# Integrated Solutions for Deployment of 6G Mobile Networks

Theodore Sizer, *Fellow, IEEE*, Dragan Samardzija, *Member, IEEE*, Harish Viswanathan, *Fellow, IEEE*, Son Thai Le, *Member, IEEE*, Sarvesh Bidkar, Pascal Dom, Ed Harstead, and Thomas Pfeiffer, *Fellow, OSA*

*(Invited Paper)*

***Abstract*—The promise of future generations of mobile communication, both 5.5 and 6G, is that of continued increases in capacity and coverage of the wireless communication network together with novel applications demanding higher levels of performance between the mobile devices and their applications on servers in the cloud. In addition, the growing shift towards virtualization of network function itself offers perhaps the most stringent requirements on the network. To continue to offer ever higher capacities and speeds, future networks will be required to further densify addressing capacity and coverage demands through the use of small cells or new radio spectral bands, such as 7-20GHZ or sub-THZ, with inherently shorter range. Therein lies the dilemma. A denser and ever more complex network of access points, with higher speeds and performance, but continued pressure on the deployment and costs. To address this challenge solutions which address all aspects of the End to End network must be considered together – the mobile access points, transport networks, deployment options, and edge cloud all contribute equally to the success of the new consumer and industrial applications promised for next generation networks as well as the operation of the networks themselves. In this paper we will outline the expected requirements of next generation networks as well as new technologies and methods which address the simultaneous challenges of higher capacity, lower costs, and reliable deterministic performance.**

***Index Terms*—5G, 5.5G, 6G, end to end networks.**

## I. Introduction

THE challenges society has felt during the recent pandemic has clearly illustrated the growing reliance on communication – communication with each other as well as our work, our schools, and our health providers. One month into the pandemic we saw capacity grow by 30–50%, machine to machine traffic serving us increase by 100% and, unfortunately, a 40% increase in malicious online attacks. [1] Future networks must be able to support the growing reliance on our communications networks with greater capacity and reliable, deterministic performance.

Future networks will continue the adoption of servers in far edge and edge clouds to support both user and machine applications as well as the operation of the network itself. Connections between the users, the network, and the cloud will require performance that is deterministic, meeting the different application requirements of capacity, security, reliability, latency and jitter. The number of network connections will grow, and access points densify as capacity demand drives towards more small cells and new radio spectral bands at frequencies which have inherently shorter range. Driven by the need to support low latency applications, new edge and far edge cloud data centers will proliferate moving geographically closer to the end devices to meet the shorter latency requirements.

This proliferation of network connections will encourage the use of shared connections to reduce the cost of deployment and cost of ownership of these networks rather than point to point links typically used today. Clearly, the urgency to minimize deployment time and cost while increasing the number of network connections will demand a diversity of solutions depending upon available assets and capabilities. There will be no single solution for next generation networks, but a set of solutions which can be adapted to both meet the performance requirements and minimize the cost of deployment.

Increased levels of integration of radio access points and optical fiber connections offer significant advantages in size, weight, and power of the radio units as well as shifting processing from the remote site to the cloud where it can be more economically managed. The tighter integration can offer unique advantages, particularly for massive MIMO arrays.

This paper will begin by detailing the expected requirements for 5.5 and 6G networks in terms of the capacity and latency requirements as well as the implication upon the distance between the users and the edge cloud serving their application. Recognizing that there will not be a single network transport solution we will detail a set of optical solutions which support the growth in capacity and performance for both IP/Optical networks and PON based networks. In addition, we will share examples of cross domain integration bringing significant advantages to 6G networks.

Manuscript received June 14, 2021; revised July 30, 2021; accepted July 31, 2021. Date of publication September 8, 2021; date of current version January 16, 2022. *(Corresponding author: Theodore Sizer.)*

Theodore Sizer, Dragan Samardzija, Harish Viswanathan, and Son Thai Le are with Nokia Bell Labs, Murray Hill, NJ 07974 USA (e-mail: theodore.sizer@nokia-bell-labs.com; dragan.samardzija@nokia-bell-labs.com; harish.viswanathan@nokia-bell-labs.com; son.thai_le@nokia-bell-labs.com).

Sarvesh Bidkar and Thomas Pfeiffer are with Nokia Bell Labs, 70469 Stuttgart, Germany (e-mail: sarvesh.bidkar@nokia-bell-labs.com; thomas.pfeiffer@nokia-bell-labs.com).

Pascal Dom is with Nokia Fixed Networks Business Division, Antwerp, Belgium (e-mail: pascal.dom@nokia.com).

Ed Harstead is with Nokia Fixed Networks Business Division, Murray Hill, NJ 07974 USA (e-mail: ed.harstead@nokia.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2021.3110436.

Digital Object Identifier 10.1109/JLT.2021.3110436

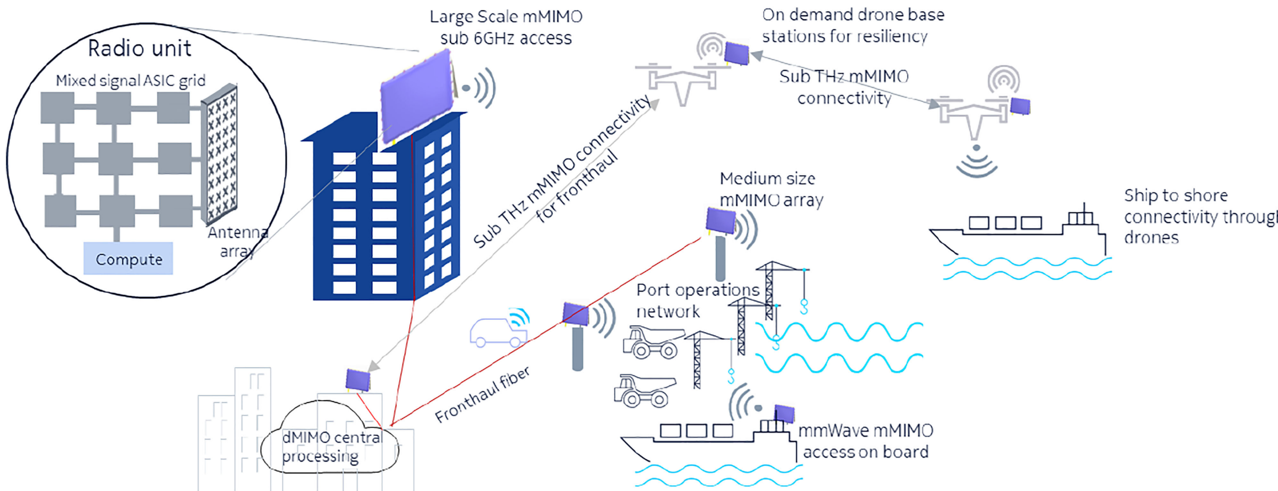


Fig. 1. Illustration of envisioned next generation access network.

## II. 6G Network Requirements

With the rapid deployment of 5G underway, research has shifted focus towards defining the vision and technologies for 6G and there is already substantial consensus on the vision [2]–[7]. The creation and consumption of entire digital worlds, twins of the physical world or virtual worlds, will be the hallmark of the next decade. It will be the foundation for numerous new use cases in a variety of domains such as entertainment, education, healthcare, and remote control of machines much as the multi-media experience is today. Dynamic, high resolution mapping of cities in near-real time will require enormous amount of capacity on the uplink and its consumption will require very high throughputs on the downlink. With increasing automation in driving, there will be substantially more opportunity to consume large amount of content in vehicles, driving up the need for outdoor capacity. New spectrum bands and extreme massive MIMO and distributed MIMO base stations will be required to achieve such capacities. A new generation of standards is required to facilitate low cost implementation of such networks and could potentially involve new waveforms, coding techniques etc. Furthermore, wireless backhaul and fronthaul integrated with access can facilitate lower cost deployment.

New immersive reality experiences in homes, factories and enterprises will demand reliable networks with ultra-high throughputs and low latencies. Examples of new use cases are augmented reality, multi-sensory telepresence, industrial co-design across factories, and cooperative robots requiring remote navigation. Network with very high data rates possibly exploiting spectrum available in mmWave and sub-THz bands will be required.

Fig. 1 illustrates the system we envision for a future network involving use of multiple spectrum bands and very large antenna arrays interconnected by high data rate backhaul connectivity. Furthermore, distributed MIMO processing should be optimally split between the radio units at sites and the central processing entity to optimize the bandwidth on the fronthaul links.

With increasing network densification, use of wide bandwidths, massive MIMO beamforming, and sophisticated AI based signal processing built into the systems for communication, radio sensing from the same infrastructure is an exciting new possibility for cellular networks. It can create new services indoor and outdoor for operators to offer to customers. Optimizing the air-interface for joint communication and sensing can result in significant deviation from current 5G specifications that a new generation of air-interface will be more appropriate.

