Comparative Analysis of Terahertz MAC Protocols for Wireless Data Center

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Abstract. Over the last few years, generation of Internet data by the users has drastically increased. As this data is accessed, processed, shared, and delivered through the data centers (DC), therefore bandwidth requirement for DC is increasing. Although, wired technologies are being used, but at the cost of high maintenance, limited flexibility, and high energy consumption. Wireless Terahertz (THz) links can help to overcome these challenges of wired technologies and can also provide high data rates upto Terabits-per-second (Tbps) with low latency due to very high bandwidth availability. However, THz band itself has some challenges including high spreading, molecular, and material penetration losses. In the same way, the challenges for a DC includes its unique environmental and traffic characteristics which are in form of blockages, and different packet sizes (small and long flows) and traffic patterns. With these factors communication in DC can become challenging, so to ensure reliable and efficient communication it is necessary to understand the effect of these factors in the existing THz Medium Access Control (MAC) protocols. In this paper, we compare the existing THz MAC protocols, considering the unique environment and characteristics of DC like blockages and different packet sizes which will provide the basis to design and develop new THz MAC protocols. These protocols are implemented and evaluated on NS-3, and results show that the performance decreases when the unique requirements of THz band and DC environment are considered.

Keywords: Blockages · MAC protocol · Packet flows · Terahertz wireless links · Wireless data center

1 Introduction

In today's world as more and more people and devices are connecting to the Internet, the generation of data has also increased. Cisco [1] reported that in 2023, the devices which will be connected to the Internet will be approximately three

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times the population of humans, and 4.8 zetta-bytes of data will be generated annually. As this data is accessed, processed, shared, and delivered through the data centers (DC), therefore, DC need to support high bandwidth. Additionally, bandwidth requirement of these DC is also increasing with exponential growth which is double down each year [2]. Therefore, higher data rate has become the requirement of these DC. In present DC, wired technologies are being used in the form of copper and fiber optics cable which are costly, takes up lots of space and affects cooling [3]. Additionally, with the use of traditional topologies in wired DC, there is a hotspots and oversubscription problem. In a hotspot problem, a server in the DC significantly receive more network traffic comparing to other server nodes. An oversubscription problem occurs in communication between the server racks when the maximum demand for bandwidth exceeds the available bandwidth [4]. Therefore, to solve the problems of wired DC and provide higher data rate upto Tbps, THz wireless communication can be considered as a potential technology for future DC.

Considering DC specific environment, THz wireless links can be used in between inter-rack and intra-rack communication. By using THz wireless links, cables (wires) can be reduced which can help in reducing cabling complexity, and reduction in cooling as well as airflow will not be blocked. There are some other benefits too of using THz wireless link like flexible and new topologies can be designed which can help to reduce the deployment cost and provide energy efficient design for DC [5]. Additionally, the hotspot and oversubscription problem can be solved by using THz wireless links in the high demand area with more bandwidth availability. Moreover, THz bands have huge bandwidth availability due to which they can provide high data rates. Whilst the THz has many advantages, it has some challenges as well which include high spreading and molecular absorption loss, high scattering and reflection losses, and material penetration losses (blockages due to materials) [6,7]. Similarly, the challenges for a DC include its unique environmental and traffic characteristics [8]. Due to these issues, the use of THz wireless links in DC can become challenging.

In the context of a DC, the efficiency and reliability of data transfer is important, so it is necessary to understand the complications posed by the environmental and traffic characteristics of the DC which are blockages and different packet size respectively. Within the DC there is presence of racks, and cables which makes the DC environment dynamic and unique. Since THz band cannot penetrate a lot of materials and are sensitive to obstacles. Therefore, using THz band in this unique environment can bring up issues whilst designing communication protocols especially at the MAC layer for a DC. Through blockages, the signal gets attenuated which affects the received signal power, due to which the overall Quality of Service (QoS) can be degraded, and communication can become challenging. In addition to the unique environment, the nature of DC traffic can also bring up a problem whilst designing a THz MAC protocol specific to DC. The DC traffic characteristics includes two types of flow; short and long flows, amongst them short flows used for latency sensitive applications, for example query traffic often require packets with smaller size [9]. Moreover, in a DC majority of traffic is short flow which consists of packets with smaller size [10,11], so by not using optimal size for short flow in a DC can bring up latency, throughput and longer cycle time concerns. These blockages and small packet size can degrade the overall performance of the MAC protocol. Hence, to ensure reliable and efficient communication in a DC it is necessary to first analyse the effect of these characteristics in existing THz protocols, before proposing a MAC protocol specific for DC. Primarily, the function of MAC protocol is to ensure that if nodes (devices) want to communicate with each other, how they can access the medium, what rules they can follow to access the medium. Unlike the traditional MAC protocols which mainly focused on contention of nodes to access the channel, in THz band, as there is huge bandwidth available, so nodes do not aggressively contend to access the channel. But the focus in THz MAC protocols is coordination and scheduling. More specifically, through coordination in THz MAC for DC, blockages issue can be mitigated by using an alternate path for communication link [5]. Similarly, scheduling mechanisms can be used for packets with small size from which the packets can be transmitted quickly, increasing the throughput, and lowering delay.

