Nano Communication Networks 9 (2016) 36–42

Contents lists available at ScienceDirect

Nano Communication Networks

journal homepage: www.elsevier.com/locate/nanocomnet

TAB-MAC: Assisted beamforming MAC protocol for Terahertz communication networks

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ARTICLE INFO

Article history:
Received 15 July 2016
Accepted 24 July 2016
Available online 21 September 2016

Keywords:
Terahertz band communication
MAC protocol
Assisted beamforming
2.4 GHz Wi-Fi

ABSTRACT

Terahertz (THz) communication is envisioned as one of the key technologies to satisfy the increasing demand for higher-speed wireless communication networks. The very high path loss at THz frequencies and the power limitations of THz transceivers limit the communication distance in THz networks. Beamforming directional antennas are needed simultaneously in transmission and in reception to communicate over distances beyond a few meters. This results in many challenges at the link layer, which cannot be easily addressed with existing Medium Access Control (MAC) protocols. In this paper, an Assisted Beamforming MAC protocol for THz communication networks (TAB-MAC) is presented. The protocol exploits two different wireless technologies, namely, WiFi at 2.4 GHz and THz-band communication. In particular, nodes rely on the omnidirectional 2.4 GHz channel to exchange control information and coordinate their data transmissions (Phase 1), whereas the actual data transfer occurs at THz frequencies only after the nodes have aligned their beams (Phase 2). A mathematical framework is developed to analyze the performance of the TAB-MAC protocol in terms of packet delay and throughput, and theoretical upper bounds are derived as functions of total data size, data frame size, node density and data rate in THz band. Numerical results are provided to evaluate the performance of the proposed protocol under different scenarios and define the protocol design guidelines. The results show that the proposed protocol maximizes the THz channel utilization and achievable throughput.

1. Introduction

Over the last decades, wireless data rates have doubled every eighteen months to satisfy the explosive growth of data traffic. Following this trend, it has been envisioned that Terabit-per-second (Tbps) links will be required in the near future. Unfortunately, such high data rates are beyond the reach of the traditional wireless communication systems (under 5 GHz), and even the recently investigated millimeter-wave (mm-Wave) communication solutions (30–300 GHz). This motivates the exploration of higher frequency bands and their corresponding communication solutions. In this context, the Terahertz (THz) band (0.1–10 THz) has been promoted as a key wireless technology to satisfy this requirement [1,2].

With the development of compact THz transceivers and antennas [3–5], THz communication networks are becoming a reality. However, the peculiarities of the THz channel introduce several challenges for THz communications over distances beyond a few meters [6]. On the one hand, the much smaller effective area of THz antennas, which is proportional to the square of the carrier signal wavelength, results in a very high spreading loss. On the other hand, the absorption from water vapor molecules further increases the path-loss and limits the available bandwidth for distances above several meters. Given the limited output power of THz transceivers, high-gain directional antennas are needed to communicate over distances beyond a few meters [7,8].

Similarly as in lower frequency communication systems, beamforming antenna arrays are recommended to implement directional transmission and improve the network performance. Some Medium Access Control (MAC) protocols have been designed for directional transmission [9–11], but these are unsuitable for THz communication networks. The main reason for this is because existing directional MAC protocols consider that a wireless link can be established as long as at least one of the nodes has a directional antenna (usually only the transmitter). However, for THz networks, the very high path-loss at THz frequencies requires directional antennas in transmission and in reception

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http://dx.doi.org/10.1016/j.nancom.2016.07.003
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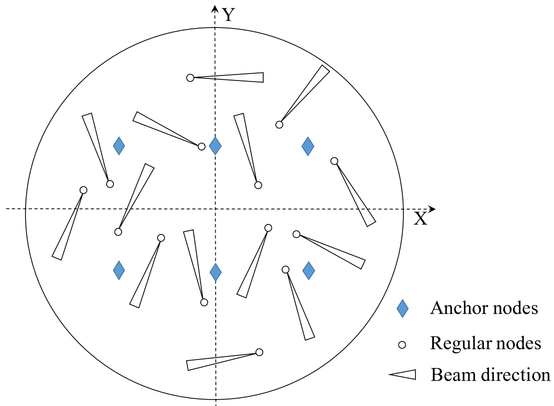

Fig. 1. Network model.

