Radio over Fiber in 5G and 6G Networks

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Abstract

Throughout the years, extensive research has been made on Radio over Fiber (RoF) technologies, due to the high impact it has in the field of scientific and business technology domains. In this document we are getting involved with the RoF technology regarding 5G and 6G networks because of the fact that emerging wireless communication networks provide increased opportunities for photonic technologies to play a prominent role in the realization of the next generation integrated wireless networks. Starting with the differences and the potentials of each analog and digital signal transport schemes over RoF. Thereafter, we touch on the fact that there's a growing interest and research at the 60GHz frequency region and we recommend some transmission schemes, that could be successfully real-life simulated. Furthermore, we point out the fact that lately, an increasing number of mobile network operators are replacing the traditional decentralized network's structure with the cloud radio access network (C-RAN) approach and we also get familiar with the key elements of Converged Fiber-Wireless Access Networks and millimeter-wave (MMW) technologies. Combining all the aforementioned knowledge, we introduce a new distributed architecture, designed to meet the requirements of the future 5G and 6G wireless communication networks, known as cloud RoF access system. In this document we display the fundamental structure and the benefits of the latter technology, but also we highlight some of the challenges, which are emerging by the deployment of the proposed architecture of cloud RoF access systems. While we try to understand better the C-RAN approach, we introduce the Common Public Radio Interface (CPRI) and finally we consider how DAS behaves over RoF technology.

1 Introduction

Today the capabilities of wireless networks are progressing more rapidly than ever before, in order to meet the increased users' demands of multimedia and cloud services. The amount of users that are connected to 5G cellular networks is daily increasing globally, while lots of research on future high performance networks, as 6G network and its' features, is being happening. Throughout the years there is an exponential increase of the number of mobile subscribers, with an increasing demand of broadband services and an unprecedented demand for wireless access to high-speed data communications, resulting to a sustained pressure on mobile networks' provided capacity. RoF technologies have the potential to significantly impact the realization of converged optical/wireless networks, for wireless systems operating both at MMW and terahertz-wave (THzW) frequencies. Fiber-optic remoting of radio signals has a well established use in a diversity of wireless networks, including indoor/in-building distributed antenna systems and outdoor cellular networks, creating a reliable service for both fixed and mobile users. Over the years, different operators have proposed a number of multifarious schemes, trying to dominate in the battle of future communication networks. An emerging distributed architecture, the so-called Cloud RoF access systems, seems to fulfill all the requirements of 5G and 6G cellular technology.

2 RoF Signal Transport Schemes

RoF technology involves the use of optical components and techniques to allocate radio frequency (RF) signals from the central office (CO) to the base station (BS). Thus, RoF makes it possible to centralize the RF signal processing function in one shared location, with use of single mode optical fiber that has a very low signal loss to distribute the RF signals to the BSs.

Both analog and digital signals can use the RoF signal transport scheme, with each technique having certain advantages and disadvantages. In Figures 1 and 2 there is a portrayal of the two main implementations of a fiber optic antenna remoting link for transmission of radio signals in a converged optical/wireless network architecture.

Table 1 explains the acronyms of both fig. 1 and 2.

In Figure 1 the fiber optic links between the remotely located antenna unit (BS) and a central office (CO) are realized as analog fiber optic links. In the downlink, in which the route of the radio signal is from the CO to the remote antenna site, the wireless digital data is first modulated into an RF carrier signal with a frequency f_c, corresponding to the wireless frequency, which is afterwords modulated into an optical carrier via an E-O conversion process.

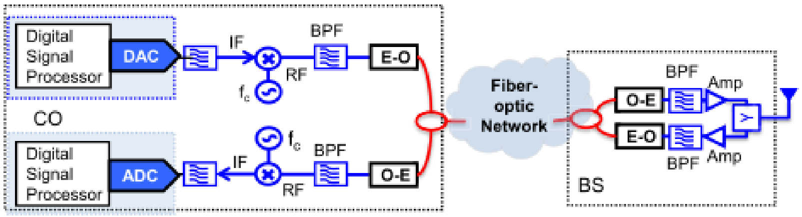

Figure 1: RoF signal transport between an antenna BS and CO using analog fiber optic links

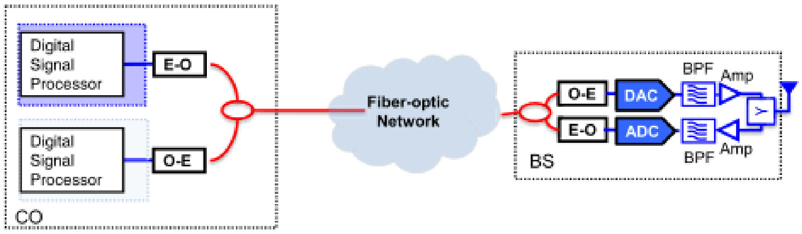

Figure 2: RoF signal transport between an antenna BS and CO using digitized fiber optic links

Table 1: Parameters Used in Figures 1, 2

Parameter Acronym	Parameter Name
IF	Intermediate Frequency
$E-O$	$Electrical-to-Optical$
$O-E$	$Optical-to-Electrical$
DAC	$Digital-to-Analog$ Converter
ADC	$Analog-to-Digital$ Converter
BPF	BandPass Filter
Amp	Amplifier

At the BS, the optical signal is photodetected, by an O-E conversion, is amplified and then is directed to the antenna for wireless transmission. An equivalent procedure takes place for the uplink, which is the path of the wireless network, with analog fiber optic links, to the radio signals from the BS to the CO.