Currently, for the DC environment, only one work is available [12] who have presented two THz MAC protocols as HCU and HTS-MAC. They mainly proposed a hybrid model with (carrier sense multiple access) CSMA and TDMA with two way handshaking mechanism for HCU MAC, and TDMA with one way handshake mechanism for HTS-MAC. However, the architecture and implementation details are not sufficiently mentioned like TDMA slot structure, guard time, timeslots etc. The unique environmental characteristics of DC scenario are also not considered including channel propagation, link losses and blockages. Terahertz MAC protocols have been proposed for applications like cellular net- work, Wireless Personal Area Network (WPAN), and Wireless Local Area Network (WLAN) [13]. In [13], two versions of an adaptive directional antenna MAC protocol (ADAPT) as ADAPT-1 and ADAPT-3 are presented. ADAPT-3 with three way handshake and ADAPT-1 with one way handshake. They have considered the centralized network architecture and addressed issues like synchronization, low channel utilization and collision avoidance. In ADAPT-3, they have used adaptive modulation coding scheme, and adaptive sector time and addressed co-ordination problem among the nodes. Whereas in ADAPT-1 they have partially used adaptive sector time to improve channel utilization. The recent THz MAC protocol (TAN-MAC) is proposed [14], however for airborne networks with ultra high range of 10 km, and with main focus on mobility and velocity of nodes. Therefore, in our analysis we are not considering this protocol, because of its non-suitability for DC environments.

To the best of our knowledge, nobody has analyzed the performance of existing THz MAC protocols for the suitability of a DC considering the environmental and traffic characteristics of the DC. Hence, we aim to bridge this gap by providing the performance comparison of THz MAC protocols in data center environment. The main contribution of our work includes the comparative analysis of existing receiver-initiated carrier sensing based THz MAC protocols [13] in the

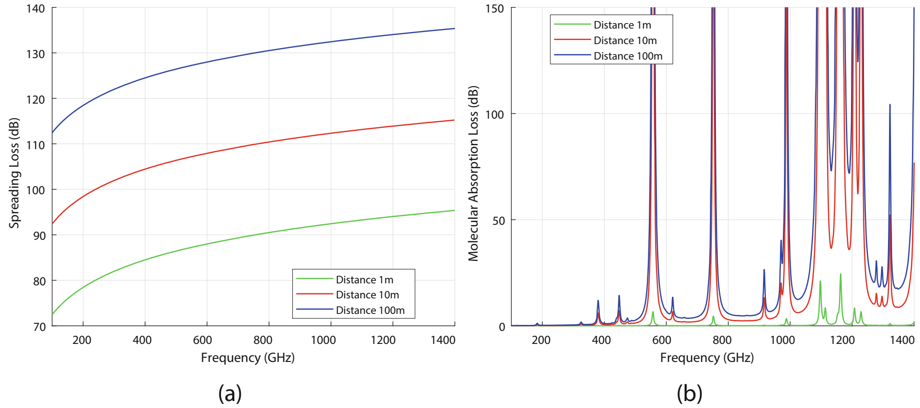

Fig. 1. Terahertz Channel Characteristics. (a) Spreading Loss directly proportional to distance and frequency. (b) Molecular Absorption Loss increasing with frequency.

context of DC, we will analyze how THz MAC behaves in DC environment while considering the two important factors, the environmental characteristics (blockages) and traffic characteristics (small packet size). This performance analysis will provide the basis to design and develop new THz MAC protocols considering DC specific constraints.

