Photonically Generated Millimetre-Wave and THz Links for Wireless Fronthaul and Backhaul

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***Abstract*—Requirements for backhaul and fronthaul links in future cellular wireless networks and the potential role of photonically generated millimetre-wave and THz wireless signals for these applications are discussed. An experiment demonstrating photonically generated 50 Gb/s 16QAM wireless transmission at 182 GHz for backhaul and 7 Gb/s fronthaul at 31 GHz is presented and analysed. The fronthaul link uses a novel digital radio-over-fibre compression system which allows 14 LTE channels to be transmitted within the 10 Gb/s line rate.**

Keywords—Wireless networks, millimetre wave, THz, fronthaul, backhaul, optical heterodyne

I. INTRODUCTION

5G trends such as higher user data rates with enhanced mobile broadband and the use of millimetre-wave bands in small cells will greatly increase the capacity required on the physical layer links between the base stations at the edge of the network and the core. As illustrated in Fig. 1, the move to a centralised radio access network (CRAN) is seeing traditional base station functions pushed further back towards the core [1], with several remote radio units (RRUs) connected to a baseband unit (BBU) pool, or further splitting of the BBU into a central unit (CU) and a distribution unit (DU). In addition to the traditional backhaul connecting the base station to the core, the CRAN architecture gives rise to the concepts of fronthaul, between the BBU or DU and the RRU, and midhaul, between the CU and DU.

Fronthaul is often implemented in a form of digital radio over fibre (DRoF) as defined in the common public radio interface (CPRI) protocol. The in-phase and quadrature (IQ) components of the signal transmitted to/from the RRU are digitised with 15-bit resolution and the resulting bit stream inserted into frames together with control and management and synchronisation data. To carry a single 20 MHz long-term evolution (LTE) channel, an overall bit rate of 1.23 Gb/s is required, even though the maximum wireless data rate to the user equipment is 75 Mb/s [2]. CPRI line rate options up to 24.3 Gb/s are specified [3], but applying the same approach to 5G applications delivering wireless data rates of tens of Gb/s could result in fronthaul data rates of hundreds of Gb/s [2]. To address this, evolved CPRI (eCPRI) has been developed, which greatly reduces the data rate required to transport a given wireless signal, but with some loss of flexibility [4].

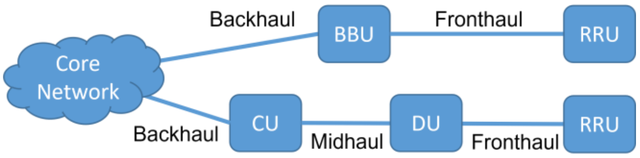

Fig. 1. Centralised radio access network splits. (BBU: baseband unit; CU: central unit; DU: distribution unit; RRU: remote radio unit.

In a recent report, Ericsson estimates that the backhaul/midhaul data rate per distributed site could be as high as 20 Gb/s by 2025 [5]. This excludes connections from the BBU and CU to the core network in the CRAN architecture outlined above, as these sites typically connect through metro networks. Even so, with aggregation of the backhaul from several sites at a gateway site, the total backhaul rate could reach many tens of Gb/s.

While fronthaul is usually implemented over fibre (the CPRI specification [3] defines an optical interface), backhaul has historically made considerable use of microwave links [5]. The proportion of fibre backhaul connections is expected to increase over the next few years with the introduction of 5G, but, by 2025, Ericsson estimates that 38% of backhaul connections will use microwave links globally, and this figure rises to over 60% when countries such as China, Japan and North Korea, which have invested heavily in fibre infrastructure, are excluded.

Microwave backhaul is particularly attractive in dense urban areas, where link distances are relatively short and the

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cost of installing new fibre may be prohibitive. As backhaul data rates increase, it will be necessary to look at using millimetre-wave (mmW) and THz bands to deliver wireline data rates. In the case of fronthaul, the densification of the network as 5G is deployed and the high cost of installing new fibre to many small cells may make fronthaul over mmW or THz bands attractive.

