

Radio-over-Fiber Technologies for Emerging Wireless Systems

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Abstract— Radio-over-fiber transmission has been studied extensively as a means to realizing a fiber optic wireless distribution network that enables seamless integration of the optical and wireless network infrastructures. Emerging wireless communication networks that support new broadband services provide increased opportunities for photonics technologies to play a prominent role in the realization of next generation integrated optical/wireless networks. In this paper, we present a review of recent developments in radio-over-fiber technologies that can support the distribution of broadband wireless signals in a converged optical/wireless network. We also describe some of the challenges for the successful application of radio-over-fiber technologies in future wireless systems, such as 5G and 60 GHz networks.

Index Terms— Microwave photonics, radio-over-fiber, millimeter-wave communications, 60 GHz wireless, RF over Fiber systems.

I. INTRODUCTION

Microwave photonics has evolved significantly in scope and technical maturity over the years. Since the first pioneering experiments in the 1970's, spurred by interest in exploiting the many benefits of optical fiber as a transmission medium for transporting analog RF signals, the field has expanded considerably and today comprises a diversity of applications [1 – 7].

The predominant commercial application of microwave photonic technology to date has been in the transport and distribution of radio signals over optical fiber. It has been almost three decades since the first publications proposing the

use of optical fiber feeder links to extend wireless coverage in radio communication systems [8 – 10]. Since then, the convergence of optical and wireless networks has continued to evolve. Fiber-optic remoting of radio signals is used in a diversity of wireless networks, including indoor/in-building distributed antenna systems and outdoor cellular networks. The benefits of creating end-to-end integrated network solutions that can provide reliable service for both fixed and mobile users, have become well established.

Today the capabilities of wireless networks are progressing more rapidly than ever before. The proliferation of connected high capacity smart devices as well as the increase in the number of broadband multi-media services available to the consumer, has led to an unprecedented demand for wireless access to high-speed data communications. The realization of integrated optical/wireless networks that can reliably and cost-effectively support current and future capacity demands, traffic growth rates, new services, as well as multiple wireless standards, is presenting new challenges and opportunities for emerging advanced radio-over-fiber technologies.

Existing wireless services and standards such as IEEE 802.11x, GSM (Global System for Mobile Communications), UMTS (Universal Mobile Telecommunication System), and LTE (Long Term Evolution) are concentrated in the lower frequency microwave bands; 700 MHz up to 6 GHz. Recently however, the millimeter-wave (mm-wave) frequency region is being actively pursued for the provision of future broadband wireless services [11, 12]. The unlicensed and globally available 60 GHz frequency region in particular, has led to huge worldwide interest; the multi-Gb/s data rates that can be supported at these wireless carrier frequencies offer great potential to satisfy growing capacity demands. The inherent high propagation loss characteristic of wireless signals at these frequencies leads to network architectures featuring significantly smaller cell sizes (picocells). Integrating a 60 GHz wireless system with a fiber optic distribution network would enable the efficient delivery of the high data rate wireless signals to the large number of wireless access points, ensuring optimized radio coverage [13].

In this paper we discuss some of the advanced radio-over-fiber technologies that may be able to support the implementation of emerging wireless systems integrated with optical fiber networks. The paper is organized as follows.

Manuscript received September 21, 2015. This work was supported in part by the National Science Foundation under Grant IIP-00924028.

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Section II introduces the various radio-over-fiber signal transport schemes that can be implemented in integrated optical/wireless networks and discusses their potential trade-offs. Section III then describes a digitized radio-over-fiber signal transmission scheme that uses bandpass sampling in order to alleviate some of the challenges associated with using digitized fiber optic links in next generation wireless networks. In Section IV we describe some advanced technologies that are being developed specifically for application in future mm-wave wireless systems employing fiber optic signal distribution networks. Finally, conclusions are presented in Section V.

II. RADIO-OVER-FIBER SIGNAL TRANSPORT SCHEMES

Both analog and digital photonic links can be used to transport radio signals over optical fiber, with each technique having certain trade-offs [14]. Fig. 1 illustrates the two main approaches to implementing a fiber optic antenna remoting link for transmission of radio signals in a converged optical/wireless network architecture [15]. In Fig. 1(a), the fiber optic links between the remotely located antenna unit or base-station (BS) and a central office (CO) are realized as analog fiber optic links. In the downlink of Fig. 1(a) (radio signal transport from the CO to the remote antenna site), the wireless digital data is first modulated onto an RF carrier signal with a frequency, f_c , corresponding to the wireless frequency and then modulated onto an optical carrier via an electrical-to-optical (E-O) conversion process. At the remote antenna BS, the modulated optical signal is photodetected (O-E conversion), amplified and directed to the antenna for wireless transmission. A similar process takes place for the uplink path of the wireless network with analog fiber optic links transporting the radio signals from the BS to the CO. Fig. 1(b) shows the alternative radio-over-fiber signal transport scheme to the analog approach. In this digitized RF fiber optic link configuration, the wireless carrier RF signal is first digitized prior to transport 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 key advantage of the analog radio-over-fiber signal transport scheme is the potential to significantly reduce the complexity of the remote antenna site hardware, since only O-E conversion and RF amplification is required, while also enabling centralized control and management of the wireless signals. This is a particularly compelling benefit for the realization of fiber distributed millimeter-wave wireless systems which inherently require the deployment of a large number 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 [16, 17].

