Integrating THz Wireless Communication Links in a Data Centre Network

Sean Ahearne, Niamh O'Mahony
Dell EMC Research Europe
Dell EMC, Cork, Ireland
[sean.ahearne; niamh.omahony]@dell.com

Noureddine Boujnah, Saim Ghafoor, Alan Davy
TSSG
Waterford Institute of Technology, Waterford, Ireland
[bnoureddine; sghafoor; adavy]@tssg.org

Luis Gonzalez Guerrero, Cyril Renaud
Department of Electronic and Electrical Engineering
University College London, London, UK
[luis.guerrero.14; c.renaud]@ucl.ac.uk

***Abstract*—Modern data centre networks are increasingly made up of optical fibre connections and controlled by software defined networking. Recent advances in THz wireless technologies have paved the way for ultra-high bandwidth wireless communication, reaching the point where these wireless links can begin to compete with optical fibre links. This work investigates the feasibility of integrating wireless THz links in a data centre network, reporting on the performance that can be achieved at the physical layer, proposing an architecture for the data link layer and illustrating, through network emulation, how these wireless links could be used to reduce congestion in a network.**

***Index Terms*—Terahertz communications, wireless data centre networks, software-defined networking, DLL functionalities, hardware demonstrator**

I. Introduction

With ever-increasing demand for high bandwidth communications in the age of 5G and beyond, researchers have turned their focus to previously un-used parts of the spectrum, including the THz band, in a bid to achieve the coveted goal of 1 Tbit/s wireless transmission. Data centre networks (DCNs) have been identified as a promising proving ground for ultra-high bandwidth THz wireless communications, as they provide controlled environmental conditions and well-organised geometric layouts that allow line-of-sight to be achieved, as required by THz, and they require the transmission of large volumes of data across short distances, achievable by THz wireless links.

As software-defined networking (SDN) becomes mainstream in data centre networks , gains in flexibility and scalability are limited by the physical constraints imposed by wired communication links, whereby communication between any two nodes within the data centre is only possible when there is a cabled path between them. Thus, the ability to make changes in the logical network topology is restricted by the physical connectivity and configurability comes at a high cost, through a high degree of redundancy in cabling or through manual (and potentially error-prone) re-cabling.

The integration of configurable wireless links within the DCN may open the door for dynamic, demand-driven configuration of the network, both in the logical and physical domains, allowing the use of network resources to be optimised for efficiency, throughput, latency and other performance targets. These wireless links may augment or replace existing wired links in the DCN, depending on the use case under consideration.

This paper reports on an investigation, undertaken as part of the TERAPOD project, into the feasibility of integrating THz wireless links in a data centre network, focusing on the physical, data link and network layers. The investigation takes the form of physical experimentation, simulation, emulation, and theoretical modelling of ultra-high bandwidth THz wireless links. The motivation for this investigation is to determine the effectiveness of high-speed wireless links in the data centre, their future potential, and the new features that they can provide, relative to traditional cabled optical networks. The investigation follows the steps listed below:

1. Determine the potential use cases for THz wireless links in the data centre and their associated functional and non-functional requirements.
2. Demonstrate that the devices can achieve an acceptable communication performance at the physical layer.
3. Design simulation and emulation scenarios based on the use cases that show effective use of wireless links, with the physical characteristics demonstrated.
4. Deconstruct the events and data in each scenario to two of the OSI (Open Systems Interconnection) layers; Network, and Data Link.
5. Collect simulation data and present results from each scenario.

Here, steps 2-5 are reported, with use cases and their requirements available to the interested reader in .

The paper is structured as follows: Section II provides some background information and relevant state of the art for data centre networks. Section III discusses the demonstration of the capabilities of THz wireless links in the physical layer. In Section IV, the proposed architecture for the data link layer (DLL) is presented, whilst Section V describes the emulation of network layer functionality. The initial results from the DLL and network layers are presented in Section VI, followed by discussion and future research directions in Section VII.

II. Background

In a modern data centre, connections between hosts and racks are made using an array of network switches. These switches are most commonly arranged in what is known as a fat tree topology. This topology is effective at distributing traffic load across a large-scale data centre and allows for link aggregation and redundancy. Figure 1, below, depicts the typical network architecture found in a fat tree topology. Hosts on a single rack connect to an edge switch, which is then connected to an aggregation layer of switches, followed by a core layer.

