Integrated Wireless Backhaul Over Optical Access Networks

John E. Mitchell

(Invited Paper)

Abstract—**Recent technological advances and deployments are creating a new landscape in access networks, with an integration of wireless and fiber technologies a key supporting technology. In the past, a separation between those with fiber in the access networks and those with wireless networks, the relatively low data-rate requirements of backhaul and the relatively large cell sites, have all combined to keep fiber deployment low in wireless backhaul. As fiber has penetrated the access network and the latest wireless standards have demanded smaller, higher bandwidth cells, fiber connectivity has become key. Choices remain as to where the demarcation between key elements should be in the network and whether fiber should be used as just a high data-rate backhaul path or if a transition to radio-over-fiber techniques can afford benefits. This paper will explore the network options available in particular those demonstrated in recent European Union (EU) projects, how they can be integrated with existing access networks and how techniques such as radio-over-fiber can be deployed to offer increased functionality.**

Index Terms—**Microwave photonics, optical access networks, wireless standards.**

I. INTRODUCTION

MOBILE data traffic looks set to increase 1000 fold by 2020 from the level of 2010 [1]. However, it seems obvious that this increase cannot be met simply by a linear increase in capacity. As well as more bandwidth, smaller cells and increased spectral efficiency must all play a part. 3GPP release 12, due in June 2014, is likely to introduce a number of innovations which will build on existing technologies to make significant steps towards increased data rates. Technologies such as enhanced multi-antenna multiple-input multiple-output (MIMO), carrier aggregation, downlink and uplink cooperative multipoint with non-ideal backhaul, and integrated support for small cells are likely to be deployed in the relatively near-term. All of these advances require additional backhaul capacity and support ar-

guments for changes in the fundamental network architecture from a distributed to a more highly centralized network.

This paper outlines the technologies that are being proposed to integrate wireless backhaul and optical fiber networks. It outlines the key roles that optical technologies can play and identifies the challenges that the optical fiber communications community face if we are to fully support the next generation of wireless access networks.

Following this introduction, Section II explores the network architectures that are being proposed for next generation wireless access, describing the architectures considered and the rational for their use. Section III gives an overview of how optical technologies can be deployed in the radio access network (RAN). Section IV, then considers the specific optical transport requirements of the wireless front/back-haul networks proposed. How these might be integrated into optical access networks is explored in Section V, first reviewing current standards before considering a number of proposed solutions for future optical access networks. In particular, it highlights a number of EU research projects that have made developments in this area. Section VI summarizes the network configurations that are expected to be utilized, drawing on the discussions in previous section, before Section VII presents the major conclusions for future integrated wireless/optical networks. Throughout, we attempt to outline the challenges and opportunities for radio-over-fiber (RoF) to play a role in supporting emerging distributed antenna system (DAS) standards through to being a key component of a future cloud radio access network (cloud-RAN or C-RAN) enabling dynamic capacity and mobility management in a converged optical/wireless networks.

II. RADIO ACCESS ARCHITECTURES

Historically there has been a move toward decentralization of the radio-access network, moving much of the radio-related processing towards the base-station (BS) or even closer to the antenna. A traditional RAN has a BS at each cell site providing the majority of the required processing functions at layers 1, 2 and 3. This is connected, historically by coaxial cables, more recently by fiber to remote radio heads (RRHs) at a co-located mast with a fixed number of antennas, serving a number of radio sectors. The site must be provisioned for the peak load required by each sector and for a fixed set of wireless standards and frequency bands. The coverage area is also typically fixed. It is inherently limited by the interference from surrounding cells and the available power per carrier. The processing unit itself requires a significant power supply and other services such as air

conditioning, which may account as much as half of the power consumption [2].

A more recent trend has seen mobile operators reconsidering decentralization of the radio-processing resources. This follows global trends of centralization of infrastructure to create a cloud-RAN or C-RAN [2]. The deployment of a C-RAN has been proposed as a solution to the rapidly increasing demands on capacity of future wireless access standards such as long-term evolution (LTE), LTE-Advance and those being proposed under the banner of 5G. In particular, centralization is seen as a solution which addresses the loss of predictability that has been witnessed in wireless traffic as it has evolved from solely telephony services to a dominance of Internet Protocol (IP) based data services. This will continue further with the growth in machine-to-machine applications making use of the RAN. This shift, in tandem with the overall growth in traffic, has significantly increased the peak to average load ratio of BSs, leading to poor equipment utilization and low energy efficiency. The centralization of services, allows resources to be shared and allocated on a dynamic basis following traffic as it moves around the network, thereby providing load balancing between high and low demand areas [3]. In addition, it offers support to a number of techniques that have been developing which require greater coordination between BSs. This is much easier to provide when processing resources are pooled in a single location.

For some time there have been technologies that move away from the traditional network architecture of Fig. 1(a) which shows a coax connection between antenna and BS and digital backhaul. In this example, an S1 interface is shown which is the standardized interface between an LTE eNodeB and the evolved packet core is shown, but this could be the IuB interface in UTRAN (3G) or ABIS in GSM. Many current implementations distribute radio signals from a baseband unit (BBU) located at the BS to a RRH below the antenna using optical fiber as shown in Fig 1(b). Techniques applied might make use of either analogue or digital transport of the radio signals as will be discussed in Section III. C-RAN takes this a step further, as shown in Fig. 1(c), by centralizing the BBUs and increasing the range of the distribution to RRHs using optical technologies, potential making use of existing access infrastructure, as will be discussed in Section V. These techniques create a new paradigm of 'front-haul' to identify the connection from the BBU to the RRH as opposed to 'backhaul' which is from the BBU back into the core network.

The C-RAN concept creates a centralized pool of base-band processing units which allows elastic allocation of capacity to any of the cell sites within the area controlled. This centralization also provides for co-operative radio techniques, such as cooperative multipoint (CoMP), which are typically limited today by the timing and synchronisation constraints of a distributed network to be efficiently implemented. One of the champions of this technique within the operator community has been China Mobile who have been deploying trails of TD-SCDMA networks in Zhuhai City of 18 macrocell sites covering around 30 Square km. A second phase of trials is underway and linked with the current deployment of TD-LTE [4].