The transmission of digitized RF signals over fiber can be a more viable alternative to analog radio-over-fiber signal transport for realizing converged optical/wireless networks, since it can take advantage of the improved performance of

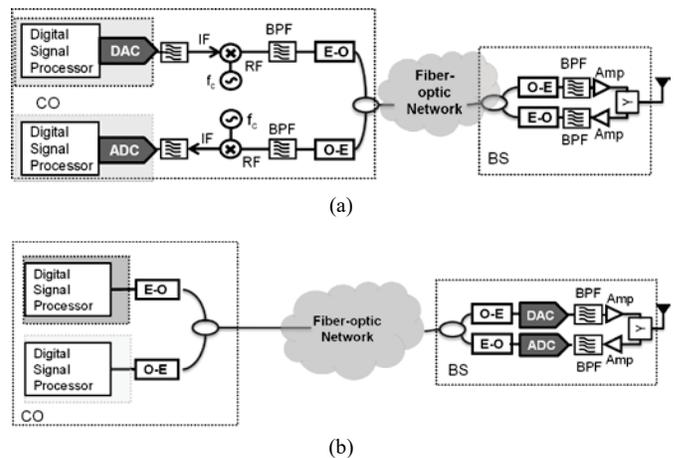


Fig. 1. Radio-over-fiber signal transport between an antenna base-station (BS) and Central Office (CO) using (a) analog fiber optic links and (b) digitized fiber optic links. IF: Intermediate Frequency; RF: Radio Frequency; E-O: Electrical-to-optical; O-E: Optical-to-Electrical; DAC: Digital-to-analog converter; ADC: Analog-to-digital converter; BPF: band-pass filter; Amp: Amplifier.

digital optical links. It is well-established that in a typical wireless network with multiple RF carriers, linearity plays an important role in the achievable system dynamic range [18]. The non-linearity of the optical devices used to convert between the microwave and optical domains can dramatically limit the performance of the analog radio-over-fiber link [19, 20]. This can be clearly seen in Fig. 2, which shows the calculated link dynamic range of an analog fiber optic link and digitized RF optical link as a function of fiber transmission distance [21]. In Fig. 2 dynamic range is defined as the ratio of the strongest to weakest RF signal power that can be supported by the link without distortion. It is evident that the dynamic range in the analog link decreases steadily with the length of the fiber link. In contrast, the digitized radio-over-fiber link is able to maintain a constant dynamic range until the transmission distance reaches a certain length, at which point it rolls off sharply due to synchronization loss arising from the receiver's particular sensitivity and clock recovery threshold. By increasing the optical power launched into an analog link (from $I_o = 3$ dBm to 16 dBm as depicted in Fig. 2), it is possible to achieve the same performance as a digital link,

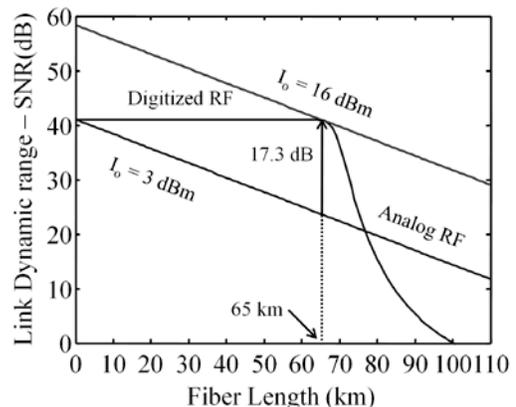


Fig. 2. Comparison of dynamic range for analog and digitized radio-over-fiber signal transport schemes. I_o : optical launch power.

as occurs at a fiber transmission length of 65 km in Fig. 2. However this will add further complexity through increased effects of nonlinearity in the system. The issue of nonlinearity in wireless networks employing radio-over-fiber technologies has been widely investigated and numerous approaches to improving the dynamic range of analog optical links have been reported in the literature [22 – 27].

Digitized radio-over-fiber links are typically used in today's traditional macro-cellular 3G and 4G wireless communication networks which feature a distributed base station architecture in which the radio hardware is positioned in close proximity to the tower-mounted passive antennas. This remote radio head (RRH) contains the RF circuitry as well as the ADCs (analog-to-digital converters), DACs (digital-to-analog converters), and frequency conversion components. Meanwhile the base station server (BTS) or baseband unit (BBU) comprising the digital baseband processing circuitry is located separately and interfaces with the RRH via a digital fiber optic link; CPRI (Common Public Radio Interface) and OBSAI (Open Base Station Architecture Initiative) are two standards that have been developed for this serial link.

One emerging architecture concept attracting significant interest for meeting the growing capacity and traffic demands of future wireless networks is the selective deployment of smaller sized cells that would coexist with, and complement larger macro-cells. As part of this trend, the cell site hardware is also becoming more advanced. Active antenna systems (AASs) are key examples of this technology innovation, an extension of the distributed base station concept in which the RRH functionality is now directly integrated with the antenna elements [28]. The active antenna is also becoming more intelligent since its coverage can be adapted to support changing capacity demands and even multiple wireless standards in the one cell. Several different aspects of realizing high performance AAS are actively being investigated, including novel technologies related to adaptive beamforming technologies, RF/antenna integration techniques, as well as wideband, small form factor antenna array designs [29].

Alongside the move towards smaller cell sites with integrated antennas and RRH functionality, the interconnections between the active antenna systems and the baseband units are also evolving. In the traditional arrangement the BBU is located in a cabinet at the base of the cell tower however the concept of a centralized architecture in which a number of BBUs are remotely co-located together in a secure CO, as depicted in Fig. 3, is being actively investigated [30, 31]. In this scenario, the conventional CPRI digital fiber-optic link between the active antenna system and the BBU would be longer in length and the optical distribution network comprising the digital links constitutes the fronthaul of the wireless network. A centralized BBU architecture would lead to savings in OPEX (operational expenditure) as well as improved performance since there is no transmission delay between adjacent cells. If the co-located BBUs are also pooled together such that the baseband processing resources can be effectively shared across a large number of cell sites in a "virtual" configuration, the resulting cloud radio access

network (C-RAN) can also enable CAPEX ((capital expenditure) reductions while enabling the connectivity between different wireless network layers to be optimized.