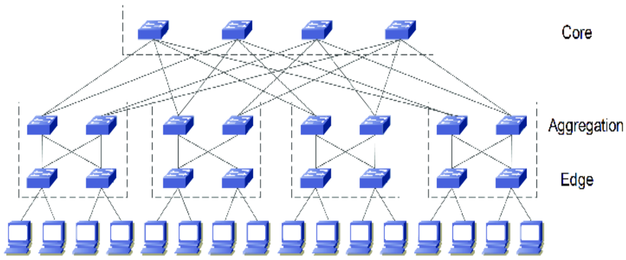

Figure 1 A typical fat-tree topology

In terms of bandwidth, hosts connect to an edge switch using a Small Form-factor Pluggable (SFP+) optical transceiver operating at bitrates of approx. 10Gbps. Links between edge and aggregation layer switches may also operate at 10Gbps or may use the Quad-SFP standard with bitrates of 40Gbps. In a similar fashion, links between Core and Aggregation switches often operate at 40Gbps or will use the QSFP28 standard which operates at a bitrate of approx. 100Gbps.

For THz wireless links to be feasible in the data centre, they must be capable of achieving these bitrates. Initial hardware tests of THz wireless links in a benchtop lab environment show that a single THz wireless channel can achieve a bit-rate of 20Gbps. Using wireless channel aggregation, bitrates of 100Gbps are possible. These bitrates show that THz links can compete with existing optical fibre links in a data centre network and possibly exceed them in the future.

SDN is becoming a critical element for modern data centre networks, as it allows for centralized and autonomous management of large-scale network fabrics. It also enables features such as Network Function Virtualization (NFV), a feature which is of great importance to 5G and wireless networks, as it enables the virtualization of wireless hardware functions, thereby improving performance and reducing resource usage. Centralizing the control plane into an SDN controller enables the controller to become fully aware of logical topology of both switches and hosts, using the Link Layer Discovery Protocol (LLDP). Being fully aware of the end-to-end network topology within a data centre can allow the SDN controller to make more informed routing decisions than traditional switches and react quickly to network events.

As data centres evolve to all-optical configurations, a key requirement for the wireless link is to be transparent to fibered networks. It was therefore decided that the key user-based scenario would be a wireless bridge connecting two portions of an optical link. As will be detailed in Section III, the THz technology used in the experiments for this work was a combination of devices developed within the TERAPOD project (THz emitter) and off-the shelf components (THz receiver).

III. THz Physical Demonstrator

The THz signal, at a carrier frequency of 250 GHz, was generated by beating two laser tones in a uni-travelling carrier photodiode (UTC-PD). One of these laser tones was previously modulated by 16-quadrature amplitude modulation (QAM) signals at two different bit rates: 40 Gbit/s (passband bandwidth of 11.25 GHz) and 20 Gbit/s (passband bandwidth of 5.75 GHz). A pair of 25 dBi horn antennas plus two 5-mm diameter Teflon lenses were used for wireless transmission. The received THz signal was down-converted to an intermediate frequency (IF) with a sub-harmonic mixer (SHM), based on a Schottky barrier diode (SBD). After electronic amplification, the IF signal was fed to an optical intensity modulator (IM). After filtering out the low frequency sideband, the resultant signal was sent to an optical receiver where the signal was detected and digitized. Digital signal processing (DSP) was then used to down-convert the signal to baseband and to mitigate various impairments such as: timing and frequency offset, phase noise, channel response and fiber dispersion.

A simplified version of the experimental arrangement used in the transmissions is shown in Figure 2. In a datacentre, the optical transmitter and receiver blocks would correspond to the transmitter rack/switch and receiver rack/switch, respectively. A total length of optical fiber of 50 km (10 km between CO and Tx remote antenna unit (RAU) and 40 km between Rx RAU and ONU) was used. Whilst for intra-datacentre communications, the optical fiber length is expected to be much shorter (possibly in the range of few m), this shows the potential of the approach, in terms of optical transmission distance, and its suitability for other applications. Note that, due to the lack of more lasers, the same external cavity laser (ECL) had to be shared between the Tx and Rx antennas. In a realistic scenario a separate laser would be used in each unit.

