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Review

Transport Schemes for Fiber-Wireless Technology: Transmission Performance and Energy Efficiency

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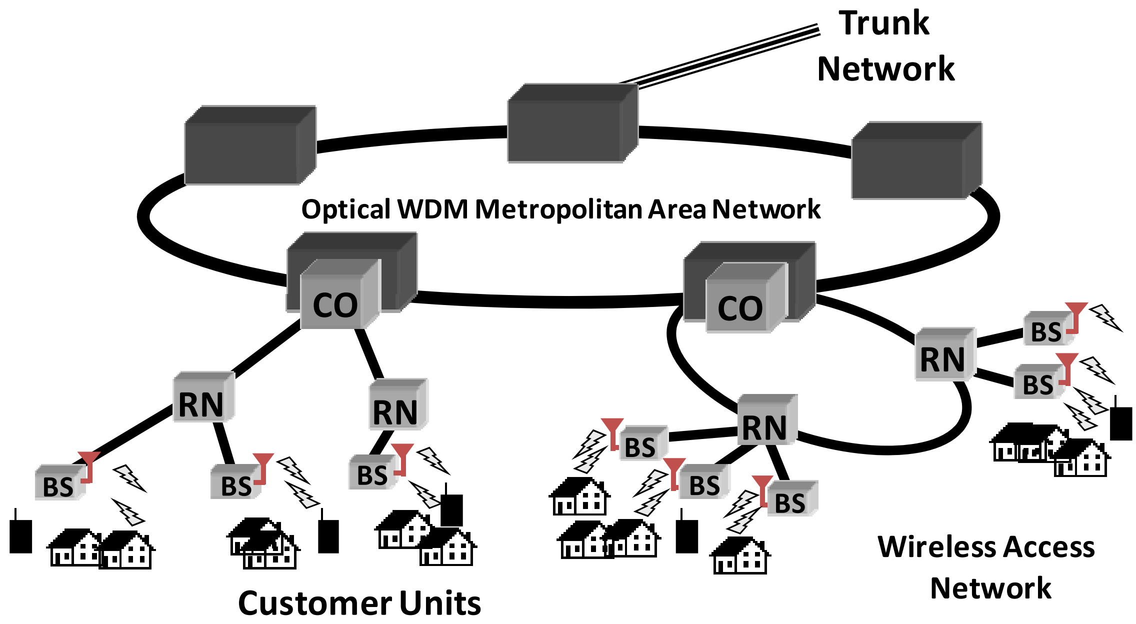
Abstract: Fiber-wireless technology has been actively researched as a potential candidate for next generation broadband wireless signal distribution. Despite the popularity, this hybrid scheme has many technical challenges that impede the uptake and commercial deployment. One of the inherent issues is the transport of the wireless signals over a predominantly digital optical network in today's telecommunication infrastructure. Many different approaches have been introduced and demonstrated with digitized RF transport of the wireless signals being the most compatible with the existing optical fiber networks. In this paper, we review our work in the area of digitized RF transport to address the inherent issues related to analog transport in the fiber-wireless links and compare the transmission performance and energy efficiency with the other transport strategies.

Keywords: fiber-wireless; radio-over-fiber; digitized RF transport

1. Introduction

Fiber-wireless technology has gained significant momentum as the "last mile connectivity" in the last two decades in order to address the increasing demand for larger capacity and faster transmission speeds, fuelled by the proliferation of affordable smart phones and tablets packed data-intensive multimedia applications [1–3]. In addition, this hybrid technology is able to leverage on existing optical fiber infrastructure and, hence, is able to unify the telecommunication backhaul infrastructure by using a common backhaul network to support both wired and wireless services. Figure 1 illustrates a typical infrastructure of a fiber-wireless system with a central office (CO) serving multiple base stations (BSs) interconnected by high speed optical fiber based backhaul while the BSs serve end users wirelessly. It is well-established that centralized control in fiber-wireless system enables simple, low-cost design antenna base stations to be widely deployed where most hardware intelligence are located in a central location.

Figure 1. Fiber-wireless network.