The remainder of this paper is organized as follows: We have provided the description of THz Channel Characteristics and Data Center Environment in Sect. 2. In Sect. 3, we have discussed the mechanism of MAC protocols. Section 4 provides the description of performance evaluation with simulation results. Finally we have drawn the conclusion in Sect. 5.

2 THz Channel Characteristics and Data Center Environment

In this section, we discuss the channel characteristics of Terahertz band. Additionally, to compare the performance, and suitability of THz MAC protocols in order to work in a DC scenario its necessary to understand its unique environmental factors and characteristics. Therefore, in this section, we also discuss the unique environment of data center, and unique requirement for THz MAC for wireless DC.

2.1 Channel Characteristics of THz Band

In electromagnetic spectrum, THz band ranges between 0.1 to 10 THz (100 GHz–10000 GHz), and it is in between microwave and infrared band. The key challenge include its high path loss which is due to spreading and molecular absorption loss, and it increases with increasing distance and frequency as shown in Fig. 1.

Due to this spreading loss, transmission of signal is affected, and it also creates the distance problem due to which directional antennas are used in THz to increase the coverage range [6].

Similarly, molecular absorption loss is occurred as THz signals gets absorbed through water vapours (H_2O) in the atmosphere. Additionally, THz signals are also absorbed by molecules of (0_2) oxygen in the atmosphere [15]. Since the molecular absorption loss is very less for the selected frequency i.e. 0.021868 dB, and it can be seen in Fig. 1, therefore it can be neglected.

Spreading loss can be calculated as [6],

$$Spreading\ Loss = \left(\frac{4\pi f d}{c}\right)^2 \tag{1}$$

where; c is the speed of light, f is the central frequency, and d the distance between transmitter and receiver.

Molecular absorption loss can be calculated as [6],

$$Molecular\ Loss = e^{kf \cdot d} \tag{2}$$

where; kf is the absorption coefficient at specific frequency, and is calculated using High resolution transmission molecular (HITRAN) database, and d is the distance.

To calculate the received power we have used the channel model as described in [6].

$$P_r(d) = \int_B PSD_t(f)|H_c(f,d)|^2 G_t(f) G_r(f) df, \tag{3}$$

where channel frequency response $H_c(f,d)$ is calculated using losses, G_t, G_r are the gain of antennas, and PSD_t represents one sided power spectral density of transmitted signal.

2.2 Data Center Unique Environment

1. **Blockages:** In a DC environment, there are blockages in form of racks and cables as discussed by Cheng et al. [8]. In their DC environment, servers were arranged on the metallic racks, and the rack consist of mesh type structure door to maintain the cooling inside the racks. Moreover, the racks also consist of cables. They performed their measurement by considering different propagation scenarios. They concluded that in the DC, pillars of server racks can be utilized as a reflecting material to assist communication, and optical lenses can be helpful to provide gain in both LoS and NLoS communication. On the other hand, power cables can cause a signal loss of 20 dB. Similarly, mesh door of servers racks can also cause signal attenuation of 5.7 dB. These losses are computed from mean path loss of LoS, OLoS, NLoS, ONLoS [8].
   Mean path loss can be calculated as [8],

$$Mean\ Path\ Loss = \frac{1}{N}\sum_{i=1}^{N} |H(f_i)|^2 \tag{4}$$

where; $H(f_i)$ denotes the channel transfer function, N denotes to total number of frequency tones.
These blockages affects the performance of THz MAC protocol, as there are losses from these blockages due to which received signal power is affected, signal noise increases which decrease the throughput, and causes delay in transmission.

2. **Reflections and Scattering:** Eckhardt et al. [16] have done measurement in inter-rack and intra rack communication. They concluded in a DC environment there are reflections. Similarly, Song et al. have performed inter-rack communication [17] and they concluded that there is scattering in DC environment which is cause by metal racks.

2.3 Unique Requirements of THz MAC for Wireless DC

1. **Data packet size:** In a DC there are two types of flow, short flow (mice flow) and long flow (elephant flow) [18]. In [18], it is reported that almost 80% flow of packet in a DC is less than 10 kB which is a short flow, and in [10] it is reported that 70% of flow is a short flow, which is less than 10 kB. The example of short flows includes the query traffic and has the size between 2–20 kB [9]. In ADAPT [13], the data packet size used is 65 kB. Using a larger data packet size can affect in increased latency, error probability and cycle time. The THz MAC protocol must be designed to support short flows.
2. **Throughput and Delay:** In a DC environment, due to the sharing of bandwidth between the nodes (devices), the MAC protocol should provide higher throughput and low latency for reliable communication [5].
3. **Power efficient:** The MAC protocol should support mechanism for minimizing transmission power through power control strategies. Low transmission power is required in context of DC to save energy.

