Beyond 5G: THz-Based Medium Access Protocol for Mobile Heterogeneous Networks

Angela Sara Cacciapuoti, Kunal Sankhe, Marcello Caleffi, and Kaushik Roy Chowdhury

The authors present a network architecture for the next generation of MHNs, where mmW, terahertz, and conventional mW bands coexist, with cost-benefit trade-offs of each type of link. They envision a radically different communication paradigm and outline a MAC protocol design that switches among the aforementioned bands for data transmissions, falling back on the slower link each time for the reverse channel ACKs.

ABSTRACT

This article presents a network architecture for the next generation of MHNs, where mmW, terahertz, and conventional mW bands coexist, with cost-benefit trade-offs of each type of link. We envision a radically different communication paradigm and outline a MAC protocol design that switches among the aforementioned bands for data transmissions, falling back on the slower link each time for the reverse channel ACKs. The use of the higher-capacity link in the forward direction for data communication and the slower reverse channel for the returning ACKs allows for uninterrupted unidirectional communication and efficient use of the channel. The article discusses the challenges in analyzing and parameter setting for the various features of the protocol, and identifies candidate solutions. A performance evaluation of the approach is undertaken using a realistic scenario of vehicle-to-infrastructure communication enabling data center traffic backhauling. This performance shows that by adopting the proposed MAC protocol data transfer of around 100 Terabits, it is possible for typical vehicle-to-infrastructure contact times.

INTRODUCTION

The ever increasing demands for high bandwidth connectivity and emerging class of real-time, interactive applications, like autonomous vehicles and virtual reality (VR), are catalysts for creating the next generation of wireless technologies. The ongoing fifth generation (5G) standardization, driven by advancements in millimeter-wave (mmW) technology in the 57–64 GHz band, is a candidate solution to alleviate the bandwidth crunch that is already prevalent today. However, projections in [1] suggest that even the forthcoming 5G standard will not be able to completely match the predicted growth rate of mobile data traffic over the next decade. As an example of currently existing commercial off-the-shelf (COTS) technology, the 802.11ad standard in the 60 GHz industrial, scientific, and medical (ISM) band can achieve up to 6.8 Gb/s, although our experiments reveal close to 1 Gb/s in indoor laboratory environments. Given this upper bound on the effective data rate, practical deployment of fully autonomous/driverless vehicles on a busy highway [2] or collaborative virtual reality (VR) in indoor spaces, two fast-emerging market segments, will continue to be impaired within the mmW standard. For example, an uncompressed ultra high-definition (UHD) video may reach 24 Gb/s rate, and an uncompressed 3D video with UHD can reach 100 Gb/s [3]. Thus, we believe that forward-looking and transformative wireless technologies that go beyond mmW bands will be the key enablers toward a paradigm shift from multi-gigabit-per-second up to terabit-per-second data rates. We believe that many emerging applications will succeed in widening their user base by leveraging the THz frequency region, ranging from 0.1 to 10 THz [3].

While great strides have been made in the device design of THz wireless transceivers, efforts on configuring network protocols to efficiently utilize the band have remained in a nascent stage. In this article, we propose a network architecture and a medium access protocol (MAC) that exploit the THz band for the next generation of mobile heterogeneous networks (MHNs).

We first describe constraints on a THz-based network that influences protocol design.

CONSTRAINTS ON THZ-BASED MHN DESIGN

Limitations of Distance: Propagation in THz bands is limited by the severe path loss and molecular absorption. These in turn make the communications in THz bands more sensitive to blockages compared to that in the mmW bands.

To overcome the significant attenuation and extend coverage, high directivity gain antennas must be used. However, utilizing directional transmissions can extend the link distance in THz bands on the order of a few meters. As a consequence, it is unrealistic to expect universal coverage with only THz communications. A likely deployment scenario for the next generation of MHN is that mmW wireless technology coexists with THz, giving an additional range of approximately 200 m at ultra-high data rates [4], along with conventional omnidirectional wireless technologies in the microwave[1] (μW) bands. The next sections revisit this design choice to have all three types of wireless interfaces in the same device.