In the rest of this paper, we review work on photonically generated mmW and THz wireless communications and its potential application to fronthaul and backhaul in future wireless networks. Collaborative work done within the UKRI-funded COALESCE project ("Converged Optical and Wireless Access Networks") will be described.

II. PHOTONICALLY GENERATED MMW AND THZ WIRELESS

The method of generating radio frequency (RF), mmW and THz signals by the heterodyne beating of two optical signals on a high-speed photodiode is now well established [6]. When one of the optical signals is modulated, the modulation is transferred to the down-converted signal at the output of the photodiode, so this approach can leverage the high-speed optical modulators developed for optical fibre communications at wavelengths around 1.5 µm, enabling the generation of complex modulation formats such as quadrature amplitude modulation (QAM) at symbol rates of tens of Gbaud. The optical signals may be easily transported over optical fibres to a remote antenna unit, where the wireless signal is generated, providing a seamless converged optical and wireless system.

Using these techniques, wireless links with data rates comparable to state-of-the-art single-wavelength optical signals have been demonstrated in the wide bandwidth windows at sub-THz frequencies: first reaching 100 Gb/s [7, 8], then exceeding 250 Gb/s [9], and recently reaching over 600 Gb/s, using polarisation multiplexing to double the throughput [10]. At lower frequencies, in the mmW D-band (110 – 170 GHz), an aggregate data rate of over 1 Tb/s has been demonstrated, using multiple carriers and polarisation multiplexing [11]. However, due to the low wireless power generated and high free-space path loss at these frequencies, these demonstrations are limited to transmission distances of a few metres or less. The transmission distance can be extended by using high-gain antennas, but this comes at the cost of the need for increased pointing accuracy.

Given the link data rates required for 5G wireless backhaul outlined in the Introduction, data rates exceeding 100 Gb/s may not be required in the immediate future. There is sufficient bandwidth for such signals at lower mmW frequencies, such as the W-band (75 – 110 GHz), where the free-space path loss is lower. At 94 GHz, transmission at 54 Gb/s (polarisation multiplexed 9 Gbaud 8QAM) has been demonstrated over 2.5 km in good weather conditions [12]. Such a link may be well suited to last-mile wireless backhaul in an urban setting.

III. DROF FRONTHAUL COMPRESSION

As discussed earlier, the CPRI protocol results in a fronthaul data rate many times that of the rate of the wireless data carried, making its scalability to high-rate 5G applications challenging. Compression of the digitised I and Q signals by a factor of around 3 has been demonstrated by various techniques [13], allowing a single 20 MHz LTE channel to be transmitted at a line rate of around 400 Mb/s. An additional problem with CPRI is that its commercial implementations are often vendor specific. A neutral-host DRoF system with data compression and a novel digital automatic gain control has recently demonstrated simultaneous transmission of 14 wireless services from three mobile network operators over a 20km 10 Gb/s optical link [13].

IV. DEMONSTRATION OF CONVERGED OPTICAL AND MMW/THZ FRONTHAUL AND BACKHAUL

To demonstrate some of the potential of photonically generated mmW and THz fronthaul and backhaul in a converged optical and wireless network, we have carried out an experiment which emulates a "gateway" site which combines the functions of aggregating backhaul traffic from remote BBUs over wireless links, while simultaneously providing wireless fronthaul to RRUs served by its own BBU [14]. The experimental arrangement is summarised in Fig. 2. The fronthaul and backhaul remote antenna units (RAUs) for the gateway site are connected to the BBU and backhaul aggregation site through 1 km of multicore fibre (MCF). Downlink (DL) and uplink (UL) data signals and optical local oscillators for photonic heterodyning can conveniently be carried over separate cores of the MCF, reducing the number of physical fibres required to connect to the RAUs.