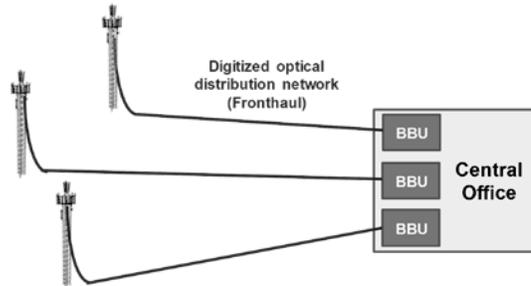


Fig. 3. Schematic showing the concept of a centralized BBU architecture for future converged optical/wireless networks.

One of the key challenges associated with remoting pooled BBUs from the active antenna systems in next generation wireless networks is the very high bit-rates that must be accommodated by the digital links since the data rate will depend on the sampling frequency (which is proportional to the wireless data bandwidth) as well as the resolution of the ADC in bits [32]. This problem becomes more pronounced with the trend towards using multiple transmit and receive antennas at the cell site as a means to increase capacity. For example, an LTE network with 20 MHz bandwidth, 2×2 MIMO (Multiple Input, Multiple Output) in the downlink, and 3 sectors (RRHs) per cell site would equate to an aggregate data rate of more than 7 Gb/s after digital sampling of the analog radio signals [31]. The implementation of AASs with multiple radios that support a diversity of wireless standards could lead to expected data rates well in excess of tens of Gb/s over the next few years. In addition, there are strict requirements on transmission latency and jitter that must be satisfied, which are even more stringent for emerging higher data rate 5G wireless networks [32]. Ultimately these constraints will limit the fiber distances between the active antenna systems and the baseband processing hardware to a few tens of kilometers.

III. DIGITIZATION OF RF SIGNALS USING BANDPASS SAMPLING

It is evident from Fig. 2 that digitized radio-over-fiber signal transport offers a distinct advantage over analog fiber links, although the capabilities of the ADC/DAC technology intrinsic to a digitized fiber optic link will ultimately determine the achievable link performance. A summary of the performance of state-of-the-art ADC devices can be found in [33]. While ADC sampling rates approaching several tens of Gigasamples/second are now being reported, the effective resolution and resulting signal-to-noise (SNR) is limited. In addition, the jitter requirements at higher sampling frequencies in order to achieve adequate resolution are challenging; $\ll 1$ ps. One approach to relaxing the constraints on the required ADC/DAC performance in these systems is to use a different

type of sampling scheme. Since the majority of wireless systems feature signal bandwidths that are just a small fraction of their carrier frequencies, bandpass sampling [34] may be a potential solution for enabling a much lower sampling rate. In this approach, the sampling rate is more comparable to the wireless information bandwidth rather than the wireless carrier frequency itself [35].

An important consideration for 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. Fig. 4 illustrates an example of the sampling requirements established by the bandpass sampling technique [36]. In Fig. 4, the IEEE 802/16a WiMAX (Worldwide Interoperability for Microwave Access) standard is depicted with a channel frequency of 2.475 GHz and data bandwidth of 20 MHz. Taking into account the guardband and filter rolloff characteristics, the resulting total channel bandwidth is 50 MHz and the sampling frequency is 125 Msamples/s, significantly less than the 5 Gsamples/s that would be typically be required in a conventional sampling scheme [37].

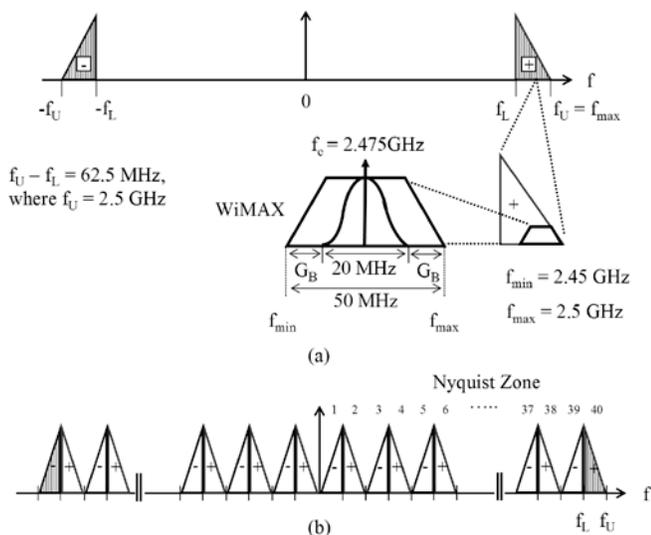


Fig. 4. (a) Frequency domain representation of a WiMAX channel as per the IEEE 802.16a wireless standard and (b) resulting frequency spectrum after bandpass sampling, showing multiple frequency bands (Nyquist zones) containing replicas of the digitized narrowband signal.

By virtue of bandpass sampling many replicas of the bandpass signal can be found, as shown in Fig. 4(b), with their center frequencies aligned with integer multiples of the sampling frequency; these replicas in frequency are called Nyquist zones. Selecting the appropriate Nyquist zone provides either the frequency downconverted or the original bandpass RF carrier modulated signal. Although the higher frequency Nyquist zones suffer from frequency rolloff associated with the DAC, if the signal is once again passed through a suitable DAC with an appropriate frequency response, it is possible to reconstruct the signal at the original frequency. Furthermore, the bandpass sampling technique is independent of the type of

modulation scheme of the wireless carrier signal modulated data.