In order to estimate transport network requirements, we consider a single cell, with the full utilization of wireless channel resources and peak data rates. The expected frequency bands and corresponding bandwidths and antenna arrangements have been considered. Every new generation of wireless communications standard so far has introduced wider carrier bandwidths along with other improvements in comparison to the previous one. Digital mobile communications started with 200kHz in 2G GSM and evolved to 1.25 MHz/5 MHz in 3G, 10 MHz in LTE and now to 100 MHz in 5G in the sub-6 GHz bands. It is essential that the next generation systems are designed for wider bandwidth carriers, for example, 400 MHz. New spectrum bands will be made available in the time frame of 6G with such wider bandwidths such as the 7 GHz-20 GHz range or the sub-THz range of 100 GHz – 300 GHz for short range applications. Today's mMIMO radio units for 5G are designed with 64 transceiver chains and about 200 antenna elements in the 3.5 GHz band. New spectrum in the 7 GHz to 10 GHz bands that may become available for next generation will make it possible to deploy arrays with at least four times as many antenna elements for the same form factor. For example, in 7 GHz spectrum, it is possible to have 1024 radiators in 37 cm $\times$ 71 cm, which is about the size of a 5G mMIMO array. Larger arrays will need to be exploited by supporting more simultaneous data streams or users. Furthermore, various functional splits, assumed to be equivalent to the current 5G ones, between the radio unit and distributed baseband unit have been considered.

The data rate estimates are presented in Table I. Various functional splits can be considered with different levels of functionality in the radio unit and the distributed unit of the base station [8], [9]. In 7-2 only the fast Fourier Transform (FFT) and the first stage beamforming aspects of the Layer 1

TABLE I
TRANSPORT NETWORK REQUIREMENTS – COLUMN TITLES DENOTE THE APPLIED FUNCTIONAL SPLIT

| | 7-2 | 7-3 | F1 |
|---|---|---|---|
| *[Band] [Bandwidth] [Streams]* | *[GBPS]* | *[GBPS]* | *[GBPS]* |
| 3GHz-6GHz 100 MHz DL/UL:16/8 | DL: 35 UL: 17 | DL: 18 UL: 16 | DL: 5 UL: 2.5 (6 bps/Hz/stream) |
| 7GHz-20GHz 400 MHz DL/UL: 64/32 | DL: 560 UL: 272 | DL: 288 UL: 256 | DL: 77 UL: 38.5 (6 bps/Hz/stream) |
| mmWave 800 MHz DL/UL:8/8 | | | DL: 16 UL: 16 (5 bps/Hz/stream) |
| sub-THz 10 GHz DL/UL:2/2 | | | DL: 50 UL: 50 (5 bps/Hz/stream) |

processing are included in the radio unit. In other words, beam space I-Q streams are transported to the base band unit. The transport network requirement is calculated based on the number of frequency domain symbols (which in turn depends on the bandwidth), the resolution of each symbol, and the number of streams.

In 7-3, in addition, channel estimation and interference rejection combining, or minimum mean squared error receiver processing are also implemented in the radio unit and thus detector outputs per layer are transported from the radio unit to the base band unit. In the downlink, modulation symbol streams are transported from baseband to radio unit for both 7-2 and 7-3. In the case of F1, all Layer 1 and real-time Layer 2 functions are included in the cell site and decoded information bits are transported to the central unit. The figures in the table do not include any compression of the streams and further reduction in the transport requirements may be possible through the introduction sophisticated compression schemes for 7-2 and 7-3. The compressed data rates are not included in the table since further work is required to determine the extent of compression that can be achieved for the 6G fronthaul interface especially when taking into account the latency implications of compression. Prior work on compression has focused primarily on the CPRI interface [10], [11].

## III. OPTICAL NETWORK SOLUTIONS

### A. Challenges in FH Transport

*1) Cost Effective Capacity Scaling:* With the expected increase of both the radio bandwidth and the number of UL/DL streams, the fronthaul (FH) transport throughput in 5.5G and 6G RAN will increase dramatically, regardless of the chosen FSs. As discussed in the previous section, FH capacity requirement per single cell can go beyond 500 Gb/s. This is an order of magnitude higher than the FH capacity requirement for today's 5G networks. At large cell sites with multiple radio units (RUs), the aggregated FH traffic might exceed 1 Tb/s or even 10 Tb/s.

To date, the capacity of 100 Tb/s per fiber can already be achieved with advanced fiber transmission techniques [12]. Therefore, from the technical point of view, the FH capacity demand of 5.5G and 6G networks can be attained in one way or another. However, fiber transmission technologies developed for long-haul, metro and datacenter interconnect networks bring high cost, which is a big concern for the competitive RAN market segment. It is getting more and more challenging to scale up the capacity while reducing the cost per transported bit. Fortunately, due to the maximum acceptable latency of 5.5G and 6G RANs, the FH reach, which is already relatively short (<20 km), will be further reduced. This relaxes the optical link budget and other specifications, which allow to leverage low-cost components and simplified architecture for FH optical transceivers to reduce the cost.

In addition, although Radio over Fiber (RoF) had been proposed as a lower cost solution for transport in earlier generations, RoF has been used sparingly. Our conjecture is that the TCO as well as the densification pressure to move to a larger number of access point sites in 6G will increase the opportunity to use this technology. Densification will be driven by the increased capacity demands, new bands with reduced propagation distance, and increased use of multi-site technologies (such as dMIMO). In addition, RoF, as detailed in this paper, has new capabilities which reduce technical limitations which may have been present in the past.

*2) Reduced Latency and Jitter:* In LTE and 5G FH networks, the propagation delay, which is approximately 5 $\mu$s/km, dominates the RAN latency. However, as the FH reach keeps decreasing in 5.5G and 6G networks, the contribution of processing and especially the decoding Forward Error Correction (FEC) latency becomes more critical. As increasing the signal processing and FEC complexity comes at a cost of increasing latency, optical transceivers for 5.5G and 6G FH RANs might have a more stringent latency requirement compared to its counterparts in other optical networks (e.g. long-haul/metro/datacenter interconnect). This will create a distinct market segment for FH optical transceivers and at the same time accelerate the integration of optics with the RU as this approach would be greatly beneficial in reducing the latency. Furthermore, for latency-critical applications, novel FH transmission techniques with lean DSP and without FEC will be of a great interest.

What might be more important than the latency itself is its determinism. To be more precise, the requirement on one-way delay (OWD) variation of packets (or "jitter") will be more stringent in 5.5G and 6G FH networks. Ethernet is low-cost and flexible but this technology lacks determinism. Currently, several projects for time-sensitive networking (TSN) are ongoing [13] to define Ethernet extensions for mobile fronthaul applications [14]. These specifications, when fully developed, will certainly play a critical role in 5.5G and 6G RANs. Another approach is using a dedicated fiber to connect DU and RU. The diversity of network assets and service priorities suggest that dedicated fiber will continue as a viable deployment option in 5.5G and 6G RANs.

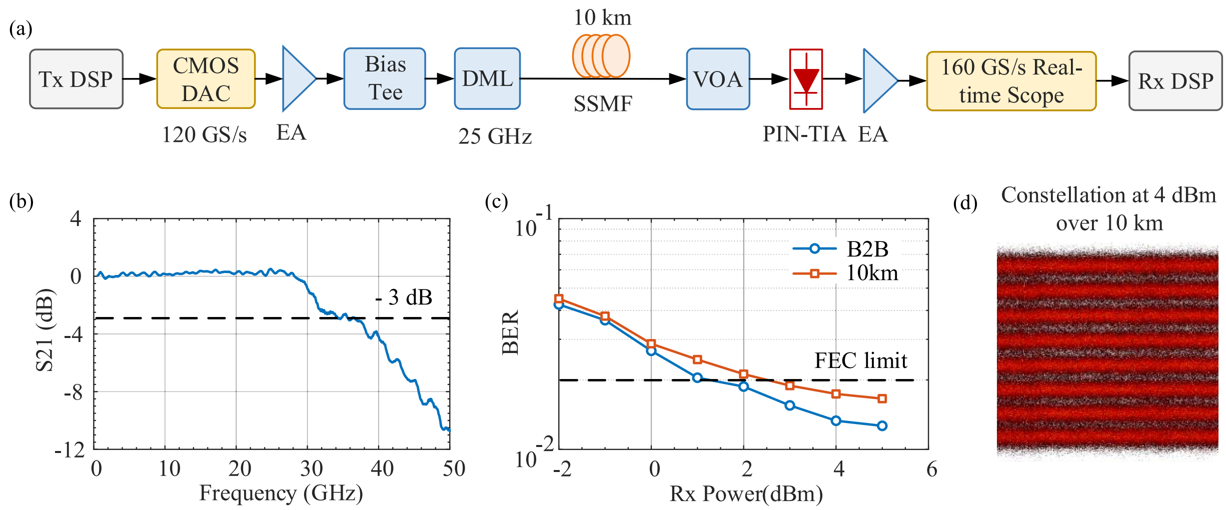


Fig. 2. (a) – Experimental setup for 80 Gbaud PAM-8 IM/DD transmission over 10 km of SSMF; EA – Electrical amplifier. (b) – S21 response of the DML; (c) – Sensitivity measurement in B2B and over 10 km; (d) – PAM-8 constellation over 10 km.