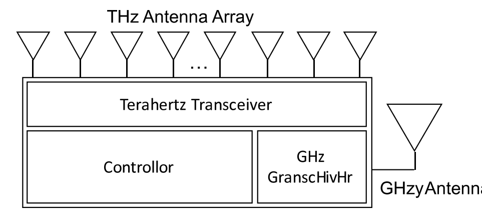

Fig. 2. Node architecture.

simultaneously. In this direction, in [12], a new MAC protocol for THz communications was proposed. The fundamental idea was to utilize a "turning" directional antenna at the receiver combined with a receiver-initiated handshake, as a way to overcome the "facing" problem between transmitter and receiver. While this was shown to properly work in centralized networks, the performance of such approach is limited in ad-hoc networks, in which any node can be transmitting or receiving at any time. Recently, some works, focusing on mm-Wave communications, begin to design the macro-assisted network architecture to decouple the control plane and data plane [13,14].

In this paper, we propose an Assisted Beamforming MAC protocol for THz communication networks (TAB-MAC). The protocol exploits two different wireless technologies, namely, WiFi at 2.4 GHz and THz-band communication, to drastically improve the throughput of wireless networks. The operation of the protocol is divided into two phases: in Phase 1, nodes rely on the omnidirectional 2.4 GHz channel to exchange control information and coordinate their data transmissions; in Phase 2, nodes proceed with the actual data transfer at THz frequencies, after aligning their beams. We develop a mathematical framework to analyze the performance of TAB-MAC protocol in terms of packet delay and throughput, and we derive their theoretical upper bounds as functions of total data size, data frame size, node density and data rate in THz band. Finally, we provide numerical results to illustrate the performance of the proposed protocol under different scenarios and define the protocol design guidelines. The results show that the proposed protocol maximizes the THz channel utilization and achievable throughput.

The remainder of the paper is organized as follows. In Section 2, we describe the system model and establish the relation between the transmission distance, required gain and resulting beamwidth in transmission and in reception. In Section 3, we describe the detailed operation of the proposed TAB-MAC protocol in the two phases. In Section 4, we develop the mathematical framework to analyze the performance of the proposed protocol in terms of failure probability, packet delay and the available throughput. We provide extensive numerical results in Section 5, and we conclude the paper in Section 6.

2. System model

2.1. Network model

We consider the network is composed by data-transmitting regular nodes as well as location-helpers or anchor nodes, as shown in Fig. 1. Both anchor nodes and regular nodes can communicate at 2.4 GHz by means of omnidirectional antennas. In addition, regular nodes are equipped with beamforming antenna arrays for THz communication as shown in Fig. 2. Anchor nodes are aware of their positions, either by being equipped with a GPS module or through manual configuration.

On the one hand, in order to solve the "facing" problem in THz communication networks, we consider that nodes can estimate their positions and communicate them, upon request, to their intended transmitters or receivers by using WiFi at 2.4 GHz. This wireless technology is chosen for control information exchange due to its implicitly advantages in term of transmission distance (much longer than with THz communication) and omni-directivity (allows broadcasting and multicasting information). Anchor nodes periodically broadcast beacon signals, which are used by regular nodes to determine their positions. Three non-collinear anchor nodes are needed to locate one regular node in two dimensions, while at least four non-coplanar anchor nodes must be present to estimate the position of a regular node in three dimensions. In this paper, we do not develop new localization algorithms, but aim at leveraging the results from existing works [15,16].

On the other hand, in order to establish a THz link between two regular nodes, THz beamforming antenna arrays at the transmitter and the receiver need to be properly aligned. This can be easily done provided that the nodes have been able to estimate their location. Due to the severe path loss and the limited transmission power of THz systems, very high directivity gains or, equivalently, very narrow beam-widths are needed. These depend on specific transmission frequency as well as on the distances between the transmitter and the receiver, which can be computed from the nodes' positions.

2.2. Adaptive beamforming

From the perspective of the receiver, the transmitted THz signal can be received successfully only when the received signal power is beyond the minimum threshold of Signal-Noise-Ratio (SNR). According to the THz channel model [17], the received signal power P_r is given by

$$\begin{aligned} P_r &= \int_B S_r(f, d)df \\ &= \int_B S_t(f)\frac{c^2}{(4\pi fd)^2}G_tG_re^{-k_{abs}(f)d}df \geq P_{N_0}SNR_{\min}, \end{aligned} \tag{1}$$

where B refers to the bandwidth of adopted frequency sub-band, f is the transmission frequency, $S_r(f, d)$ and $S_t(f)$ refer to the power spectral density (p.s.d.) of the received and transmitted signal, respectively. d refers to the transmission distance, G_r and G_t refer to the antenna gains of the receiver and transmitter, respectively. $SNR_{\min}$ refers to the minimum SNR threshold, P_{N_0} refers to the noise power. $k_{abs}(f)$ is the absorption coefficient, which is a function of transmission frequency, and is also dependent on the composition of the transmission medium [6].