Directional Challenges: Different from conventional omnidirectional communications in the μW bands and similar to mmW communications [4, 5], with highly directional transmissions and sensitivity to blockage, the interference is greatly reduced in THz-based networks. This implies that the ensuing communication can be considered mainly noise-limited rather than interference-limited.

Despite this positive aspect, directional communications require beams to be aligned and steered

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[1] The prefix micro- in microwave is not meant to suggest a wavelength in the micrometer range. Indeed, microwave denotes RF bands currently used for mobile networks.

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to avoid the deafness problem, that is, a situation in which the main beams of the transmitter and the receiver do not exactly point to each other, making it impossible to establish high-quality links [6]. This issue is even more crucial in THz-based networks than in mmW networks, since directionality is greater in the former. Hence, THz-band transmissions involve larger overhead of beam training/beam alignment, as opposed to the mmW band. COTS mmW devices such as 802.11ad routers require several milliseconds to complete the beam training, which will only increase for THz links.

Complexity of Transceiver Design, Operational Cost: While close to 7 GHz chunks of contiguous bandwidth are available in the 57–64 GHz mmW bands, current standards such as 802.11ad define smaller channels, around 2 GHz. While THz bands with channel bandwidths in excess of 20–100 GHz may be theoretically possible, the energy costs in continuously operating key processing components, such as the analog-to-digital converter, at such high sampling rates can become prohibitive. Thus, we believe the THz transceivers may be activated in short bursts for improved trade-off in achievable bandwidth vs. energy/complexity costs.

Real-Time vs. Delay-Tolerant Applications: While some applications require gigabit-per-second rates for their real-time operation [7], many others generate terabits of data that can be processed offline [8]. The choice of the wireless technology to be used may also take into account the specific considered application. With this in mind, in the next sections we clarify and discuss how our approach guides the selection of the transmission technology by relying on the differentiation of the traffic into these two classes.

Impact of Constraints on MAC Protocol Design

Based on the above considerations, we propose a network architecture for the next generation of MHNs that switches between three different wireless access technologies: classical-low bandwidth µW (e.g., LTE), mmW band, and THz band access technologies. This choice is motivated by the observations made above, where we state that it is not possible to obtain universal coverage with only THz communications.

For this network architecture we propose a MAC protocol as detailed below. This article focuses mainly on the MAC functions of transceiver selection and configuration in terms of channel access duration for each of these wireless technologies. It aims to achieve the maximum data transfer possible for the choice of the wireless link along with the assurance of an error recovery capability. This deviation from the classical MAC design that prioritizes interference management is intentional and based on the unique characteristics of the THz and mmW bands as described above. We recall that networks operating in these bands are mainly noise-limited rather than interference-limited. We note that since many existing MAC protocols focus on µW communications, we mainly describe the protocol operation in the mmW and THz bands.

Classical protocol design such as 802.11-based WiFi uses in-band data and acknowledgments (ACKs), with a gap of about 20 µs called short inter-frame spacing between successive data and ACK packets. From the considerations made above, reversing the communication direction for the ACKs over the same link used for data transmissions introduces many challenges in completing a new round of beam training, alignment, and synchronization. Hence, due to the complexity of the design, we use unidirectional flow of data using the best available wireless access technology, and delegate the slower and more reliable access technology for the returning ACKs.

We also discuss how the nature of the traffic impacts the selection and configuration of each of the considered wireless technologies.

In summary, the novel contribution of the article is a completely different architecture design that separates ACK (control signals) from the data and uses three different PHY layer technologies (THz, mmW, and µWave communications). As highlighted later, we identify the unique set of challenges within the resulting architecture, and list both the candidate solutions and the open research problems.

The rest of the article is organized as follows. In the following section we describe the details of our MAC protocol. Following that we discuss some open problems along with some possible solutions. Then we quantify the benefit of the proposed medium access protocol for an example scenario of a vehicle enabling data center traffic backhauling. Finally, we conclude the article.