*3) Deployment and Operation Constraints:* For early-deployed 5G networks, direct fiber connectivity (using a fiber pair for connecting a DU with a RU) is a popular deployment option as it benefits from the lowest cost gray optics and deterministic performance. This deployment, however, is feasible only in fiber-rich areas. On the other hand, fiber resource is a scarce asset in dense urban areas and in many cases, it may be impossible to deploy new fibers. Such situations will likely remain unchanged for 5.5G and 6G networks. In addition, densification of cell sites as well as small cells in 5.5G and 6G RANs will demand more fronthaul connectivity. As a result, the adoption of WDM technology in FH networks [15], where each antenna site is allocated with a single or a group of wavelengths, will be further accelerated. This, however, will create network operation challenges as the transport equipment is now co-located with radio equipment in a remote, outdoor environment. In addition, the high cost of tunable WDM optical transceivers would represent a big barrier for large-scale deployment. For reducing the end-to-end system's cost, co-integration of the optics in the RU is certainly an attractive direction.

### *B. PHY Layer Transport Solutions*

In this sub-section, we will discuss several promising optical transport solutions for addressing both the near-term and long-term challenges in 5.5G and 6G FH transport as outlined above. We expect that there is no one-fits-all transport solution. Instead, the most suitable transport solution will be defined for each deployment scenario based on the fiber infrastructure and network requirements.

*1) High Spectral Efficiency Digital Radio Over Fiber:* Currently, most of FH links use intensity-modulated direct detection (IM/DD) transceivers with NRZ format offering a SE of 1 bit/symbol. That situation will change in 5.5G and 6G FH networks, where both IM/DD and coherent transceivers providing significantly higher spectral efficiency (SEs) will be used based on the capacity demand and the cost constraints.

In the fiber-rich areas, dedicated fiber connectivity with gray optics is the preferred deployment option due the low-cost of IM/DD transceivers. State-of-the-art IM/DD transceivers already offer data rates up to 100 Gb/s per lane (using PAM-4 format) over up to 10 km [16]–[17]. For achieving the next logical data rate of 200 Gb/s per lane, a common approach is doubling the symbol rate to 106.25 Gbaud [18], [19]. However, in this case, achieving a reach of 10 km, which would be required for covering FH networks, is extremely challenging due to the significant impact of chromatic dispersion (CD) on 106.25 Gbaud system. A realistic target for 200 Gb/s PAM-4 IM/DD transmission, therefore, is only 2 km [18], which makes it more suitable for intra-datacenter networks.

One promising approach for increasing the reach of 200 Gb/s IM/DD system is to leverage a more spectral-efficient format at a reduced baudrate. Perhaps, the most suitable option in this direction is 80 Gbaud Nyquist -shaped PAM-8. This system requires ∼40 GHz of bandwidth which can be effectively supported by commercial low-cost directly modulated laser (DML) [20] and commercial CMOS DAC and drivers [21]. Fig. 2 shows the experimental setup and transmission result for an 80 Gbaud PAM-8 IM/DD system using commercial DML at 1312 nm and a CMOS DAC. The DML has a 3-dB modulation bandwidth of ∼34 GHz. The sensitivity measurements in B2B and over 10 km shown in Fig. 2(c) clearly indicate that BER below the 20% overhead FEC limit can be achieved. This result shows that 200 Gb/s over 10 km is achievable using commercial DML and CMOS DAC.

Even though 200 Gb/s IM/DD transmission over 10 km is achievable, its limited CD tolerance does not allow for multiplexing more than a few channels on a single fiber. Even for 100 Gb/s IM/DD transmission, multiplexing more than 4 channels at 10 km of reach is already very challenging. This problem can be overcome using an advanced transmission technique called vestigial sideband (VSB) discrete multitone (DMT). A DMT ASIC [22] has been designed for such systems. Real-time measurements of a 4 × 100 Gb/s VSB DMT transmission in the C-band over distances up to 40 km are depicted in Fig. 3 [23]. This result indicates that VSB DMT format can effectively

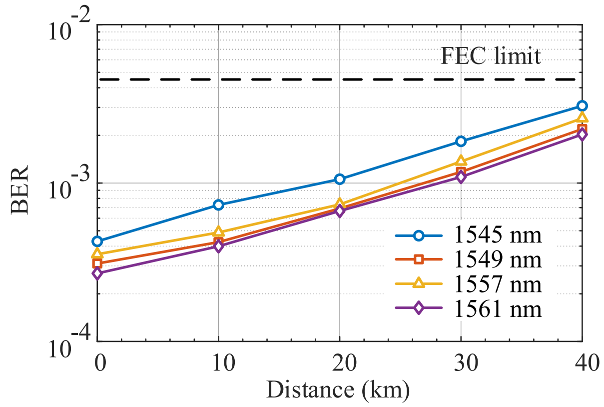


Fig. 3. Performance of real-time 4 × 100 Gb/s VSB DMT transmission in the C-band at a received signal power of −1 dBm/channel.

mitigate the CD-induced performance penalty in IM/DD transmissions. As a result, it opens the door for massive WDM IM/DD transmissions at data rates of 100 Gb/s per channel and beyond for 5.5G and 6G FH networks.

Due to the many technical challenges for further increasing the symbol rate and the intolerable impact of CD, 200 Gb/s is likely the highest interface rate where IM/DD transceivers will still be more cost-effective than coherent transceivers, especially for 10 km of reach. For RoF applications of 400 Gb/s [24] per channel and beyond, coherent receivers will likely be the most attractive option if the latency constraints can be met given the extensive signal processing required.

*2) DSP Assisted Analog RoF:* Low-PHY FS options (e.g. option 6 and 7) certainly provide a big benefit in reducing the FH capacity. On the other hand, the trade-off is that significant signal processing power is required at the RU, e.g. FFT/iFFT and digital beamforming (Fig. 4(a)). This increases the complexity, weight, size, and power consumption of the RU. In many application scenarios, complex and power-hungry RUs are not desirable. In the light of that, FS option 8 might regain interest for 5.5G and 6G networks.

For efficiently implementing FS option 8, spectrally efficient channel aggregation and de-aggregation will be required. Such aggregation techniques can be implemented in the DSP domain using either time-division multiplexing (TDM) [25], [26] or frequency division multiplexing (WDM) [27], [28] and the resulting transmission technique is called DSP-assisted analog RoF [29] (Fig. 4(b)). A detailed total cost of ownership (TCO) calculation in [29] suggests that DSP assisted analog RoF can provide ∼2× reduction in the 10-year TCO compared to the digital RoF option.

Another important feature of DSP assisted analog RoF is that, with a clever choice of the channel aggregation and optical modulation techniques, it is possible to "integrate" the optical channel to the radio channel to form a single channel from the baseband unit (BBU) to the end user [30]. In this case, the encoding layer and equalization for the optical channel can be removed as shown in Fig. 4(c). This transmission scheme is referred to as the transparent digital RoF. The simplification of transparent digital RoF scheme provides an efficient path for integrating FH transport interface to the RU, which can enhance the end-to-end system performance while reducing the cost.

The first demonstration of a transparent digital RoF scheme supporting 64 × 400 MHz UL radio channels over 40 km of FH link is shown in Fig. 5. In this scheme, radio signals from 64 antennas are aggregated using a TDM approach as illustrated in Fig. 5(b). For the optical modulation, a single-sideband (SSB) modulation technique with an optical I/Q modulator is adopted. The benefit of SSB modulation is that the CD only leads to a linear impairment which can be compensated at the BBU through MIMO signal processing. This effectively means that the channel distortions of both the wireless channel and the optical channel are compensated by the BBU jointly. The results obtained in [30] indicates that 40 km of fiber has negligible impact on the end-to-end system performance, which confirms that the presented scheme effectively removes the need for an additional coding layer and equalization for the optical channel.

Transparent digital RoF technology is still in its infancy. The added cost due to optical I/Q modulator and the complexity of the KK front-end correction in the proposed scheme above should be further evaluated. However, based on many potential benefits of the transparent digital RoF concept, further research efforts in this direction can bring great impact to 5.5G and 6G networks.