Although the concept is being discussed as the next big thing, it is actually a formalization of an argument put forward by the
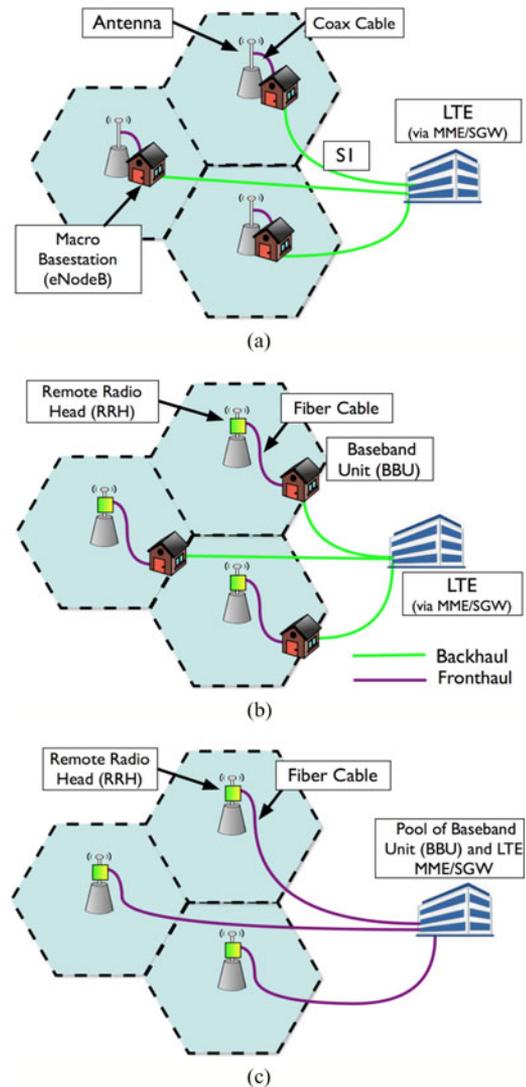
Fig. 1.   Typical wireless network implementations. a) traditional basestation architecture of macrocells. b) Distributed basestation architecture. c) Cloud radio access network architecture.

RoF community for many years; small cells with simple remote antenna units (RAUs), which are the analogue equivalent of an RRH, with fiber based backhaul and a centralized baseband processing unit. This simplifies the equipment installed at the antenna site, moving the complexity further back in the network to a centralized point. It offered all the advantages discussed above of a Cloud-RAN, well before the term 'cloud' had come into such popular use.

The development from the relatively mature technology of DASs to the emerging technology of C-RAN offers significant advantages for network operators. The justifications for such systems are well rehearsed. With a larger number of smaller cells, significant cost savings can be made by reducing the size and functionality of the equipment in the field at each site and by reducing long feeder cables between the RF front end and the antenna. Advocates have argued for many years that the concept of a 'basestation hotel' where multiple services, including support services such as air-conditioning, main and backup powering, etc., are shared can produce significant cost savings. Operational cost savings occur from the reduction in both energy

and maintenance costs, while capital cost savings come from the higher utilization of equipment and the smoother deployment path. Some examples exists, but typically only in situation were the user density is so high that traditional approaches where not viable.

The pooling of BBUs provides opportunities to implement dynamic capacity reconfigurability and a reduction in operational expenditure from centralization and consolidation of equipment. It has also been argued that this type of functionality is key in supporting advanced co-processing functions such as Heterogeneous Networks [5] and CoMP [6] which are hotly tipped to be fundamental features of next generation wireless networks. These take place in what is expected to be a huge market for high density access. It is being predicted that small cells and carrier WiFi deployments will generate nearly $350 billion of revenue from mobile data services by the end of the decade [7].

The logical conclusion of this concept is to implement a completely centralized and virtualized RAN. This type of virtualization, made popular as part of the software-defined network paradigm, makes use of the centralization that C-RAN offers to pool resources at all levels integrated with virtualization of hardware. This would allow a central controller to allocate wireless resources which may take the form of spectrum but may also be to create virtual basestation controllers (BSCs) or BBUs and/or the required network connections between them to enable cooperative working. This central location would offer, what some are terming, a multi-site/multi standard baseband unit [8]. This unit has the ability to offer processing of multiple wireless standards (potential from 2G to 4G and beyond) to geographically dispersed cell-sites. Each of which may be of a completely different configuration in terms of level of sectorization and coverage (macro, micro, pico). One example is OpenRAN [9], a proposed architecture for software defined radio access networking which could be used offer such infrastructure as a service (IaaS).

III. TECHNOLOGIES TO SUPPORT RAN

Fig. 2 shows a number of potential implementations that use optical fiber to support the deployment of RANs. Fig. 2(a) shows a traditional cell-site, containing all the radio, baseband and higher layer processing, which is connected back into the network using a baseband digital optical link. The following three configurations remote some or all of the processing to a centralized location. Fig. 2(b) is an example of full centralization of all baseband functions to a centralized pool of BBUs by transporting a digitized version of the RF signal. In such systems the backhaul makes use of baseband digital channels, such as Ethernet, to transport the down-converted and oversampled baseband I and Q streams using one of the two main standards; Common Public Radio Interface (CPRI) [10] or Open Base Station Architecture Initiative [11]. These create a high reliability connection between the radio equipment control in the central office and the radio equipment at the BS, specifying performance parameters and electrical interfaces. As will be explored in Section IV these links require relatively high date rates due to the direct, high-quality sampling of the RF waveform. One alternate network configuration to reduce this bandwidth is keep the lower
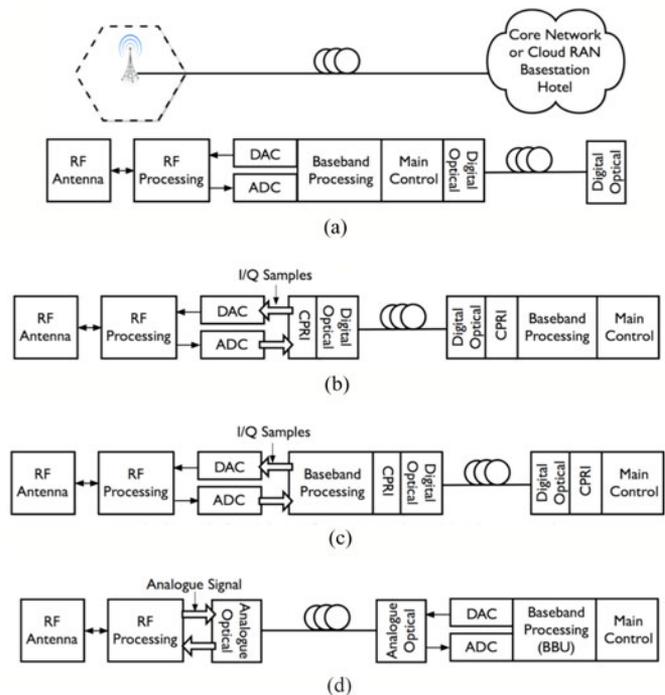
Fig. 2. Typical implementations of a) conventional macrocells, b) Digital-RoF using the CPRI interface standard with all baseband functions are centralized, c) Digital-RoF where the higher layer functions are centralized while radio and lower layer baseband functions remain at the RRH (split eNodeB), and d) Analogue RoF. DAC = digital-to-analogue converter ADC = Analogue to digital converter.

layer baseband functions at the RRH while only centralizing the higher layer baseband functions. This is often described as split eNodeB processing as shown in Fig. 2(c). Although this reduces the requirements, the trade-off is a reduction in the flexibility and adaptability of the link. Typically this separation of processing may reduce the date rate required to serve a particular site to around a tenth [8]. Systems making use of these techniques are already commercially available, for example, Alcatel-Lucent's LightRadio [12] compact RRH and Nokia-Siemens Networks' Liquid Radio [13] which also provides beam steering capabilities.