Proposed Medium Access Protocol

As described above, the objective of the article is to design a MAC protocol that is able to select and configure the mmW and THz communication modes so that the maximum data transfer can be achieved along with the assurance of an error recovery capability. The guiding approach here is to always select the THz link wherever possible. As the range is limited to only a few meters, active THz links can be achieved at specific locations with distance limitations between the transceiver pair.

Distance-Dependent Spectrum Switching

To avoid the challenges in repeated beam training and alignment and synchronization associated with reversing the same link for data and ACK, we maintain the unidirectional flow of data and delegate the slower and more reliable access technology for the returning ACKs. This results in three scenarios:

- When the THz link is active, the mmW link is used to report the ACKs from the receiver to the sender.
- When the mmW band is used for data communication, the classical mW link is used for reporting ACKs.
- When both mmW and THz links are inactive due to higher separation distance between the transceiver pair, the mW link is used for both data and ACKs, as is already done today.

Let the maximum distance between a transceiver pair at which communication becomes possible for the mmW and the THz channels be given by $d_{\text{th}}^{\text{mmW}}$ and $d_{\text{th}}^{\text{THz}}$, respectively.[2] $d_{\text{th}}^{\text{mmW}} \gg d_{\text{th}}^{\text{THz}}$, where the mmW links extend up to 200 m, whereas the THz links are around 10 m. As THz bands allow transmission rates several orders of magnitude higher than mmW, we propose to use this mode whenever possible, by also accounting for the traffic nature of the considered application. Thus, the communicating node pair switches to THz communication when the separation distance is less than $d_{\text{th}}^{\text{THz}}$, and to mmW band when $d_{\text{th}}^{\text{THz}} \leq$

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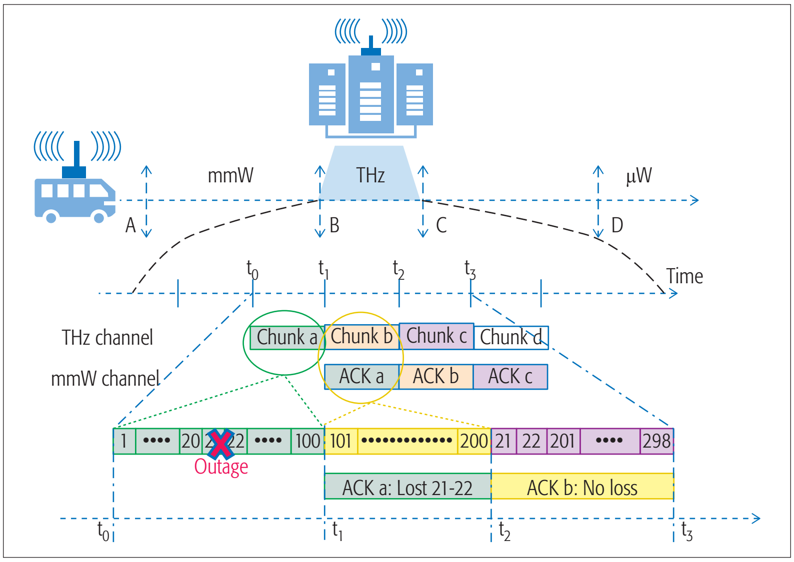

Figure 1. Protocol overview when the distance between the pair nodes is smaller than the THz threshold. The data chunks are labeled with literals, whereas the numbers represent the packet IDs. A similar procedure applies when mmW band is used for data communications.

$d \leq d_{th}^{mmW}$, as shown in Fig. 1. The mobile node, represented as a vehicle, moves from left to right, and in the process reaches closer to the data offloading node represented as a base station (BS). THz communication is only possible between B-C, and the mmW communications may be used in both the A-B and C-D portions of the journey. At any point before A or after D, the communicating node pair switches to the conventional μW link.