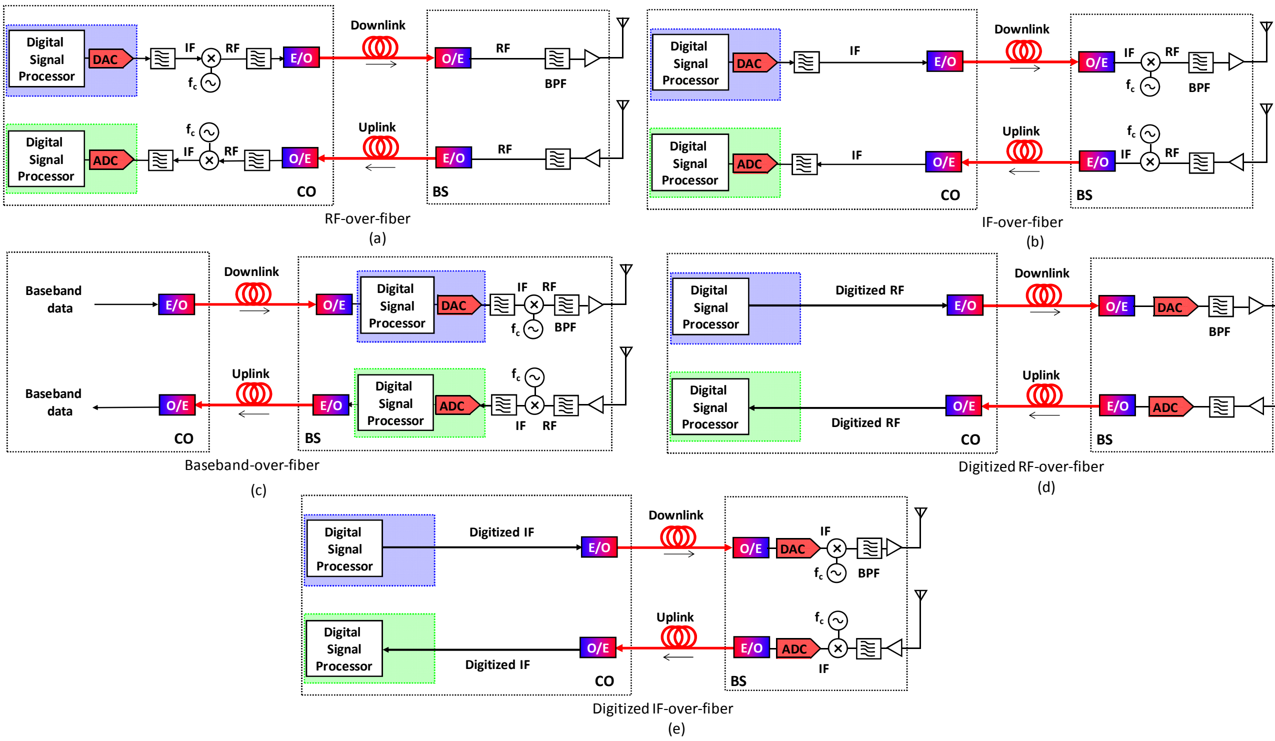
One strategy to establish centralized control is to optically distributing the wireless signals at the wireless carrier frequencies in an analog fashion. Despite the elegance of the hybrid fiber-wireless infrastructure, the performance is limited by the inherent properties of analog optical link [3,4]. Although many techniques have been proposed to improve the performance of analog optical links for the transport of wireless signals including linearization [5–10], predistortion [11], and modulation depth optimization [12–15], they demand for complex implementation with precise control which negates the cost effectiveness of fiber-wireless scheme.

We have previously demonstrated an alternative transport scheme based on digitization of the wireless signals using bandpass sampling technique [16,17] to improve the fiber-wireless link dynamic range and to overcome the inherent issues of analog optical link. In this paper, we review the work we have carried out in this area in particular focusing on strategies to improve the performance, capacity and energy efficiency of fiber-wireless links with respect to other transport schemes. The paper is organized as follows. Section 2 describes and reviews the different transport schemes with respect to their roles and the base station configurations in fiber-wireless link, and Section 3 presents the experimental investigations comparing analog optical transport *versus* digitized transport based on bandpass sampling technique for the transmission of broadband wireless OFDM signals. Section 4 governs the study and quantification of energy consumption for different transport schemes with respect to base station site power consumption and wireless cell size.

