Evaluation of Channel Capacity of Millimeter-Wave WBAN Considering Human Body Blocking in User-Dense Condition

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***Abstract*—Millimeter-wave (mmW) wireless body area network (WBAN) is effective as one of the methods to reduce inter-WBAN interference even in user-dense conditions because of human body blocking. In this paper, we evaluate intra-WBAN channel capacities in user-dense situation considering the inter-WBAN interference model by using elliptic cylinder approximation of the human body. We obtain the result that the intra-WBAN channel capacity of over 50 Mbit/s at cumulative distribution function (CDF) of 0.1 was ensured with the system bandwidth of 100 MHz, even in the case of a high user density of 200 users/100 m^2 by the computer simulation.**

I. Introduction

Wireless body area network (WBAN) is widely used for applications such as medical, sports and entertainment with human body area communication. The inter-WBAN interference is one of the problems of WBAN which happens among nearby WBANs. WBAN communication with a user-dense condition is shown in Fig. 1. The WBAN node of the user (Tx) interferes to the node in another WBAN (Rx).

We have studied a millimeter-wave (mmW) WBAN that decreases inter-WBAN interference [1]–[3]. The mmW WBAN is effective for suppressing the inter-WBAN interference at user-dense condition, because their large attenuation of free space loss and human body attenuation compared with conventional WBAN using microwave bands as shown by Fig. 1.

The mmW WBAN has been investigated for human body attenuation in intra-WBAN in the 60 GHz [4] and it also has been investigated interference propagation characteristics in a line-of-sight environment with the condition of the nearby two users in the 60 GHz [5]. The number of interference users of mmW WBAN considering the inter-WBAN interference model by using cylinder approximation of the human body is evaluated in the reference [3]. In this paper, we examined the total interference power and channel capacity of intra-WBAN communication by considering the elliptic cylinder model.

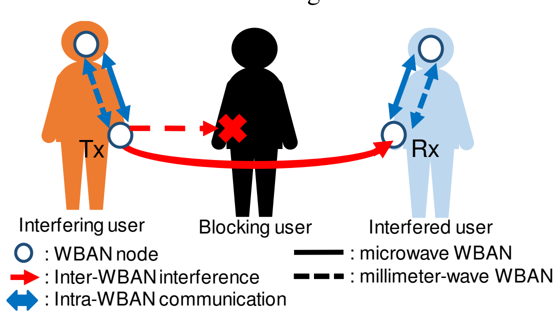

Fig. 1. WBAN communication with a crowded condition.

II. Modeling of Inter-WBAN Interference

A. Link Budget of Inter-WBAN Interference

The inter-WBAN interference model is shown in Fig. 2. In this paper, we assume the interference between the nodes around the waist. There are attenuations by four type causes: (1) free space loss based on Friis formula L_{free} [dB], (2) self-body blocking of interfered user (Rx user) L_{Rx} [dB] depending on the Rx antenna mounting position, (3) self-body blocking of interfering user (Tx user) L_{Tx} [dB] depending on the Tx antenna mounting position, and (4) human body attenuation of user between Tx and Rx L_{shadow} [dB]. The inter-WBAN interference power I is calculated by Eq. (1),

$$
\begin{aligned}
I = {} & P_{\text{Tx}} + G_{\text{Rx}} + G_{\text{Tx}} \\
& - L_{\text{free}} - L_{\text{Rx}} - L_{\text{Tx}} - L_{\text{shadow}},
\end{aligned}
\tag{1}
$$

where P_{Tx} [dBm] is transmission power, G_{Rx} [dB] is Rx antenna gain, G_{Tx} [dB] is Tx antenna gain. We set the receiver sensitivity of -80 dBm assuming the bandwidth of 100 MHz, and $d_{\min}$ is the minimum distance between adjacent users, which is assumed 0.5 m. The parameters using in Eq. (1) is shown in table I. From Eq. (1) and Table I, when $L_{\text{free}} + L_{\text{Rx}} + L_{\text{Tx}} + L_{\text{shadow}} \geq 80$ [dB], the interference power less than the receiver sensitivity