A typical RoF implementation where the link is analogue-RoF is shown in Fig. 2(d). The waveform is transported in an analogue format over optical fiber to be processed at the central site. However, the most commonly cited concerns are the inherent linearity problems and noise tolerance of analogue transmission. However, this is a relatively mature field, with over 30 years of research work in the area, including a huge body of knowledge published in the pages of this journal. However, those often involved in the design of wireless networks are far more at home in the digital domain and hence naturally look there for solutions. Despite this it is hard to overlook the main advantage presented by analogue systems which is the true transparency they offer.

For some features, a high degree of centralization is not strictly necessary. For example, CoMP functions are typically between neighbouring cells. Having said that, more centralization (which in essence means the larger the geographic area covered by a central office) still results in fewer communications links to enable intercell communication.

One key advantage of a high degree of centralization is the possibility to make available a wide bandwidth channel that can be reconfigured from the central location. It can also change the way legacy technologies can be support. For example, a band may be dynamically partitioned across technologies in response to instantaneous traffic demands. This transparent nature offers very low latency, as virtually no additional processing enters the signal chain. All of these features are very appealing to network operators. The end result is that the total equipment inventory can be scaled to be far closer to the total sum of all capacity required across all technologies. Whereas, when equipment is developed at the cell site the total inventory is the sum of the requirement at each cell. When coupled with virtualisation, significant savings are possible.

In terms of supporting emerging network configurations, however, multiplexing of multiple antennas or MIMO systems can be more challenging than digital techniques. As these systems generate multiple signals at the same frequency either multiplexing in the wavelength domain through wavelength division multiplexing (WDM), frequency translation to provide sub-carrier multiplexing (SCM) [14] or most recently, polarisation based techniques [15] are required. In terms of cost, SCM is usually preferable. Analogue techniques also offer the simplest BS configuration, despite having limitations due to nonlinear fiber effects and difficulties in implementing remote management and control functionalities due to the transparent nature of the link. However, this problem is also shared, to some degree, with digital RoF implementations.

IV. REQUIREMENTS OF WIRELESS FRONT/BACK-HAUL

This section will investigate some of the requirements that next generation networks will put on the supporting optical front/back-haul networks.

A. Capacity

For baseband transport of processed data from a wireless BS the total capacity requirement is simply the sum of the total user data available at the cell-site once all available channels are considered and including all sectors plus the control and signaling overhead. For a UMTS NodeB this will be of the order of Mbit/s, whereas for LTE eNodeB, it may reach a few hundred Mbit/s. This has allowed both point-to-point microwave links, leased lines or fiber to be viable options. The CPRI specification requires both high-speed and low-latency backhaul links, leading many to suggest that fiber is the only viable option. In the downlink, the RRH/RAU consists of basic RF processing (amplification, filtering and gain control) followed by down-conversion, digitization and multiplexing of channels (i.e., for MIMO or sectoring). This digitized signal is then transported across the network by the CPRI interface at one of the specified line rates that are multiples (1, 2, 4, 5, 8, 10, 16) of 614.4 Mbit/s [10].

Detailed knowledge of the radio channels used is required to accurately calculate the capacity required, with 1 Gbit/s per Antenna-Carrier being quoted as a rule of thumb [5] figure for a current LTE implementation. Let's take the example of a single
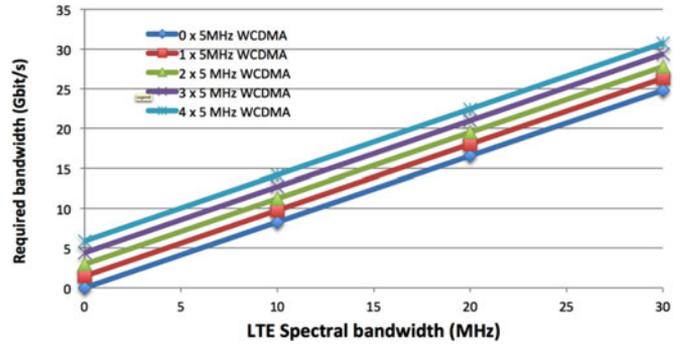
Fig. 3. Required bandwidth for each cell-site in Gbit/s for CPRI backhaul interconnections with no compression. Adapted from [3].

sector, LTE FDD cell-site with two transmit and two receive antennas, 20 MHz total bandwidth, 16-bit sampling, two times oversampling and 20% overhead. The CPRI defined line bit-rate required would be 4.9152 Gbit/s. Fig. 3, considers how the bandwidth requirement for a combined interface link with both LTE and WCDMA in a typical three sector cell-site changes with different capacity configurations. This demonstrates that for most implementations capacity beyond 10 Gbit/s is required on the uncompressed CPRI interface.

There are also other tolerances that add additional design constraints to the front/back-haul network. The links are required to operate with a maximum bit error rate of 10^{-12} (ideally without needing forward error correction to reduce latency), sub ms round trip delay (for GSM = 78 km or $\sim$380 μs), 3G = 40 km or $\sim$190 μs, LTE = 20 km or $\sim$95 μs), delay jitter in the range of 10's of *ns* and frequency jitter of $< \pm 0.002$ pm [4]. Further analysis of the capacity requirements have suggested that expansion to 100 MHz channels, which is expected in future systems, requires bit-rates in excess of 24 Gbit/s [16]. Some are even suggesting that if all the features of LTE-Advanced are enabled this may push the backhaul traffic requirement up to 100 Gbit/s per site [17].

RoF techniques on the other hand have the advantage that they do not inflate the bandwidth required by oversampling and high precision quantization. Although there are multiplexing challenges to integrate MIMO, they provide front/backhauling of considerably wider bandwidth channels using much lower optical bandwidths. There have been a number of examples of analogue transport of a wide variety of wireless standards, from early examples of W-CDMA (UMTS) [18] and WiMAX [19] to multiple wireless standards, i.e., LTE/WiMAX/UWB [20]. This work needs to continue to provide robust evidence to demonstrate that the transport of the type of multi-antenna systems being deployed is achievable.

B. Cooperative Multipoint

A new requirement of future wireless access is the need for high-speed, inter-BS communications channels. These links must provide low latency channels between BSs to enable the co-processing operations that are used to increase bandwidth by mitigating inter-cell interference. One example is cooperative or coordinated multi-point (CoMP), which is a key component within LTE and LTE-Advanced networks. It uses inter-cell

interference to extend single-cell MIMO techniques, such as multi-user MIMO, to multiple cells to significantly increase spectral efficiency [21]. This is particularly true at the cell-edge. To achieve these gains, multi-cell, joint signal processing is required in both directions. In the uplink cooperative decoding is required between two cells, whereas in the downlink coordinated joint transmission is required from two BSs. The gains that can be achieved have recently been demonstrated in field trials [22] but these trials have also shown the challenges of implementing such technologies. To achieve physical layer cooperation, high-speed and delay sensitive communications channels between BSs are required.