THROUGHPUT MAXIMIZATION AND PACKET AGGREGATION

As an alternate option, an argument could be made that mmW links are used only for data contemporaneously with THz communications and wherever THz are unavailable, and the μW links are used for acknowledgment of both mmW and THz transmissions. Since the THz transmission rate for data is several orders of magnitude higher than the μW transmission rates, acknowledgment of THz transmissions on the mW link could introduce excessive delay for receiving an ACK. This will force the THz transmitter to stop waiting for the acknowledgments. In this case, clearly, the advantage of massive levels of bandwidth in the THz frequencies is lost.[3] The above consideration and the ones made earlier suggests the benefit of sending the ACK packets for the THz data communication on the mmW links. We note that this introduces beamforming overheads similar to those mentioned above, as the communications must be directional.

Since the second-best wireless link at any stage is considerably slower than the forward data link, each ACK cumulatively validates the data packets aggregated into a unit, called a *data chunk*. Classical stop-and-wait-based ACKs that are present in classical 802.11-based WLANs acknowledge every packet. Adopting the same approach for the forward THz and mmW ACK channel fails to leverage the massive levels of bandwidth in the THz frequencies.

ERROR RECOVERY

Due to the huge difference among the transmission rates of the considered technologies, as described above, the size of a chunk needs to be chosen so that both the forward (i.e., data) and the reverse (i.e., ACK) channels remain saturated. Ideally, data packets are sent continuously without any gaps, and they are periodically validated with cumulative ACKs received through the reverse channel to allow efficient error recovery. When some packets of a data chunk are received with errors, these errors are reported back to the sender through the second best performing ACK channel so that the sender can selectively re-transmit the lost data over the forward channel. As shown in Fig. 1, once the ACK is received through the reverse channel at the sender side, the lost packets are identified and re-transmitted within the next data chunk[4] by prepending them to the new data. Errors within the THz communication range are reported to the sender by using the mmW band, allowing the sender to re-transmit in the active THz band. A similar process is used when ACKs are sent over μW band and data communication occurs over mmW frequencies.

In Fig. 1, two packets with IDs 21 and 22 belonging to the first chunk, say chunk *a* transmitted at time t_0, are lost due to an outage event. The sender becomes aware of such a packet lost at time t_2 upon reception of the corresponding ACK *a*. Hence, it re-transmits these two packets with the third chunk. Missing ACKs are handled in a conventional manner, that is, the entire packet train (i.e., entire chunk) represented by that ACK is re-sent in the forward channel.

PROTOCOL DESIGN CHALLENGES

In this section, we study the challenges in parameter settings that influence the protocol design. Some of these remain open-ended, and we propose possible candidate solutions for integrating them into our protocol.

THZ CHANNEL AND BLOCKING MODELS

The analysis of the MAC protocol depends on the bit error rate on the forward channel. This in turn is dependent on the signal propagation in the mmW and THz bands. The signal propagation in the THz band is mainly affected by molecular absorption, which results in both molecular absorption loss and molecular absorption noise. In particular, the molecular absorption defines several transmission windows along the frequency scale with varying widths that are, to some extent, defined by the molecular composition of the medium. These environment-specific characteristics make communications increasingly sensitive to blockages in THz over mmW band.

As a consequence, to better understand the error probability, we need not only well defined THz channel models but also experimentally validated THz blocking models, similar to those that exist for the mmW bands [4]. So far, the published works on THz channel modeling are mainly focused on the lower end of the THz band, that is, 0.06 to 1 THz [9–11], with an absence of models for the blockages in the higher THz spectrum.

From these considerations, to assess the benefit of our approach we assume that any blockage instantaneously disrupts the THz communications, whereas for the mmW channel we adopt a widely validated blocking model [4]. All the mathematical details can be found in [2]. Better channel and blockage models will results in more accurate analysis of the system.

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[2] Through d_{th}^{mmW} and d_{th}^{THz}, we can account for the overhead needed to establish an mmW or a THz link. Specifically, d_{th}^{mmW} and d_{th}^{THz} can be set for a soft handover: mmW communications continue until a THz link is established, and, similarly, mWave communications continue until an mmW link is established.