The performance of digitized RF-over-fiber links is dependent on many sources of noise arising from different parts of the link; the main contributors to the signal-to-noise ratio of the link are ADC noise due to aliasing, jitter and quantization, thermal noise from the unamplified optical link, and jitter noise at the optical receiver from the DAC. During the RF signal digitization process using bandpass sampling, aliasing of the thermal noise into the Nyquist zones [31] will result in degradation of the SNR of the sampled signal. In addition to aliasing of thermal noise, aperture and clock jitter also degrade the output SNR of the ADC [38] while quantization of samples results in distortion being introduced onto the signal.

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 [39]. Consequently, bit errors in the detected signal can introduce noise onto the reconstructed analog signal. While data and clock recovery circuits of the receiver may also introduce additional errors, they can be assumed to be negligible for situations where clock and data recovery is possible and synchronization can be easily achieved. The DACs in the receiver can also introduce jitter, however the sinc-function-like frequency response inherent in the DAC output helps to attenuate the jitter noise at higher frequencies [39].

Fig. 5 highlights the performance trade-offs of a digitized radio-over-fiber link, showing the calculated SNR at each stage of the link as well as the total SNR of the link as a function of the ADC resolution in bits. It is evident from this plot that the link SNR is dominated by the quantization and the jitter noise contributions from the ADC. Quantization noise is dominant when the effective resolution of the ADC is less than around 6, while jitter noise becomes dominant when the effective ADC resolution is greater than ~ 6 bits. The SNR

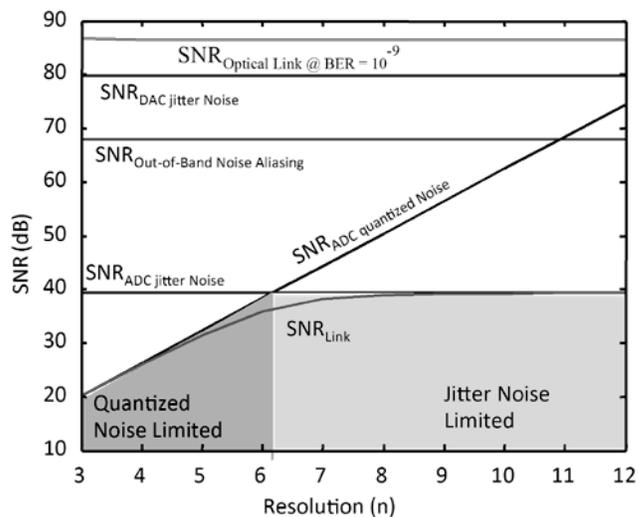


Fig. 5. Degradation in SNR in a digitized radio-over-fiber link due to key contributing factors as a function of the resolution of the ADC, in bits.

of the link converges to a value determined entirely by the jitter noise of the ADC when the resolution is greater than 7 bits. As a result, increasing the resolution of the ADC beyond 8 bits will not yield any improvement in system signal-to-noise ratio.

Fig. 6 shows an experimental set-up highlighting the use of bandpass sampling to create a digitized radio-over-fiber link [40]. In this experiment multiple wireless signals were digitized with a vector signal generator (VSG) used to generate notional WiMAX (2.475 GHz, 16 QAM, 6 MS/s) and GSM (1.95 GHz, GMSK, 270.833 kb/s) RF signals. An ADC with 8 bits of resolution carries out the direct digitization of the RF signals using the bandpass sampling technique in addition to quantization and coding functions. Prior to digitization, both the GSM and WiMAX signals are first bandpass filtered to remove out-of-band noise using suitable bandpass filters. Bandpass filtering before sampling is important to reduce the impact of noise resulting from bandpass sampling. In this experiment the ADC sampling functionality was emulated using a Tektronix TDS6154C Digital Sampling Oscilloscope (DSO). The sampling frequency of the DSO is adjustable in steps up to 40 GS/s and

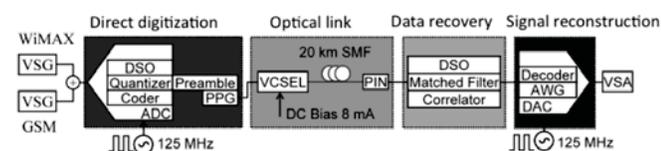


Fig. 6. Experimental set-up for the transmission of digitized radio-over-fiber signals comprising GSM and WiMAX wireless channels.

the bit resolution of the ADC was 8 bits. The composite WiMAX and GSM RF signal was bandpass sampled at 125 MSamples/s and 400 ms of time window (containing 50,000 samples) was captured using the DSO. With software implemented quantizer and coder functions, samples were processed off-line, first normalized to the ADC dynamic range and then coded and appended with a preamble. The overhead due to the preamble was negligible as it consisted of only 16 bits which led to a data bit rate of 1 Gb/s for the 8-bit ADC resolution.

The resultant binary digital stream was electrically generated using a pulse pattern generator (PPG). The serial bit stream of the digitized RF signals then directly modulated a commercially available uncooled, 2.5 Gb/s, 1.55 μm vertical cavity surface emitting laser (VCSEL) which was biased at 8 mA. The modulated signal was transported over 20 km of single mode fiber (SMF) before being detected by a PIN photoreceiver at the end of the link. To emulate data recovery the optically modulated signal was detected and captured using the DSO. The data recovery block consisted of a sampler followed by a correlator. The sampler was implemented using the same DSO and its main function was to capture the PIN receiver output. The DSO was configured to capture 1 ms of time window in the PIN receiver output, chosen such that the binary data pattern output of the PPG

would always fall in this time window. The reconstructed RF spectra of the WiMAX and GSM wireless signals were then passed to a vector signal analyzer (VSA) for testing. Fig. 7(a) shows a trace of the PIN receiver output after transmission over 20 km of SMF and Fig. 7(b) shows the measured BER (bit-error-rate) curves for 8-bit ADC resolution. The receiver sensitivity measured after 20 km of fiber at a BER of 10^{-9} was -22.5 dBm.