In an LTE deployment, there are two key channels to consider. The first is the S1 interface, which connects the newly formed BBU pool serving a cluster of RRHs back into the network to the LTE signaling gateway/mobility management entity. It provides both a user and a control interface to management functions and inter-cluster handover. The second is the X2 interface, which has grown in significance with the introduction of cooperative techniques. This interface provides interconnections between eNodeBs in an LTE network, with one of its key functions being to provide a communication channel for handover. The decentralization of the network and the lack of a radio network controller as used in UMTS/3G networks also introduced the need for load balancing over the X2 interface to provide a distributed radio resource management function. This is done through the exchange of load information between eNodeBs [23].

There are a number of possible options to support such a cooperative network based on the requirement of a communication channel between the sectorized cell-sites to jointly process the communication with the mobile entity. The traditional approach would require a dedicated link to form a high bandwidth and low latency X2 interface directly connecting the two cells. Only if this link were deployed would such cooperation be possible. As identified in [17], this has significant scaling problems if one wants to deploy such a technique across a large network. If a C-RAN type architecture is implemented, then the coordination function takes place within the pool of resources with external interfaces, as necessary, at the cluster edge. This offers significant simplification of the synchronisation needed between eNodeB's and is inherent in both digital or analogue implementations, although analogue is likely to offer slightly superior latency performance. The EU project Fibre Optic Networks for Distributed, Extendible Heterogeneous Radio Architectures and Service Provisioning (FUTON) [21] has given one of the most comprehensive demonstrations of how RoF techniques could be used to support such a cooperative RAN. It has shown that joint processing from remote RAUs carried over analogue optical fiber links are possible for typical LTE bandwidths and antenna configurations [24].

V. INTEGRATING BACKHAUL AND OPTICAL ACCESS NETWORKS

A key problem for many operators is deployment of, or access to, the optical fiber infrastructure to support mobile front or back-haul. Where they are able to provide the bandwidth, microwave point-to-point links are often favoured due to the lower deployment costs and fast provisioning. However, the bandwidth demands of future standards are stretching traditional microwave links and, as discussed above, are clearly not practical for front-haul systems using CPRI. Hence, there is considerable interest in the reuse of deployed fiber networks. With the recent growth in the deployment of optical access networks, optical fiber is now no longer only found in the core, but is almost ubiquitous and found very close to customers, exactly where it is required for small-cell access networks.

Some challenges remain before typical passive optical network (PON) deployments can be used to support the RAN. A major concern is the quality of service (QoS) provision for typical broadband customers compared to that required for mobile access. In particular, the latency and reliability offered. Such requirements are not uncommon for business providers and so can be accommodated but require careful engineering which is not always present. In this section, we explore how a RAN infrastructure may be integrated with current and future optical access network standards.

A. Digital Baseband

The use of PONs for mobile backhaul of baseband data from traditional BSs has been investigated [25], [26] and trialed for a number of current standards. Although the capacity requirements are well within the capabilities of PON, asymmetric delay characteristics [26] causes performance concerns which, in ethernet-PON (EPON) requires modification of the scheduler to prioritize backhaul traffic. To meet QoS demands on availability, consideration must also be given to full protection strategies which are typically not implemented in PONs [27].

Due to the data rates required for Digital-RoF, discussed in Section IV, it seems unlikely that significant integration of this technology with operational E-PON (1 Gbit/s) or G-PON (2.5 Gbit/s) networks will occur, as even a fairly small BS will quickly use up the capacity available. The development of 10 Gbit/s PON systems within the NG-PON [28] and 10 G-EPON standards [29] offer increased bandwidth better suited to supporting Digital-RoF. These new standards include the possibility of long-reach operation of up to 60 or 100 km which will result in significant timing challenges due to increased delay. It has already been shown that the reach of standard WiFi transported over fiber is limited to less than 10 km due to the inherent fiber delay [30]. Although most cellular standards are more delay tolerant than WiFi, we have also seen that the introduction of techniques such as CoMP place much stricter requirements on delay and delay jitter.

As new standards emerge that offer even greater bandwidth it is possible that the integrated transport of DRoF systems with high capacity baseband services may be possible. One technique being investigated for next generation PONs is the Orthogonal Frequency Division Multiple Access—Passive Optical Networks (OFDMA-PON), which uses OFDM as a technique to segregate high-bandwidth channels. This technique allows a number of services to be shared within a PON including, as

demonstrated in the EU Framework 7 (FP7) project ACCOR-DANCE which showed the transport of 16 CPRI channels [31] over their PON architecture. It is always possible that direct point-to-point links could be utilized to support remote-radio heads especially as data-networking technologies such as 10 G Ethernet are now becoming commodity items. This may be an attractive option for many operators.

B. Wavelength Overlay in Current Standards

Techniques to enable the integration of wireless transport into optical access networks has been considered within a number of projects such as:

- ACCORDANCE [32] where integrated wired and wireless standards are delivery over an OFDMA-PON.
- FIVER [20] which considered triple-play LTE, WiMAX, Ultra-wideband (UWB) as well as transmissions at 60 GHz.
- BONE [33] which covered a wide range of bench-top network combinations including a number of studies on the distribution of LTE and WiMAX.
- ISIS [34] a range of systems from UWB to WiMAX and 3G standards.
- FUTON [21] which demonstrated a complete network transporting LTE and enabling centralized CoMP.
- e-Photon/One [25] which produced trials of UMTS (3G) transport over GPON.
- WiSePON [35] and others [36], [37].

Considering analogue transport methods, a number of challenges occur when RoF channels are overlaid on baseband PON wavelengths. The most difficult of these is how to address the individual BSs connected to the PON when the physical architecture is broadcast and select [38]. Solutions involve either wavelength or RF mapping techniques to route wireless channels to specific end points. As only broad wavelength selective elements are available in most cases this requires additional optical infrastructure in the PON which is typically not desirable.

The generic set of options for multi-wavelength networks were demonstrated in [38] where systems where categorized depending on the method and degree of wavelength selectability they afforded. The use of a sub-set of the wavelengths, provides a basic backhaul functionality, however, the availability of a full-duplex, WDM overlay, capable of delivering RoF services coupled with a centralized pool of baseband processing units provides a degree of reconfigurability not currently available. This has the potential to allow capacity to be dynamically distributed to end points depending on user activity. Although, possible in digital-RoF systems, the ease of transporting broader bandwidths in analogue-RoF provides greater flexibility and ease of reconfiguration of resource provision to enable dynamic capacity allocation.