[3] In future work, we aim to perform an analytical comparison between the aforementioned two scenarios.

[4] Although the ACK processing delay could require that the lost packets be re-transmitted at some future time slot, we omit these particulars from Fig. 1 for the sake of simplicity.

SIGNALING OVERHEAD

Our MAC protocol must switch between the different transmission types at very specific separation distances. Simple probing is ineffective as link disruptions caused by temporary blockages can be considered as long-term distance-dependent switching points. Hence, our approach requires geolocation knowledge of the involved nodes to determine the relative distances, and the tracking of the sender and the receiver during an ongoing communication to correctly shape the directional transmissions in mmW and THz bands.

These requirements for continuous location updates may increase the signaling overhead and hence the complexity of our approach. As one possibility, techniques for tracking the sender/receiver during an ongoing communication have been proposed in mmW and THz channels as in [10].

As a totally different approach, a software-defined network (SDN) controller can help in handling the signaling traffic for seamless communications [12]. This allows pre-setting directives for control plane switching for activating different wireless technologies and also provide support for mobility [13]. Furthermore, an SDN controller can also easily account for the traffic nature of different applications when it has to decide which one of the wireless access technologies should be selected, as highlighted above. This modified architecture is depicted in Fig. 2 for the case of communication between a mobile vehicle and two different BSs.

There are several nontrivial trade-offs that play a role in the SDN controller deciding which one of the wireless access technologies should be selected. The mmW allows communication to commence at a greater separation distance, and thus can result in longer connected durations if there is relative motion between the nodes of the link. On the other hand, data exchange in the THz range may incur additional time for the node pair to be aligned in close proximity, but then it quickly ramps up by leveraging massive levels of bandwidth in such frequencies.

To assess the benefit of adopting our proposal below, we assume a simple rule based on distance alone to determine the switching moments, leaving for future work the analysis of the aforementioned trade-off on the performance of the proposed MAC protocol.

CHUNK SIZE DETERMINATION

The size of a data chunk needs to be chosen so that both the forward data and the reverse ACK channels remain saturated. This necessitates determining the optimal choice for the chunk size. In particular, in the case of mobile nodes, the duration of their relative contact times (i.e., the length of the A-D segment) should be taken into account, as this ultimately impacts the chunk size. The greater the size of a chunk, the higher the channel saturation, although there is an inherent danger that the connection in the best-performing channel may be suddenly interrupted before the complete reception of the chunk.

We assume constant chunk durations, leaving for future work the analysis of the chunk size effects on the proposed mac protocol.

PERFORMANCE EVALUATION

In this section, we quantify the benefit of the proposed MAC protocol for an example scenario of vehicle-enabling data center traffic backhauling,

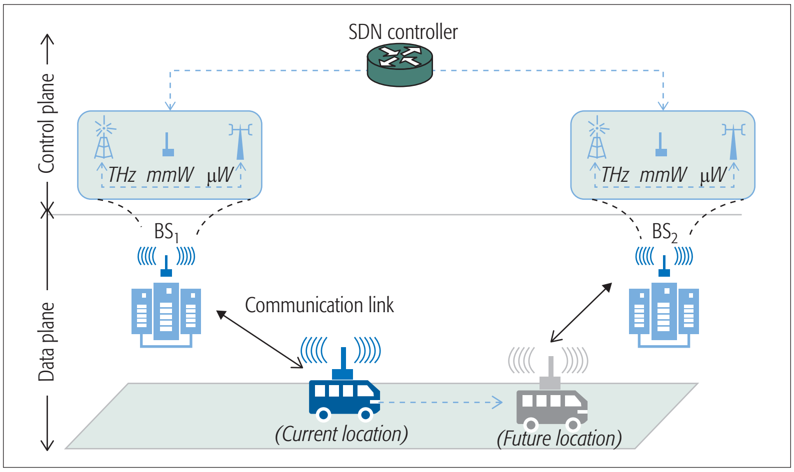

Figure 2. SDN controlled mmW/THz/mW connections.

that is, ferrying large volumes of delay-tolerant data between nearby data centers [14]. Specifically, we assess the achievable amount of exchanged data for backhauling by exploiting the mmW and THz bands.[5] The results shown in this section are extracted from [2], to which we refer for the mathematical details.