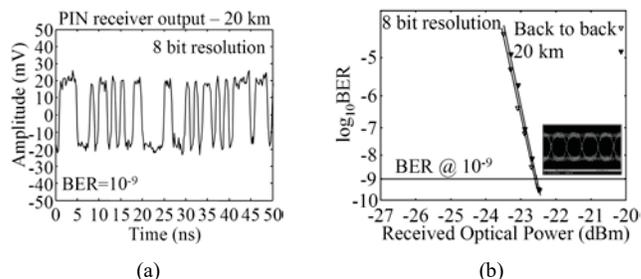


Fig. 7. Measured characteristics of the digitized optical link with bandpass sampling (a) traces of the PIN receiver output and (b) BER curves for 20 km fiber transmission in comparison to back-to-back optical link.

Fig. 8 shows close-up views of the RF spectra of the DAC output and corresponding constellations of recovered data. The spectrum shown in Fig. 8(a) relates to a downconverted signal at a lower order Nyquist Zone at 25 MHz while Fig. 8(b) shows the same signal at its original WiMAX RF frequency of 2.475 GHz. Similarly, Figs. 8(c) and 8(d) show the downconverted signals at 50 MHz and at the original GSM RF frequency of 1.95 GHz, respectively. The increase in insertion loss and reduced SNR at the higher order Nyquist

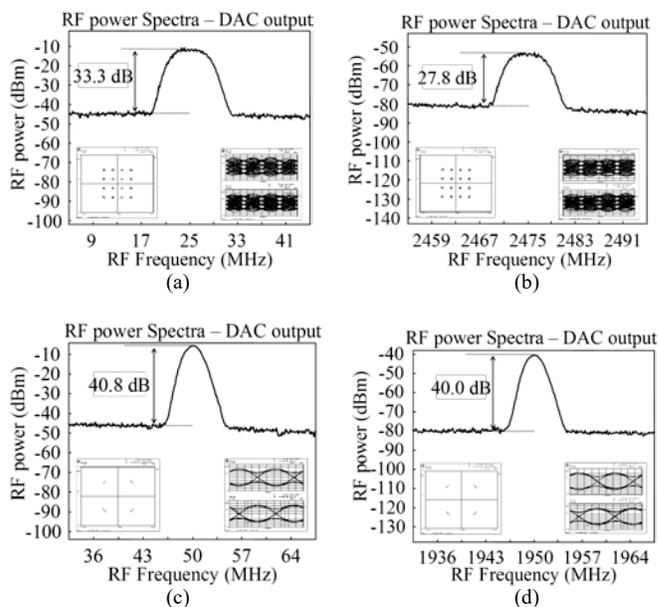


Fig. 8. Measured RF spectra and constellations corresponding to (a) low order Nyquist zone image of WiMAX (a downconverted signal), (b) higher order Nyquist zone image of WiMAX (c) low order Nyquist zone image of GSM (a downconverted signal), and (d) higher order Nyquist zone image of GSM channels.

zones is due to the frequency rolloff of the DAC's frequency response.

The results shown in this section highlight the potential for using bandpass sampling to help alleviate the high link data rates that result in a digitized radio-over-fiber system. For wireless networks that operate in the millimeter-wave frequency bands however, the implementation of digitized fiber optic links becomes significantly more challenging since the electronic sampling systems need to be able to accommodate these very high RF frequencies. At such high frequencies, analog radio-over-fiber optical links become a viable alternative and may be even be advantageous for next generation wireless networks. By removing the need for sampling, an analog optical distribution network connecting the AASs and BBUs could more easily support future wireless networks offering multiple broadband services by exploiting readily available optical transceivers [29]. It would also greatly simplify the cell site hardware and reduce power consumption since the ADC/DACs and frequency up/downconversion circuitry are no longer required. Such an analog based connection however, would limit the feasible architecture options for the optical network that interfaces multiple small cell sites to a centralized pool of BBUs since this signal transport scheme is not compatible with TDM PONs (Time Division Multiplexing Passive Optical Networks).

IV. FIBER REMOTED 60 GHz WIRELESS LINKS

As discussed earlier, the 60 GHz frequency region is receiving significant attention worldwide as a way to both provide high data rates to the user and satisfy growing capacity demands through the deployment of small cells. 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 radio-over-fiber transport approach for such an application would bring a number of benefits, including a significantly less complex RRH while enabling the antenna site to be independent of the air interface. Since there are a number of 60 GHz wireless standards that are currently being developed, this latter advantage is particularly relevant [13].

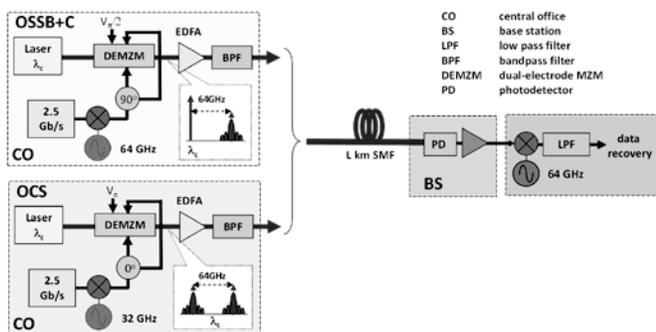


Fig. 9. OSSB+C and OCS dispersion tolerant modulation schemes for fiber distributed 60 GHz wireless links.