A. *50 Gb/s backhaul at 182 GHz*

A 50 Gb/s backhaul DL signal (16QAM at 12.5 Gbaud) was modulated onto the output of an external cavity laser (ECL) operating at a wavelength of 1552.62 nm by an IQ optical modulator driven with electrical signals derived from two 50 GSa/s arbitrary waveform generators (AWGs) with 12 GHz analogue bandwidth. The complex baseband signal was electronically upconverted and filtered to give a single-sideband (SSB) signal with passband bandwidth of 13.75 GHz centred on 7 GHz. At the RAU, the backhaul signal was heterodyned with an optical local oscillator (an ECL operating at a wavelength of 1554.03 nm) on a uni-travelling photodiode (UTC-PD) to give a signal at 182 GHz which is radiated over a 10 cm wireless link.

At the backhaul wireless receiver, the THz signal was downconverted using a sub-harmonic mixer (SHM) to an intermediate frequency (IF) of approximately 12 GHz and amplified. This IF signal was then either digitised using a real-

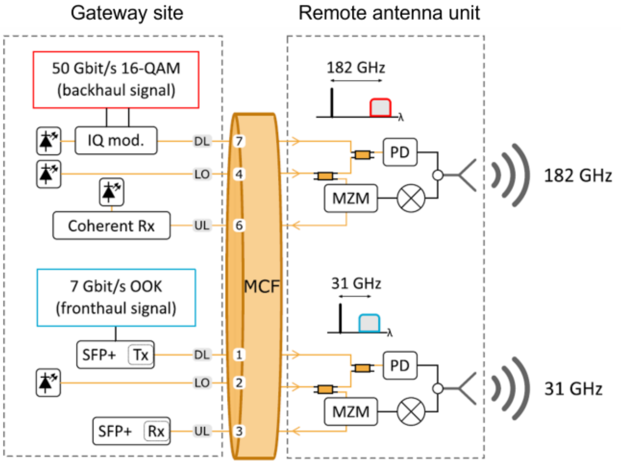

Fig. 2. Simplified diagram of the experimental arrangement for the demonstration of mmW/THz fronthaul and backhaul [14].

time oscilloscope (80 GSa/s, 36 GHz analogue bandwidth) for subsequent offline processing to evaluate the performance of the DL or was used to emulate the received UL signal and modulated onto an optical carrier using a Mach-Zehnder modulator (MZM). A SSB optical UL signal was generated by using a narrow-bandwidth optical filter after the MZM to remove one sideband and returned to the gateway site over a separate core of the MCF. The UL optical carrier was derived from the optical LO used for the photonic heterodyning of the DL signal. The UL signal was recovered at the gateway site by using coherent optical detection. Heterodyne coherent detection on a single PD was employed in the experiment, giving an IF signal at approximately 20 GHz, but an IQ coherent receiver of the type used in optical fibre systems could also be employed here to recover the baseband signals directly.

The UL and DL digitised IF signals were evaluated using offline digital signal processing (DSP) algorithms which performed the following functions: down-conversion to baseband, matched filtering, equalisation, frequency offset estimation, and phase noise compensation. Sample lengths allowed 2.5 x 10^5 bits to be analysed to obtain bit error ratio (BER) measurements down to about 10^{-5}.

Fig. 3 shows the BER obtained as a function of the square of the PD photocurrent (which is proportional to the transmitted / received mmW or THz power) and examples of the received 16QAM constellations for both DL and UL. At the optimum photocurrent, BER below 10^{-5} was obtained for the DL. At higher photocurrents, the performance degrades because of saturation in the UTC-PD used to generate the THz signal, as is evident from Fig. 3(d). The UL performance shows a similar trend, but with a large penalty (~10 dB). This is attributed to the roll off of the frequency response the MZM and the electronic amplifiers after the SHM. For both DL and UL, BERs below the 7% FEC limit are obtained.