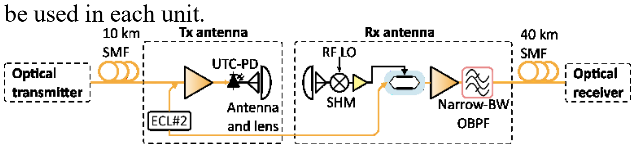

Figure 2 Simplified version of the experimental arrangement used for the transmission experiments. SMF: single mode fiber; ECL: external cavity laser; SHM: second harmonic mixer; OBPF: optical band pass filter

The transmission distance was kept rather short (approx. 12 cm between lenses) due to the low THz power generated by the UTC-PD (estimated to be in the order of few µW). This UTC-PD was fabricated in University College London (UCL), where a new generation of UTCs with expected powers of tens of µW is currently being developed and packaged. With such power levels, it will be possible to increase the transmission distance up to several meters. The other key THz component used in this demonstration, the THz mixer, was acquired from Virginia Diodes (WR3.4SAX module). In future work, this component will be replaced with a solution fully developed within the TERAPOD project.

In Figure 3, the bit error rate (BER) of the 20 Gbit/s and 40 Gbit/s signals is plotted against the UTC-PD photocurrent squared, which is proportional to the emitted THz power. As can be seen from the constellation diagrams, the signal suffers from compression effects for photocurrents higher than 3 mA (through link budget analysis the received power associated to this photocurrent was estimated to be around -30 dBm). Since this saturation effect came from the enclosed receiver, these results suggest that the transmission distance could be further increased while maintaining a BER below the hard decision-forward error correction limit (HD-FEC).

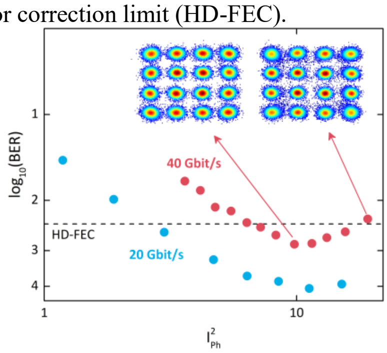

Figure 3 BER vs. photocurrent squared for 20 and 40 Gbit/s signals

IV. Data Link Layer Model

The Data Link Layer (DLL) is the layer between the networking layer of the data centre and the physical layer. For THz links, this layer will adapt incoming packets from the network layer to the physical medium. In the Section III, the possibility of transmitting a physical throughput of 40Gbps using 16QAM modulation was demonstrated. A throughput of 20Gbps, using the same modulation format, was also demonstrated. In both cases, the resulting BER was shown to be below the HD-FEC threshold. With lower symbol rates, the BER can be further improved, at the expense of lower throughput. The DLL can enhance link performance by implementing functionalities such as error control. However, links with high BER can lead to buffer overload and low useful throughput. Further theoretical study on BER for the datacentre use case and design parameters that can affect its value can be found in .

Figure 4 shows the initial proposed architecture for the DLL in a THz wireless data centre, highlighting functionalities and interfaces between the DLL and the physical and networking layers. The main functions and interfaces are described below.

A. DLL Functions

Medium Access Control (MAC)/scheduler: In a network topology, nodes should efficiently use the shared medium and schedule their future transmissions. The MAC/scheduler module receives information related to the number of frames in the buffer and their delays. Frames successfully received should be removed from the buffer queue. A time-based MAC technique, using one carrier frequency, is suitable for THz communication using directional antenna, hence, a beam steering and switching algorithm should be implemented in the MAC/scheduler module.

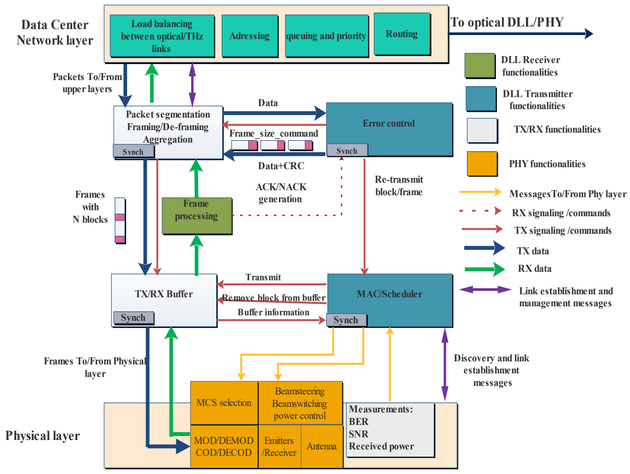

Figure 4 Initial functionalities and interfaces proposed for THz data centre DLL

DLL synchronization: For a distributed network architecture, each node collects information from other nodes periodically to update its transmission table. The transmission table includes transmission time and the number of time slots dedicated for each node. Timing for nodes synchronization is very important and reference times should be shared between all nodes which are, for example, the starting time of discovery procedure, and link establishment. Each node should store, in its memory, the appropriate time for node discovery and link establishment. Little research has been conducted in THz network synchronization. The authors in evaluated the performances of synchronization procedure for macroscale THz network using a receiver-initiated handshake. Synchronization is an important aspect of THz wireless links, starting with bit synchronization at the physical layer. For the DLL, synchronization of the transmit and receive times between nodes is an important function.