3 MAC Protocols Mechanism

In this section, we discuss the working of existing MAC protocols namely ADAPT-1, ADAPT-3.

3.1 ADAPT-1 MAC Mechanism

ADAPT-1 is a receiver initiated MAC protocol in which a receiver initiates its communication which has a rotating directional antenna. The client nodes also have directional antenna but with fixed direction towards the receiver. The receiver announces its status (ready to receive) by broadcasting a call-to-action (CTA) packet in all directions. After sending CTA packet, the receiver use a partially adaptive sector time mechanism in which it waits for a certain period for the client to send data otherwise it moves to a new sector. If the client node has data to send, it transmits it to the receiver, and waits for the acknowledgment as illustrated in Fig. 2(a) [13].

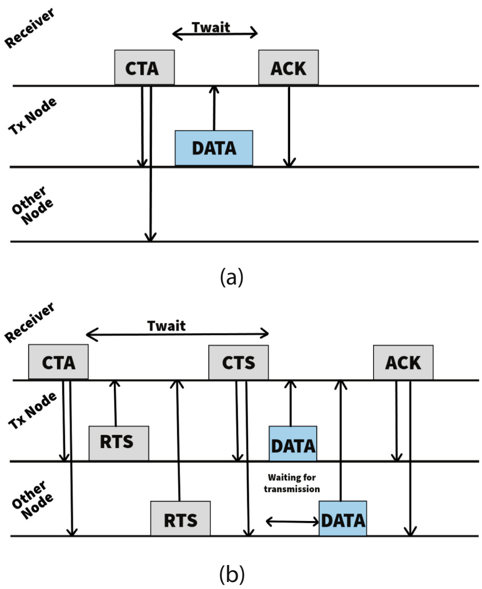

Fig. 2. MAC protocol mechanism. (a) ADAPT-1. (b) ADAPT-3.

3.2 ADAPT-3 MAC Mechanism

ADAPT-3 follows the similar architecture as ADAPT-1 and differs mainly in its working. Client node when receives CTA from receiver waits for random backoff time to avoid collision. After waiting time, it sends (request to send) RTS packet to the receiver when it has data to send, if timeout expires it retransmits the packet for maximum five times before discarding the packet. During the waiting time, the receiver uses adaptive sector time in which it sets its time according to the received RTS packets. If client node wants to complete the data transmission it will wait otherwise it will move into a new sector. The receiver also decides which specified sector can be used by the client nodes through the sector white list mechanism. When the receiver receives RTS packet, it analyzes it using adaptive modulation and coding scheme. Through recording the SNR from the client node, it selects the highest order of modulation scheme. If it does not receive RTS, it moves to another sector. Now the receiver sends clear to send (CTS) packet to give channel access to client node in which it has the information of modulation and coding scheme, also receiver allocates the time of transmission slot to client nodes to avoid collision between the client nodes so the nodes can transmit data on their specified time slot. After receiving CTS, client node waits for transmission slot then it selects the modulation scheme indicated by the receiver, these details are present in the CTS packet. If the client node has data to send, it transmits it to the receiver and waits for the acknowledgment as illustrated in Fig. 2(b) [13].

Table 1. Simulation Parameters

Frequency range	252.72–321.84 GHz
Channel bandwidth	69.12 GHz [13]
Central frequency	287.28 GHz [13]
Modulation scheme	16-QAM
Transmitted power	10 dBm [21,22]
Noise figure	7 dB [13]
Packet Size	65 kB [13], 9 kB
Communication Range	4.86 m
Antenna type	Directional
Beamwidth	12°
Antenna Gain	24.57 dB
No of sectors	30
Blockages considered	Cables, Mesh doors

4 Performance Evaluation

Simulations are performed for comparison of existing THz MAC protocols including ADAPT-1 (1-way), and ADAPT-3 (3-way). The blockages and different packet size (for short flows) are considered for the analysis. For blockages we consider the racks, and the mesh doors and cables within a rack. The measurements works shows that the blockages can affect the link performance [8]. We also consider the short packet size for our analysis. To measure the performance, we used throughput as a parameter to analyse the efficiency of THz MAC protocols and link performance.