2. Wireless Signals Transport Strategies for Fiber-Wireless Link

To understand how wireless signals are distributed in a fiber-wireless link, Figure 2 shows the different link configuration for a simple point-to-point transmission connecting a CO and an antenna BS. Regardless of the wireless carrier frequencies, the wireless signals can be distributed based on five transport schemes namely RF-over-fiber (RFoF), IF-over-fiber (IFoF), Baseband-over-fiber (BBoF), Digitized RF-over-fiber (DRFoF) and Digitized IF-over-fiber (DIFoF) as shown in Figure 2.

Figure 2. Schematic showing the transport scheme for (**a**) RF-over-Fiber (RFoF) (**b**) IF-over-Fiber (IFoF) (**c**) Baseband-over-Fiber (BBoF) (**d**) Digitized RF-over-Fiber (DRFoF) (**e**) Digitized IF-over-Fiber (DIFoF).



The simplest scheme for transporting wireless signals via an optical fiber backhaul network is to directly transport the wireless signals at the wireless carrier frequency without any further frequency processing at the base station via RF-over-fiber transport scheme (Figure 2a). In this configuration, the wireless signals are modulated onto an optical carrier and the optically modulated wireless signals are transported in an analog format over the optical link. RF-over-fiber has the advantage of simple base station design with added benefits of centralized control, wireless signal transparency and multi-band wireless support. However one of the major drawbacks is the needs for optical devices with speeds matching that of the wireless carrier frequency which becomes more stringent for wireless signals beyond the microwave bands. It is also well-established that optically modulated wireless signals suffers from fiber chromatic dispersion which degrades the received RF power and limits the fiber transmission distance [18,19].

In contrast, IF-over-fiber transport scheme transports the wireless signals at a lower intermediate frequency (IF) over the optical platform (Figure 2b) which in turn relaxes the requirements for high-speed optoelectronic hardware. The optical distribution of the IF signals also has a much reduced fiber chromatic dispersion impact. However this is at the expense of a more complex antenna BS design where it necessitates a stable local oscillator (LO) and mixers for frequency translation purposes.

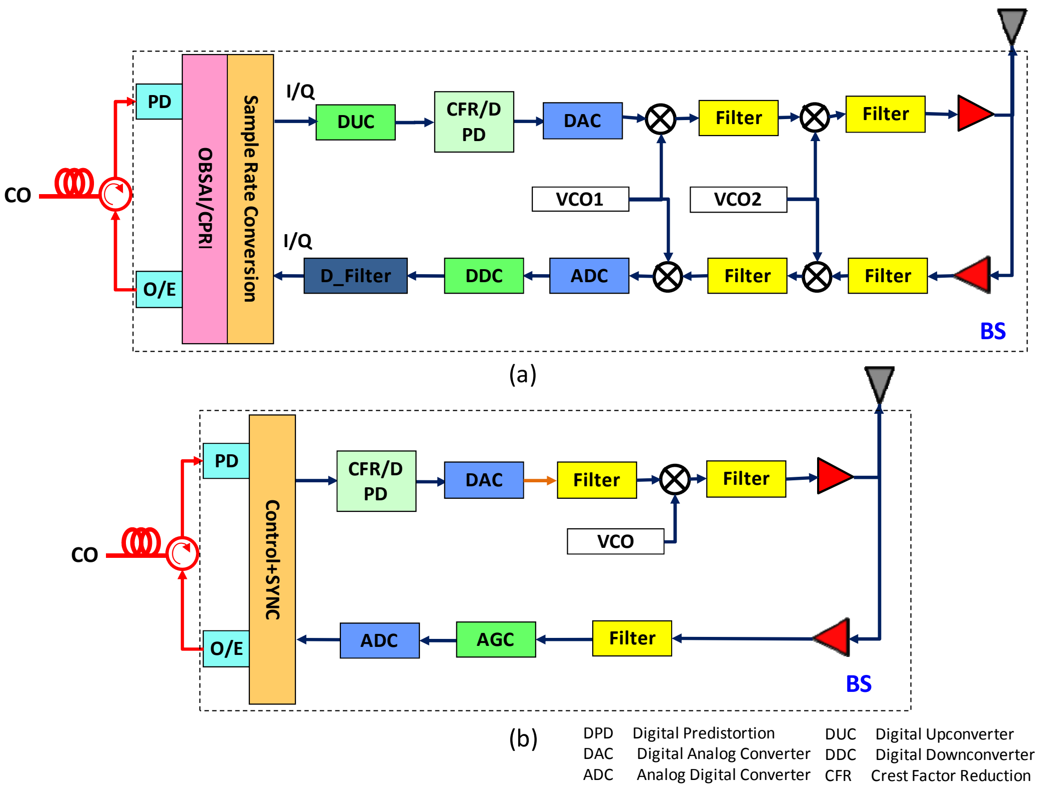
Figure 2c shows the architecture for baseband-over-fiber transport where the wireless signal is transported as baseband data optically and the wireless signal is processed entirely at the antenna BS. This transport scheme is compatible to existing optical networks where data are transmitted in a predominantly digital environment. Despite the simplicity in the optical domain, the antenna BS for baseband-over-transport has to house additional hardware to electronically process the wireless signals which increases the BS complexity while decreases the link transparency. In the recent years, a new transport scheme based on digitization of the wireless signals have been proposed and demonstrated [16] for fiber-wireless application that exploits the superior digital optical links while maintaining a relatively simple BS design. As opposed to baseband-over-fiber transport where the wireless signals are transported at the information level and all signal processing are carried out in the antenna BS, digitized wireless transport essentially digitized the wireless signals before the optical transport. Digitized wireless transport can be further classified into Digitized RF-over-fiber (DRFoF) transport and Digitized IF-over-fiber (DIFoF) transport.