Link establishment and parameters coordination: In a data centre scenario, establishing a communication link between two top-of-rack THz nodes is non-trivial, due to distance and directional antenna requirements. Efficient mechanisms are required to establish links with minimum delay and coordination, by exchanging information like beam direction, beam width, transmission power and others.

Error Control: includes techniques to protect frames from errors. Protection bits are inserted at frame or block tail, Cyclic Redundancy Check (CRC) is the commonly used technique for error detection. Frames can be fully or partially retransmitted. The error control module generates a message to the MAC/scheduler to allocate resources to frames and for re-transmission.

Channel condition affects the frame error ratio (FER), which is given by:

$$P_f = 1 - (1 - p)^{L_{frame}} \quad (1)$$

where L_{frame} is the frame size and p is the BER.

Frame construction: In a data centre scenario, packets are typically characterized by high data rate flow. By using the THz link, the DLL should adapt the frame size and inter-arrival time to the transmission medium. Long packets are split into blocks, to each block is inserted a CRC sub-field, then blocks are aggregated together to build frames with different sizes. Frame error increases with frame size and number of blocks per frame, so an adaptive algorithm can receive information about the channel to select the most suitable length.

Buffering: The buffer contains frames waiting for future transmission or re-transmission. Messages are exchanged between the buffer and MAC/scheduler, including buffer status and waiting time for each frame. The arrival rate of frames to the buffer depends on frame rate generation, *f*, and on channel conditions when retransmission is activated. The buffer capacity depends also on transceiver technology, the DLL should avoid buffer overload and increased queue waiting times. The data waiting time is a function of the number of re-transmissions and framing rate.

Frame arrival rate, λ_a, to the buffer, when considering retransmission, is given by:

$$\lambda_a = (1-(1-p)^{KL_{block}})\mu + \frac{\bar{L}_{packets}}{KL_{block}}\lambda_{packet} \quad (2)$$

where, μ is the frame service rate, λ_{packet} the packet arrival rate, L_{block} the block size and K the number of blocks per frame. λ_a should satisfy the condition, $\lambda_a < \mu$, to avoid buffer load.

B. Interfaces between data link layer and other layers:

Incoming and outgoing data interface: Packets from/to network and frames from/to physical layer.

Incoming and outgoing DLL frames: generated frames are processed at the physical layer, bits for error detection and correction using FEC will be inserted to enhance the link quality.

Incoming and outgoing control message: Messages preceding and during the link establishment and the communication phase. Message exchange should be optimized to reduce link establishment time and message overhead.

Measurement reports: Measurements are used for DLL decisions, and reflect the status of each layer, for example, signal-to-noise ratio (SNR) for the received signal, received power. For the data centre scenario, transmission conditions are not changing very fast. A dedicated channel should be reserved for measurements.

Antenna module interface: To mitigate channel impairment, antennas with high gain are deployed at the transmitter and the receiver. Antenna beam steering and switching should be synchronized with the transmission as described in Figure 4.

Modulation and coding: based on measurement reports gathered by the physical layer, the DLL can send a command to increase or decrease the modulation and coding scheme (MCS) order. For good channel conditions, high order modulation and low FEC overhead can be used to increase spectral efficiency.

V. AUGMENTING OPTICAL LINKS WITH WIRELESS THZ AT THE NETWORK LAYER

In this section, the integration of the THz wireless links in the data centre at the network layer is considered through network emulation.

A. Overview and Scenario

A simple scenario was created to test the feasibility of using THz wireless links, based on use cases and requirements defined in the TERAPOD project for the integration of THz wireless links in a DCN. The scenario demonstrates the use of THz links to augment the network of existing optical fibre links, with the goal of improving throughput between hosts in a data centre by providing dynamically configurable alternate routes through which a portion of the network traffic can be diverted. The network topology is illustrated in Figure 5. It consists of a 4x4 grid of hosts, using a collapsed FAT tree topology for the fibre network. Several point-to-point THz wireless links were also created to form a multi-hop path from host H6 to host H3. All network switches and wireless and optical links within this topology are controlled by an SDN controller. The SDN controller must be capable of operating both types of links (wireless and wired) concurrently to improve network performance. The performance evaluation was performed using the network layer emulator tool, Mininet . This application and the SDN controller were operated within a virtual machine with 16 CPU cores and 32GB of RAM.