4.1 Simulation Setup

The setup, and implementation details, are discussed below.

Environment: We used NS-3 for simulation, and more specifically we have used Terasim module [19] which is the extension of NS-3 and it is designed specifically for simulating communication protocols in THz communication. We have used the parameters for a DC, as mentioned in Table 1. For calculating the communication range, we used 16-QAM modulation scheme with 10 dB transmission power. The traffic model used in the simulation is taken from Morales et al. [13], it follows a poisson process. In our simulation, the inter-arrival time of packets is set to 400 μs which is the time duration in between the arrival of two consecutive packets at a node, and inter-arrival of packets follows the exponential distribution. Similarly, the rate of packet arrival which is the rate of poisson process will be the inverse of inter-arrival time. Therefore, for 400 μs inter-arrival time, the rate of packet arrival is 2500 packets/sec.

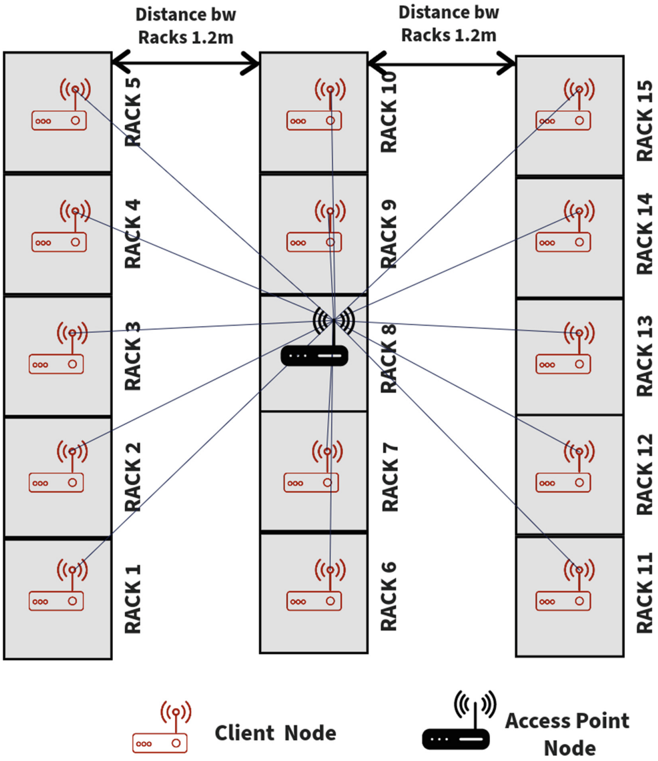

Fig. 3. Centralized Network Architecture for wireless DC in which each server rack has THz transceiver at ToR.

Network Topology: The network topology is shown in Fig. 3, in which three rows of racks are used each with 5 racks. Each server rack has a top-of-rack (ToR) THz node. The distance between the two opposite racks is 1.2 m and the rack dimensions are 0.58 m (width) and 0.67 m (depth [20,23]. In this paper we have considered the inter-rack communication, in which there is a central access point (AP) at Rack No.8 with rotating directional antenna at ToR, and all other racks are client nodes with a directional antenna pointing its beam towards the AP. In our design, for simplicity of the analysis we have not included a client node in the rack with AP. In our simulation we varied number of client nodes (2, 4, 6, 8, 10, 12, 14), these client nodes communicate with AP node. For example if there is a four node scenario, there will be one AP receiver which is rotating, and four transmitter nodes (client nodes).

Implementation Details: Extensive simulations are performed to analyse the performance of THz MAC protocols under the presence of blockages (cables and doors of racks). We included path loss for OLoS, and LoS from which the total loss of mesh doors was computed. Additionally, we included the cable loss as well.