One of the well documented issues of implementing analog fiber optic transport schemes in higher frequency wireless systems is the signal fading effect of fiber dispersion on the detected mm-wave wireless signals. This effect can be mitigated using techniques that modify the optical spectrum, such as optical single sideband with carrier modulation (OSSB+C) [16] or optical carrier suppression (OCS) [41, 42]. Fig. 9 shows how each of these approaches can be realized using a single dual-electrode Mach-Zehnder modulator (DEMZM). The OCS modulation technique is an example of a dual-wavelength optical source, where the mm-wave signal is produced by mixing two optical wavelengths (the two modulation sidebands in the optical spectrum) in a high-speed photodetector. The dispersion tolerance of the OSSB+C and OCS modulation schemes is highlighted in Fig. 10, which shows the power penalty at a BER of 10^{-9} as a function of fiber transmission distance for the two transport schemes [41]. Both schemes provide minimal RF power penalty due to fiber dispersion for fiber distances of up to 30 km; more than adequate for the anticipated fiber delivery distances in these systems.

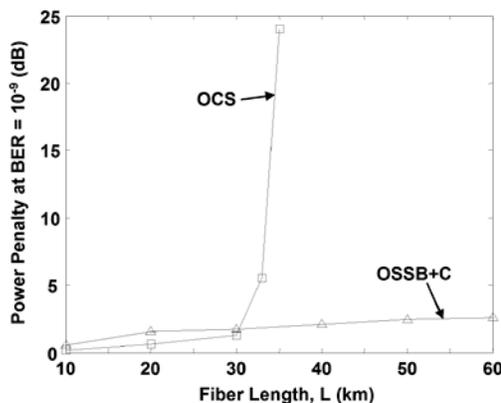


Fig. 10. Power penalty at BER = 10^{-9} as a function of fiber distance for OCS and OSSB+C modulation formats established using a single DEMZM.

Another approach to realizing a dual-wavelength optical source for dispersion tolerant signal transport in a fiber remoted 60 GHz wireless link, is the use of a dual-wavelength SBS (stimulated Brillouin scattering) fiber laser [43]. Two key benefits of the SBS fiber laser as an optical mm-wave 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 mm-wave carriers up to 100 GHz with low phase noise properties independent of carrier frequency [44]. Fig. 11 shows the set-up of a transmitter implemented to demonstrate Gb/s data wireless transmission at 60 GHz using the SBS fiber laser [45]. To encode the data onto the output of the laser, the two SBS laser wavelengths are first demultiplexed and one directed to an electro-optic phase modulator where it is encoded with data. In the particular experiment described here, the modulation format and data rate were BPSK (binary phase shift keying) and 1.65 Gb/s, respectively. The other wavelength of the SBS

laser output is left unmodulated, and combined with the encoded optical subcarrier using a standard fiber-optic coupler.

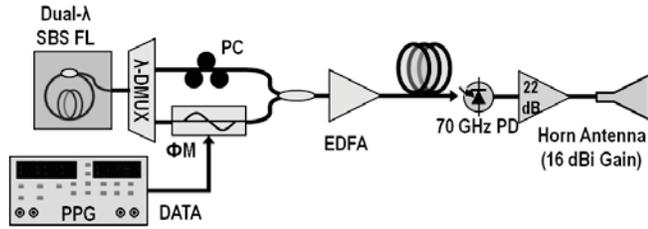


Fig. 11. Experimental set-up for high data rate encoding of a dual wavelength SBS laser and free-space transmission at 60 GHz.

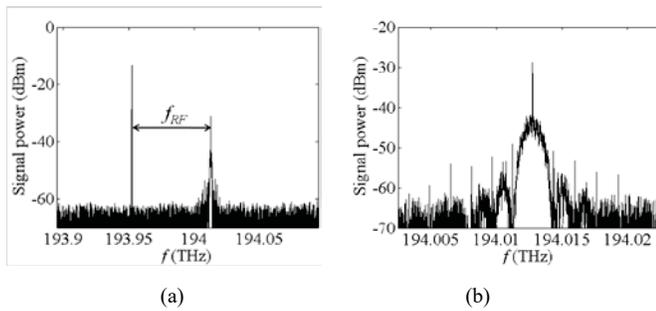


Fig. 12 Measured optical spectrum at the input to the photodetector in Fig. 11. (a) Full spectrum, showing both sidebands, and (b) Close-in view of the upper sideband showing the 1.65 Gbps BPSK modulated data.

Fig. 12 shows the measured optical spectrum of the recombined optical signal with a close-in view of the modulated upper wavelength in Fig. 12(b). The regularly spaced tones that can be seen in Fig. 12(b) 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.

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 (PD) 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. Fig. 13 shows the receiver used in the 60 GHz wireless link experiments. The received 60.8 GHz signal is first downconverted to an intermediate frequency (IF) of ~6 GHz using a mm-wave 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. The recovered baseband data was then analyzed using a BER tester and oscilloscope.

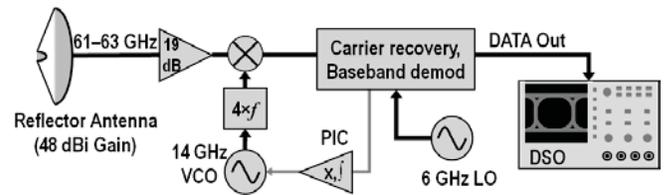


Fig. 13. Experimental set-up of the receiver used in the SBS fiber laser fed 60 GHz wireless link.