Digitized RF-over-fiber scheme as illustrated in Figure 2d digitizes the wireless signal to produce a sampled digital data stream in a serial format that can directly modulate the optical source. This enables the use of digital photonic link to transport the wireless signals overcoming the inherent issues related to analog photonic links. Since the wireless signals are transported in a digital format, the dynamic range of the optical link is independent of the fiber transmission distance until the received signal goes beyond the link sensitivity. In this scheme, the complex signal processing functionality is carried out in the CO while only a minimal set of frontend components consisting of the analog-to-digital (ADC) and digital-to-analog (DAC) converters are located in the antenna BS. The link is able to maintain its transparency as the BS does not require full processing of the wireless signals. The key enabler for this scheme is the ADC/DAC technology. To digitize the wireless signals, the analog bandwidth of the ADC must be larger than the wireless carrier frequency and with sufficient sampling rate and resolution. This requirement becomes more stringent for wireless signals beyond the microwave bands. To overcome this limitation, digitized IF-over-fiber is introduced whereby the wireless signal is first downconverted to an IF frequency to cater for the limitations of current ADC technology. This scheme is depicted in Figure 2e.

Open base station architecture initiative (OBSAI) [20] and Common Public Radio Interface (CPRI) [21] are two initiatives to create an open market for cellular networks by providing specifications for interface of wireless base stations. OBSAI and CPRI are based on digitized IF-over-fiber scheme and the base station architecture is shown in Figure 3a. In the downlink direction, the optical digital datastream is recovered using a photodetector (PD) and digitally processed before the analog signal at an IF frequency is reconstructed using a DAC. The wireless signal is then generated after two stages of frequency upconversion process. Likewise in the uplink direction, the wireless signal is downconverted using two frequency translation stages before the IF signal is digitized, processed and modulated onto an optical carrier to be transported back to the CO.

We can further relax the requirements on the ADC technology by using bandpass sampling technique [22] rather than direct sampling, especially given that for most wireless applications the required information bandwidth is only a small fraction of the wireless carrier frequency. Bandpass sampling undersamples the wireless signal using a much lower sampling frequency that is comparable to the wireless information bandwidth instead of the wireless carrier frequency [22]. Therefore upon sampling, it will generate an infinite number of image replicas of the wireless signal. The sampling frequency has to be carefully chosen to minimize noise aliasing from adjacent images. Since an infinite number of image replicas are generated, the wireless signal can be recovered using appropriate bandpass filter. Hence we are able to perform frequency translation without using LO and mixers. Shown in Figure 3b is the BS architecture of a fiber-wireless link incorporating digitized IF-over-fiber transport based on bandpass sampling. The benefit of using bandpass sampling reflects in the uplink path where no frequency translation stage is required which can further simplify the base station design.

Figure 3. Possible base station configuration for (**a**) digitized IF-over-Fiber transport and (**b**) digitized IF-over-Fiber transport incorporating bandpass sampling technique.