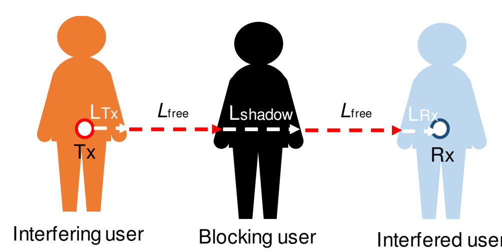

Fig. 2. The Link Budget of WBAN model.

TABLE I
PARAMETERS OF MMW WBAN

RF frequency	60 GHz
Channel bandwidth B	100 MHz
Transmission power P_{Tx}	0 dBm
Tx antenna gain G_{Rx}	0 dBi
Rx antenna gain G_{Tx}	0 dBi
Receiver sensitivity	-80 dBm

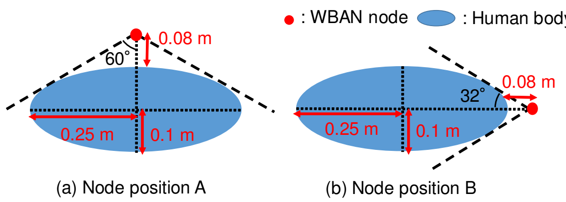

Fig. 3. The top view of user's body and node position.

can be ignored. As shown in Fig. 2, only the interference between the nodes around the waist is considered in this study.

B. Inter-WBAN Interference Condition

The top view of the user's body is shown in Fig. 3. WBAN nodes are indicated by the red plot. It is assumed that each user wear the WBAN node at the position A in Fig. 3(a) or the position B in Fig. 3(b). We also assume that the distance between the body and the WBAN node is 0.08 m. The conditions of inter-WBAN interference are divided into the following conditions (i) and (ii). If (i) or (ii) are satisfied, the interference power received from a Tx user can be ignored.

Condition (i) Blocking by user on propagation path: The interference condition depending on the user on the propagation path is shown in Fig. 4. When a user is in the propagation path like Fig. 4(b), the propagation loss should be considered with L_{free}, L_{Rx}, L_{Tx}, and L_{shadow}. Since the distance between Tx and Rx is larger than $2d_{\mathrm{min}}$ = 1 m, it is ensured that $L_{\mathrm{free}} \geq 68$ [dB]. From the measurement result of the human body blocking attenuation between Tx and Rx antennas at 60 GHz [1], $L_{\mathrm{shadow}} \geq 12$ [dB] when a user blocks the line of sight (LoS) line connecting the Tx and Rx antennas. As a conclusion, one or more user bodies shadow the direct propagation path (Non-line-of-sight), the interference power is ignored.

Condition (ii) Self blocking by Tx or Rx user: The interference condition depending on the position of the Tx and Rx users is shown in Fig. 5. When users in the propagation path do not exist, L_{free}, L_{Rx}, and L_{Tx} are considered. The L_{free} is equal to 62 dB in the case of the distance of d_{min} = 0.5 m. When L_{Rx} or L_{Tx} ≥ 18 [dB], the interference power I becomes less than the receiver sensitivity. From the measurement result of the human body blocking attenuation wearing Rx antennas at 60 GHz [2], L_{Rx} or $L_{\mathrm{Tx}} \geq 18$ [dB] when the WBAN node is at position A and another node existing within the backward $\pm 60°$. Since the tangent drawn from

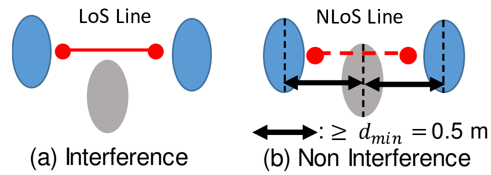

Fig. 4. The interference condition (i).