According to the proposed network model, each coupled regular nodes need to adjust their own transmission directions to point each other. In order to guarantee the connection of the coupled regular nodes with beamforming antenna arrays, it is necessary to explore the relation between the transmission distance, required gain and resulting beamwidth. Without loss of generality, the antenna gains of the transmitter and the receiver are considered to be identical, i.e., $G_t = G_r = G$, and constant within the transmission bandwidth. Thus, the required antenna gain for transmission over the distance d can be computed as

$$G \geq \frac{4\pi d}{c}\sqrt{\frac{P_{N_0} SNR_{\min}}{\int_B S_t(f) f^{-2} e^{-k_{abs}(f)d} df}}. \quad (2)$$

Given the benefits of the planar arrays, such as directional beams with much higher directivity and symmetrical patterns with low side lobes, in this paper, assume that the beamforming antenna array at each regular node is a nearly broadside planar array. By using the array solid beam angle Ω_A, the approximate directivity of the beamforming antenna array can be calculated by [18]

$$D_0 = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\theta_h \phi_h} \geq G, \quad (3)$$

where θ_h and ϕ_h refer to the Half Power Beam Width (HPBW) in the elevation plane and azimuthal plane, respectively.

Particularly, given a large array, assume the HPBW in the elevation plane and azimuthal plane are identical, i.e., $\theta_h = \phi_h = \Phi$, which can be computed with (2) and (3) as follows:

$$\Phi \leq \sqrt{\frac{c}{d}\sqrt{\frac{\int_B S_t(f) f^{-2} e^{-k_{abs}(f)d} df}{P_{N_0} SNR_{\min}}}}. \quad (4)$$

3. Assisted beamforming MAC protocol

The functioning of the proposed TAB-MAC protocol is summarized as follows. When a regular node wants to communicate with another node, it first broadcasts its request by using WiFi technology and exchanges the location information with the intended receiver. Based on the exchanged information, the transmitter and the receiver steer their THz beamforming antennas to point to each other with a specific beamwidth, computed from the transmission frequency, communication distance and output power given by (4). Once the coupled regular nodes are facing each other, the data transactions at THz frequencies proceeds. This presents an effective and efficient solution to address the "facing" problem in THz communication networks as well as to mitigate interference. However, the time delay introduced by the cooperation between two types of wireless technologies should be comprehensively investigated.

In detail, the whole TAB-MAC protocol as shown in Fig. 3 can be divided into two phases as follows:

3.1. Phase 1—node discovery and coupling

Phase 1 is designed to discover and couple the transmitter and receiver through the benefits of omnidirectional 2.4 GHz communication, and then make their THz beamforming antennas point to each other for data transmission. Firstly, the transmitter sends one extended Request-To-Send (RTS) frame with Node Information, named as RTS-NI frame, which contains the information of node position. The receiver will reply an extended Clear-To-Send (CTS) frame with its Node Information, named as CTS-NI, when it is available. Once these two nodes obtained each other's node positions, they can compute the Line-of-Sight (LoS) distance between them, and steer their beamforming antennas pointing to each other with a specific beamwidth.

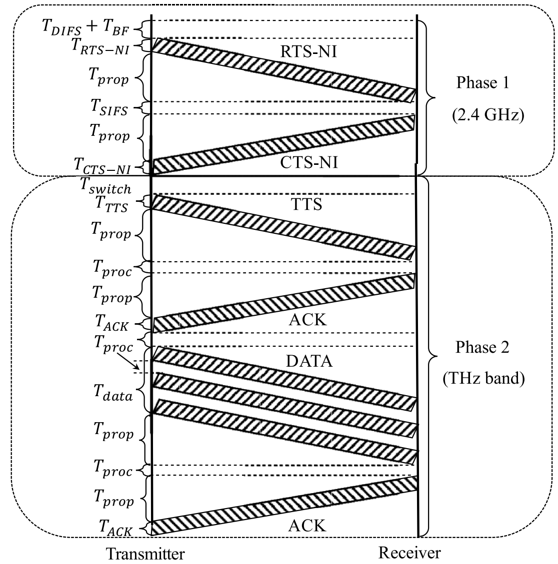

Fig. 3. TAB-MAC protocol.