Figure 2 represents an alternative to the analog approach, regarding the RoF signal transport scheme. In this RF fiber optic link configuration, the wireless carrier RF signal is first digitized prior to the transportation over the optical link. The digitization of RF signals produces a sampled digital signal in serial form that can be used to directly modulate a semiconductor laser, transmitted over the fiber optic link, and then detected like any other digital information.

The principal benefit of the analog RoF signal transport scheme is the potential to significantly reduce the complexity of the remote antenna site hardware. This is because of the fact that it only requires O-E conversion and RF amplification, while also enabling centralized control and management of the wireless signal. This is a significant benefit for the realizations of fiber distributed MMW and THzW wireless systems, which inherently require the deployment of multitude of antenna units. As the wireless carrier frequency increases however, the deleterious impact of fiber chromatic dispersion on the photodetected signal power becomes more pronounced.

Nevertheless, the transmission of digitized RF signals over fiber can be a viable alternative to analog RoF signal transmission, for realizing converged optical/wireless networks, since it can take advantage of the improved performance of digital optical links. It is a fact that linearity plays an important role in the achievable system dynamic range, in a typical wireless network with multiple RF carriers. Non-linearity of the optical devices used to convert between the microwave and optical domains can dramatically limit the performance of the analog RoF link. It is commonly known that the dynamic range in the analog link decreases steadily with the length of the fiber link. On the contrary, the digitized radio-over-fiber link is able to maintain a constant dynamic range until the transmission distance reaches a certain length, at which occurs a sharply roll off due to the possibility of synchronization loss arising from the receiver's particular sensitivity and clock recovery threshold.

Despite the fact that the capabilities of the ADC/DAC technology of a digitized fiber optic link are the ones that plays the ultimate role to determine the achievable link performance, the transportation of digitized radio-over fiber signal offers a distinct advantage in comparison with analog fiber links. Even though the ADC sampling rates are capable of approaching several tens of Gigasamples/second, the signal-to-noise (SNR) is limited. In addition to that, when having higher sampling frequencies, the jitter requirements for achieving adequate resolution are quite challenging («1ps). In order to relax the constrains on the required ADC/DAC performance in these systems, the approach of bandpass sampling is a solution with a lot of potential of enabling much lower sampling rate. In this approach, its sampling rate is more comparable to the wireless information bandwidth rather than the wireless carrier frequency itself.

A significantly important detail of an ADC designed for bandpass sampling, is that it must be able to effectively operate on the highest frequency component of the bandpass modulated signal while performing the sampling function at a sampling rate greater than or equal to twice the message bandwidth. The benefit of bandpass sampling is that many replicas of its signal can be found with their center frequencies aligned with integer multiples of the sampling frequency. These replicas in frequency are called Nyquist zones. When selecting a Nyquist zone, we provide either the frequency down converted or the original bandpass RF carrier modulated signal. Despite the fact that the higher frequency Nyquist zones have the downside of suffering from frequency roll-off associated with the DAC, it is possible to reconstruct the signal at the original frequency, if the signal is once again passed through a suitable DAC with an appropriate frequency response. Additionally, the bandpass sampling technique is independent of the type of modulation scheme of the wireless carrier signal modulated data.

During the RF signal digitization process using bandpass sampling, aliasing of the thermal noise into the Nyquist zones will result in degradation of the SNR of the sampled signal. On top of that, aperture and clock jitter also degrade the output SNR of the ADC, while quantization of samples results in distortion being introduced onto the signal. Consequently, it can be assumed that the performance of the RF-over-fiber is dependent on contributors, such as ADC noise due to aliasing, jitter and quantization, as well as thermal noise from the unamplified optical link, and jitter noise at the optical receiver from the DAC. The performance of a digital optical link without any amplification is largely limited by the thermal noise of the receiver, which can result in bit errors in the detected output. This results to bit errors in the detected signal which can respectively introduce noise into the reconstructed analog signal. Apart from that, data and clock recovery circuits of the receiver may also introduce additional errors. This can be addressed by assuming that these errors are to be negligible for situations where clock and data recovery is possible and synchronization can be easily achieved. Another technique that helps resolve another issue, by helping attenuate the jitter noise at higher frequencies, is the sinc-function-like frequency response inherent in the DAC output.

The implementation of digitized fiber optic links, for wireless networks that operate in the MMW and beyond (THzW) frequency bands, is significantly challenging, since the electronic sampling systems need to be able to accommodate these exceptionally high RF frequencies. At such high frequencies, analog RoF optical links are the promising alternative and is quite advantageous for these next generation wireless networks. By removing the need for sampling, the analog optical distribution network connecting the active antenna systems (AASs) and baseband units (BBUs) is easily supporting future wireless networks offering multiple broadband services, by exploiting readily available optical transceivers. Furthermore, it substantially simplifies the cell hardware and reduces power consumption, since the ADC/DACs as well as the frequency up/down conversion circuitry, are no longer required. Although this approach has plenty of benefits, it limits the feasible architecture options for the optical network that interfaces multiple small cell sites to a centralized pool of BBUs, since his signal transport scheme is not compatible with TDM PONs (Time Division Multiplexing Passive Optical Networks).