*3) Analog RoF:* In many application scenarios in 5.5G and 6G networks, such as distributed antennas systems (DAS) [31], [32], lightweight, low-power consumption RU are strongly desirable. In such cases, analog RoF, either directly at the RF frequency or at an intermediate frequency (IF), can be a more attractive solution compared to the digital RoF approach. Both analog RoF and analog IF-RoF schemes aim to transport the radio signals over the fiber channel without using a DAC/ADC (Fig. 6). Compared to the IF-RoF scheme, direct RoF provides a more simplified RRU architecture as it does not require a mixer. However, direct RoF has a more stringent requirements on the bandwidths and also the linearity and noise performance of the optical modulator and photodetector.

Fig. 7 shows SNR measurements for direct analog RoF at 28 GHz of carrier frequency and IF-RoF at 3 GHz for a 64-QAM OFDM signal with 800 MHz of bandwidth. The optical modulator is a 25 GHz DML discussed before. One can note that, for both cases, excellent performance can be achieved when the input signal power is above −5 dBm (over 10 km). Both RoF and IF-RoF cases show linear dependency between the input signal power and the link SNR, which suggests that the nonlinear distortion is negligible in the considered operation regime. Due to lower modulation efficiency, the RoF scheme requires ∼ 6 dB higher input signal power to achieve a similar link SNR as compared to the IF-RoF scheme. Overall, the ability to operate at relatively low input signal power (<−5 dBm) eliminates the long-held concern about the impact of transceiver nonlinearity [33], [34] on the transmission quality of an analog RoF system. This result also indicates that the quality of commercial DML might be already good enough to support analog RoF transmission even at 28 GHz. Once the quality of transmission is met, the adoption of either RoF and IF-RoF solution will depend on its cost and implementation efficiency and flexibility compared to the digital RoF schemes discussed above.

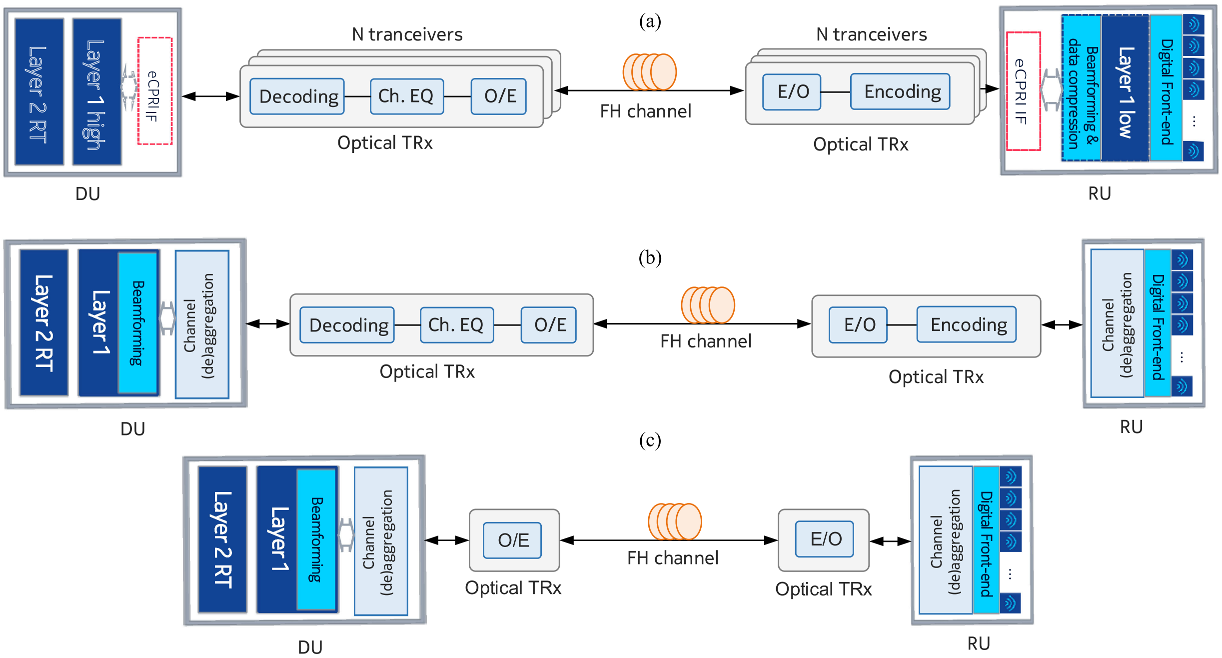


Fig. 4. (a) – FH transport with low-PHY FS (e.g. option 7.2) using digital RoF for massive MIMO applications; Due to the high capacity, more than one optical transceiver pairs might be required to support one DU/RU connection; (b) – DSP assisted analog RoF transmission with FS option 8 and channel (de) aggregation; (c) – Transparent digital RoF.

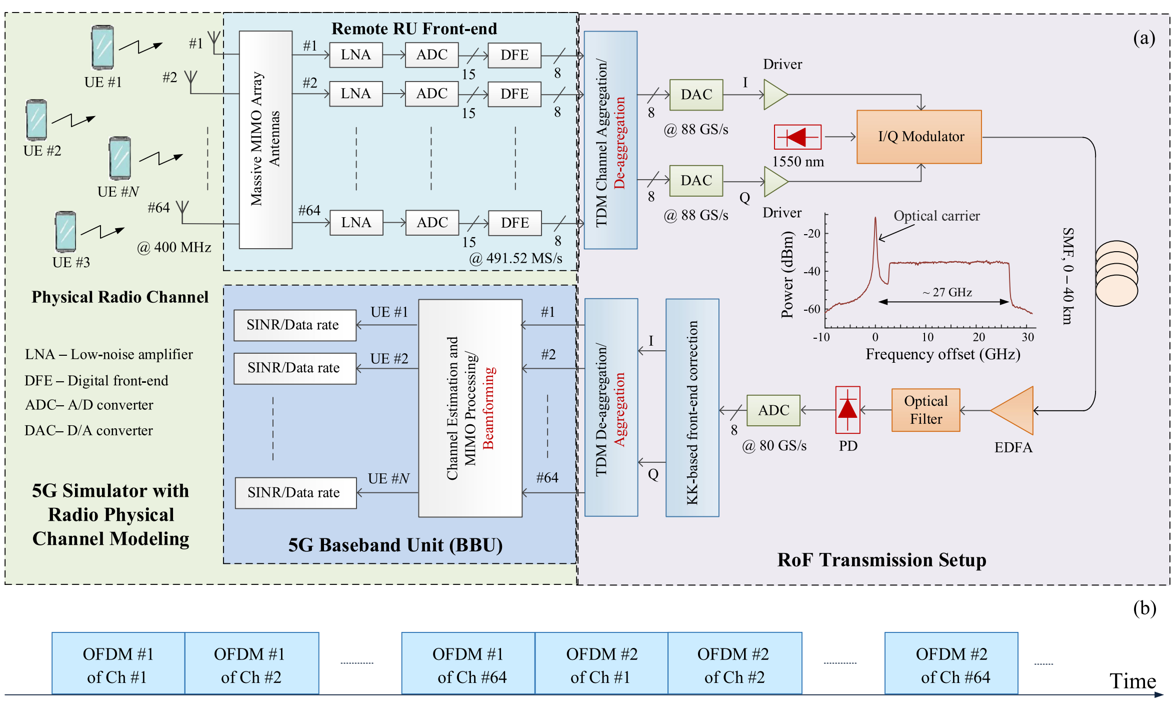


Fig. 5. (a) – Experimental setup for a transparent digital RoF transmission supporting 64 × 400 MHz UL radio channels using SSB optical modulation format and Kramers-Kronig Rx front-end correction; inset shows the optical spectrum of the modulated signal with ∼27 GHz of optical bandwidth; (b) – TDM channel aggregation technique.

## IV. PON Network Solutions

Mobile backhaul was originally comprised of T1/E1 TDM circuits over copper and microwave facilities. In the voice-dominated era, if more bandwidth was required, additional circuits were added. With the coming of LTE at the beginning of the last decade, the poor scalability of TDM circuits to meet the demand of data services led to a transition to Ethernet-based backhaul, with copper being replaced by fiber.

At the same time, GPON was on its way to becoming the most widely deployed technology for FTTH. GPON also appeared to be a good candidate for mobile backhaul. Commercial GPON solutions satisfied backhaul requirements for capacity, latency, and synchronization. Because of its point-to-multipoint topology,

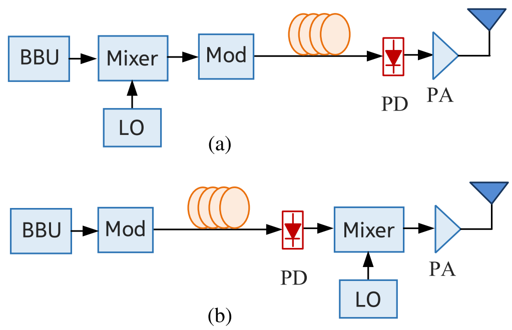


Fig. 6. (a) – Basic block diagram of a direct analog RoF transmission; (b) – Basic block diagram of a direct analog IF-RoF transmission; LO – local oscillator; PA – power amplifier.