Traffic was generated using both the Transmission Control Protocol (TCP) and Universal Datagram Protocol (UDP) transport layer protocols. These protocols behave differently under high network loads, with TCP re-transmitting packets lost during transmission, while UDP does not. This characteristic is important when determining network application performance. As such it is represented in each protocol as a Key Performance Indicator (KPI), with TCP noting the number of re-transmissions required during a single connection. UDP monitors this KPI by determining the total number of packets sent by the transmitter versus the number received. This allows the protocol to calculate the KPI as the percentage of packets lost during transmission.

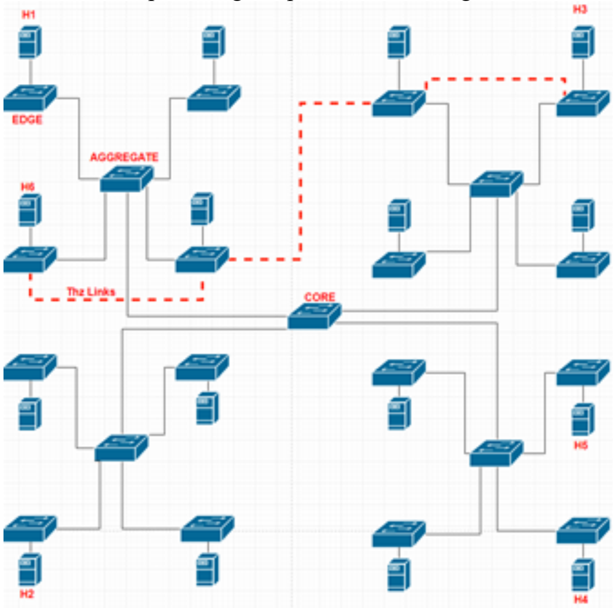

Figure 5 Network topology for multi-hop scenario showing fibre and wireless links

B. Assumptions

For this scenario, a maximum throughput of 10Gbps is assumed for both the THz and wired links. This value was chosen as it is, currently, the maximum achievable using physical network switch hardware. This limitation stems from the optical interface between SFP+ optical transceivers used in switches and in the THz wireless transmitter photodiode. The THz transmitter requires an optical signal input at a wavelength of 1550 nm; this wavelength is only supported by available network switch transceivers at a maximum bitrate of 10Gbps.

It is also assumed that the maximum distance between wireless links is 4.5m, as this was the maximum distance measured between data centre racks in a physical data centre used in the TERAPOD project. Link budget calculations, based on the performance of the THz physical demonstrator described in Section III, verify that THz wireless links are capable of achieving 10Gbps at the all distances measured for this data centre.

VI. Initial DLL Simulation and Network Emulation Results

A. DLL simulation

A wireless THz link with BER < 10^{-3}, framing, buffering and error control functionalities is assumed for each node in the simulation. Through simulation in MATLAB, the effect of packet arrival rate, for three traffic profiles, and of retransmission, due to frames lost, on the buffer load is studied. For this simulation, transmitted and received frames had a size range between 8,000 to 12,000 bits. This range was based on traffic traces generated by TCP traffic in the network layer emulation. The goal of the simulation was to show that it is possible to optimize the data link performance, in terms of buffer load, by the appropriate selection of frame size. Here, a single link was simulated, assuming that BER information and data centre traffic exist. The extension of this simulation to the 4x4 topology that was described in Section Vand involving the MAC/scheduler and additional DLL functionalities will be the subject of future work.

