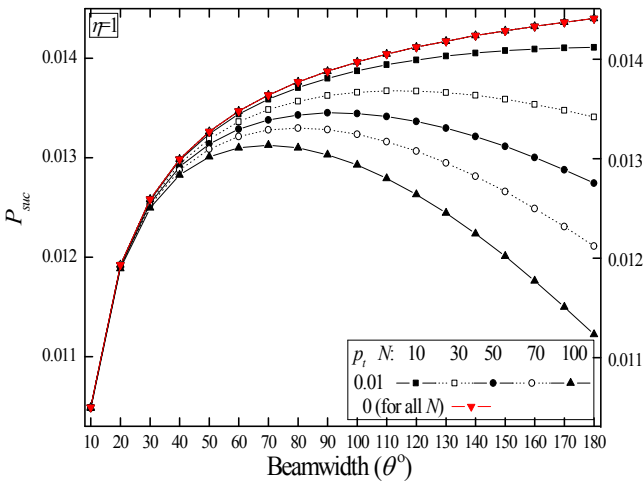


Figure 3. Transmission success probabilities for varying N and p_t .

ACKNOWLEDGMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0022282).

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