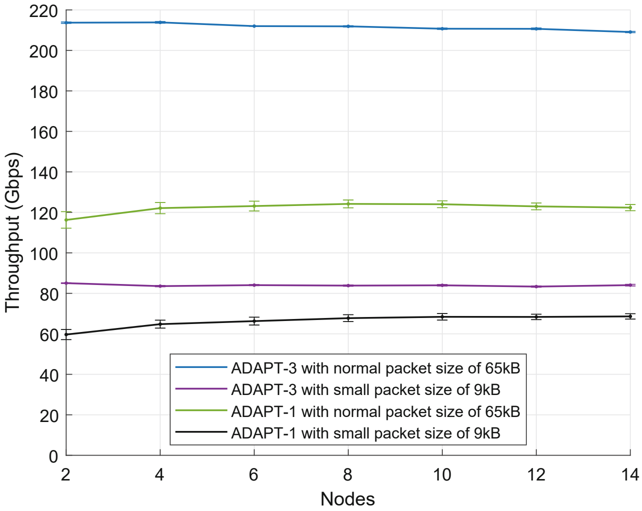

Fig. 4. Average Throughput of ADAPT-1, ADAPT-3 with normal and small packet size.

4.2 Performance Metrics

The performance of the THz MAC protocols is evaluated using key metrics of throughput, which is discussed below.

Throughput: This metric is defined to capture the efficiency of data transmission. It is the rate of data packets that are successfully transmitted by the nodes per unit time. More precisely, it is computed by dividing the packet size of successfully transmitted data of client node with the transmission time (in seconds), and is measured in bits/second [13]. Throughput is calculated for the client nodes that are involved in a successful transmission to the AP, i.e. the data was successfully sent by a client node.

4.3 Simulation Results

In this section, we present the outcomes of our simulation analysis. Our results in the following subsection are averaged over fifty simulation runs. Additionally, simulation results are with 95% confidence intervals.

Analysis of Packet Size: Figure 4 compares THz MAC protocols average throughput, with two different packet sizes 9 KB (small packet size) and 65 KB (normal packet size). The 9 kB is indicative for short flows inside the data center specifically for latency sensitive applications such as query traffic. The small packet size is chosen for the analysis because majority of the flows in data centers (almost 70–80%) comprises of short flows [10,18].

When the packet size decreases from 65 kB to 9 kB the average throughput decreased by approximately 60%, 46% for ADAPT-3 and ADAPT-1 respectively as shown in Fig. 4. There are two main reasons for less throughput when using a smaller packet size of 9 kB which are overhead due to handshake and synchronization, and inefficient use of transmission opportunity. Firstly, the ratio of overhead to data packet will be more in smaller packet size compared to larger packet size involved in transmission. This overhead will be from handshaking and from the synchronization between client nodes and AP node which is established frequently for each data transmission. Secondly, the reason behind the less throughput for small packet size is because it will not be utilizing the transmission opportunity more efficiently compared to large packet size as the packets with smaller packet size will be sending less bits compared to the packets with larger size.

Impact of Blockages on Throughput: Blockages which are present in the DC in the form of cables and rack doors has reduced the average throughput of THz MAC protocols leading to degraded performance. As these MAC protocols are designed with the goal to maximize the throughput so it will worsen the overall performance of MAC protocol. To investigate the effect of blockages on THz MAC protocol we have investigated three scenarios in this paper with two different packet sizes (65 kB - normal packet size & 9 kB - small packet size) which includes, without blockages, with blockages from mesh doors of racks, and with blockages from cables.

In the scenario where there are no blockages, a signal is directly transmitted by the client nodes to the receiver, and there is a direct link without any obstructions. Due to direct link, there is no signal attenuation from cables and mesh doors. As there are no obstructions THz MAC protocols are performing adequately as shown in Fig. 4. Comparatively, ADAPT-3 and ADAPT-1 are providing higher throughput as they are receiver-initiated communication protocols and client nodes only send the data when they receive indication from the receiver which ensures no packet is discarded.

In contrast to without the blockages, there is a significant reduction in the average throughput with the blockages from cables for 65 kB packet size. There is reduction of approximately 81% and 75% specifically for 8 nodes scenario in the ADAPT-3 and ADAPT-1 respectively as shown in Fig. 5(a). ADAPT-1 and ADAPT-3 MAC protocols are giving zero throughput for 2, 4, and 6 nodes scenario due to severe attenuation, since the receiver (AP node) is not able to receive the signal from the client nodes with sufficient power strength as the signal to interference noise ratio (SINR) is below the threshold value from which there is weaker signal.

Additionally, from blockages due to mesh doors as shown in Fig. 5(b) there is a decrease in the average throughput which is approximately 17% and 16% for ADAPT-3 and ADAPT-1 respectively for normal packet size compared to without blockages.