The most recent standard for optical access was agreed at the April 2012 full service access network group meeting. It concluded that time-wavelength division multiplexing-PON (TWDM-PON) was to be the primary solution for Next Generation-PON2 (NG-PON2). This is the first PON standard to go beyond 10 Gbit/s total bandwidth and the first to use the wavelength domain for capacity increase (it is already being used for
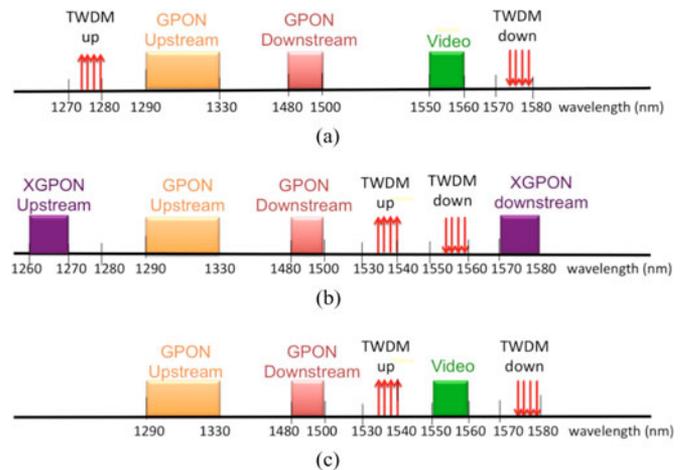
Fig. 4. Proposed TWDM-PON wavelength bands. a) with reuse of existing NG = PON bands, b) use of the C-band if XG-PON bands used but no video overlay present, c) use of C and L bands if video overlay present but no XG-PON [39].

duplex operation in single-fiber-working systems and for overlay services such as video). The full system rate of 40 Gbit/s is created by 4×10 Gbit/s WDM channels that can be further divided in time to each customer [39]. Originally, it was hinted that NG-PON2 might also be the first standard to move away from a completely passive and non-wavelength selective optical distribution network (ODN). However, this did not materialize. Although true wavelength division multiplexing (WDM-PON) and stacked XG-PON solutions with array-waveguide gratings in the network (AWGs) where proposed the eventual solution maintains simplicity in the network at the expense of tunable wavelength selectivity at the customer node [40].

One very important statement for the integration of wireless overlays was present in the announcement. "The agreed upon approach is a time and wavelength division multiplexed (TWDM) solution with optional wavelength division multiplexed (WDM) overlay extensions designed for the next generation PON." [40]. This provides options for the delivery of wireless front/backhaul services in an NG-PON2 network by means of wavelength extension as well as by making use of the digital baseband. To maintain backwards interoperability with existing PON standards a range of wavelength allocations are proposed depending on the legacy systems to be supported. The three main options are shown in Fig. 4.

C. Wavelength Overlay in Future Systems

Most recent studies have considered integration with WDM-PON architectures, where multiple wavelengths and wavelength selectivity already exist. WDM-PON is attractive, as it provides a substantial reduction in the amount of fibers used, while providing a number of high-bit-rate channels. In addition, ultra-dense WDM-PON (UDWDM-PON) systems have proposed as many as 1000 wavelengths [41] with extensions now boasting channel rates of 10 Gbit/s [42]. This work was one of the first excursions into a new area of PON research, studying the use of coherent receiver technologies in PONs. Although many

originally dismissed this option on cost grounds due to the requirement for a relatively narrow linewidth tuneable laser in the customer equipment, it is gaining momentum. Originally championed by NSN [41], projects such as CRITICAL [42], [43] and more recently COCONUT [44] are demonstrating impressive results.

The main interest for the RAN comes from the very high number of assignable wavelengths available. This allows broad addressing of a number of RAUs or RRHs from the optical access network. A key advantage of coherent techniques comes from the power budget gains provided by the use of coherent reception. In a PON, one of the main limitations comes from the power splitting that forms the core of the ODN architecture. In all short reach deployments this limits performance, while in most long reach systems, amplifiers are necessary to overcome the increased distance [45]. The additional gain provided by coherent reception means that systems with link budgets beyond 40 dB are possible. A second key advantage is that the process of coherent reception inherently provides wavelength selectivity at the receiver without the need for tuneable filters at the receiver or AWGs in the network, which are necessary in most WDM-PON implementations. This is of huge significance and provides those considering optical distribution of radio signals a number of opportunities due to the flexibility in addressing and bandwidth allocation. For digital transport, the techniques required are fairly clear. For analogue transport, it is less obvious. The digital signal processing that enabled coherent systems to be implemented without locked, optical frequency sources mean that the analogue transport of microwave wireless signals (for example, 800 MHz to 3 GHz) is difficult. However, development of low-cost tuneable laser technology for coherent access provides an opportunity for RoF techniques. It is possible to use this technology in heterodyning techniques which are capable of generating RF carriers at any desired frequency although, typically this would be used in the 60 GHz and E-band regions (70, 80, 90 GHz commonly). Here there are wide-bandwidth channels, with the optical techniques enabling frequency translate from IF or bandband to millimeter wave bands. This is the focus on a new EU FP7 project IPHOBAC-NG [46].

VI. POTENTIAL SOLUTIONS

This paper has aimed to identify a number of different techniques whereby integration of optical transport into the RAN provides additional functionality. In this section, aim to draw this together and present my personal view of what a network that leverages these techniques and technologies might look like. Fig. 5 shows how a number of different PON architectures could be used to deliver wireless channels over both standard and WDM-PON architectures.

In the short term, and in particular to support smaller cells, deployed GPON (less so EPON networks due to timing and QoS constraints) may be used to provide front-haul services using Digital Radio Over Fiber over the CPRI interface as well as analogue transport from RAUs. This will continue the trends of DASs which are currently being deployed, predominantly in high coverage density areas. In addition, deployed PONs will

be used to provide baseband transport for traditional BSs. This will be far more prevalent for smaller cells than for larger BSs where backhaul will be through dedicated optical links (or will continue to be microwave) due to the operation and maintenance functions required.

The most radical changes will start to appear as future releases of LTE begin to be deployed. The wide variability of load between cells will require operators to consider centralized network functions to make cost effective use of baseband resources. This will be spurred on by the further difficulties inherent in the distribution of coordinated functionality across a network, which will be necessary to provide increases in capacity. Deployments are likely to be on the basis of clusters of high capacity / high density areas where the pressures, as well as the opportunities, for centralization and virtualisation of services are greatest. These would typically service areas of up to 5–10 km.

The million dollar question is "What technology will be used to support C-RAN?". Three key options were outlined in Fig. 2. Early deployments may well choose the partially centralized approach, although it is likely that this will not be satisfactory longer term due to the restrictions it places on how adaptable the network can be. Full centralization is likely to win out with some opting to move straight to this technology. Whether the links are digital or analogue RoF will depend heavily on the progress in the next few years of each technology. Digital has the advantage of already being well understood by the mobile network operators, forming the core of their backhaul networks. There is still work to be done on developing suitable compression algorithms to reduce the bandwidth from the excessive, uncompressed levels seen in some early examples, but work in this area is already underway [47]. In addition, with the cost of digital transceivers of the required bit rate likely to reach commodity levels in the next few years, many will be drawn to this solution.