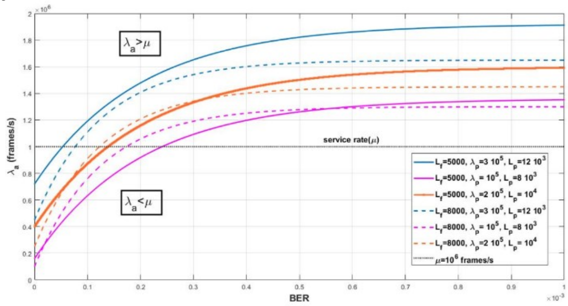

Figure 6 Frame arrival rate to the DLL buffer as function of BER for different traffic profiles and frame size

Figure 6 shows the variation of the frame arrival rate to the DLL buffer, as function of the BER of the link, when frame retransmission is activated, for three traffic profiles and using two frame lengths. The number of frames transmitted by time unit is fixed to μ=10^6 frames/s. It should be noted that, for high data rate, using short frames leads to buffer overload for high BER and, for low data rate, long frames lead to buffer overload. To get the best results, dynamic frame size, as function of channel condition, packet rate and packet length, is considered. Further enhancements in BER can reduce the buffer overload when using error control at DLL. As mentioned in Section III, the BER of the THz link can be improved by using a UTC-PD with higher output power and higher antenna gain.

B. Network Emulation

For the scenario described in Section V, all hosts except H6 and H3 were configured to generating traffic across the core network switch constantly, in order to emulate network congestion across the core network links. The throughput between H6 and H3 while this congestion was present was measured. The SDN controller then reconfigured the THz wireless links to form a multi-hop route from H6 to H3, to avoid the core network congestion. The throughput between both hosts was measured once again while traffic congestion on the fibre links was still present.

The results of these measurements can be seen in Table 1. While the THz links are inactive, congestion reduces the throughput between H3 and H6 to 2.11 Gbits/s for the TCP flow and results in 45% packet loss on the UDP flow. Following the activation of the multi-hop THz route, throughput between H3 and H6 increases to 9.68 Gbits/s for the TCP flow, close to the maximum possible bandwidth of 10 Gbit/s and reduces the packet loss for the UDP flow to 0.3%. The reason for the apparent reduction in UDP bandwidth is due to a virtual machine performance limitation while using Mininet. The net effective UDP throughput is still improved. This result shows that THz wireless links can be effective in augmenting existing optical links in a data centre environment by performing dynamic topology reconfigurations with an SDN controller based on traffic flow demands.

Table 1 Output from Mininet network emulation

THz Offloading	Protocol	Bandwidth	Comments
Inactive	TCP	2.11 Gbits/s	Re-transmits = 18435
Inactive	UDP	9.34 Gbits/s	Packet Loss = 45%
Active	TCP	9.68 Gbits/s	Retransmits = 315
Active	UDP	6.85 Gbits/s	Packet Loss = 0.3%

VII. Discussion

Based on the results presented in the previous sections, it can be concluded that THz links can replace or augment wired links in a data centre environment. In terms of hardware, after a stage of technology validation, effort will now focus on increasing the transmission distance. The required increase in UTC output power to achieve this will be obtained by optimising the antenna design. Current work is focusing on the design of a slot antenna for operation at 300 GHz. First simulation results are predicting around 100 μW power at such frequency. After optimization of a single antenna element, the work will focus on the development of a 4 antenna array for power combining and beam steering. The required phase control unit will be implemented as a photonic integrated chip (PIC) consisting on ring resonators and Mach-Zehnder interferometers. For the final data centre demonstrator, two boxes—one for the THz transmitter and the other for the THz receiver—will be assembled at UCL and carried to the DELL data centre in Cork. The content of each box will be similar to that in Fig. 2, with the only difference that each box will have its own laser. Each box will be connected to a different rack through an optical interface.

From the DLL point of view and inspired by data collected at the network layer, it is possible to create frames by segmenting packets into blocks, and framing. A model for the DLL functions and its interfaces with the physical and network layers has been proposed and the net DLL throughput, while considering error control, has been formulated. It has been shown that DLL performance depends on upcoming traffic parameters as well as on channel condition. As future work, the effect of the upcoming traffic in 4x4 data centre network and channel condition, involving more DLL functionalities such as MAC/scheduler and beam switching capabilities will be studied.

The point-to-point nature of the initial THz wireless links, demonstrated in this work, allows them to be seamlessly placed in an existing data centre and to operate alongside wired links in an SDN. Future THz links will be capable of point-to-multipoint communication. This is an important feature that will allow dynamic spatial reconfiguration of THz links, based on network conditions, and will enable far greater network flexibility than is possible using wired links. For example, an SDN controller optimising the path between two nodes can consider more than just the distance or number of hops, by including more advanced parameters, such as current load on each switch, interference levels, existing links, and more, whilst removing the physical restrictions imposed by cabled connectivity. Additional parameters from both higher and lower layers could also be considered, in order to make an informed decision that optimises the utilisation of all available resources. The implementation of this feature in SDN could revolutionise data centre networking and will be the subject of future research.