3. Transmission Experiment Comparing Analog and Digitized RF-over-Fiber Transport

Numerous transmission demonstrations have been carried out for different transport schemes to quantify the performance of the fiber-wireless link with the main focus on increasing the transmission capacity, improving the link dynamic range and transmission distance [23–27]. One strategy to increase the transmission capacity is to efficiently utilize the wireless bandwidth by incorporating advanced modulation format in conjunction with broadband orthogonal frequency-division-multiplexing (OFDM). The demand for larger transmission capacity is driven by the emergence and proliferation of bandwidth-hungry applications such as real-time high-definition video streaming and graphic intensive online gaming.

OFDM with its inherent advantages of spectral efficiency, immunity to multipath fading and dispersion tolerance, is currently the leading modulation for current wireless standards ranging from

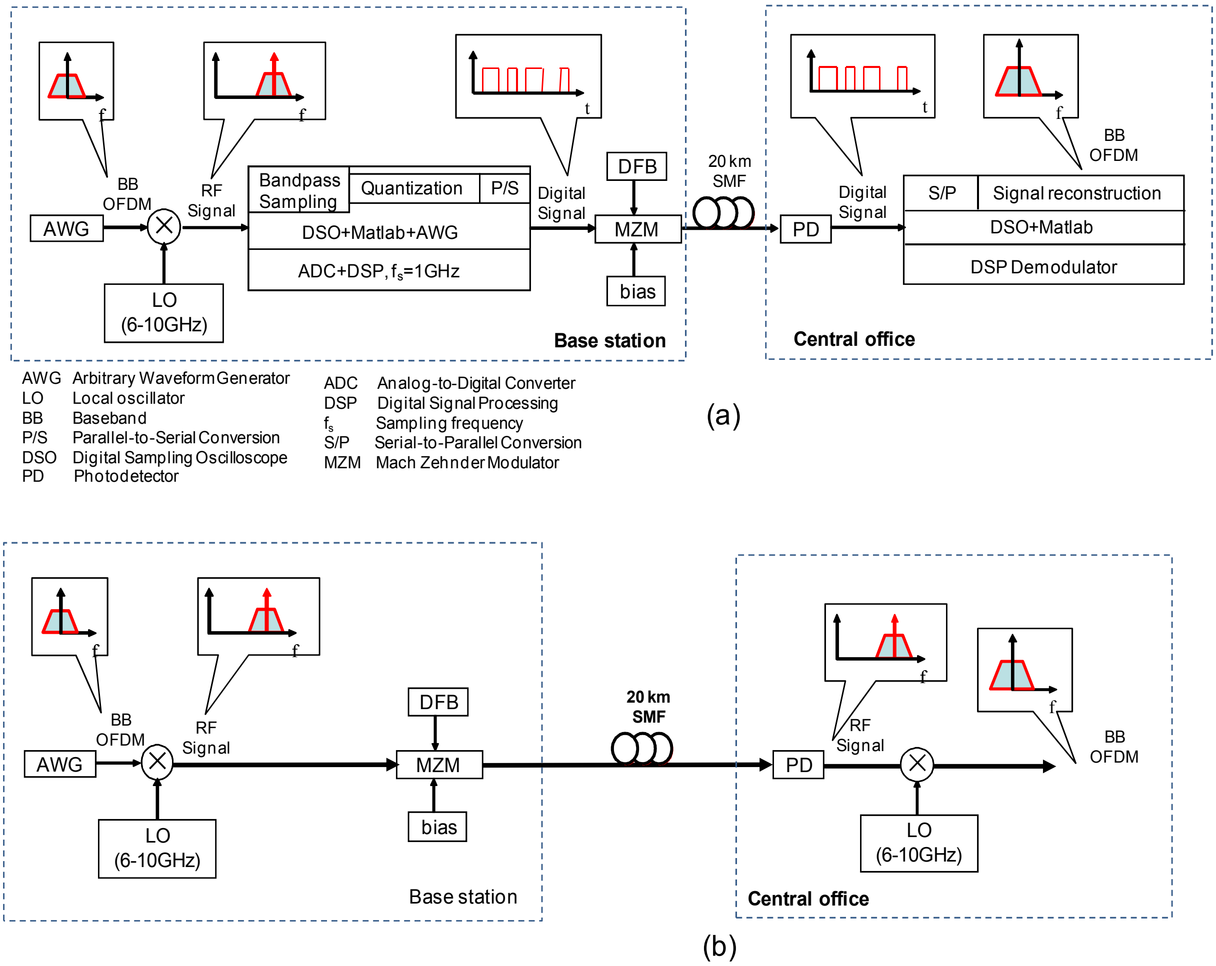
3GPP Long Term Evolution (LTE) to personal area network ultra-wideband (UWB). The multi-carrier nature of OFDM demands for highly linear transmission link with the ability to handle large peak-to-average power (PAPR). This requirement becomes more stringent for wideband (>1 GHz) signals. Although many different demonstrations have been carried out for the distribution of OFDM signals over fiber-wireless links using analog optical transport [28–33], the linearity requirement has necessitates the use of low modulation depth which leads to large received DC power at the photodetector and hence, power wastage. On the other hand, digitized transport may emerge as an ideal candidate for the distribution of broadband OFDM signals in fiber-wireless links which overcomes the nonlinearity issue associated with analog transport. However, the needs for highspeed ADC and DAC coupled with excessive optical bit rate after digitization may render the digitized transport scheme unattractive. Given the pros and cons of the analog and digitized transport, we have previously carried out an experimental comparison for the distribution of a 1 GHz OFDM signal using both analog and digitized RF-over-fiber transport schemes [34].