Analogue transmission has always had its sceptics, but in this situation the ultimate flexibility it provides may prove to be compelling. To gain the support of the mobile access community, clear demonstrations of the performance over broad bandwidths and a range of standards are necessary. There are many examples of such work available already, but the variation in their experimental construction and typical concentration at the physical layer, mean that cross comparison between demonstrations is difficult. However, such demonstrations are necessary to enable operators to gain a complete picture of the overall performance. This is needed to dispel concerns over noise and linearity, with a good example of this type of work being [48].

There is also a need for a conclusive demonstration of how multiplexing in large antenna count cells will occur. In a three sector cell with 4×4 MIMO, there will be 12 carriers all of the same frequency and of 10 or 20 MHz bandwidth in the current state-of-the-art, and perhaps up to 100 MHz in the near future. How will RoF systems multiplex these? Certainly sub-carrier multiplexing schemes look favourable, and have already been demonstrated [14], [50], but again, some still need convincing that the integration of these techniques does not raise cost and linearity concerns.
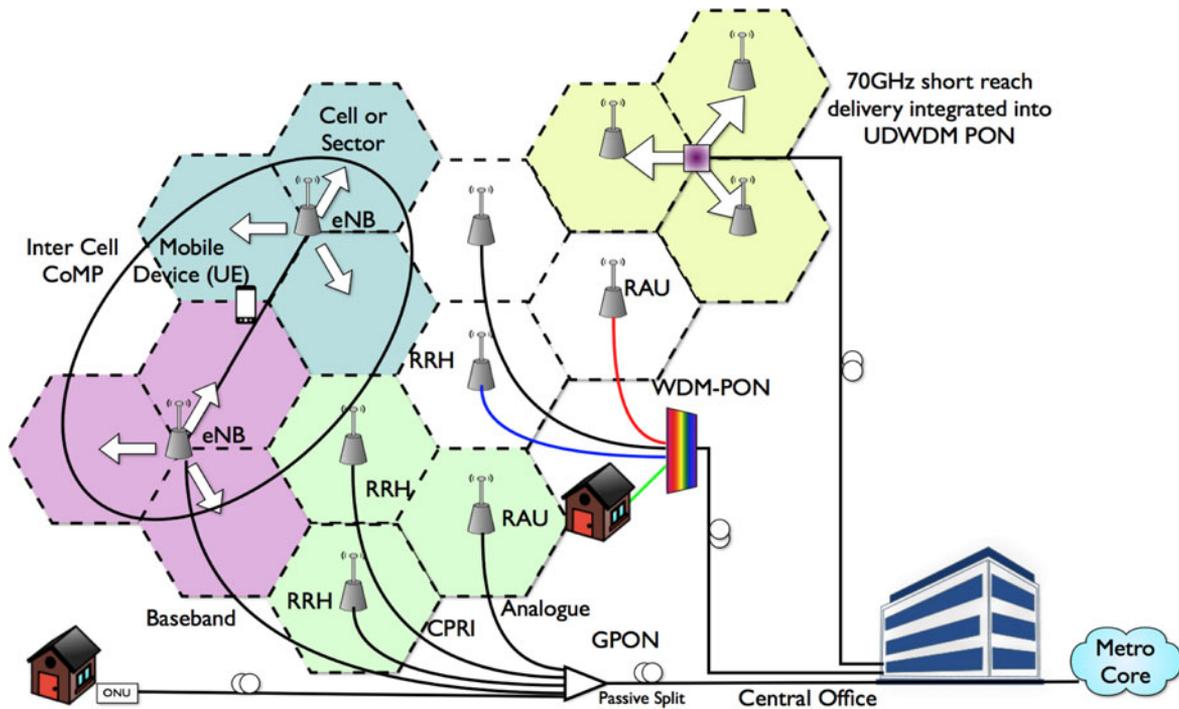
Fig. 5.   Possible implementation of radio-over-PON, including WDM-PON with wavelengths dedicated to basestations, CPRI over NG-PON or baseband data over PON to UMTS eNodeBs (eNB). It also shows how inter cell CoMP operates between two connected cells. AWG = Arrayed Waveguide Grating.

A final area where there maybe significant development is in the final few 10 or 100 s of meters used to deliver radio signals to the RRH or RAU in a small cell environment. This is shown in the right most cell in Fig. 5. The last drop, to a customer or to a cell, is always of critical cost concern and one where fiber deployment can be costly or difficult. One option is to use high-bandwidth wireless techniques, which to be highly cost effective should be integrated with the optical access network. A large amount of current academic research is investigating the integration of current and emerging PON standards with millimeter-wave techniques. These are typically in either the 60 GHz un-licensed bands where around 7 GHz of bandwidth is available or the bands at 70, 80 or 90 GHz, often termed the E-band, where 4.75 or 5 GHz of bandwidth is available. Although these could also be used for the wireless channel to the user, they will, more likely, be used as high-bandwidth, short-reach backhaul from pico/micro-cell sites to aggregation points where fiber drops are not cost effective or to speed deployment as capacity grows. Additionally, there is also interest in the 40 GHz bands, such as the MIWEBA project [49], [50] which is considering the use of this band to provide an overlay of mm-wave cells on top of the current cellular network.

Data rates of 12.5 Gbit/s were achieved within the European IPHOBAC project with wireless transmission over 50 m using a photonic wireless system operating in the 60 GHz band in 2008 [51]. This was followed in 2009 by a world record 27 Gbit/s wireless transmission within in the 60 GHz band using a photonic wireless system and a 16-QAM OFDM modulation format with a spectral efficiency close to 4 bit/s/Hz [52]. A new extension of this project IPHOBAC-NG [46] aims integrate these high-bandwidth solutions into coherent UDWDM-PONs

to provide a flexible and efficient option for mobile back/front-haul. This will allow fast and efficient deployment of the RAN in virtually all network scenarios.

VII. CONCLUSION

The concept of simple, RAUs, which has been championed by the RoF community for many years, is now becoming a reality and a key component of the next generation of wireless networks. However, transport of digitized RF pervades over analogue techniques typically favored by proponents of RoF. Although digital transmission removes linearity concerns in the optical devices and simplifies some control and management functions, the data-rates required quickly become excessive. In addition, they do not enable the full flexibility and dynamic capacity allocation potential of analogue techniques. With the development of WDM-PON technologies the ability to overlay multiple channels, mixing baseband and RF transmission becomes possible without upgrades to the optical infrastructure. This provides great opportunity for RoF techniques to see widespread deployment beyond the niche applications in which they are more typically found, if a compelling and well evidenced case for their additional benefits can be made.