B. *7 Gb/s fronthaul at 31 GHz*

A similar arrangement was used to demonstrate mmW fronthaul of a 7 Gb/s DRoF signal. In this case, the optical LO for the optical heterodyning at the RAU was set to generate a mmW signal at 31 GHz, using a PIN-PD. The mmW signal was not transmitted in the experiment, but was down-converted using a mixer and re-modulated onto the UL optical carrier in a similar manner to the backhaul experiment. Narrow-band filtering was again used to produce an SSB optical UL signal.

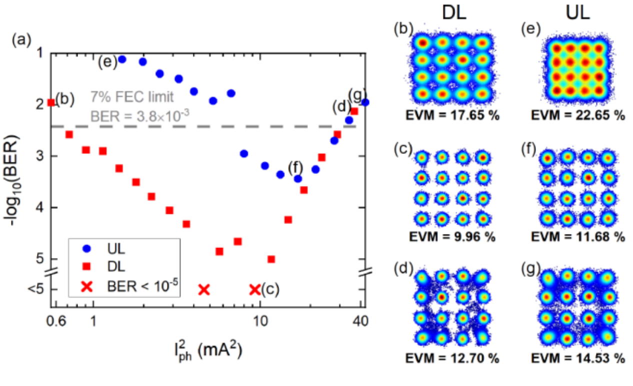

Fig. 3. (a) BER measurements for the backhaul experiment, and (b) – (g) received 16QAM constellation plots for the conditions indicated with the same letter on the figure in (a) [14].

The optical modulation format for the fronthaul experiment was on-off keying (OOK), generated by an enhanced small form-factor pluggable (SFP+) transceiver, operating at a wavelength of 1538.98 nm. The optical LO was generated by an ECL with wavelength 1539.23 nm. Since the SFP+ receiver is colourless, the UL OOK signal at 1539.29 nm could be directly detected by it.

The data feeding the SFP+ transmitter was generated from a novel DRoF unit using a compression technique that reduces the fronthaul transmission rate by a factor of three compared to the CPRI protocol [4, 13]. The DRoF unit consists of an analogue front end to convert an applied RF signal to an IF, which is then digitised at 150 MSa/s with 14-bit resolution. A digital automatic gain controller ensures the dynamic range is maintained after compression. Two compression stages are applied, one at the IF and one at baseband, and the resulting data stream packetized. At the receiver, the reverse process is applied. In this experiment, the DSP steps were implemented using a Stratix IV FPGA.

A 20-MHz LTE-compatible 16QAM signal from a vector signal generator was digitised and compressed by the DRoF transmitter to a rate of 400 Mb/s. This signal was replicated before packetization to simulate transmitting 4 or 14 channels simultaneously, giving line rates of 2 Gb/s and 7 Gb/s.

The performance of the fronthaul transmission was quantified by the error vector magnitude (EVM) of the LTE signal, which was measured using a vector signal analyser. In Fig. 4(a) the performance of the DL optical link is shown in terms of EVM against received optical power. It can be seen that the recommended EVM for 16QAM LTE is achieved for optical powers above -31 dBm for the 4-channel, 2-Gb/s case and -27 dBm for the 14-channel, 7-Gb/s case. Similar results are shown for the UL in Fig. 4(b), but in this case the EVM is plotted against the estimated mmW power generated from the PIN-PD at the RAU. Including an estimated 1-dB cable loss between the PD and the mixer input, the minimum received mmW power to achieve the required EVM performance in the UL is -23.5 dBm for the 2-channel case and -17.5 dBm for the 14-channel case.