3.1. Experimental Demonstration

Shown in Figure 4a is the experimental setup for the uplink broadband wireless OFDM signal transmission over a fiber-wireless link incorporating digitized RF-over-fiber transport [34]. In this demonstration, the baseband (BB) OFDM was programmed in Matlab and physically generated using an arbitrary waveform generated (AWG). To avoid using high-speed I/Q mixers, we make corresponding frequency components conjugate complex to ensure Q equal to zero all the time. The signal bandwidth was limited to 1 GHz and there were 128 carriers with 80 being modulated with 4-QAM data, resulting in a data rate of 1.25 Gb/s. The OFDM signal was upconverted to 10 GHz using a local oscillator (LO) to generate the 10 GHz broadband OFDM wireless signal. In the BS, the OFDM signal at 10 GHz was bandpass sampled using an 8-bit and 1 GSample/s ADC in a digital sampling oscilloscope (DSO). After bandpass sampling, the samples were quantized, serialized and processed offline before the digital data was generated using an AWG. Here the 10 GHz OFDM signal was converted to an 8 Gbps digital data stream. For this demonstration, a DFB laser in conjunction with a Mach-Zehnder (MZM) was used to modulate the digital data stream onto an optical carrier before it was transported over 20 km of standard fiber (SMF). In the CO, the optical signal was detected with a PIN photodetector and the digital data stream was processed offline.

For comparison, the same 10 GHz OFDM signal was distributed using analog RF-over-fiber transport scheme and the experimental setup is shown in Figure 4b. The upconverted OFDM signal was externally modulated onto the optical carrier using a MZM before transported over 20 km of SMF. Upon reception at the CO, the received 10 GHz OFDM was downconverted to baseband and processed offline. In order to maintain good link linearity, the peak-to-peak driving voltage of the RF signal into the MZM was fixed at one tenth of the MZM switching voltage (Vpi). This corresponds to a modulation depth of 0.16.

Figure 4. Experimental setup for (**a**) digitized RF-over-fiber transport and (**b**) analog RF-over-fiber transport of wideband OFDM signal. © [2008] IEEE. Reprinted, with permission, from *IEEE OSA Lightwave Technology, Journal.*