Fig. 14 shows the measured BER of the SBS laser fiber remoted 60 GHz wireless link as a function of distance between the antennas. The logarithm of the error ratio increases monotonically with the logarithm of the range, illustrating effectively error-free operation to beyond 20 m. Fig. 14 also shows an eye diagram of the demodulated BPSK data at a wireless range of 15 m, where the data was essentially error free with $BER < 10^{-12}$. The photodetected RF power coupled into the transmit antenna was -12 dBm. An outdoor 60 GHz link experiment was also conducted using the SBS fiber laser; here the transmitter used a 48-dBi reflector antenna identical to that used in the receiver and the laser and data encoding hardware was separated from the remote transmitter containing the photodetector and high power amplifier by approximately 1 km of SMF. In the outdoor

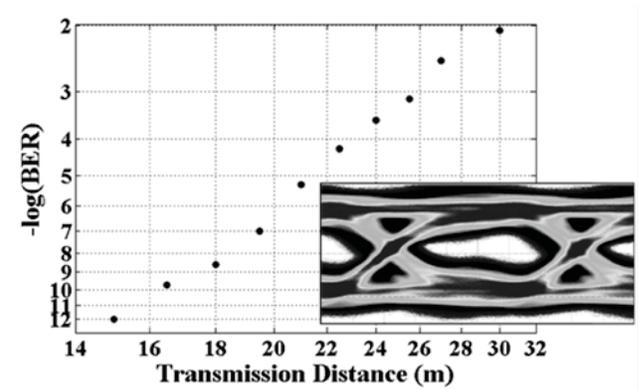


Fig. 14. Measured BER as a function of wireless transmission distance for an indoor 60 GHz wireless system with a fiber distribution scheme incorporating a dual-wavelength SBS laser.

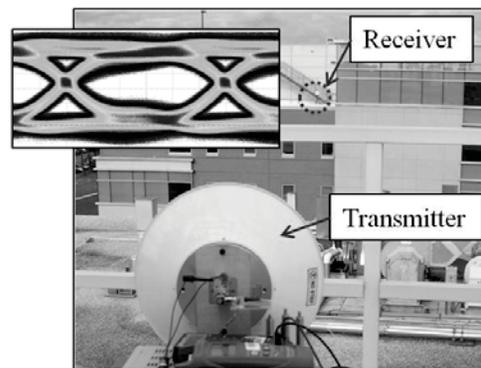


Fig. 15. Photograph of the outdoor building-to-building 60 GHz wireless link experiment with a fiber distribution scheme incorporating a dual-wavelength SBS laser.

experiment the transmitter was placed on the roof of one building and the receiver on the roof of a second building with a wireless transmission distance of approximately 78 m. Fig. 15 shows a photograph of the set-up and the measured eye diagram of the recovered data highlighting the low BER achieved; less than 10^{-12} . The indoor and outdoor wireless link distances that could be achieved using this experimental set-up were determined by the receiver sensitivity of -55 dBm. In addition, the bandwidth of some of the receiver components limited the data bandwidth to less than 3 Gb/s.

The fiber remoted RRH of a 60 GHz small cell requires an efficient radiating solution where the antenna is capable of providing both high gain as well as the typical radiation pattern required in a cellular infrastructure. Silicon-based phased arrays could provide a potential solution [46, 47] although a high gain, multi-beam technique may be more feasible. Fig. 16 shows the configuration of a printed quasi-Yagi antenna that has the potential to meet the bandwidth requirements of a 60 GHz RRH, while also being highly efficient. This is due to the traveling-wave nature of the antenna. A printed antenna lens configuration will also have low feed loss while featuring a small form factor to achieve high gain.

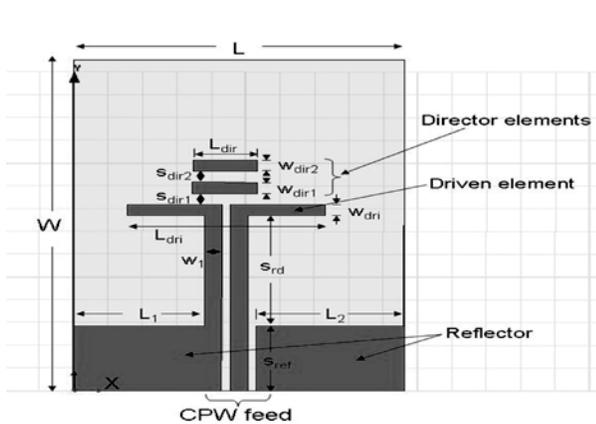


Fig. 16. Configuration of a coplanar waveguide-fed quasi Yagi antenna.

Fig. 17 shows the concept of the overall radiating structure created for a fiber distributed 60 GHz RRH. It incorporates a feed array of printed quasi-Yagi antennas with an extended hemispherical lens to achieve the appropriate radiation pattern, while the dielectric layers used to create the antenna are

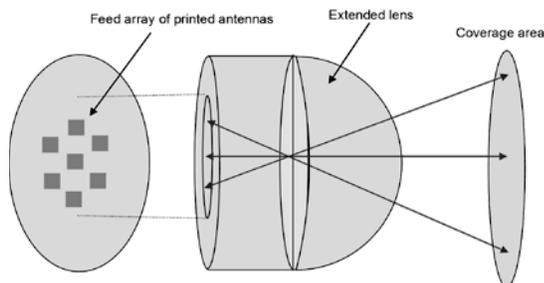
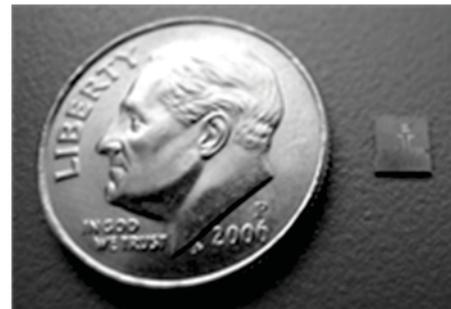