In order to be compatible with the existing MAC protocols, the frame header and footer are defined as in IEEE 802.11ac standard and the protocol specific information is transmitted as part of the *Frame Body*. The detailed frame formats of TAB-MAC protocol are shown in Fig. 4. Particularly, the *Frame Control* field occupies 2 bytes. The type of frame is decided by the subfield type and subtype in *Frame Control* field as required. The *Duration* field with 2 bytes represents the life time of this frame. The size of the *Address Information* field depends on the frame type. For the RTS-NI and DATA frames, the *Address Information* field includes both the transmitter and receiver addresses, while it only contains the receiver address for the ACK and CTS-NI frames. Each address takes 6 bytes. The *Sequence Control* field is 2 bytes in length. The *Frame Check Sequence* (FCS) contains an IEEE 32-bit cyclic redundancy code (CRC). The *Frame Body* field is dependent on the frame types as shown in Fig. 4. Both RTS-NI and CTS-NI frames have the same payload structure with three 2-bytes fields for regular node's position in 3D space, and 4 bytes for the beamforming antenna information, such as the beamwidth and pointing direction. Test-To-Send (TTS) frame is a short frame with 4 bytes of test data as the payload, which will be described in Phase 2.

Given $T_{RTS\text{-}NI} = T_{CTS\text{-}NI} = T_{NI}$ as a result of the identical frame length, the time delays of successful communication and time-out in Phase 1 can be given as follows:

$$T_{succ}^{P_1} = T_{DIFS} + T_{SIFS} + 2T_{NI} + 2T_{prop} \quad (5)$$

$$T_{out}^{P_1} = T_{DIFS} + T_{SIFS} + 2T_{NI} + T_{BF} + 2T_{prop} \quad (6)$$

where T_{DIFS} and T_{SIFS} are time delay for DCF interframe space and short interframe space in IEEE 802.11ac standard, respectively. Moreover, $T_{DIFS} = T_{SIFS} + 2\tau$, where τ is the time slot. T_{prop} refers to the propagation delay over the distance between the transmitter and the receiver. T_{BF} is the exponential back off time, and can be computed as

$$T_{BF} = \left[\mathrm{Rnd}(\cdot) \times (2^{CW} - 1)\right] \cdot 2\tau \quad (7)$$

where $\mathrm{Rnd}(\cdot)$ refers to a random function between 0 and 1. CW is the back off window between retransmission times and 10, i.e., $CW = \min\{N_i, 10\}$, where N_i represents the ith retransmission.

3.2. Phase 2—THz data transfer

After Phase 1, the beamforming antennas of the transmitter and receiver have been steered to point each other, i.e., the transmitter

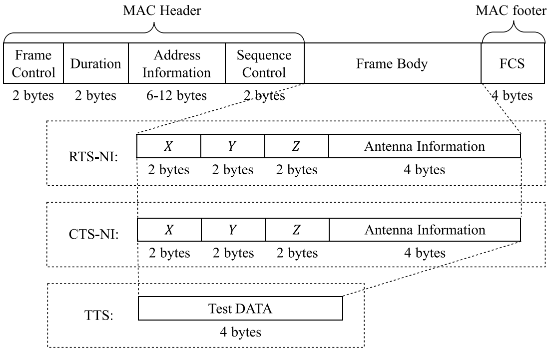

Fig. 4. Frame format.

is ready to transmit data in the THz band. Firstly, in order to check the channel condition between the transmitter and the receiver, the transmitter will send one TTS frame to make sure that their directional antennas are pointing to each other and the LoS propagation between them is available. Once receiving the Acknowledgement (ACK) from the receiver, the transmitter will begin the data transmission. The total time delay in Phase 2 can be expressed by

$$T_{phase2} = T_{test} + T_{DATA}, \tag{8}$$

where T_{test} is the total time delay for the test process, and can be obtained by

$$T_{test} = T_{switch} + T_{TTS} + T_{ACK} + T_{proc} + 2T_{prop}, \tag{9}$$

where T_{switch} refers to the switching time from 2.4 GHz omnidirectional antenna to THz beamforming antennas. T_{proc} refers to the short processing time for high data rate in THz band, T_{TTS} refers to the transmission time for one TTS frame. T_{ACK} refers to the transmission time for ACK. T_{DATA} is the required time to transmit all data frames L_{data} from the transmitter to the receiver. If the maximum size of data frame is limited by L_{one}, then the total time T_{DATA} can be computed as follows:

$$T_{DATA} = \frac{L_{data}}{r_{THz}} + \left(\left\lfloor \frac{L_{data}}{L_{one}} \right\rfloor + 2 \right) T_{proc} + 2T_{prop} + T_{ACK}, \tag{10}$$

where $\lfloor \cdot \rfloor$ returns the biggest integer number which is smaller than the operand, r_{THz} refers to the data rate in THz band. One processing time T_{proc} is required between two data frames as a result of the fast data rate in THz band.