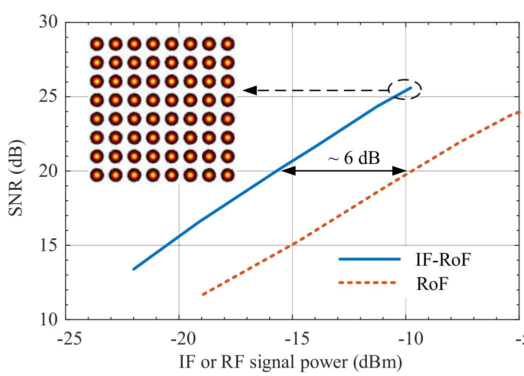


Fig. 7. SNR measurement for RoF at 28 GHz and IF-RoF at 3 GHz with 800 MHz OFDM signal; The distance is 10 km.

it had the advantage of lower cost compared to point-to-point fiber technologies, namely because of (1) fiber sharing, (2) fewer optical interfaces and (3) low cost aggregation. Operators with existing FTTH footprint could leverage PON backhaul for faster-time-to market, either for their own mobile services or to wholesale to others.

However, with few exceptions, GPON was not used for mobile backhaul. The savings were not compelling enough compared to the total cost of ownership of cellular macro cells; not enough for operators to adopt a technology wholly unfamiliar to their mobile network engineers. The lesson quickly learned was that PON backhaul would only become attractive when cell sites were deployed more densely. Not necessarily as densely as FTTH, but more densely than macro cells.

Subsequently, hockey-stick shaped forecasts for LTE small cells became prevalent. Again GPON appeared to be an ideal fit, this time for small cell backhaul. However MNOs soon realized that they could mostly satisfy bandwidth demands more cheaply by upgrading macro cells rather than deploying denser small cells.

We are now at the beginning of 5G. Many of the first 5G radios were, not surprisingly, deployed at existing LTE cell sites. However the promise of cell densification appears to be more real than before. There is an expectation that sub-6 GHz spectrum will not be able to keep pace with enhanced mobile broadband (eMBB) demands, leading to the usage of mmWave spectrum. mmWave, due to its limited propagation characteristics, may need to be deployed more densely. Another use case, fixed wireless access, is also expected to require cell densification, whether mmWave or sub-6 GHz. The densification business case is challenging and minimizing transport costs is critical. PON technologies, especially when existing FTTH footprint can be leveraged, will be impossible to be ignored for 5G. In fact, operators are increasingly interested in mobile transport over PON [35] and there is a new operator-initiated project in ITU-T SG15/Q2 studying the use of TDM PONs for 5G backhaul and midhaul, “G.sup.5GBH”.

Currently FTTH is in the early phase of its transition from GPON to various flavors of 10G PON. 10G PONs have enough capacity to satisfy FTTH demands for a long time. That capacity is also adequate for 5G backhaul and midhaul, although may be lacking sufficient headroom to accommodate growth. Accordingly, symmetrical 25GS PON [36], just now coming to market, is seen as a better and perhaps ideal solution. Its optical componentry is essentially the same as 10G PON, just leveraging data center components for higher speed and launching a few dB higher power.

The above discussion concerns TDM PONs. WDM PONs have been a favorite topic of research for decades, but due to expensive optics, lack of business needs and missing standards there have been virtually no deployments so far. WDM PONs provide a dedicated high-speed low latency static pipe to each endpoint. While not a good fit for highly stat-muxable residential traffic, it is a good fit for mobile fronthaul traffic, and may find at least a niche application in this space.

### A. *PON Readiness for 6G Transport*

The readiness of PON as a transport technology for 6G radio networks (6G RAN) is evaluated against the requirements as described in section II above.

First, 6G will be in open cloud-native networks deployed in heterogeneous cloud environments. Transport networks will be integrated into this architecture as disaggregated Software Defined Network (SDN) controlled functions. The PON broadband access networks are already upgraded for open network automation, providing a dynamic management of the OLT’s aggregation mechanism with a SDN access controller. [37] This can avoid overprovisioning and over-dimensioning, while reducing the ever more important factor of energy footprint for RAN transport. Openness is already established based on the Yang model definitions for PON of Broadband Forum [38]. Evolving further from the first Transport Network (TN) 4G/5G Slicing [39], the 6G era will have their own models that will incorporate AI/ML natively.

The new immersive reality experiences will demand more high-availability networks with low latencies. 6G transport in cloud networks for end-to-end virtual function interconnect can be based on the evolution of Metro Ethernet Forum (MEF) implementation agreements for mobile transport [40]. The PON networks will be part of an ‘access E-line’ service with associated Class of Services (CoS) and service monitoring (Service-OAM). With this E-line the necessary availability (service up time of more than five-nines) can be architected including distribution via PON. Active/stand-by redundancy of OLT and shared feeder sections, even with simplex ONU (Type-B protection) [41] are considered as fitting RAN connectivity requirements even for the critical 6G network services in a cloud environment.

TDM PON's DBA latency has been considered to be incompatible with the HARQ-loop and low latency requirements of <100µs including additional L2 switching delays in the nodes and propagation delays. The work in both O-RAN and ITU-T on transport convergence includes the standardization of Cooperative Transport Interface (CTI) for eCPRI fronthaul [42], which enables cooperation between mobile scheduler (in the O-DU) and PON TDMA schedulers in order to decongest the traffic flows and achieve ultra-low latency at higher data-rates as it avoids upstream buffering in ONU.

This readiness check finally includes the transport capacity dimensioning, of future higher speed PON technologies for ultra-high throughput depending on the enormous amount of capacity on the uplink and very high throughputs on the downlink as addressed in the next section.

### *B. Xhaul Traffic Requirement for 6G*

The theoretically calculated peak traffic requirements assuming perfect channel conditions for a single cell of the configurations in Table I scale linearly with carrier bandwidth and spatial streams (MIMO layers). However, due to the radio channel conditions and the user traffic statistics in the multi-cell environment, the theoretical peak is rarely achieved. Therefore, to understand the statistical nature of the traffic at different xhaul interfaces, we conducted system level radio simulations for 5G scenarios as specified by 3GPP and reported for the first time a detailed xhaul traffic analysis in [43].

The radio units assumed for the system level radio simulations in [43] have carrier frequency of 3.5 GHz, carrier bandwidth of 100 MHz and support 4 spatial streams. The simulation program generates the eMBB type of data traffic per user. The radio scheduler uses a proportional fair scheduling algorithm while considering the radio channel conditions and corresponding link adaptation techniques to achieve a certain Block Error Rate (BLER) target (e.g., 10% in the case of eMBB services). The output of the simulation is the time-series of UE scheduling information in the downlink direction for each radio slot of 0.5 ms. The UE scheduling information is then used to calculate xhaul traffic demand for each cell per radio slot at the F1 (HLS) interface, split 7.3 and split 7.2× low layer split (LLS) interfaces. In the xhaul traffic analysis, 95%-ile values are used from the distribution of the sum of F1 traffic requirements of a certain number of cells per radio slot, whereas maximum (i.e., 100%-ile) values are used for LLS traffic requirements. As F1 interface traffic is latency-tolerant for eMBB services, the instantaneous traffic exceeding the provisioned capacity will not necessarily lead to packet loss. However, as LLS traffic is latency sensitive, it needs to be provisioned for the maximum requirement. Since we want to calculate the mean xhaul traffic requirements for the aggregation of multiple cells, the traffic requirements from multiple randomly combined cells of a given group size is

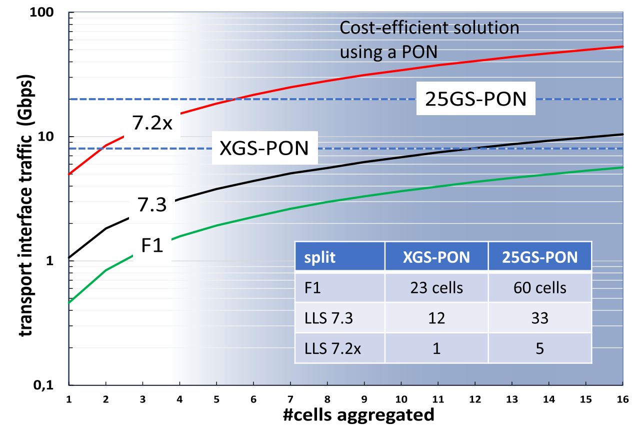


Fig. 8. 6G xhaul traffic requirements for sub-6Ghz radio example.

averaged (e.g., taking the mean of 50 random combinations of 10 cells from the 57-cell scenario).