We consider the actual positions of existing data centers located in Boston for simulating realistic backhauling conditions. Out of 22 available data centers, we choose two locations in downtown Boston as typical use cases: the first is located at *1 Summer Street*, owned by *XO Communications*, and the second is located at *451 D St.*, owned by *Markley Group LLC*. Through Google Maps, we obtain the shortest vehicular route between the two considered data centers, shown in Fig. 3. The vehicle route length is roughly 1.2 miles long with an estimated travel time ranging between 7 and 19 minutes. The inline picture shows a zoomed view of the route near the first center. Our simulation takes into account minute topographical features, such as constraints arising from buildings and lanes. Based on the antenna positions, we can estimate the distance between transmitter and receiver as a function of time. We emulate a vehicle-assisted deployment where antennas are placed on vehicle rooftops and streetlight poles closest to the chosen data center, respectively. The rationale for this choice is twofold:

- The corresponding antenna heights agree with those used in mmW channel measurements [15], allowing us to adopt the corresponding experimental mmW channel model.
- The antenna positioning ensures that the THz link is not affected by outage events caused by pedestrians or vehicles blocking the LoS path.

The values for all the relevant parameters, used in this section are summarized in Table 1.

Figure 4 shows the amount of transferred data, which we refer to as a *data shower*, as a function of both the minimum distance between the antennas of the transmitter and the receiver, and the average vehicle velocity. Specifically, we show the amount of bits that can be transferred in a one-way journey between the vehicle, moving at constant speed along a straight trajectory, and the data center by adopting the proposed THz/mmW mode selection. Figure 4 is derived from

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[5] We underlined that the impact of the data which can be exchanged through conventional mW bands has not been considered.

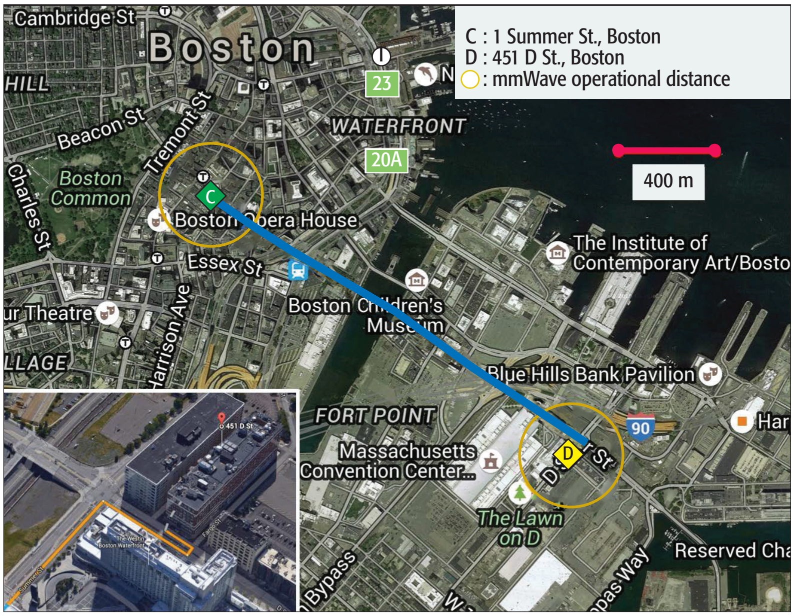

Figure 3. Google Maps showing the suggested route for a vehicle moving from 1 Summer Street to 451 D St. Map data source: Google, DigitalGlobe. The end-to-end distance is roughly 1.2 miles and the estimated travel time is about seven minutes, depending on the traffic conditions.

the mathematical model given by [2, Eq. 13]. Through such a mathematical model we are able to account for the link establishment overheads in both mmW and THz bands, and qualitatively study the throughput loss. With this model, we account for the times needed to calibrate the transceivers at a finer granular level for both the mmW and THz technologies, and the time spent in switching from transmitting mode to receiving mode and vice versa when the access technology changes. The setting of these parameters is beyond the scope of this article, but it does raise interesting design possibilities that we intend to explore in our future work.