V. DISCUSSION

The experiment described shows the potential of mmW and THz fronthaul and backhaul at rates from 2 – 50 Gb/s per channel. In 5G (and beyond) scenarios with wide bandwidth channels and massive MIMO, higher fronthaul and backhaul rates will be required. Particularly in urban areas, there will be more, smaller cells, meaning that multiple wireless channels for fronthaul and backhaul will be required. This may make

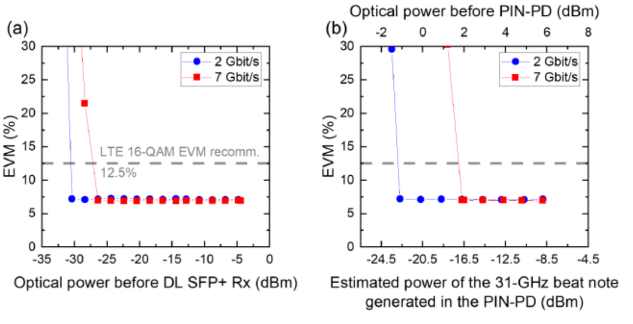

Fig. 4. EVM measurements for the fronthaul experiment, (a) for UL, and (b) for DL [14].

the use of THz bands, e.g. the 220 – 330 GHz band, more attractive for these fixed wireless links. The challenge with using these bands is the high free-space path loss and low transmitter power, necessitating high-gain antennas and high pointing accuracy.

Wireless bridging experiments carried out at 250 GHz [15] have shown only slightly degraded performance compared to that of the demonstrated 50 Gb/s UL configuration at 182 GHz. The IF power required to achieve BER = 3.8×10^{-3} (7% FEC threshold) with 12.5 Gbaud 16QAM was estimated to be -39 dBm in those experiments. The IF power for the same performance in the DL configuration (i.e. without re-modulating the IF onto the UL optical carrier) can therefore be expected to be around -49 dBm (based on the 10 dB observed penalty between UL and DL). This is approximately 10 dB higher than the theoretical value based on SNR considerations. Even if this implementation penalty cannot be reduced, there is scope for reducing the UL penalty by using IF amplifiers and an MZM with better frequency response. A conservative and hopefully achievable goal for the required IF power might therefore be -45 dBm for the UL configuration. Assuming antenna gain of 55 dBi at both transmitter and receiver (e.g. Cassegrain antennas), transmit power of 0 dBm, and SHM conversion loss of 10 dB, transmission over 1 km is in principle possible, with 5 dB of margin, for this IF power. This transmission distance would be suitable for our proposed backhaul scenario. Applied across the band of frequencies from 250 to 320 GHz, this would allow backhaul from 5 remote BBUs, with a total capacity of 250 Gb/s.

With lower antenna gain of 50 dBi at both transmitter and receiver, and making the same assumptions for the other parameters, transmission over 300 m would be possible, which might be suitable for fronthaul to micro cells in dense urban areas. The reduced antenna gain would increase the beam divergence by approximately a factor of 2, reducing the pointing accuracy required.

VI. CONCLUSIONS

We have proposed and demonstrated a converged fibre-wireless architecture for wireless fronthaul and backhaul in future 5G (and beyond) wireless networks. A wireless backhaul rate of 50 Gb/s at 182 GHz using 12.5 Gbaud 16QAM, and 7 Gb/s fronthaul at 31 GHz using OOK have been demonstrated with performances meeting the 7% FEC threshold and LTE EVM recommendation, respectively. The fronthaul was demonstrated using a novel DRoF compression system, allowing 14 LTE channels to be carried using 7 Gb/s line rate.

Wireless transmission was performed over only 10 cm in the backhaul link, but by extrapolating the performance and making some relatively conservative assumptions, transmission distances up to 1 km are predicted for 50 Gb/s 16QAM at 250 GHz, provided high-gain antennas (up to 55 dBi) are used. Such antennas require accurate pointing, but this should be realisable on these fixed links. The use of multiple channels in the 250 to 320 GHz band would potentially allow total capacity of 250 Gb/s for backhaul or fronthaul links in future wireless networks.