3 ISSUES AND MITIGATIONS AT IMPLEMENTING HIGH WIRELESS LINKS

As it has been clear 5G and 6G are currently studied worldwide, so it's quite expected that the 60 GHz (and above) frequency regions are receiving striking attention, as it's a way to provide both high data rates to the user, as well as, satisfying the growing capacity demands through the deployment of small cells. As expected, integrating a 60 GHz wireless system with a fiber-optic signal distribution network would enable the efficient delivery of the high data rate signals to a large number of antenna units, thereby ensuring optimized radio coverage. An analog RoF transport approach for such an application would bring a number of benefits, including a significantly less complex remote radio head (RRH), while enabling the antenna site to be independent of the air interface.

However, a well known issue of implementing analog fiber optic transport schemes in higher frequency wireless systems is the signal fading effect of fiber dispersion on the detected MMW wireless signals. Luckily, this issue can be mitigated using techniques that modify the optical spectrum, such as optical single sideband with carrier modulation (OSSB+C) or optical carrier suppression (OCS), by using a single dual-electrode Mach-Zehnder modulator (DEMZM). The OCS modulation technique is an example of a dual-wavelength optical source, where the MMW/THzW signal is produced by mixing two optical wavelengths (the two modulation sidebands in the optical spectrum) in a high-speed photodetector.

Another approach is the use of a dual-wavelength stimulated-Brillouin-scattering (SBS) fiber laser. SBS fiber laser can help us realize the dual-wavelength optical source for dispersion tolerant signal transport in a fiber remoted 60 GHz wireless link. The two benefits of this optical MMW/THzW signal generation technique are its ability to provide both wide tunability and ultra-low phase noise. The SBS laser has been shown to be capable of generating MMW/THzW carriers up to 100 GHz with low phase noise properties independent of carrier frequency. In order to encode the data into the output of the laser, the two SBS laser wavelengths are first demultiplexed and directed to an electro-optic phase modulator where they are encoded with data. Quite often, there are line rate harmonics of the baud rate which originate from the non-ideal response of the modulator driver amplifiers. They have a negligible impact on the overall system performance since they represent a very small fraction of the RF power after frequency upconversion and do not affect the eye opening along its primary dimension. With proper bandwidth limiting, such as low pass filtering in the receiver, all tones except for the residual carrier tone are filtered out.

Figures 3 and 4 show the measured optical spectrum of the optical signal with a close-in view of the modulated upper wavelength of this approach. Those regularly spaced tones that are visible in figure 4 are line rate harmonics of the baud rate which originate from the non-ideal response of the modulator driver amplifiers. They have a negligible impact on the overall system performance since they represent a very small fraction of the RF power after frequency upconversion and do not affect the eye opening along its primary dimension. With proper bandwidth limiting such as low pass filtering in the receiver, all tones, except for the residual carrier tone, are filtered out.

Measured optical spectrum at the input to the photodetector:

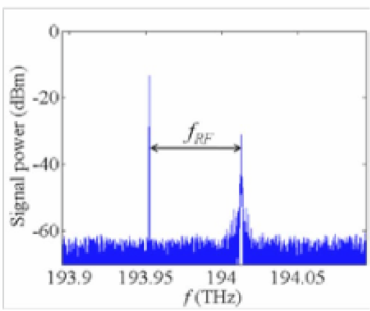

Figure 3: Full spectrum, showing both sidebands

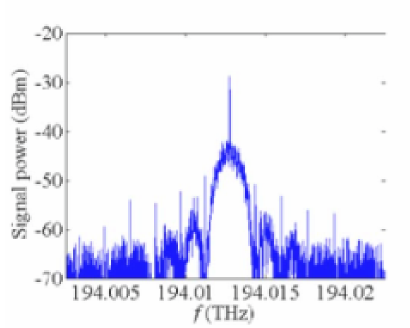

Figure 4: Close-in view of the upper sideband showing the 1.65 Gbps BPSK modulated data.

The combined optical signal was amplified using an erbium doped fiber amplifier (EDFA) and directed over a length of optical fiber to a high speed (70 GHz) photodetector, which upconverted the Gb/s data onto the phase of the generated RF beat signal that had a frequency defined by the two optical carriers from the dual wavelength SBS fiber laser, 60.8 GHz. In figure 5 we see the receiver used in 60GHz wireless link experiments. The received 60.8 GHz signal is first down-converted to an intermediate frequency of 6 GHz using a MMW mixer. Since the transmitter and receiver are physically separated, the wireless carrier is recovered and tracked in a phase-locked loop in order to accurately demodulate the phase-encoded data. Since the transmitter and receiver are physically separated, the wireless carrier is recovered and tracked in a phase-locked loop in order to accurately demodulate the phase-encoded data. The recovered baseband data was then analyzed using a BER tester and oscilloscope.