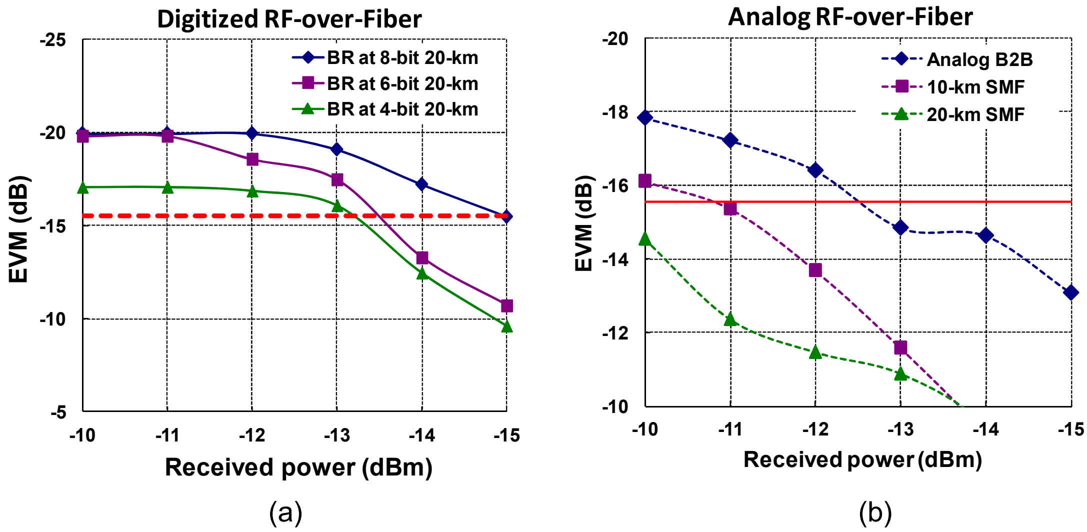


3.2. Experimental Results and Discussions

Shown in Figure 5a is the measured error vector magnitude (EVM) plotted as a function of received optical power (dBm) for digitized RF-over-transport after transmission over 20 km of SMF for a bit resolution of 8 bits. Also plotted are results for an ADC bit resolution of 4 and 6 bits [34]. The dotted line indicates error-free reception for 4-QAM signal (corresponding to a bit-error-rate of 10^{-12}). The results indicate that the performance of the link is not sensitive to the received optical power until the received optical power goes beyond the link sensitivity whereby the performance degrades drastically with decreasing optical power. For a 4-bit resolution, a minimum received optical power of −13 dBm is needed to achieve error-free transmission. The same trend was seen for 6-bit and 8-bit resolution but with better EVM performance and lower received optical power requirement (−13.5 dBm and −15 dBm).

Figure 5b shows the measured EVM for the analog RF-over-fiber transport of the OFDM signal for transmission over 0, 10 and 20 km of SMF [34]. The performance of the analog link degrades steadily with increasing transmission distance and with decreasing received optical power. Error-free reception is only possible for a received optical power of >−11 dBm for a transmission distance of 10 km and is not achievable for 20 km of SMF for received optical power <−10 dBm. Comparing the two results from Figure 5a,b, we can see that for an error-free transmission over 20 km of SMF analog RF-over-fiber requires higher received optical power compared (>−10 dBm) to digitized RF-over-fiber transport (−15 dBm for 8-bit resolution). Even for a 4-bit ADC resolution, optical bit rate of 4 Gb/s and received optical power of −13 dBm, the digitized RF-over-fiber link outperforms the analog link distributing the same OFDM signal at 10 GHz with an received optical power of −10 dBm.

Figure 5. Error vector magnitude measured for (**a**) digitized RF-over-fiber transport and (**b**) analog RF-over-fiber transport over 20 km of fiber. © [2008] IEEE. Reprinted, with permission, from *IEEE OSA Lightwave Technology, Journal.*



4. Energy Consumption of Different Transport Schemes

Despite the fact that digitized transport is more superior in terms of dynamic range performance compared to analog transport, other factors such as energy consumption have to be taken into consideration. Telecommunication networks have been identified as one of the major contributors to the overall ICT energy consumption with wireless access network being the largest contributor to CO_2 emissions [35–37]. With the wireless base station contributing approximately two-thirds of the CO_2 emission, it is imperative to first reduce and optimize the energy consumption of wireless base station in order to minimize the carbon footprint [35–39]. On the other hand, the proliferation of smart devices in recent years has put a massive burden on our current mobile networks. The most straightforward upgrade is to reduce the cell size and increase the number of mobile base stations. However this will further increase the proportion of base station energy consumption, further compounding the energy crisis. To address this issue we introduce fiber-wireless technology with optical fiber backhauling the small cells with majority of the processing power located in a central location. This architecture results in a simple, compact and energy-efficient base station.