Acknowledgment

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement 761579 (TERAPOD).

References

[1] A. Davy, C. Renaud, E. Wasige, M. Naftaly, T. Keurner, G. George, L. Pessoa, O. Cojocari, N. O'Mahony and M. Garcia Porcel, “Building an end user focused THz based ultra high bandwidth wireless access network: The TERAPOD approach,” in *2017 9th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, Munich, 2017.

[2] D. Levin, M. Canini, S. Schmid and A. Feldmann, “Incremental SDN deployment in enterprise networks,” in *ACM SIGCOMM Conference*, Hong Kong, China, 2013.

[3] TERAPOD Consortium, “TERAPOD Project,” [Online]. Available: terapod-project.eu. [Accessed May 2019].

[4] TERAPOD Consortium, “TERAPOD D2.1 - Initial Requirements and Scenario Specification,” 2018. [Online]. Available: https://terapod-project.eu/results/deliverables/.

[5] TERAPOD Consortium, “TERAPOD D2.2 - Revised Requirements and Scenario Specification,” 2019. [Online]. Available: https://terapod-project.eu/results/deliverables/.

[6] S. Habib, F. S. Bokhari and S. U. Khan, “Routing Techniques in Data Center Networks,” *Handbook on Data Centers,* 2015.

[7] T. Wang, Z. Su, Y. Xia and M. Hamdi, “Rethinking the Data Center Networking: Architecture, Network Protocols and Resource Sharing,” *IEEE Access,* vol. 2, pp. 1481 - 1496, 2014.

[8] J. Zhou and H. Runjing, “High-speed SFP+ signal integrity simulation and measurement,” *Journal of Communication and Computer,* vol. 11, pp. 371-377, 2014.

[9] A. Narashimha and et al., “A 40-Gb/s QSFP Optoelectronic Transceiver in a 0.13μm CMOS Silicon-on-Insulator Technology,” in *Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*, San Diego, CA, 2008.

[10] H. Nasu, K. Nagashima, Y. Ishikawa, A. Izawa, Y. Nekado and T. Kise, “28-Gb/s× 4-channel solderable optical transceiver module for QSFP28,” in *IEEE CPMT Symposium Japan (ICSJ)*, Kyoto, Japan, 2016.

[11] A. Seeds, H. Shams, M. Fice and C. Renaud, “Terahertz photonics for wireless communications,” *Journal of Lightwave Technology,* vol. 33, no. 3, pp. 579-587, 2015.

[12] H. Shams and e. al., “100 Gb/s multicarrier THz wireless transmission system with high frequency stability based on a gain-switched laser comb source,” *IEEE Photonics Journal,* vol. 7, no. 3, pp. 1-11, 2015.

[13] K. Wang, Y. Wang, D. Zeng and S. Guo, “An SDN-based architecture for next-generation wireless networks,” *IEEE Wireless Communications,* vol. 24, no. 1, pp. 25-31, 2017.

[14] Z. Shu, J. Wan, J. Lin, S. Wang, D. Li, S. Rho and C. Yang, “Traffic engineering in software-defined networking: Measurement and management,” *IEEE Access,* vol. 4, pp. 3246-3256, 2016.

[15] N. Boujnah, S. Ghafoor and A. Davy, “Modeling and Link Quality Assessment of THz Network Within Data Centre,” in *European Conference on Networks and Communications (EuCNC) [in press]*, Valencia, Spain, 2019.

[16] J. Lin and M. Weitnauer, “Pulse-level beam-switching MAC with energy control in picocell Terahertz networks,” in *IEEE Globeal Communications Conference (GLOBECOM)*, Austin, TX, 2014.

[17] Q. Xia, Z. Hossain, M. Medley and J. M. Jornet, “A Link-Layer Synchronization and Media Access Control Protocol for Terahertz-Based Communication Networks,” in *IEEE Global Communications Conference (GLOBECOM)*, 2015.

[18] Mininet Team, “Mininet: An Instant Virtual Network on your Laptop (or other PC),” [Online]. Available: http://mininet.org/. [Accessed May 2019].

[19] MathWorks, “MATLAB,” MathWorks, [Online]. Available: https://uk.mathworks.com/products/matlab.html. [Accessed May 2019].