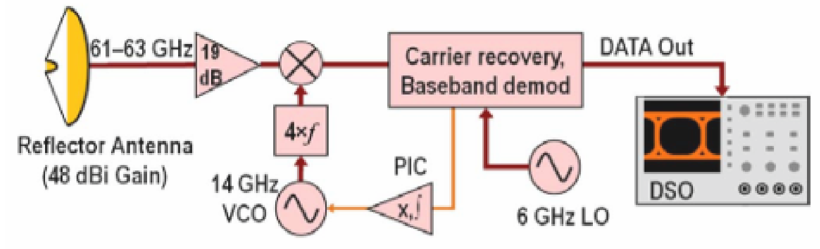

Figure 5: Experimental set-up of the receiver used in the SBS fiber laser fed 60 GHz wireless link.

Another challenge that has to be encountered at implementing high wireless links in the nonlinear distortion. It has become clear that a major problem that can occur in these networks is the nonlinearity of the various devices used. The systems that use direct modulation of the laser transmitter with the multi-channel RF signal, the dynamic nonlinearity of the laser diode may impose serious limitations on the system performance due to inter-modulation distortion (IMD) effects.

The method of reducing the nonlinearity of laser diodes is the use of external injection into the directly modulated laser from a second laser source. Under external injection conditions, the relaxation frequency of the laser may be increased significantly and the modulation response at lower frequencies can be made significantly more linear than that without external injection. Nevertheless, the nonlinear response of the laser with external injection may still cause problems for multi-carrier RoF systems. A vector control theory (VCT) based circuit provides the third-order inter modulation (IMD3) suppression for two-tones. To improve the link performance, the second- and third-harmonic generations of single- and two-tone RoF systems can be minimized using external-laser modulation techniques with EDFA. To also minimize the nonlinear effects from optoelectronic conversion, the amplitude of the drive signals need to be kept low.

While still adhering to optical and wireless transmission standards regarding MMW/THzW wireless systems with RoF distribution, lately the attention has sifted towards the maximization of the wireless throughput. There are quite some successful multi-Gb/s NRZ OOK data rates implementations, using a coherent RoF system, compatible with the existing passive-optical-networks (PON) architectures, which uses a free running laser diode at the remote antenna unit. Wireless data rates in excess of 100Gb/s were also implemented, by using a combination of coherent optical techniques and polarization diversity. Another approach incorporated advanced digital-signal-processing (DSP) techniques into MMW RoF systems, with regard to realize high multi-Gb/s wireless data rates.

4 MMW And THzW Transmission Schemes

Following the above implementations, in order to meet the growing capacity and traffic demands of 5G and 6G wireless networks, there are presented multiple seamless fiber-wireless system demonstrations. In this section, we review the recent research activities on MMW and THzW over fiber systems for future mobile networks. Using photonic technology for the signal generation, transmission, and up-conversion, and new developed devices, can help to realize simple, low-latency, high-capacity, and high-performance seamless fiber–wireless systems.

•***Low-latency radio-on-radio-over-fiber system***

This system demonstration is about the encapsulation of numerous radio signals in the conventional microwave bands to the MMW band and later to the THzW band, using photonic technology. It is quite promising for low cost, flexible and low latency mobile fronthaul systems. In this particular system, numerous radio signals can be combined before modulating an optical two-toned signal. After a direct optical up-conversion to MMW/THzW band, by a high-speed photomixer, the signal encapsulation gets realized. Even so, the generation of a frequency and phase-stabilized optical MMW/THzW signal using a high-precision optical modulation technology is very important to ensure the signal performance. In addition, at the receiver's end, a self-homodyne signal detection method can help to reduce the improve the receiver sensitivity and electrical phase noise. Lastly, a bidirectional system capable of supporting a full-duplex signal transmission can also be realized using frequency-division multiplexing in the wireless link and wavelength-division multiplexing in the optical link.

•DSP-aided seamless fiber-wireless system
In order to support the deployment of multiple-input-multiple-output (MIMO) and/or multiple radio access technologies (RATs), a simultaneous transmission of multiple radio signals over a fiber and/or fiber–wireless system would be substantial. There is also, a prospect of co-transmission of mobile signals and wireless fronthaul signals in different frequency bands. In order for such transmission to be accomplished and supported, a digital signal processing (DSP)-aided fiber and fiber-wireless system is required. A DSP algorithm can map different radio signals, such as MIMO and/or RAT signals, to a common optical channel. At the receiver's end, a demapping DSP algorithm can recover the transmitted signal components from the received signals. An optical local oscillator (LO) signal can also be transmitted from the transmitter side for up-conversion of received optical signals to a MMW/THzW signal. Both MMW/THzW RoF systems using an optical up-conversion and intermediate frequency-over-fiber systems using an electrical up-conversion at the optical receiver can be used. In both cases, the generation of a high-quality optical MMW/THzW signal is of significant value, in order to secure the signal transmission performance.