REFERENCES

[1] CISCO VNI, Global Mobile Data Traffic Forecast. (2013, Feb.) [Online]. Available: www.cisco.com

[2] China Mobile Research Insititute, C-RAN: The road towards green ran. (2011, Oct.), [Online] Available: http://labs.chinamobile.com/cran/wp-content/uploads/CRAN_white_paper_v2_5_EN.pdf

[3] D. Bojic, E. Sasaki, N. Cvijetic, W. Ting, J. Kuno, J. Lessmann, S. Schmid, H. Ishii, and S. Nakamura, "Advanced wireless and optical technologies for small-cell mobile backhaul with dynamic software-defined management," IEEE Commun. Mag., vol. 51, no. 9, pp. 86–93, Sep. 2013.

[4] C. L. I , "Optical networks enabled C-RAN Fronthaul," presented at the IEEE ICC Workshop Optical-Wireless Integrated Technologies for Systems and Networks, Budapest, Hungary, Jun. 2013.

[5] S. Dahlfort and K. Laraqui, "Exploring the antenna lambda connection," presented at the Optical Fiber Communication Conf. Exposition, Los Angeles, CA, USA, 2012, paper NTh4E.5.

[6] R. Irmer, H. Droste, P. Marsch, S. Brueck, H. –P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," IEEE Commun. Mag., vol. 49, no. 2, pp. 102–111, Feb. 2011.

[7] The HetNet Bible (Small Cells and Carrier WiFi) - Opportunities, Challenges, Strategies and Forecasts: 2013–2020 – With an Evaluation of DAS & Cloud RAN. SNS Research, Dubai, UAE.

[8] B. Haberland, F. Derakhshan, H. Grob-Lipski, R. Klostsche, W. Rhem, P. Schefczik, and M. Soeliner, "Radio base station in the cloud," Bell Labs Techn. J., vol. 18, no. 1, pp. 129–152, 2013.

[9] M. Yang, Y. Li, D. Jin, L. Su, S. Ma, and L. Zeng, "OpenRAN: A software-defined ran architecture via virtualization," in Proc. ACM SIGCOMM Conf., 2013, pp. 549–550.

[10] CPRI Specification V4.2. (2010). [Online]. Available: http://www.cpri.info/spec.html

[11] OBSAI Specification V4.2. (2010). [Online]. Available: http://www.obsai.com

[12] Alcatel-Lucent Techzine, lightRadio Network: A New Wireless Experience, (2012, Feb.) [Online]. Available: http://www2.alcatel-lucent.com/techzine/lightradio-network-a-new-wireless-experience/

[13] Nokia-Siemens Networks, Liquid Radio, White Paper. (2013). [Online]. Available: nsn.com/system/files/document/liquid_radio_white_paper_280611.pdf

[14] C. P. Liu and A. J. Seeds, "Transmission of wireless MIMO-type signals over a single optical fiber without WDM," IEEE Trans. Microw. Theory Techn., vol. 58, no. 11, pp. 3094–3102, Nov. 2010.

[15] M. Morant, R. Llorente, and J. Prat, "LTE advanced carrier aggregation supporting fully standard 3GPP MIMO by optical polarization multiplexing," presented at the Optical Fiber Communication Conf., San Francisco, CA, USA, 2014, paper M3D.2.

[16] D. Wake, S. Pato, J. Pedro, E. Lopez, N. Gomes, and P. Monteiro, "A comparison of remote radio head optical transmission technologies for next generation wireless systems," in Proc. IEEE Photon. Soc. Annu. Meeting, Oct. 2009, pp. 442–443.

[17] V. Jungnickel, K. Manolakis, S. Jaeckel, M. Lossow, P. Farkas, M. Schlosser, and V. Braun, "Backhaul requirements for inter-site co-operation in heterogeneous LTE-advanced networks," in Proc. IEEE Int. Workshop Opt.-Wireless Integr. Technol. Syst. Netw., Jun. 2013, pp. 905–910.

[18] D. Wake and R. E. Schuh, "Measurement and simulation of W-CDMA signal transmission over optical fibre," IEE Electron. Letts., vol. 36, no. 10, pp. 901–902, May 2000.

[19] J. E. Mitchell, "Performance of OFDM at 5.8 GHz using radio over fibre link," IEE Electron. Letts., vol. 40, no. 21, pp. 1353–1354, Oct. 2004.

[20] R. Llorente, M. Morant, T. Quinlan, M. Medina, and S. Walker, "Optical architectures evaluation for triple-play distribution in FIVER project," in Proc. Future Netw. Summit, 2011, pp. 1–8.

[21] F. Diehm, J. Holfeld, G. Fettweis, N. J. Gomes, D. Wake, A. Nkansah, and E. L. Casariego, "The FUTON prototype: Broadband communication through coordinated multi-point using a novel integrated optical/wireless architecture," in Proc. IEEE GLOBECOM Workshops, 2010, pp. 757–762.

[22] P. Marsch and G. Fettweis, "Static clustering for cooperative multi-point (CoMP) in mobile communications," presented at the IEEE ICC Workshop Optical-Wireless Integrated Technologies for Systems and Networks, Budapest, Hungary, Jun. 2013.

[23] S. Sesia, I. Toufik, and M. Baker, LTE - The UMTS Long Term Evolution: From Theory to Practice. New York, NY, USA: Wiley, 2009.

[24] F. Diehm, P. Marsch, and G. Fettweis, "The FUTON prototype: Proof of concept for coordinated multi-point in conjunction with a novel integrated wireless/optical architecture," in Proc. IEEE Wireless Commun. Netw. Conf. Workshops, 2010, pp. 1–4.

[25] H. Le Bras and M. Moignard, "Distribution of 3G base stations on passive optical network architecture," in Proc. Int. Topical Meeting Microw. Photon., 2006, pp. 1–4.

[26] E. Mallette, "Mobile Backhaul for PON: A case study," presented at the Nat. Opt. Fiber Eng. Conf., Los Angeles, CA, USA, 2012, paper NTh4E.4.

[27] K. M. Maamoun and H. T. Mouftah, "Survivability models for radio-over-fiber passive optical networks (RoF-PON)/PON," in Proc. 7th Int. Comput. Eng. Conf., 2011, pp. 13–18.

[28] J. I. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey, and S. Rodrigues, "Next-generation PON—Part I: Technology roadmap and general requirements," IEEE Commun. Mag., vol. 47, no. 11, pp. 43–49, Nov. 2009.

[29] IEEE Standard for Ethernet – Amendment 1: Physical Layer Specifications and Management Parameters for 10Gb / s Passive Optical Networks, IEEE Std 802.3av-2009, 2009.

[30] B. Kalantari-Sabet, M. Mjeku, N. J. Gomes, and J. E. Mitchell, "Performance impairments in single-mode radio-over-fiber systems due to MAC constraints," J. Lightw. Technol., vol. 26, no. 15, pp. 2540–2548, Aug. 2008.