In this paper, we use the xhaul traffic analysis from [43] for a fully loaded radio network and extrapolate the results based on 6G radio configuration for sub-6GHz band radio units in Table I. The extrapolation involves multiplying the traffic requirements by a factor of 4 considering it has same carrier bandwidth but supports 4× spatial streams compared to the simulated 5G radio unit. The results for this extrapolation are shown in Fig. 8. They show that the theoretical peak traffic for LLS split 7.2 is ∼2× higher than the traffic from the simulated multi-cell radio network scenario described in [33]. In case of LLS split 7.3 and F1 interface, the theoretical peak traffic is ∼5–6× higher than the traffic from simulated scenario. This is due to the realistic channel conditions in a multi-cell environment and UE traffic statistics. The results in Fig. 8 only provide a guideline towards the evolution of traffic requirements in 6G RAN and they need to be refined with a similar xhaul traffic analysis of [43] based on system level simulations of 6G RAN and future user/machine applications. In the meantime, if we assume that PON solutions become interesting at minimum of 8 cells per PON, we see the minimum PON speeds (assuming 80% effective throughput after overhead):

- F1 HLS requires a 25G PON
- 7.3 LLS requires a 25G PON
- 7.2 LLS requires a 200G PON

### *C. 6G Cell Cluster Dimensioning for Future TDM-PON Rate Evolution*

The results in Fig. 8 show that the statistical traffic on all xhaul interfaces results in a significantly lower capacity than the sum of peak capacities of a set of cells. Therefore, the transport capacity for aggregating multiple cells can be dimensioned for a lower than peak capacity to optimize the transport costs. Based on the simulation results presented in Fig. 8, we consider that 20% of the peak capacity of F1 and split 7.3 and 50% of the peak capacity of 7.2 split fronthaul is actually realized in a multi-cell environment. Using these factors, we can further calculate the transport dimensioning requirements for large networks. We

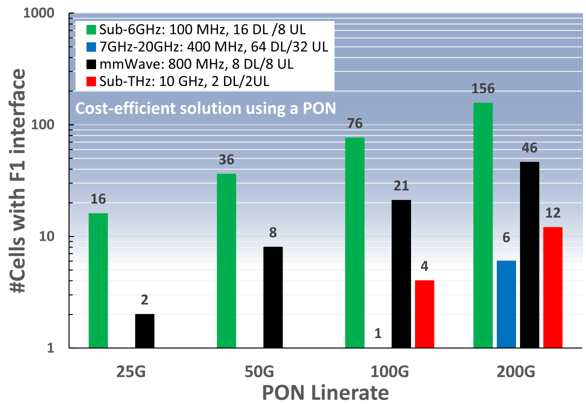


Fig. 9. 6G cell F1 interface dimensioning for TDM-PON rate evolution.

TABLE II
PON Capacity Required for 6G Transport Use Cases Assuming 8 Cells Per PON and Peak Transport Rates Per Cell As Shown in Table I

| | 7.2 | 7.3 | F1 |
|---|---|---|---|
| Band: 3 GHz- 6 GHz Bandwidth:100 MHz Streams DL/UL:16/8 | 200G PON | 25G PON | 25G PON |
| Band: 7 GHz- 20 GHz Bandwidth:400 MHz Streams DL/UL:64/32 | No PON solution expected | No PON solution expected | 200G+ PON |
| Band: mmWave Bandwidth:800 MHz Streams DL/UL:8/8 | - | - | 50G PON |
| Band: sub-THz Bandwidth: 10 GHz Streams DL/UL:2/2 | - | - | 100G PON |

now focus on the F1 interface transport capacity dimensioning which is based on a previous NGMN study about the transport dimensioning of LTE backhaul [44]. The transport dimensioning rule used in this study for a N cell cluster is:

$$Transport\ capacity = 1 * peak + (N - 1) * mean.$$

The mean value in this case is the F1 rate at 20% of the peak capacities from Table I. Based on this formula, transport dimensioning requirements for different radio frequency scenarios of Table I can be calculated. These requirements can be then easily translated in terms of #cells that can be aggregated over future TDM-PON rate evolutions which is visualized in Fig. 9. Again, assuming that PON only becomes interesting when it can support at least 4 and more likely 8 radios, we can see that 25G PON, as noted already noted above, is enough to support transport for the sub-6 GHz band. At least 50G PON will be required for the mmWave band and possibly 100G PON, and 200G PON for sub-THz. Even 200G PON will be borderline for the 7–20 GHz band.

Table II summarizes the PON capacity required for the 6G use cases analyzed in this paper. Recall that we have assumed no compression for 7.3 and 7.2 fronthaul; compression would ease the capacity requirements. Also, for F1 HLS we have assumed the ratio of downlink to uplink traffic in Table II. In the worst case, at any given moment, all 6G resources could be allocated to the downlink or the uplink. However, if such cases are only momentary, the transport can cope with it.

### *D. Brief Forecast of the Implementation of NG PONs*

How will PON capacity evolve to support the transport capacity requirements of 6G? After 25G PON will be 50G PON. A single-wavelength asymmetric (maximum 25G upstream) 50G PON standard has just been approved by ITU-T [45]. It will likely depend on a high power 50G OLT transmitter and strong DSP equalization of a 25G-class receiver at the ONU [46]. For that reason commercial deployments are expected to start only in the second half of this decade.

As 25G PON will be the last generation of TDM PON that can be realized without optical amplification, 50G PON may be the last generation of TDM PON that employs IM-DD. While it may be possible to place enough optical amplification at both the transmitter and receiver to overcome at least 29 dB optical path loss at 100G [47], it may not be practical, and what about higher optical path losses of 32 dB or more? Unless there are further innovations in IM-DD, 100G is likely the tipping point for PON in the adoption of coherent technology. We would not expect 100G PON to re-use the conventional DP-QPSK transceivers used in the core, metro and datacenter interconnect spaces. These high-performance modules cost thousands of dollars and are not likely to cost-erode to PON price points in the required timeframe. A performance-cost trade-off will be necessary. 100G single wavelength coherent PON has been a research topic for several years and a concise survey of this field is available [48]. Also, there may be synergies with the intra-data center ecosystem, which may face a similar challenge with IM-DD at 200G per wavelength at reaches as low as 10 km.

Finally, it's difficult to imagine how 200G PON might be realized without coherent reception.

### *E. Nested PONs for Long Distance Mid and Fronthaul*

In this section we introduce an approach for smoothly migrating mobile macro cell networks towards heterogeneous ultra-dense networks by attaching small cells over fronthaul links later on. We consider the case of a backhaul / midhaul link to a macro cell being provided over a residential FTTH PON, and show how the small cells can then be served from the macro cell over fronthaul links across the drop section of the PON [49]. At the beginning of this Section IV, it has been discussed that the business case for such scenarios can be challenging, and that a potential driver for this may come up with the introduction of mmWave small cells. The xhaul architecture discussed in this part now is based on the assumption that the business case will be positive. As shown below, this architecture does not need much modification of the passive ODN, and no modification of the active system equipment. So it is actually an optional modification that can be realized at any time later on, when a network is to be highly densified.

In the network scenario shown at the top of Fig. 10 the mobile service area coincides with a residential FTTH service area, both being attached to a common edge cloud using a power splitter based PON. It is assumed that the service area is located at a distance that would typically not allow the antenna sites

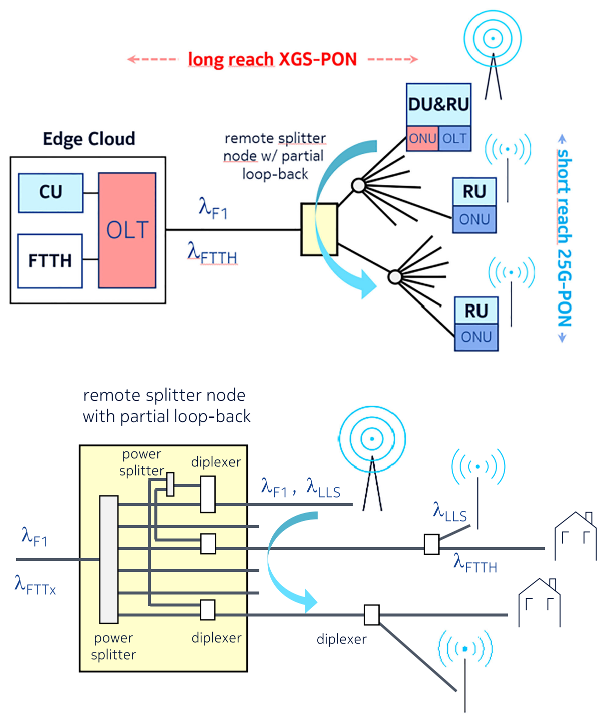


Fig. 10. Nested PON architecture for long distance midhaul and local fronthaul using a modified remote splitter node (yellow) for looping back fronthaul signals within the drop section (top); and internal architecture of the modified remote splitter node (bottom) [49].

to be connected via the LLS interface, i.e., at up to 20 km (200 $\mu$s round trip delay) from the edge cloud. The midhaul data transmitted between the CU in the edge cloud and the DU at the macro site are transported over the (red) PON, e.g., XGS-PON, containing the F1 data for both the macro cell and for the nearby small cells. After further processing the data for both types of cells in the DU, the LLS fronthaul data are transferred to the macro cell RU via a local connection, and to the small cell RUs using the (blue) PON, e.g., 25G PON, between the OLT at the macro cell site and the ONUs at the small cell sites.