•High-capacity and seamless fiber-wireless system
By using RoF technology and coherent detection, a high-capacity seamless fiber–wireless system can be realized. Firstly, by using an optical two-tone signal generator of optical modulation technology, an optical MMW/THzW signal can be generated. Afterwords, one of the generated optical signals can be modulated at an optical IQ modulator, by a data signal. The modulated and the reference optical signals are combined and transmitted to the optical receiver. A high-speed photomixer can directly up-convert the received optical signal to a radio signal in the MMW/THzW band. After transmitting over a free space link in the MMW/THzW band, the signal is received and down-converted to intermediate frequency. Finally, the signal is sent to an analog-to-digital converter and were it gets demodulated by an offline DSP. This demonstration of High-capacity fiber–wireless systems at 92.5 GHz and 300 GHz, have been successfully demonstrated for high-speed data, such as 20-Gbaud QPSK signal.

•Power and radio transmission over fiber system
When using small cells, as well as ultra-dense small cells, simplifying remote antenna sites, would be crucial in future mobile networks. Specifically, reduction of electric power supply demand, will be of the essence for massive deployment of small cells. Another consequential approach is the remote delivery of power via fiber links, together with data signal. Recently, a simultaneous transmission of power and radio signal over a fiber system has been successfully demonstrated. In the system, a new optical-to-radio converter (ORC) consisting of a high-frequency RF amplifier and a bias-free UTC-photodiode, was developed. Additionally, a new ORC capable of generating an electrical power from the received optical signal to feed the RF amplifier was also developed. As a result, high-speed signal transmission has been successfully demonstrated over a seamless fiber–wireless system at 90-GHz band using a multicore fiber and the developed OCR, consisting of a bias-free UTC-photodiode and a high-frequency RF amplifier.

5 Cloud-Based Radio Access Networks, Converged Fiber-Wireless Access Networks and Millimeter-Wave Small Cells techniques

In this section we introduce the concepts of Cloud-Based Radio Access Networks, Converged Fiber-Wireless Access Networks and Millimeter-Wave Small Cells and we combine them in order to implement and propose a new network's architecture, called Cloud RoF access systems, designed to meet the requirements of the future 5G wireless communication networks.

- **Cloud radio access network (C-RAN)**
  Cloud radio access network (C-RAN) systems are considered to be an efficient approach for the design of the next generation wireless networks, able to meet the capacity demand of the future cellular communication networks. C-RAN is a design, proposed by China Mobile and held in high esteem by many operators and equipment vendors. This technique is deploying a distributed architecture, based on the separation of the traditional radio functionality into two different parts: the RRHs and baseband units (BBUs), in which the signal processing is taking place. In this way, the signal processing and management functionality is transferred from every RRH into the BBU and is centralized into one single location, "the cloud" (BBU pool).

The result of the latter split, is that the conventional cell sites are simplified into cheaper and power-efficient RRHs. In addition, by the centralization of the signal processing, the network becomes less complex, making the management function easier and enables more advanced and efficient synchronization among the different cells.

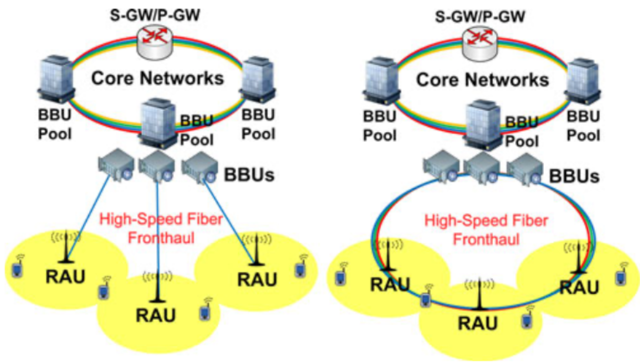

Figure 6: Two different C-RAN architectures.(a) star topology, (b) ring topology

On figure 6, there are two different possible topologies, deploying the C-RAN concept. For the star topology, on the left side, there are point-to-point links between the BBU cloud and the different RRHs. This design seems reasonable, keeping in mind the hierarchical connection between BBU pool and RRHs, but a number of difficulties is emerged, such as the great number of fiber needed for the fronthaul as well as reliability and protection matters. On the other hand, ring topology (on the right side), that connects a number of BBUs and RRHs, is gaining more interest, due to its easier deployment and management.

C-RAN architecture may have some serious advantages to offer, however whoever deploys this concept, should overcome the challenges of high-cost and the availability of fiber-optic networks that connect a number of RRHs with the BBU pool.

- **Converged Fiber-Wireless Access Networks**
  Key element of the next generation high speed RAN, is the backhaul/frontfaul network. Conventionally, such networks are based on T1 lines, microwave point-to-point links, and fiber-optic links. However, as the capacity demands of such networks increase, optical fibers, seem to be the most suitable way, to provide the requisite bandwidth. Keeping in mind that fiber-optic networks provide very-high-speed Internet access for FTTX applications and also that all of the different types of access networks, are linked to each other through a core network, that consists exclusively of fiber optics, they seem to be the future of backhaul/frontfaul networks. There is also great interest in using the existing optical fiber access networks (PONs) for mobile backhaul/fronthaul applications.

- **Millimeter-Wave Small Cells**
  As we already know, an element playing a vital role in the future 5G wireless communication is the higher radio frequency (RF). The spectrum of RF is presented in figure 7.