For a fair comparison, we assume that the transmitted powers of the mmW and THz links differ by at least 10 dBm, that is, we assume a Tx power of 30 dBm and 20 dBm for the mmW and THz links, respectively. We adopt the same transmitter power value for mmW communications used in the real-world experiments described in [15]. We note that the data shower bulk increases as the average velocity decreases, having the vehicle spending more time in the range in which an mmW/THz communication is possible. Hence, by controlling the vehicle velocity, an impressive transfer of information can easily be achieved. In particular, we observe that at the reasonable minimum distance of 4 m, we are able to transfer an amount of information exceeding 1 Tb with a single journey in the worst case, that is, when the average velocity is 10 km/h. Interestingly, when the average velocity is roughly 2 km/h, the amount of data transferred exceeds 100 Tb in a single journey for every considered minimum distance. These results suggest that by using the proposed mmW/THz switching protocol, we can exchange a much higher amount of data compared to what can be achieved with classical wired or wireless technologies.

In Fig. 5, we quantify the data shower bulk as a function of the vehicle velocity for the real journey traced in Fig. 3, with the vehicle reaching the (existing) tower located at *451 D St.* starting from the (existing) tower located at *1 Summer Street*. The distance between the vehicle and data center as a function of time has been obtained from the journey route suggested by Google Maps. Specifically, the minimum distances between the transmitter and the receiver are 5.02 and 5.03 m, respectively. The minimum and maximum average speed, obtained through the Google Map estimation of the journey time, are reported within the figure. Figure 5 confirms that a data exchange of around 100 Tb is possible with a single journey for each data center.

mmW parameter	Value
f_c: carrier frequency	73 GHz
Δf_c: uplink/downlink shared bandwidth	1 GHz
α: path loss intercept least squares fit	LoS: 69.8, NLoS: 82.7
β: path loss slope least squares fit	LoS: 2 – NLoS: 2.69
P_{tx}: transmit power	30 dBm
G: directional antenna gain	27 dB
Noise power	–87 dBm
Noise figure	5 dB
$d_{\text{th}}^{\text{mmW}}$: operational distance	200 m
$1/a_{\text{LoS}}$: LoS state probability parameter	37 m
$1/a_{\text{O}}$: outage state probability parameter	45.5 m
$1/b_{\text{O}}$: outage state probability parameter	3.3
THz parameter	**Value**
$k(f)$: frequency-dependent coefficient	$[2 \cdot 10^{-6} – 3 \cdot 10^{1}]$ cm^{-1}
f_c: carrier frequency	0.85 THz
Δf_c: uplink/downlink shared bandwidth	0.1 THz
P_{tx}: transmit power	0–20 dBm
G: directional antenna gain	27 dB
$d_{\text{th}}^{\text{THz}}$: operational distance	10 m

Table 1. Parameter setting.

CONCLUSION

In this article, we describe a network architecture where µW, mmW, and THz bands may coexist, with the cost-benefit trade-offs of each type of link. Our MAC protocol design switches between mmW and THz frequencies for data transmissions, falling back on the slower link each time for the reverse channel ACKs. We explore design issues that impact the protocol design as well as their potential solutions. In particular, we show an example scenario of vehicle-to-infrastructure communication enabling data center traffic backhauling, where our approach shows that data transfer of around 100 Tb is possible. As future work, we will explore optimal cumulative acknowledgment methods, as well as simultaneous connections with multiple candidate mmW and THz BSs.