REFERENCES

[1] T. Pfeiffer, “Next generation mobile fronthaul and midhaul architectures [Invited],” J. Opt. Commun. Netw., vol. 7, no. 11, pp. B38–B45, 2015, doi: 10.1364/JOCN.7.000B38.

[2] A. E. Willner (ed.), “Optical Fiber Telecommunications VII”, Chapter 17, doi: 10.1016/B978-0-12-816502-7.00019-1

[3] Common Public Radio Interface (CPRI): Interface Specication V7.0, Ericsson AB, Huawei Technol., NEC Corp., Alctel Lucent, Nokia Netw., Espoo, Finland, 2015.

[4] T. Li, H.Shams, C. C. Renaud, A. J. Seeds, R. Penty, M. Fice, and I. White, “Multi-service Digital Radio over Fibre System with Millimetre Wave Bridging,” MWP 2018 - 2018 Int. Top. Meet. Microw. Photonics, 2018, doi: 10.1109/MWP.2018.8552908.

[5] “Ericsson Microwave Outlook”, Ericsson, Göteborg, Sweden, 2020, https://www.ericsson.com/en/reports-and-papers/microwave-outlook [accessed 30 Sept. 2021].

[6] T. Nagatsuma, G. Ducournau, and C. C. Renaud, “Advances in terahertz communications accelerated by photonics,” Nat. Photonics, vol. 10, no. 6, pp. 371–379, 2016, doi: 10.1038/nphoton.2016.65.

[7] S. Koenig et al., “Wireless sub-THz communication system with high data rate,” Nat. Photonics, vol. 7, no. 12, pp. 977–981, 2013, doi: 10.1038/nphoton.2013.275.

[8] H. Shams et al., “100 Gb/s multicarrier THz wireless transmission system with high frequency stability based on a gain-switched laser comb source,” IEEE Photonics J., vol. 7, no. 3, 2015, doi: 10.1109/JPHOT.2015.2438437.

[9] X. Pang et al., "260 Gbit/s photonic-wireless link in the THz band," 2016 IEEE Photonics Conference (IPC), 2016, doi: 10.1109/IPCon.2016.7830951.

[10] S. Jia et al., "2 × 300 Gbit/s Line Rate PS-64QAM-OFDM THz Photonic-Wireless Transmission," Journal of Lightwave Technology, vol. 38, no. 17, pp. 4715-4721, 2020, doi: 10.1109/JLT.2020.2995702.

[11] X. Li, J. Yu and G. Chang, "Photonics-Aided Millimeter-Wave Technologies for Extreme Mobile Broadband Communications in 5G," Journal of Lightwave Technology, vol. 38, no. 2, pp. 366-378, 2020, doi: 10.1109/JLT.2019.2935137.

[12] X. Li et al., “Bidirectional delivery of 54-Gbps 8QAMW-band signal and 32-Gbps 16QAM K-band signal over 20-km SMF-28 and 2500-m wireless distance,” in Proc. Opt. Fiber Commun. Conf., Los Angeles, CA, USA, 2017, Paper Th5A.7.

[13] W. Li, A. Chen, T. Li, R. V. Penty, I. H. White and X. Wang, "Novel Digital Radio Over Fiber (DRoF) System With Data Compression for Neutral-Host Fronthaul Applications," in IEEE Access, vol. 8, pp. 40680-40691, 2020, doi: 10.1109/ACCESS.2020.2976775.

[14] L. G. Guerrero et al., "Integrated Wireless-Optical Backhaul and Fronthaul Provision Through Multicore Fiber," in IEEE Access, vol. 8, pp. 146915-146922, 2020, doi: 10.1109/ACCESS.2020.3014702.

[15] L. Gonzalez-Guerrero et al., "Pilot-Tone Assisted 16-QAM Photonic Wireless Bridge Operating At 250 GHz," in Journal of Lightwave Technology, vol. 39, no. 9, pp. 2725-2736, 2021, doi: 10.1109/JLT.2021.3053616.