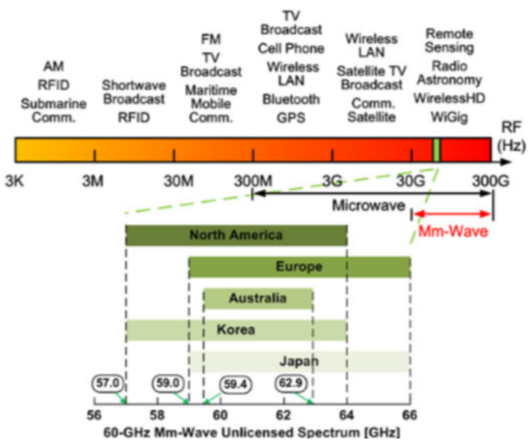

Figure 7: RF spectrum and 60-GHz millimeter-wave band

If we take a quick look in the latter figure, we can easily conclude that the lower microwave band (300MHz-3GHz), which is used by the conventional cellular services, has become overcrowded. On the other hand, the higher microwave band and the millimeter-wave (mm-wave) band (30-300GHz) in particular, has gain great interest, due to its huge spectrum efficiency, able to deliver 1000*throughput as required by 5G. Many organizations, are working on the standardization of 60-GHz band with 7-GHz license-free bandwidth for high-speed wireless communications, such as WLAN and wireless personal area networks. However, as tempting as the mm-wave band sounds, we should always keep in mind that there are many challenges, like the requirements of line-of-sight channel and high-speed but low-cost fronthaul-backhaul networks to support many mm-wave small-cell RRHs, emerging by its use in cellular communications.

6 Cloud RoF access systems

In this section, we combine the concepts introduced in section 5, in order to present an implementation of a cloud RoF access systems. By combining small-cell cloud-RAN concept with multi-band delivery capability in an integrated optical-wireless access system, the proposed architecture can realize high-speed multi service data transmission in a simplified and flexible way. In figure 8 there is an illustration of the key differences between conventional macrocells, C-RAN and the proposed cloud RoF systems.

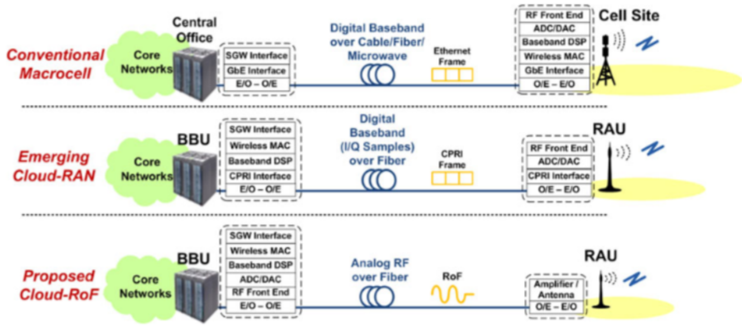

Figure 8: Design of macrocell, conventional C-RAN and the cloud RoF systems

First of all, there is a significant abatement in the mm-wave small cell radius, from 1-10 km of conventional macrocells to less than 100 m. As a transmission frequency of the small cells, could be used either the ordinary low-radio frequency microwave (700MHz-5GHz), or the mm-wave band (30-300GHz). If the network is designed to transmit data in the mm-wave band, then the cell's radius is limited around 10 m. This limitation is necessitated by the high propagation loss and makes this deployment suitable for in-building, hot-spot environments. In conventional macrocell environments the fronthaul media, could be either optical fiber, or ordinary cable. However in the proposed cloud-RoF implementation, BBU pool can only be connected with a number of RRHs, through an optical fiber channel, in order to meet the high-speed demands of the 5G communication network. In addition, there is an even more significant difference between the proposed design, macrocell and C-RAN implementations. This difference is located in the functionality of CO, in macrocell and BBUs-RRHs, in C-RAN and the signal transmission formats in backhaul-fronthaul links, compared with the proposed cloud RoF systems. More specifically, comparing the emerging cloud-RAN with the conventional macrocell, cell sites are simplified to RRHs by shifting MAC layer functions and signal processing from the CO to BBU, and digital IQ samples are transmitted in the fronthaul. In the cloud RoF system, the RRHs functionality is simplified even more, by transferring DAC/ADC and radio frequency functions to the BBU, leaving RRHs responsible only for O/E and E/O conversion and, in which only radio frequency antennas are needed. Thus, BBU is generating the radio signal, which is transmitted, through the fiber-optic fronthaul, to the RRHs. This design allows a great variety of radio frequencies (1-100GHz) to be transmitted in the cloud RoF systems. Another fundamental difference between cloud RoF and the other two systems is the format of the transmitted signal. The macrocell and C-RAN systems are following the conventional digital-baseband-transmission approach, which supports only one service at a time. On the other hand, the analog RoF method enables multi-band, multi-service, multi-operator co-existence in a shared infrastructure without extra interference. This feature can lead to a significant abatement in the cost of small cell's implementation and provide both backward and forward compatibility for existing services as well as next-generation 5G technologies.