Similar effects of decrease in throughput are also observed for both the two scenarios of blockages with smaller packet size (9 kB).

In both the THz MAC protocols there is a similar trend of decrease in average throughput when there are blockages. This decline is the indication of the dete-

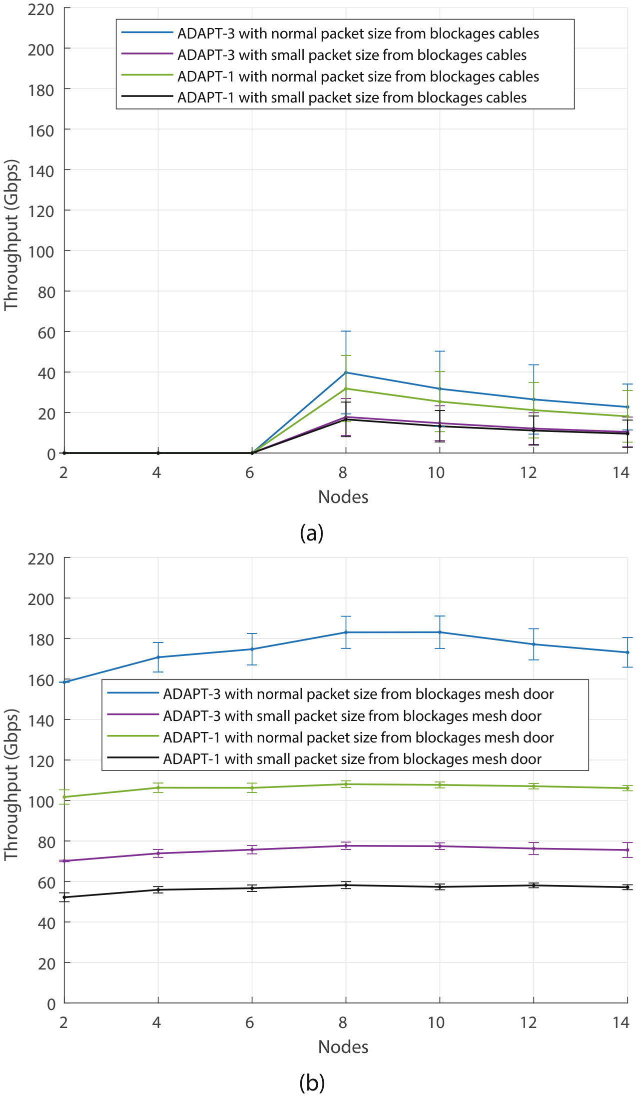

Fig. 5. Impact of blockages on average throughput of THz MAC protocols with normal and small packet size. (a) ADAPT-3, ADAPT-1 with blockages from cables. (b) ADAPT-3, ADAPT-1 with blockages from mesh door of rack.

riorating performance of the THz MAC protocols. There are two main reasons for decline in average throughput when there are blockages. Firstly, these blockages cause attenuation of signal due to which there is degradation in quality of signal then there are losses due to which received signal power is affected. These blockages affect LoS communication between the transmitter and receiver. As

LoS is blocked, signal noise increases which decrease the throughput, and causes delay in transmission.

From results, it can be concluded that the performance of the THz MAC protocols has been degraded drastically. As DC requires high throughput therefore this decrease in throughput due to blockages and smaller packet size can affect overall performance of DC. Therefore, THz MAC protocols designed for the DC environment should take in consideration the techniques and mechanisms for mitigating blockages and, handling packets with small size.

5 Conclusion

In this paper, we have performed the comparative analysis of recent THz MAC protocols including ADAPT (1-way) and ADAPT (3-way) considering unique environmental, and traffic characteristics of DC which includes blockages, and small packet size respectively. We evaluated the performance of these THz MAC protocols in the NS-3 simulator using the performance metrics of throughput. This performance evaluation is crucial to understand the effect of blockages, and small packet size on the performance of THz MAC protocols, as previously no comparative analysis has been performed considering DC specific constraints. Results shows that the peculiar characteristics of DC including blockages, and small packet size significantly decreased the average throughput by upto 80% degrading the performance of THz MAC protocol. In future work, we will consider different traffic patterns of data centre network to further analyse the performance of THz MAC protocols.

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