If the transmitter fails to receive the ACK from the receiver after sending the TTS frame, the possibilities are (i) the TTS frame is not received correctly by the receiver due to the propagation error; (ii) the beamforming antennas of the coupled nodes are not pointing to each other in the right direction; (iii) the LoS propagation between them are blocked by some obstacles. For the first case, the transmitter will try to retransmit the TTS frame again and wait for the ACK until the maximum retransmission limitation. The later two cases require the relay to finish the transmission, such as finding other relay nodes between the transmitter and the receiver or deploying smart relay mirrors at the anchor nodes.

4. Performance analysis

4.1. Failure probability in Phase 1

In Phase 1, both RTS-NI and CTS-NI frames are transmitted in 2.4 GHz, which could not be received correctly due to the multi-user interference by using omnidirectional antenna. To model the multi-user interference in Phase 1, the nodes' spatial distribution and their temporal activities need to be taken into consideration. Suppose all nodes are randomly distributed in space by following a spatial Poisson process with density λ_A. From the perspective of spatial distribution, the probability of finding n nodes in the area $A(d) = \pi d^2$ is

$$P[n \in A(d)] = \frac{(\lambda_A A(d))^n}{n!} e^{-\lambda_A A(d)}. \tag{11}$$

On the one hand, from the perspective of temporal activities in 2.4 GHz, each node generates new frames with an identical rate k_1/T_{NI}, where T_{NI} refers to the frame time in Phase 1 and k_1 is a constant. Thus, the aggregated traffic generated by n nodes in the area A is obtained as $\lambda_T = nk_1/T_{NI}$. Therefore, during the consecutive $2T_{NI}$ period, the probability that m_1 nodes, out of n nodes, are transmitting is given by

$$P[m_1 \in 2T_{NI}] = \frac{(\lambda_T 2T_{NI})^{m_1}}{m_1!} e^{-\lambda_T 2T_{NI}}, \tag{12}$$

where k_1 is dependent on the process of TAB-MAC protocol, for each node, it should be guaranteed to transmit at least one frame during the time of one successful communication in Phase 1 or DATA transmission time in Phase 2. Thus, the value of k_1 is constrained by

$$\max \left\{ \frac{T_{succ}^{P1}}{T_{NI}}, \frac{T_{DATA}}{T_{NI}} \right\} \leq \frac{1}{k_1} \leq \infty. \tag{13}$$

On the other hand, the connection in Phase 1 would fail when some nodes are unavailable due to conducting data transmission in THz band at this moment. From the perspective of temporal activities in THz band, according to the TAB-MAC protocol, the communicating nodes will not stop until all data frames are transmitted, and assume that all nodes transmit with an identical rate k_2/T_{DATA}, and k_2 is a constant. Similarly, the probability that m_2 nodes, out of $(n - m_1)$ nodes, are busy transmitting can be written by

$$P[m_2 \in 2T_{DATA}] = \frac{(\lambda_{T'} 2T_{DATA})^{m_2}}{m_2!} e^{-\lambda_{T'} 2T_{DATA}}, \tag{14}$$

where $\lambda_{T'} = (n - m_1)k_2/T_{DATA}$. Due to the high data rate in THz band, the transmitter keeps sending the data frames until the last one. Therefore, it is generally true to set k_2 as

$$k_2 = k_1 \frac{T_{DATA}}{T_{succ}^{P1}}. \tag{15}$$

Finally, the failure probability P_{f_1} of transmitting the RTS-NI frame in Phase 1 is

$$P_{f_1} = \sum_{n=1}^{\infty} P[n \in A(d)](1 - P[0 \in 2T_{NI}] \cdot P[0 \in 2T_{DATA}]). \tag{16}$$

However, for the CTS-NI frame, it only fails to be received as a result of the collision, because the transmitter is waiting for the reply after sending the request. Therefore, the failure probability P_{f_2} of the CTS-NI frame in Phase 1 is

$$P_{f_2} = \sum_{n=1}^{\infty} P[n \in A(d)](1 - P[0 \in 2T_{NI}]). \tag{17}$$

In practice, during the phase of discovery and couple, the transmitter and the receiver may not connect with each other due to the collision in 2.4 GHz or the unavailabilities of nodes communicating in THz band, as well as the frame error as a result of propagation attenuation and noise. Thus, the probability to succeed exactly at the ith retransmission in Phase 1 is given by

$$\begin{aligned} P_{s,P_1}^{i-rtx} &= P_{RTS\text{-}NI} P_{CTS\text{-}NI} \, (1 - P_{RTS\text{-}NI} P_{CTS\text{-}NI})^{i-1} \\ &= \left(1 - (1 - P_{f_1})(1 - P_{f_2})(1 - P_{NI})^2\right)^{i-1} \\ &\quad \times \, (1 - P_{f_1})(1 - P_{f_2})(1 - P_{NI})^2, \end{aligned} \tag{18}$$