Moreover, in order to increase the benefits that cloud RoF systems have to offer, by providing more flexibility to the fronthaul networks, optical wavelength division multiplexing passive optical access network (WDM-PON) techniques, could be used. The operational advantages, emerged by this integration, are introduced in the following section. First, the proposed cloud RoF system, supports the co-existence of multiple operators, in the same infrastructure, by using different WDM wavelengths and also, within each provider, multifarious services can co-propagate in the RoF backhaul, including the ordinary lower RF band, as well as the future 5G higher RF band. In addition, for each service, a variety of MIMO data streams and sub-bands can also co-exist, without significant interface. Last but not least, the same small-cell infrastructure can be used by multiple providers and wireless services, while maintaining independent configurability through the centralized management.

The proposed cloud RoF access systems' design, as tempting as it sounds, emerges significant challenges as well. First of all, the generation, detection and transmission of the optical signal, requires, high linearity. When the latter requirement is not fulfilled, severe performance degradations may occur. Moreover, the key to accomplish the proposed cloud-based radio access network, is the design of a BBU "cloud", that can detect and resolve real-time load unbalancing in the shared infrastructure or the whole network may malfunction. Finally the bandwidth requirement of analog RoF interface becomes much higher, due to the desired supporting, of both lower and higher RF bands.

7 Common Public Radio Interface (CPRI)

As the time passes, even more mobile network operators (MNOs) are replacing their traditional decentralized network's structure, with the C-RAN approach. The aforementioned technique, is based on a distributed architecture, key part of which is the separation of the radio elements of the base station (remote radio heads RRHs) from the unit, in which the process of the baseband signal is taking place (baseband units BBUs). The main idea, underlying the C-RAN approach, is to remove the intelligence from every RRH and to centralize it in a single location (cloud).

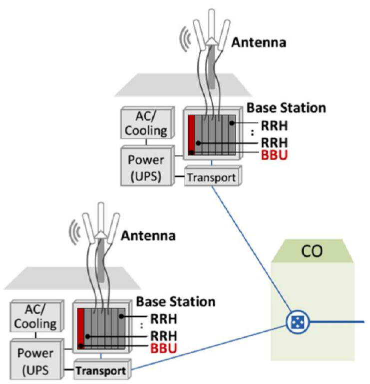

Figure 9: Traditional radio architecture

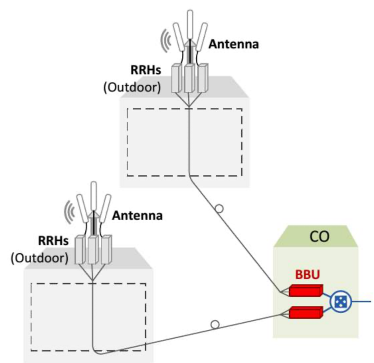

Figure 10: C-RAN architecture

This centralization has to offer a lot of benefits, such as: simpler radio equipment in the network edges, easier operation and cheaper maintenance. On the other hand, a great challenge emerges, the need of constant connection of these two parts, by a low-latency, high-speed and accurately synchronised network, the so-called fronthaul. The CPRI is the dominant technique, which is used by most global vendors, based on digital radio over fiber (D-Rof) concept, fulfilling the latter need. According to the CPRI specification "the Common Public Radio Interface (CPRI) is an industry cooperation aimed at defining a publicly available specification for the key internal interface of radio base stations between the Radio Equipment Control (REC) and the Radio Equipment (RE)." In other words, CPRI provides the demanding interface between the RRHs and BBUs, an interface which is based on the serial transmission of constant bit rate data (CBR) over a specific channel. Some of the most important features and requirements of CPRI are the following:

- CPRI specification works with a wide variety of topologies, other than the traditional point to point design. Such topology configurations could be: star, chain, tree, ring and also multihop designs

- CPRI supports multifarious radio standards, such as: Universal Terrestrial Radio Access (UTRA) FDD, 3GPP Evolved UTRA (E-UTRA, LTE), 3GPP GSM/EDGE, etc.
- The equipment, in which CPRI is deployed, should have a transmission range of at least 10 km
- Strict synchronization is required between radio equipment (RE) and radio equipment controller (REC)
- CPRI demands specific bandwidth and has low tolerance in delay and bit error rate (BER)

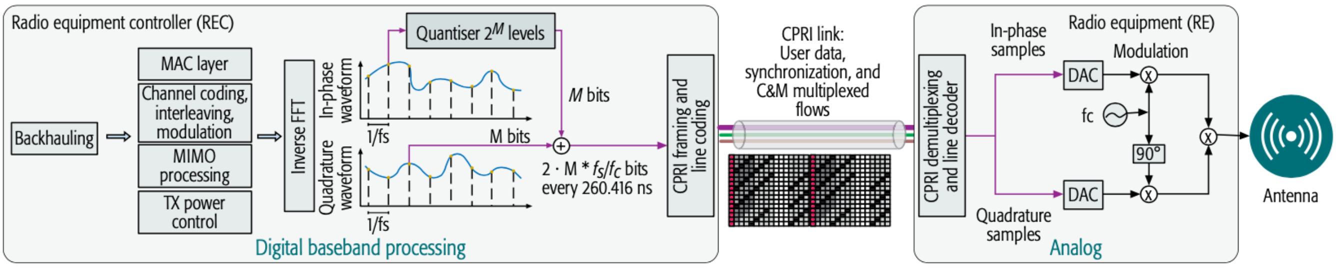

Figure 11: REC/RE functionality

As mentioned before, in CPRI specification, there is a strict split between REC and RE. Figure 11, shows the functionality of each unit. As shown, first and foremost REC is responsible for the generation and the sampling of the radio signal, and also forwards the output waveform to RE. The main functionality of RE is to reconstruct and transmit the radio signal over the air. By that split, the intelligent part of signal processing is transferred from every single RRH to the BBU, resulting to make RRHs smaller and cheaper. There are three different hierarchical framing types in CPRI:

- **Basic frame**, which is generated and transmitted every Tc=260.416 ns and consists from W=16 words of specific length.
- **Hyperframe**, which is generated every 256*Tc = 66.67 μs and consists of 256 basic frames.
- **CPRI frame**, which is the collection of 150 hyperframes.

There are four different logical connections in CPRI:

- **User Plane Data**
  These data are transported in the form of IQ data flows. Every IQ data flow, represents a single radio signal of one carrier at one independent antenna element, the so-called antenna carrier (AxC). The last 15 words of every basic frame are used for the transportation of these IQ data flows, while the first one represents information about control.
- **Synchronization Data**
  The interface, should help RE to achieve the desired frequency accuracy.
- **Control and Management**
  Necessary signals required to set up the different C&M links, including starting up, resetting, and tearing down the CPRI link, and also to handle alarms such as loss of synchronization are carried.
- **Vendor-Specific**
  These are for the transmission of vendor related data, in order to allow the manufacturers to customize their solutions

8 Distributed Antenna System (DAS) over RoF

A distributed antenna system (DAS) is a network of spatially separated antenna nodes connected to a common source via a transport medium that provides wireless service within a geographic area or structure. The main idea, underlying the DAS technology, is to replace the ordinary high power antennas, by a group of smaller and separated in space, so as to provide coverage over the same area as a single antenna but with reduced total power and improved reliability. The idea works because less power is wasted in overcoming penetration and shadowing losses, and because a line-of-sight channel is present more frequently, leading to reduced fade depths and reduced delay spread. For broadband wireless access, DAS using RoF links has been demonstrated as a commonly used infrastructure solution to provide broadband wireless coverage within a geographic area with reduced total power and improved reliability. In some DAS applications, a single set of base station facilities in the center unit is connected to multiple antenna units (RRHs) to extend the indoor coverage of one base station and to share the bandwidth resource. This DAS variation is called simulcast DAS. In a simulcast DAS, a single base station is simultaneously broadcasts signals in the downlink, while in the uplink, the user stations covered in different RRHs contend for the shared transmission medium and base-station facilities. The simulcast DAS, is held in high esteem and therefore is preferred by a significant number of providers all around the world, mainly in buildings in order to improve the quality of the indoor wireless network coverage. Wireless local-area network (WLAN) signals, are also preferred to be transmitted with the shared cable network infrastructure, in the buildings.

The IEEE 802.11 media access control (MAC) protocols were originally designed and standardized for WLANs. In a simulcast WLAN RoF DAS, the radius that an access point (AP) is covering, is enlarged. In that way, it is allowed to even more users to communicate with the AP through multiple different fiber-connected antennas.

In IEEE 802.11, there are two different coordination functions in the MAC layer, the distributed coordination function (DCF) and point coordination function (PCF). It is critical to understand the way that both DCF and PCF are working in a simulcast WLAN RoF DAS. In figure 12, two different architectures of simulcast WLAN RoF DAS are presented.

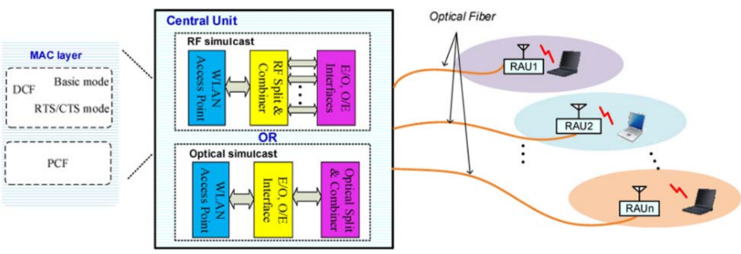

Figure 12: simulcast WLAN RoF DAS architecture.

9 Conclusion

Based on the above, it becomes thus obvious that RoF technologies and implementations for 5G and 6G networks offer great opportunities in meeting current and future capacity demands, as well as supporting multiple wireless standards, driving the evolution of wireless networks to the next level. RoF technologies have the capability to significantly impact the realization of converged optical/wireless networks for wireless systems operating at both MMW and THzW frequencies. Using photonic technology for the signal generation, transmission, and up-conversion, and new developed devices can help to realize simple, low-latency, high-capacity, and high-performance seamless fiber–wireless systems. In this document, we attempted to explain the importance of the different distributed network architectures, like C-RAN and Cloud RoF access systems, but also the reason why the aforementioned approaches can overcome the challenges and meet the requirements of the future 5G and 6G wireless communication networks.

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