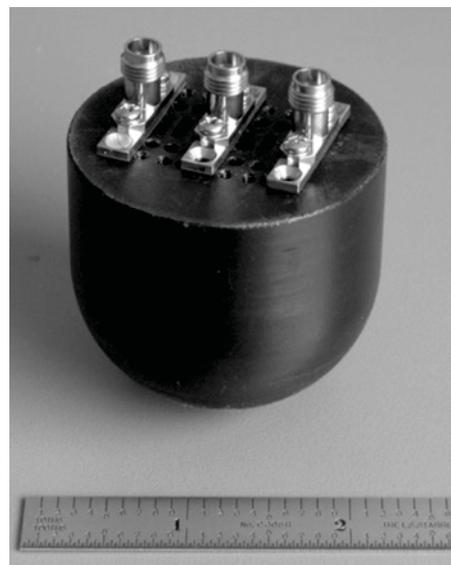
Fig. 17. Multiple beam lens based radiator structure created for fiber distributed 60 GHz small cells.

optimized to ensure maximum radiation efficiency. Nine slot positions provide the antenna with a multi-beam capability.

Fig. 18 shows a photograph of the developed 60 GHz antenna. The individual excitation radiator, the uni-planar quasi-Yagi printed antenna, is shown in Fig. 18(a). Here all the conductors, including the reflector element, were developed on a single layer and no broadband balun was used. A photograph of the 60 GHz multiple beam lens antenna that was developed based on the concept depicted in Fig. 17 is shown in Fig. 18(b). The extended hemispherical lens was made from polyethylene; the radius of the hemispherical part of the lens was 25 mm and the extension was 17 mm. To accommodate multiple quasi-Yagi antennas within the lens, slots were formed in the material. A total of nine slots were cut at a spacing of 3.5 mm to allow for wide beam coverage and minimal gain undulation between the beams. Fig. 19 shows the measured reflection coefficient of the developed quasi-Yagi 60 GHz printed antenna. The radiator had an operating frequency extending from 57 to 64 GHz with a gain of approximately 20 dBi.



(a)



(b)

Fig. 18. Photographs of a 60 GHz RRH multi-beam antenna: (a) uni-planar quasi-Yagi printed radiator element, and (b) multiple beam 60 GHz lens antenna.

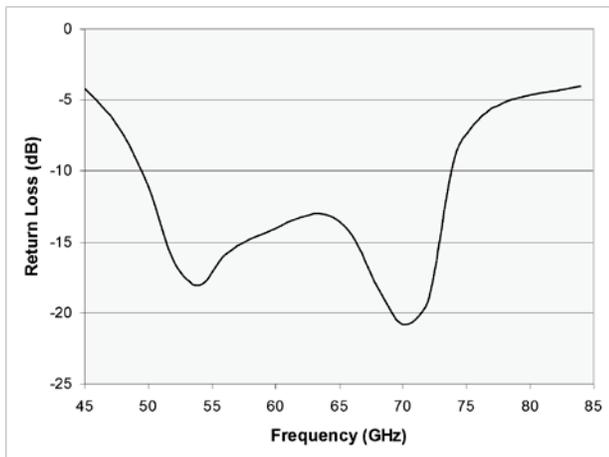


Fig. 19. Measured reflection coefficient of the developed 60 GHz multi-beam quasi-Yagi antenna.

Recently the focus in millimeter-wave wireless systems with radio-over-fiber distribution networks has shifted towards maximizing the wireless throughput, while still adhering to optical and wireless transmission standards [48 – 55]. In [48] multi-Gb/s NRZ OOK data rates were demonstrated using a coherent radio-over-fiber system which is compatible with existing PON architectures and uses a free-running laser diode at the remote antenna unit. In [49] wireless data rates in excess of 100 Gb/s were demonstrated using a combination of coherent optical techniques as well as polarization diversity. In [50] and [51] advanced DSP (digital signal processing) techniques were incorporated into a proposed mm-wave radio-over-fiber systems in order to realize high multi-Gb/s wireless data rates. These approaches, together with the array of technologies presented in this paper, will ensure that radio-over-fiber concepts will play an important role in emerging wireless systems. The high data rates proposed for future 5G networks also offer great opportunity for radio-over-fiber technologies, however much work still needs to be done to address the challenging requirements of very high bandwidth, extremely low latency and jitter, as well as very low cost.

V. CONCLUSION

Meeting current and future capacity demands and supporting multiple wireless standards continues to drive the evolution of wireless networks. Radio-over-fiber technologies have the potential to significantly impact the realization of converged optical/wireless networks for wireless systems operating at both microwave and millimeter-wave frequencies. Some of the technologies that are actively being explored and have the potential to significantly impact next generation converged networks include active antenna systems, centralized BBU architectures, and 60 GHz small cells. A major challenge in the successful realization of the optical distribution network for future wireless fronthaul will be the very large bit rates per cell site that must be supported between the RRH and BBU. The use of bandpass sampling

could help to reduce the link data rates while analog optical distribution networks may offer a viable alternative to conventional digital fiber optic links for next generation integrated networks.

The application of fiber remoting links for future 60 GHz wireless networks was also described. The use of a dual-wavelength optical source, such as a SBS fiber laser, in these systems can enable dispersion tolerant signal transport while also supporting the optical encoding and wireless transmission of high data rate signals.

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