where $P_{RTS\text{-}NI}$ and $P_{CTS\text{-}NI}$ refer to the probabilities of successfully transmitting the RTS-NI frame and CTS-NI frame, respectively. Given the same length of RTS-NI and CTS-NI frames, and their own failure probabilities given by (16) and (17), these two successful probabilities can be computed as $P_{RTS\text{-}NI} = (1 - P_{f_1})(1 - P_{NI})$ and $P_{CTS\text{-}NI} = (1 - P_{f_2})(1 - P_{NI})$, where P_{NI} refers to the frame error rate of RTS-NI or CTS-NI frame. Assume that all errors in one frame can be detected, the P_{NI}, with the length of L_{NI} in bits, is given by

$$P_{NI} = 1 - (1 - BER)^{L_{NI}}, \tag{19}$$

where BER refers to the bit error rate in 2.4 GHz.

Let $N_{\max}^{P_1}$ be the maximum number of retransmission in Phase 1. In order to obtain the average time delay in phase 1, we need to compute the expected number of retransmission $N_{avg}^{P_1}$ to successfully create the connection between the transmitter and the receiver as

$$N_{avg}^{P_1} = \sum_{i=1}^{N_{\max}^{P_1}} iP_{s,P_1}^{i-rtx} = \frac{1 - (1 - A)^{N_{\max}^{P_1}}}{A} - N_{\max}^{P_1}(1 - A)^{N_{\max}^{P_1}}, \tag{20}$$

where $A = P_{RTS\text{-}NI}P_{CTS\text{-}NI}$. As the last retransmission is successful, the average time delay introduced by discovery and couple in Phase 1 can be expressed by

$$T_{phase1} = \sum_{N_i=1}^{N_{avg}^{P_1}-1} T_{out}^{P_1} + T_{succ}^{P_1}. \tag{21}$$

4.2. Failure probability in Phase 2

After Phase 1, the connection between the transmitter and the receiver has been established, collision among nodes can be avoided as a result of considering the node availability in Phase 1, as well as the big coverage by the omnidirectional 2.4 GHz communication. However, some data frames may fail to be received due to the transmission error. Similarly, assume that all errors in each data frame can be detected, the frame error rate P_{one}, with the length of L_{one} in bits, is given by

$$P_{one} = 1 - (1 - BER)^{L_{one}}. \tag{22}$$

Let $N_{\max}^{P_2}$ be the maximum number of retransmission in Phase 2, the expected probability $P_{succ}^{P_2}$ of successfully transmitting one data frame in THz band can be computed as

$$P_{succ}^{P_2} = \sum_{i=1}^{N_{\max}^{P_2}} P_{s,P_2}^{i-rtx} = 1 - (P_{one})^{N_{\max}^{P_2}}, \tag{23}$$

where P_{s,P_2}^{i-rtx} refers to the probability of successfully transmitting one data frame exactly at ith retransmission in Phase 2, i.e., $P_{s,P_2}^{i-rtx} = (1-P_{one})\,(P_{one})^{i-1}$. In general, assume that there is no transmission error in the testing process due to the short TTS frame. Finally, the average required time of transmitting the DATA in THz band is given by

$$T_{DATA} = \left\lfloor \frac{L_{data}}{L_{one}} \right\rfloor \left((1 - P_{succ}^{P_2})N_{\max}^{P2} + 1\right) \cdot \left(\frac{L_{one}}{r_{THz}} + T_{proc} + 2T_{prop} + T_{ACK}\right). \tag{24}$$

4.3. Throughput

Let S be the node throughput, defined as the fraction of the total transmitted DATA over the total time delay. According to the proposed TAB-MAC protocol, DATA refers to all data frames transmitted in Phase 2, and the data rate in THz band is dependent on the transmission frequency and transmission distance [6]. Based on the above analysis, the throughput S and the maximum throughput $S_{\max}$ can be presented by

$$S = \frac{L_{data}P_{succ}^{P_2}}{T_{total}} \le S_{\max} = \frac{L_{data}}{T_{total}^{\min}} < r_{THz}, \tag{25}$$

where the maximum throughout $S_{\max}$ is achieved under the condition of no collision and propagation error during the transmission, and it is always smaller than the data rate r_{THz} in Phase 2, i.e., the channel capacity of the adopted THz band.