ACKNOWLEDGMENTS

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BIOGRAPHIES

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KUNAL SANKHE is currently pursuing a Ph.D. degree in the Department of Electrical and Computer Engineering, Northeastern University, Boston, Massachusetts. He works under the guidance of Prof. Kaushik Chowdhury in the field of wireless communication. His current research efforts are focused on implementing a software-defined wireless charging system, developing a cross-layer communication framework for the Internet of Things, and investigating the application of machine learning in the domain of wireless communication.

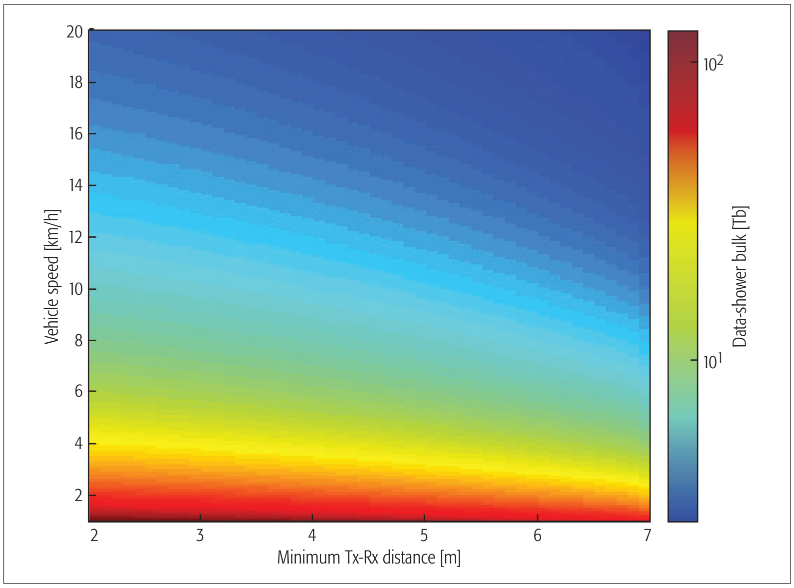

Figure 4. Data shower bulk as a function of the minimum separation distance between the transmitter and the receiver antennas and the average mule velocity. One-way journey between the vehicle, moving at constant speed along a straight trajectory, and the tower.

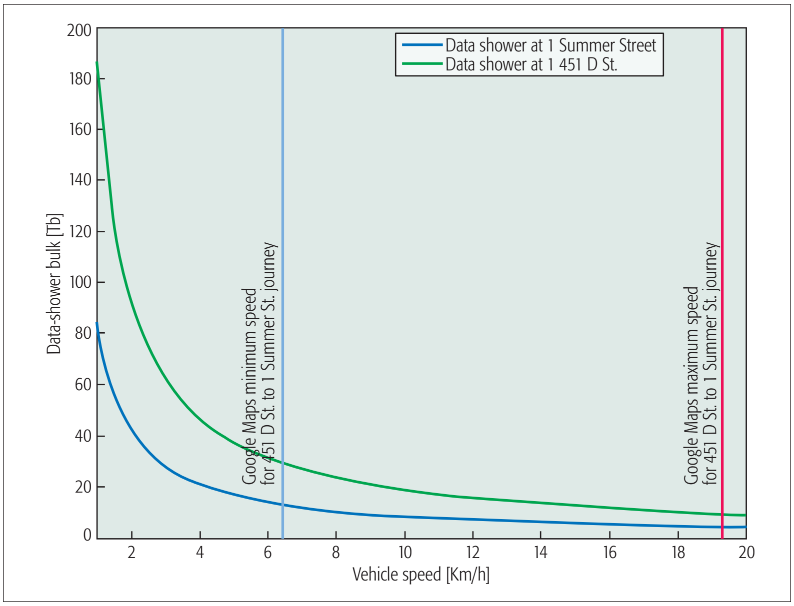

Figure 5. Data shower bulk as a function of the average vehicle velocity. One-way journey between two towers located at 451 D St. and 1 Summer Street and owned by Markley Group LLC and XO Communications, respectively, through the route suggested by Google Maps.

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