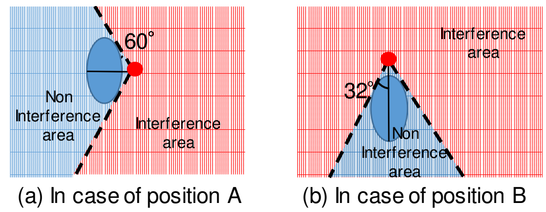

Fig. 5. The interference condition (ii).

TABLE II
THE SIMULATION PARAMETERS

User density n	1–200 users/100 m^2
Simulation area	400 m^2
Evaluation area	100 m^2
Number of trials	1000
Intra-WBAN loss L_{intra}	60 dB

the node to the ellipse is 32° in case of the WBAN node is position B, it is assumed that L_{Rx} or $L_{\mathrm{Tx}} \geq 18$ [dB] when the other node is within $\pm 32°$ behind. As shown in Fig. 5(a) and (b), when the WBAN node is at position A or B, it does not give and take interference with another node existing within the backward $\pm 60°$ or $\pm 32°$, respectively. As a conclusion, the node exists within the backward $\pm 60°$ for A or $\pm 32°$ for B, the interference power is ignored.

C. Interference Power and Channel Capacity

The total interference power received by the Rx user I_{Total} is the sum of the interference powers I of the Tx users that does not satisfy the interference condition (i) and (ii). Eq. (2) is calculated from Table I and Friis' formula,

$$I_{\mathrm{Total}} = 10 \log \left\{ \sum_{total users} 10^{\frac{I}{10}} \right\} \ [\mathrm{dBm}]. \tag{2}$$

The channel capacity of the intra-WBAN communication C is calculated from Shannon's formula as Eq. (3),

$$C = B \log_2 \left(1 + 10^{\frac{\gamma}{10}} \right) \quad [\mathrm{bit/s}], \tag{3}$$

$$\gamma = P_{\mathrm{Tx}} - L_{\mathrm{intra}} - I_{\mathrm{Total}} - N_{\mathrm{AWGN}} \ \ [\mathrm{dB}], \tag{4}$$

where γ [dB] is signal to interference plus noise power ratio (SINR), L_{intra} [dB] is intra-WBAN propagation attenuation, and N_{AWGN} [dBm] is white noise power respectively. The noise power density at room temperature used in calculation is -174 dBm/Hz.

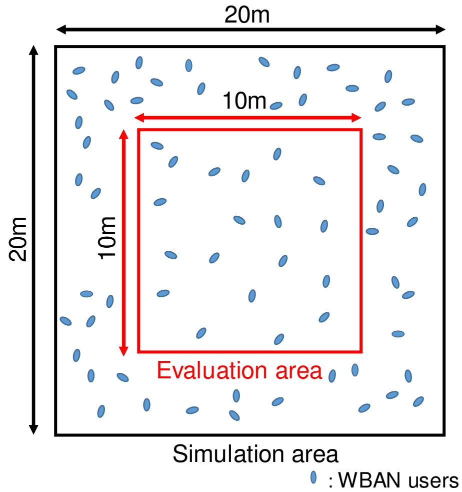

Fig. 6. The simulation model.

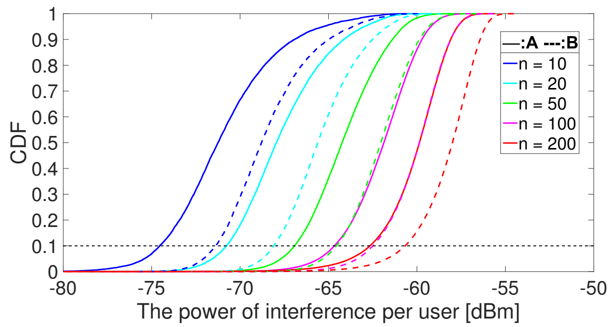

Fig. 7. The CDF of interference power.