For meeting the low latency requirements of fronthaul links, the blue short-reach PON is operated only in the distribution section of the main (red) long-reach PON. To accomplish this, the remote splitter node (yellow) is modified by adding a few passive components (bottom of Fig. 10): diplexers extract/add the downstream and upstream wavelengths of the blue PON from/to the drop fibers connecting the power splitter with the macro cell and with the small cells. A second, low split ratio power splitter (here 1:2) is added for connecting the small cells with the macro cell as shown in the figure. The number of small cells added per macro cell within a given residential PON depends on the environment (dense urban, urban, rural). It will, however, in any case be a small number ($<$8) which, together with the short fiber distances in the drop section, will allow for using PON equipment made for very low loss ODNs (not more than 15 dB). Since the small cells are attached over the drop fibers of the FTTH network, they must be connected using diplexers in the field, as shown at the bottom of Fig. 10.

The modification of the remote splitter can be accomplished by either replacing the existing power splitter with a fully integrated internal structure as shown in the figure. Alternatively, the added low ratio splitter is externally attached via diplexers to the respective ports of the existing splitter. The latter approach needs more floor space and may induce slightly higher losses, but it has less impact on the operational network, as only few ports will be affected by a short downtime.

The FTTH service is assumed to be transmitted either together with the backhaul / midhaul traffic using the red (XGS) PON, or alternatively using a third PON system, e.g., GPON. Such combinations can be used as long as the wavelength ranges of the PON systems do not overlap which is true for any combination of GPON, XGS-PON and 25GS-PON.

## V. Conclusion

The promise of 6G brings new applications to serve both consumer and enterprise applications with higher levels of performance and capacity than available today. The challenge, however, is that the total cost of ownership (TCO) of this new network with its higher density and higher performance cannot scale with the increase in capacity or performance. The worldwide communications market revenue has flattened in recent years, and thus there will be little opportunity for exceptional investment on 6G networks – the imperative is that 6G deployments bring a similar or declining TCO as compared to the 5G networks of today. Advanced automation and greater use of virtualization will bring efficiencies and lower costs to network operations. **The cost of deployment of the new high performance and densified transport network with its high costs of civil engineering remains the most significant barrier to delivering on this 6G promise**. The drive towards lower TCO in 6G networks will demand deployment of networks that leverage, to the greatest degree, the lowest cost solution available to the network provider. That will be different in different geographies and with different providers and thus will require a multitude of flexible options and solutions. There will NOT be a single solution for 6G deployment.

In this paper we have described several different solutions each of which can meet the performance requirements of 6G given different available assets. New lower cost P2P fiber solutions will improve connection to existing sites as well as for new densification. To drive down the size, weight, cost, power consumption, and rent of remote radios, RoF solutions offer great benefit at TCO reduction, particularly for remote units with high antenna count as needed for massive MIMO deployment. PON solutions for 6G offer significant TCO benefit particularly for those providers that already have PON based FTTH deployments available.

## References

[1] "Nokia deepfield network intelligence report: Networks," 2020. [Online]. Available: https://www.nokia.com/networks/solutions/deepfield/network-intelligence-report/

[2] H. Viswanathan and P. E. Mogensen, "Communications in the 6G era," *IEEE Access*, vol. 8, pp. 57063–57074, 2020.

[3] T. S. Rappaport *et al.*, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019.
[4] M. Latva-Aho, K. Leppänen, and F. Clazzer,, and A. Munari, "Key drivers and research challenges for 6G ubiquitous wireless intelligence," 6G Research Vision 1, 6G Flagship, Univ. Oulu, Oulu, Finland, Tech. Rep., Sep. 2019.
[5] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020.
[6] Samsumg, "The next hyper-connected experience for all," White paper, Jul. 2020. [Online]. Available: https://research.samsung.com/next-generation-communications
[7] Ericsson, "Ever present intelligent communication," White paper, Nov. 2020. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/white-papers/a-research-outlook-towards-6g
[8] O-RAN Alliance, "O-RAN fronthaul control, user and synchronization plane specification," O-RAN.WG4.CUS.0-v06.00, Mar. 2021. [Online]. Available: https://www.o-ran.org/specifications.
[9] V. Rodriguez, F. Guillemin, A. Ferrieux, and L. Thomas, "Cloud-RAN functional split for an efficient fronthaul network," *Int. Wireless Commun. Mob. Comput.*, 2020, pp. 245–250, doi: 10.1109/IWCMC48107.2020.9148093.
[10] B. Guo, W. Cao, A. Tao, and D. Samardzija, "LTE/LTE-A signal compression on the CPRI interface," *Bell Labs Tech. J.*, vol. 18, no. 2, pp. 117–133, 2013.
[11] D. Samardzija, J. Pastalan, M. MacDonald, S. Walker, and R. Valenzuela, "Compressed transport of baseband signals in radio access networks," *IEEE Trans. Wireless Commun.*, vol. no. 11, no. vol. 9, pp. 3216–3225, Sep. 2012.
[12] P. J. Winzer and D. T. Neilson, "From scaling disparities to integrated parallelism: A decathlon for a decade," *J. Lightw. Technol.*, vol. 35, no. 5, pp. 1099–1115, 2017.
[13] IEEE Time-Sensitive Networking (TSN) Task Group, [Online]. Available: https://1.ieee802.org/tsn/
[14] IEEE Standard for Local and Metropolitan Area Networks—Time-sensitive Networking for Fronthaul, IEEE Std. 802.1CM, 2018.
[15] J. Zou, S. A. Sasu, M. Lawin, A. Dochhan, J. -P. Elbers, and M. Eiselt, "Advanced optical access technologies for next-generation (5G) mobile networks," *J. Opt. Commun. Netw.*, vol. 12, no. 10, pp. D86–D98, 2020.
[16] 2016. [Online]. Available: https://www.ieee802.org/3/cd/public/July16/anslow_3cd_01_0716.pdf
[17] J. C. Cartledge and A. S. Karar, "100 Gb/s intensity modulation and direct detection," *J. Lightw. Technol.*, vol. 32, no. 16, pp. 2809–2814, 2014.
[18] 800G Pluggable MSA White Paper, [Online]. Available: https://www.800gmsa.com/news/white-paper
[19] X. Pang *et al.*, "Beyond 200 Gbps per lane intensity modulation direct detection (IM/DD) transmissions for optical interconnects: Challenges and recent developments," in *Proc. Opt. Fiber Commun. Conf.*, 2019, pp. 1–3.
[20] Y. Matsui *et al.*, "28-Gbaud PAM4 and 56-Gb/s NRZ performance comparison using 1310-nm Al-BH DFB laser," *J. Lightw. Technol.*, vol. 34, no. 11, pp. 267–2683, 2016.
[21] T. Drenski and J. C. Rasmussen, "ADC & DAC - technology trends and steps to overcome current limitations," in *Proc. Opt. Fiber Commun. Conf. Expo.*, San Diego, CA, 2018, pp. 1–3.
[22] [Online]. Available: https://www.eu.socionext.com/assets/downloads/37/DMT-ASSP-V06.pdf
[23] S. T. Le *et al.*, "100Gbps DMT ASIC for hybrid LTE-5G mobile fronthaul networks," *J. Lightw. Technol.*, vol. 39, no. 3, pp. 801–812, Feb. 2021, doi: 10.1109/JLT.2020.3044516.
[24] [Online]. Available: https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0_reduced2.pdf
[25] X. Liu, F. Effenberger, N. Chand, L. Zhou, and H. Lin, "Efficient mobile fronthaul transmission of multiple LTE-A signals with 36.86-Gb/s CPRI-equivalent data rate using a directly-modulated laser and fiber dispersion mitigation," in *Proc. ACP*, Shanghai, China, 2014, pp. 1–3.
[26] S. T. Le, K. Schuh, M. Chagnon, F. Buchali, and H. Buelow, "1.53-Tbps CPRI-equivalent data rate transmission with kramers-kronig receiver for mobile fronthaul links," in *Proc. Eur. Conf. Opt. Commun.*, Rome, Italy, 2018, pp. 1–3.
[27] S. Ishimura, A. Bekkali, K. Tanaka, K. Nishimura, and M. Suzuki, "1.032-Tb/s CPRI-equivalent data rate transmission using IF-over-fiber system for high capacity mobile fronthaul finks," in *Proc. Eur. Conf. Opt. Commun.*, Gothenburg, Sweden, 2017, pp. 1–3.
[28] L. Zhang *et al.*, "Toward terabit digital radio over fiber systems: Architecture and key technologies," *IEEE Commun. Mag.*, vol. 57, no. 4, pp. 131–137, Apr. 2019.
[29] A. Udalcovs *et al.*, "Total cost of ownership of digital vs. analog radio-over-fiber architectures for 5G fronthauling," *IEEE Access*, vol. 8, pp. 223562–223573, 2020.
[30] S. T. Le, S. Wesemann, R. Dischler, and S. Venkatesan, "A joint wireless-optical front-haul solution for multi-user massive MIMO 5G RAN," in *Proc. Eur. Conf. Opt. Commun.*, 2020, pp. 1–4.
[31] Minkyu Sung *et al.*, "5G trial services demonstration: IFoF-based distributed antenna system in 28 GHz millimeter-wave supporting gigabit mobile services," *J. Lightw. Technol.*, vol. 37, no. 14, pp. 3592–3601, 2019.
[32] T. Okuyama, S. Suyama, J. Mashino, and Y. Okumura, "Antenna deployment for 5G ultra high-density distributed antenna system at low SHF bands," in *Proc. IEEE Conf. Standards Commun. Netw.*, 2016, pp. 1–6.
[33] D. Novak *et al.*, "Radio-over-fiber technologies for emerging wireless systems," *IEEE J. Quantum Electron.*, vol. 52, no. 1, pp. 1–11, Jan. 2016.
[34] D. Wake, M. Webster, G. Wimpenny, K. Beacham, and L. Crawford, "Radio over fiber for mobile communications," in *Proc. IEEE Int. Topical Meeting Microw. Photon.*, 2004, pp. 157–160.
[35] Report, "5G transport strategies & vendor leadership, service provider survey," IHS Markit, Jan. 2020.
[36] 25GS-PON MSA Group, "25GS-PON specification, 25 Giagabit symmetric passive optical network," Accessed: 21, Sep. 2021. [Online]. Available: https://www.25gspon-msa.org/
[37] Tech. Rep. TR-384, "Cloud central office reference architectural framework," Issue 1, Broadband Forum, Jan. 2018.
[38] Tech. Rep. TR-385, "ITU-T PON YANG Modules," Issue 2, Broadband Forum, Oct. 2020.
[39] Tech. Specification TS 28.530 v.17.1.0, "Group services and system aspects; Management and orchestration; Concepts, use cases and requirements," 3GPP, Mar. 2021.
[40] Implementation Agreement MEF 22.3, "Transport services for mobile networks," Jan. 2018 and Amendment MEF 22.3.1 "Transport Services for 5G Mobile Networks," MEF, Apr. 2020.
[41] Supplement G.Sup51, "Passive optical network protection considerations," ITU-T, 2017.
[42] Tech. Specificaion O-RAN.WG4.CTI-TCP.0-v02.00, "Cooperative transport interface, transport control plane specification 2.0," O-Ran Fronthaul Working Group 4, Mar. 2021.
[43] S. Bidkar, P. Dom, R. Bonk, and T. Pfeiffer, "Mobile xhaul traffic modelling for high-speed TDM-PON," in *Proc. Eur. Conf. Opt. Commun.*, 2020, Paper WE2J-5.
[44] White Paper, "Guidelines for LTE backhaul traffic estimation," NGMN Alliance, Jul. 2011.
[45] Recommendations G.9804.2, "Higher speed passive optical networks: Common transmission convergence layer specification," and G. 9804.3 "50-Giagabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification," ITU-T, Apr. 2019.
[46] R. Bonk *et al.*, "50G-PON: The first ITU-T higher speed PON system," *IEEE Commun. Mag.*, Dec. 2021.
[47] R. Borkowski *et al.*, "World's first field trial of 100 Gbit/s flexible PON (FLCS-PON)," in *Proc. Eur. Conf. Opt. Commun.*, 2020, pp. 1–4.
[48] V. Houtsma, A. Mahadevan, N. Kaneda, and D. van Veen, "Transceiver technologies for passive optical networks: Past, present, and future," *J. Opt. Commun. Netw.*, vol. 13, no. 1, pp. A44–A55, 2021.
[49] Th. Pfeiffer, "PON architecture enhancements," in *Springer Handbook of Optical Networks*, Berlin, Germany: Springer, 2020, pp. 913–949.