The total time delay in the proposed TAB-MAC protocol is mainly determined by the average time delay in Phase 1 caused by the processes of discovery and coupling, and the expected time delay in Phase 2 for data transfer. Particularly, for the time delay in Phase 2, we focus on the required transmission time and processing time for all data frames, and assume the LoS propagation is available between the transmitter and the receiver. The impact of obstacles in the area, leads to no LoS propagation between the transmitter and the receiver, will be discussed in our future work. Finally, the total time delay of successfully transmitting all data frames between two regular nodes can be obtained as follows:

$$\begin{aligned} T_{total} &= T_{phase1} + T_{phase2} \\ &= \sum_{N_i=1}^{N_{avg}^{P_1}-1} T_{out}^{P_1} + T_{succ}^{P_1} + T_{test} + \left((1 - P_{succ}^{P_2})N_{\max}^{P_2} + 1\right) \\ &\quad \cdot \left\lfloor \frac{L_{data}}{L_{one}} \right\rfloor \left(\frac{L_{one}}{r_{THz}} + T_{proc} + 2T_{prop} + T_{ACK}\right). \end{aligned} \tag{26}$$

To estimate the minimum total time delay of the proposed TAB-MAC protocol, we consider that the value of $N_{avg}^{P_1}$ equals to one, i.e., no collision occurs in Phase 1, and $P_{succ}^{P_2}$ equals to one, i.e., all data frames are transmitted successfully, then the minimum total time delay is given by

$$T_{total}^{\min} = T_{succ}^{P_1} + T_{test} + \left\lfloor \frac{L_{data}}{L_{one}} \right\rfloor \left(\frac{L_{one}}{r_{THz}} + T_{proc}\right) + 2T_{prop} + T_{ACK}. \tag{27}$$

5. Numerical results

Based on the proposed TAB-MAC protocol for THz communication networks with assisted beamforming, the effects on the throughput of different parameters, such as total DATA size, DATA frame size, achievable rate in the THz channel, and node density, are comprehensively investigated in this section. The parameters used in the simulations are listed in Table 1 (the protocol parameters used in Phase 1 are the same as the IEEE 802.11ac standard).

5.1. Throughput vs. data rate

The throughput S and its maximum value $S_{\max}$, given by (25), for different sizes of DATA are shown in Fig. 5 as a function of the data rate in THz band. For a fixed payload L_{data}, the throughput increases with the data rate r_{THz} in THz band as a result of suffering less transmission time given by (26). In addition, it is observed that the

Table 1
Parameters in the simulations.

Parameter	Value
λ_A	[0.01, 0.1] nodes/m^2
$N_{\max}^{P_1} = N_{\max}^{P_2}$	5
BER	10^{-6}
Slot time 2τ	9 µs
T_{DIFS}	34 µs
T_{SIFS}	16 µs
T_{switch}	10 ns
T_{proc}	10 ns
PHY header	192 bits
RTS-NI frame, $L_{RTS\text{-}NI}$	256 bits + PHY header
CTS-NI frame, $L_{CTS\text{-}NI}$	256 bits + PHY header
TTS frame, L_{TTS}	208 bits + PHY header
ACK frame, L_{ACK}	128 bits + PHY header
DATA frame, L_{one}	10^5 bits
Transmission distance d	10 m
Data rate in 2.4 GHz	100 Mbps
Data rate in THz band	[0.1, 1] Tbps
Total data size, L_{data}	5 MB, 50 MB, 500 MB, 5 GB

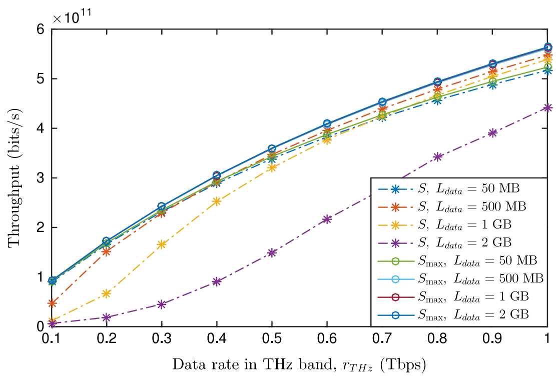

Fig. 5. Throughput vs. data rate in THz band ($\lambda_A = 0.02$ nodes/m^2, $k_1 = 10^{-3}$, $L_{one} = 10^5$ bits).

throughput experiences an increase and then follows a decrease when the payload L_{data} is enlarged from 5 MB to 5 GB, which is mainly because the relation between the total data transmission time and the number of data frames given by (24). Clearly, there is a tradeoff between the payload L_{data} and the network throughput with the fixed r_{THz} and L_{one}. Furthermore, when the channel conditions both in 2.4 GHz and THz band are very good, the maximum throughput $S_{\max}$ is achieved as no retransmission is required to overcome the transmission failures in Phase 1 and Phase 2. Moreover, with the increase of L_{data}, $S_{\max}$ coverages to an upper bound, which is mainly dependent on the data rate in THz band owing to the data transmission time dominates the total time delay given by (27).