III. Evaluation of Channel Capacity

A. Simulation Environment

Fig. 6 and Table II show the simulation model and parameters, respectively. Each user has one WBAN node. The body direction of each user set random. The simulation area sets larger than the evaluation area in order to keep the existence probability of neighboring users constant irrespective of position. We do not consider the influence of reflected waves from the floor and the wall surfaces.

B. Simulation Result

The cumulative distribution function (CDF) of interference power is shown in Fig. 7. The solid line is corresponding to the case that all users mount a node at position A. The broken line shows the case that all users mount a node at position B. This result that more than 90% of users receive interference power of $-74.5\,\mathrm{dBm}$ or more is shown. The interference power that the position B receives more than the position A tends to be less. Almost all users are affected by interference because the receiver sensitivity is $-80\,\mathrm{dBm}$.

The CDF of channel capacity is shown in Fig. 8. The channel capacity tends to be larger at position A than that at position B because the position A receives more interference power than the position B.

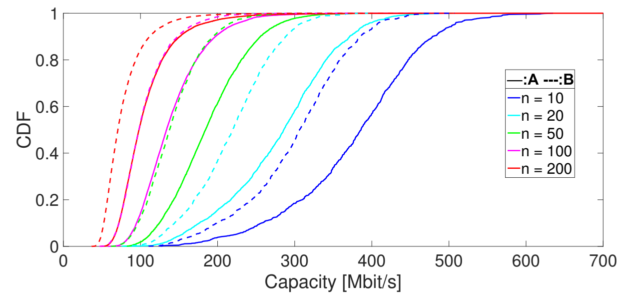

Fig. 8. The CDF of channel capacity.

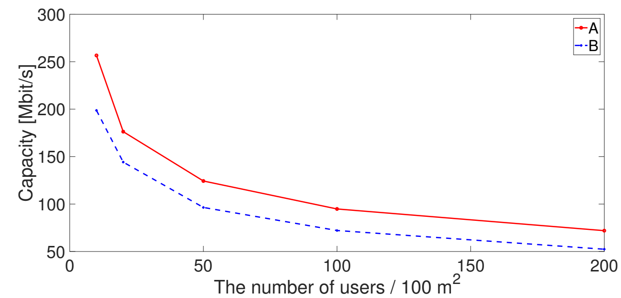

Fig. 9. The channel capacity in the case of CDF 0.1.

The channel capacity in the case of CDF 0.1 is shown in Fig. 9. Even in the case of position B that is the lower capacity, the channel capacity of around $50\,\mathrm{Mbit/s}$ can be ensured in the case of $200\,\mathrm{users}/100\,\mathrm{m}^2$, respectively. Since the bit rate of a typical full high definition (FHD) video data is at most $20\,\mathrm{Mbit/s}$, it is possible to secure sufficient channel capacity for non-medical applications. The reduction of the channel capacity is gentle as the number of users increases. The results that the mmW WBAN can ensure sufficient channel capacity in the user-dense condition is realified by this simulation.

IV. Conclusion

In this paper, we evaluate intra-WBAN channel capacities in the user-dense situation considering the inter-WBAN interference model by using elliptic cylinder approximation of the human body. The channel capacity of $50\,\mathrm{Mbit/s}$ or more in intra-WBAN communication was ensured, at low throughput environment of CDF 0.1, even in the case of a high user density. Therefore, it is concluded that the mmW WBAN has the potential for being ensured sufficient channel capacity in the user-dense condition.

Acknowledgment

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References

[1] K. Akimoto, et al., APMC 2017, Nov. 2017.
[2] K. Akimoto, et al., GSMM 2018, May 2018.
[3] K. Akimoto, et al., IEICE Trans. Commun., Vol. J102-B, No. 2, pp. 44-51, Feb. 2019.
[4] S. Alipour, et al., MILCOM 2010, pp. 719–723, Nov. 2010.
[5] X. Wu, et al., IEEE Trans. Antennas Propag., Vol. 63, No. 10, pp. 4496-4504, Oct. 2015.