**Theodore(Tod) Sizer** (Fellow, IEEE) graduated from Amherst College, United States and received the master's and Doctorate degree in optics from the Institute of Optics, the University of Rochester, United States. He is the Vice President of Optical Systems and Device Research with Nokia Bell Labs, leading teams innovating in all aspects of Optical Systems and Devices for Core, submarine, and data center communications. Prior to his current role, Tod lead Wireless Research with Nokia Bell Labs for eight years driving the vision and research of 5G. In 2012, he was the recipient of the the Popular Science Breakthrough Innovation Award for the lightRadio invention. Tod is a Fellow of Bell Labs, WWRF. He is the author of 54 US patents and a member of OSA.

**Dragan Samardzija** (Member, IEEE) received the Ph.D. degree in electrical engineering from Wireless Information Network Laboratory (WINLAB), Rutgers University, USA in 2004. Since 2000, he has been with Bell Labs, focusing on 5G and now 6G radio access and platforms for IoT, cyber-physical systems, URLLC and time-sensitive networking. has authored more than 50 peer-reviewed publications and has numerous patents granted and pending. He was the recipient of the Bell Labs Fellow Award in 2017.

**Harish Viswanathan** (Fellow, IEEE) received the B. Tech. degree from the Department of Electrical Engineering, Indian Institute of Technology, Chennai, India and the M.S. and Ph.D. degrees from the School of Electrical Engineering, Cornell University, Ithaca, NY. He is the Head of Radio Systems Research Group with Nokia Bell Labs. Since joining Bell Labs in October 1997, he has been working extensively on wireless research ranging from physical layer to network architecture and protocols including multiple antenna technology for cellular wireless networks, multi-hop relays, network optimization, network architecture, and IoT communications. He has authored or coauthored extensively with more than 100 publications. From 2007 to 2015, he was with the Corp CTO organization, where as a CTO Partner he advised the Corporate CTO on Technology Strategy through in-depth analysis of emerging technology and market needs. He is a Bell Labs Fellow.

**Son Thai Le** (Member, IEEE) is a Researcher with Nokia Bell Labs, Murray Hill, NJ, USA. Son Thai Le has demonstrated many transmission records in reach, capacity and spectral efficiency of Nonlinear Frequency Division Multiplexed and short-reach direct detection systems. His current research interests include optical single-sideband modulation, short-reach direct detection and new signaling and architecture for 5G mobile fronthaul. In 2018, He was Awarded as “Innovator under 35 Europe” and “Innovator of the year (Germany)” by MIT Technology Review for his contributions in fiber optical communications. He was the recipient of the “Best Paper Award” prizes at the German Information Technology Association (ITG) in 2018 and at NICS in 2019.

**Sarvesh Bidkar** received the M.Tech. and Ph.D. degree in computer science and engineering from the Indian Institute of Technology Bombay, India, in 2014. He is a Researcher with the Fixed Networks Research department ,Nokia Bell Labs in Stuttgart, Germany. Prior to that, he was a Senior Research Associate with High Performance Networks Group, the University of Bristol from 2014. His research interests include resource allocation in multi-domain, multi-technology converged networks, optical network design and management as well as programmable and low-latency switching and routing. His recent work focuses on optical transport architectures for next-gen radio access networks using low-latency techniques on TDM-PON technology.

**Pascal Dom** received the master’s degree in computer sciences from VUB Brussels Free University, Belgium and the executive master’s degree in business administration (eMBA) from the University of Antwerp, Belgium. He is a Senior Product Manager with Nokia with more than 25 years telecommunications experience. He is today a Contributor to the Passive Optical Networks (PON) specifications in the area of mobile transport (X-haul). He was Awarded Distinguished Member of Technical Staff of Nokia as part of the Class of 2021.

**Ed Harstead** in the 1990s led first gen WDM PON research efforts and standardization and implementation of first gen TDM PON technologies. Ed spent most of the 2000s in DWDM transport and PON product management. Since the 2010s, he supports the Nokia CTO for Fixed Networks, with a focus on the standardization of high speed PON.

**Thomas Pfeiffer** is working with Nokia Bell Labs as Principal Architect for optical communication systems and network architectures in access, focusing in particular on converged network solutions for mobile and vertical markets. He was involved in research, standardisation and product development of optical access systems for more than a decade. His active role in this field was recognized by awarding him the Bell Labs Fellow degree and the OSA Fellow degree.