[31] M. Milosavljevic, P. Kourtessis, and J. Senior, "Wireless convergence over next generation OFDMA-PONs," presented at the OSA Advanced Photonics, Toronto, ON, Canada, 2011, paper ATuB3.

[32] K. Kanonakis, I. Tomkos, T. Pfeiffer, J. Prat, and P. Kourtessis, "ACCORDANCE: A novel OFDMA-PON paradigm for ultra-high capacity converged wireline-wireless access networks," presented at the 12th Int. Conf. Transparent Optical Networks, Munich, Germany, 2010, paper Tu.A1.2.

[33] M. Milosavljevic, M. P. Thakur, P. Kourtessis, J. E. Mitchell, and J. M. Senior, "Demonstration of wireless backhauling over long-reach PONs," J. Lightw. Technol., vol. 30, no. 5, pp. 811–817, Mar. 2012.

[34] N. J. Gomes, M. Morant, A. Alphones, B. Cabon, J. E. Mitchell, C. Lethien, M. Csornyei, A. Stohr, and S. Iezekiel, "Radio-over-fiber transport for the support of wireless broadband services [Invited]," IEEE/OSA J. Opt. Commun. Netw., vol. 8, no. 2, pp. 156–178, Feb. 2009.

[35] G. Kalfas, S. Markou, D. Tsiokos, C. Verikoukis, and N. Pleros, "Very high throughput 60 GHz wireless enterprise networks over GPON infrastructure," presented at the IEEE ICC Workshop Optical-Wireless Integrated Technologies for Systems and Networks, Budapest, Hungary, Jun. 2013.

[36] N. Cvijetic, A. Tanaka, M. Cvijetic, Y. K Huang, E. Ip, Y. Shao, and T. Wang, "Novel optical access and digital processing architectures for future mobile backhaul," J. Lightw. Technol., vol. 31, no. 4, pp. 621–627, Feb. 2013.

[37] G. K. Chang, A. Chowdhury, Z. Jia, H. C. Chien, M. F Huang, J. Yu, and G. Ellinas, "Key technologies of WDM-PON for future converged optical broadband access networks," IEEE/OSA J. Opt. Commun. Netw., vol. 1, no. 4, pp. C35–C50, Sep. 2009.

[38] J. C. Attard and J. E. Mitchell, "Optical network architectures for dynamic reconfiguration of full duplex, multiwavelength, radio over fiber," OSA J. Opt. Netw., vol. 5, pp. 435–444, Jun. 2006.

[39] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time- and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation PON Stage 2 (NG-PON2)," J. Lightw. Technol., vol. 31, no. 4, pp. 587–593, Feb. 2013.

[40] FSAN News, (2012, Jul. 16). [Online] Available: http://www.fsan.org/news/.

[41] H. Rohde, S. Smolorz, E. Gottwald, and K. Kloppe, "Next generation optical access: 1 Gbit/s for everyone," presented at the 35th European Conf. Optical Communication, Vienna, Austria, 2009, paper 10.5.5.

[42] D. Lavery, M. Ionescu, S. Makovejs, E. Torrengo, and S. J. Savory, "A long-reach ultra-dense 10 Gbit/s WDM-PON using a digital coherent receiver," Opt. Exp., vol. 18, no. 25, pp. 25855–25860, Dec. 2010.

[43] D. Lavery, R. Maher, D. S. Millar, B. C. Thomsen, P. Bayvel, and S. J. Savory, "Digital Coherent Receivers for Long-Reach Optical Access Networks," J. Lightw. Technol., vol. 31, no. 4, pp. 609–620, Feb. 15, 2013.

[44] J. Prat, M. Angelou, C. Kazmierski, R. Pous, M. Presi, A. Rafel, G. Valllosera, I. Tomkos, and E. Ciaramella, "Towards ultra-dense wavelength-to-the-user: The approach of the COCONUT project," presented at the 15th Int. Conf. Transparent Optical Networks, Cartagena, Colombia, 2013.

[45] D. P. Shea and J. E. Mitchell, "Long-reach optical access technologies," *IEEE Netw.*, vol. 21, no. 5, pp. 5–11, Sep./Oct. 2007.

[46] IPHOBAC-NG Project. (May 14, 2014). [Online]. Available: http://www.ist-iphobac.org/ng/

[47] A. Lometti, C. Colombo, S. Frigerio, and V. Sestito, "Network architectures for CPRI backhauling," presented at the 14th Int. Conf. Transparent Optical Networks, Coventry, England, 2012.

[48] D. Wake, A. Nkansah, and N. J. Gomes, "Radio over fiber link design for next generation wireless systems," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2456–2464, Aug. 2010.

[49] MIWEBA Project. (May 14, 2014). [Online]. Available: http://www.miweba.eu

[50] W. Keusgen, "Mobile millimeter-wave access: Opportunities, challenges concepts," presented at the International Workshop Cloud Cooperated Heterogeneous Networks, Osaka, Japan, 2013.

[51] A. Stöhr, A. Akrout, R. Buss, B. Charbonnier, F. Van Dijk, A. Enard, S. Fedderwitz, D. Jaeger, M. Huchard, F. Lecoche, J. Marti, R. Sambaraju, A. Steffan, A. Umbach, and M. Weiss, "60 GHz radio-over-fibre technologies for broadband wireless services," *OSA J. Opt. Netw.*, vol. 8, no. 5, pp. 471–487, May 2009.

[52] M. Weiß, F. Lecoche, A. Stöhr, and B. Charbonnier, "27 Gbit/s photonic wireless 60 GHz transmission system using 16-QAM OFDM," presented at the Int. Topical Meeting Microwave Photonics, 2009, Post Deadline paper.

John E. Mitchell (M'00–SM'12) received the B.Eng. degree in electronic and electrical engineering from the Department of Electronic Engineering, University College London (UCL), London, U.K., in 1996 and the Ph.D. degree in electrical engineering, also from UCL, in 2000.

He became a Lecturer with the Department of Electronic and Electrical Engineering, UCL, in 2000, becoming a Senior Lecturer in 2006. He was the Director of the IGDP Communications for Industry programme and from 2010 to 2012 was the Postgraduate Tutor (Taught) for the department. Since April 2012, he has been on secondment to the UCL Engineering Faculty as the Director of the Integrated Engineering Programme, a cross-faculty curriculum review of the undergraduate programmes. His research is focused on optical and wireless access systems, considering optical fiber access, millimeter-wave radio access, as well as systems that combine these two areas, specifically to support mobile front/back haul systems. This work has been funded by the U.K. Engineering and Physical Sciences Research Council, the European Union (FP7, Marie-Curie), the U.K. Technology Strategy Board and industry (including BT and SELEX ES). The outputs of this work have been published widely, including as an invited speaker at a number of major international conferences.

Dr. Mitchell is a Chartered Engineer, fellow of the Institution of Engineering and Technology, and a member of the IEEE PHOTONICS, COMMUNICATIONS, AND EDUCATION SOCIETIES.