5.2. Throughput vs. node density

The throughput S as a function of node density λ_A is shown in Fig. 6 for the different values of k_1. Contrary to classical MAC protocols with directional transmission, the proposed TAB-MAC protocol takes the benefits of omnidirectional 2.4 GHz communication to address the "facing" problem in THz communication networks. However, it also introduces more time delay due to the failure probabilities in Phase 1, which is mainly governed by the node density and parameter k_1, given by (16) and (17). It is observed that the throughput is improved with a small value of k_1, because the smaller k_1 indicates the bigger T_{DATA} as T_{NI} is fixed given by (13), which contributes to more data transmission time and more transmitted data frames after establishing the link in Phase 1. It is also relevant to note that the data transmission time T_{DATA} is constrained by the DATA size L_{data} and data frame length L_{one} given

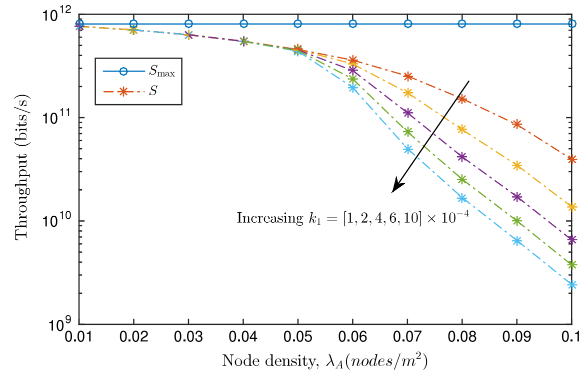

Fig. 6. Throughput vs. node density λ_A (r_{THz} = 1 Tbps, L_{data} = 50 MB, L_{one} = 10^5 bits).

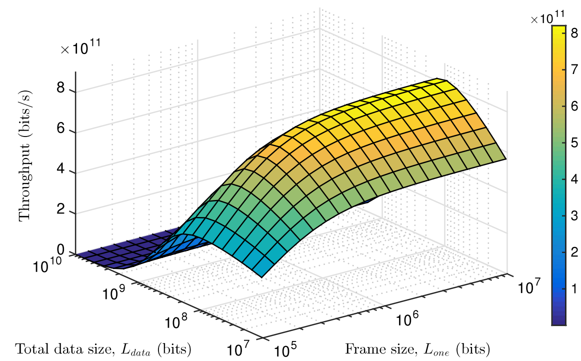

Fig. 7. Throughput vs. data size (r_{THz} = 1 Tbps, $\lambda_A = 0.02$ nodes/m^2).

by (24), which are required to be jointly optimized to achieve the maximum throughput.

5.3. Throughput vs. DATA size

The throughput S as a function of data frame size and total data size is shown in Fig. 7. There are several observations to be made. First, as the data frame size is identical, the trend of the throughput verifies the analysis of the tradeoff between the total data size and the throughput, given by (25), as discussed in the above subsection. Second, the biggest throughput can be achieved as the optimal total data size L_{data} is around 9×10^7 bits. This figure shows that if the total data size is beyond this value with fixed r_{THz} and λ_A, the larger the total data size, the lower the throughput. This is mainly as a result of introducing more data transmission time and bigger failure probability in Phase 1. Third, as the total data size is larger than one data frame size, the larger data frame size which the network uses results in the bigger throughput due to the less data transmission time. The biggest throughput is achieved 8.2×10^{11} bits/s at the point $L_{one} = 10^7$ bits, which is almost 82% of the channel capacity in the THz band.

6. Conclusion

In this paper, we proposed an assisted beamforming MAC protocol to significantly improve the throughput of THz networks, by two different wireless technologies, WiFi at 2.4 GHz and THz-band communication. The relation between the transmission distance, required gain and resulting beamwidth are established based on the adaptive beamforming. The protocol operation is divided in two phases working at 2.4 GHz and THz frequencies, respectively. According to the two phases, a mathematical framework is developed to analyze the performance of TAB-MAC protocol in terms of packet delay and throughput, and theoretical upper bounds. Simulation results are provided to evaluate the performance of TAB-MAC protocol under different scenarios, and also define the design guideline. The results show that the TAB-MAC protocol maximizes the THz channel utilization and achievable throughput of THz communication networks.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC) under Grant Nos. 61379123 and 61402414, and in part by Public Project of Science Technology Department of Zhejiang Province under Grant No. 2015C31007 and National Natural Science Foundation of Zhejiang Province under Grant Nos. LQ14F020005 and LQ15E050006.

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