4.1. Single Base Station Energy Consumption for Different Transport Schemes

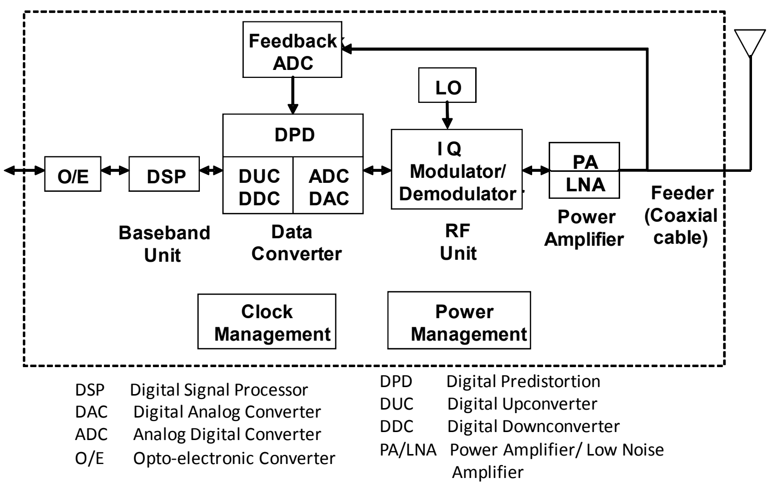
To quantify the energy consumption of the fiber-wireless network, we investigate the energy consumption per square meter for the transport schemes discussed in Section 2. We have previously presented a generalized power consumption model for fiber-wireless base stations [40] that supports a variety of wireless transport schemes. Shown in Figure 6 is the conventional base station architecture based on baseband-over-fiber transmission scheme. It consists of Baseband Unit (BBU), Data Converter Unit, RF unit, Power Amplifier, Feeder, Clock Management, Power Supply and Battery Backup, and Cooling System. The power consumption of this base station can be calculated using Equation (1) and Table 1 shows the power consumption of each unit approximated using commercially available devices [40].

$$P_{BBoF} = N_{sector} \times (P_{Tx} / \mu_{PA} / L_{feeder} + P_{BBU} + P_{DDC/DUC} + P_{ADC/DAC} + P_{DPD} + P_{RFU} + P_{M}) \times (1 + L_{PS}) \times (1 + \mu_{C}) \quad (1)$$

Table 1. Parameters used in base station model.

Parameter	Estimated Value	Parameter		Estimated Value
Power consumption of baseband unit (P_{BBU})	58 W	PA efficiency (μ_{PA})	BBoF, DIFoF, DRFoF	25%
			IFoF, RFoF	15%
Power consumption of DUC/DDC ($P_{DUC/DDC}$)	3 W	Transmitting power (P_{TX})		40 W
Power consumption of ADC/DAC ($P_{ADC/DAC}$)	2 W	Feeder loss (L_{feeder})	BBoF	0.5
			IFoF, RFoF, DIFoF, DRFoF	1
Power consumption of digital pre-distortion (P_{DPD})	5 W	Power supply loss (L_{PS})		0.15
Power consumption of RF unit (P_{RFU})	2 W	Cooling efficiency (μ_C)		0.2
Power consumption of clock management (P_C)	1 W	Number of sectors (N_{sector})		3

Figure 6. Conventional base station architecture incorporating BBoF transport scheme.



Based on the assumption that the power for each unit remains the same regardless of the transport scheme, the model can be further applied to analog RF-over-fiber (RFoF), analog IF-over-fiber (IFoF), digitized RF (DRFoF) and IF-over-fiber (DIFoF) schemes where the detailed base station architectures are shown in Figure 7a–d. It is also noted that in this study, the same ADC/DAC specifications were used for both DRFoF and DIFoF. The power consumption of the ADC/DAC is predominately determined by the bit resolution used which is the same for both DRFoF and DIFoF in this study. Plotted in Figure 8 is the power consumption per base station as a function of base station transmitting power for different fiber-wireless transport schemes [40]. From the results, it can be seen that for single base station, baseband-over-fiber transport consumes the most power while digitized RF/IF-over-fiber transport exhibit an advantage in energy-saving especially at high transmitting power.

Figure 7. Base station architectures for (**a**) Analog RF-over-fiber (RFoF) (**b**) Analog IF-over-fiber (IFoF) (**c**) Digitized RF-over-fiber (DRFoF) and (**d**) Digitized IF-over-fiber (DIFoF).

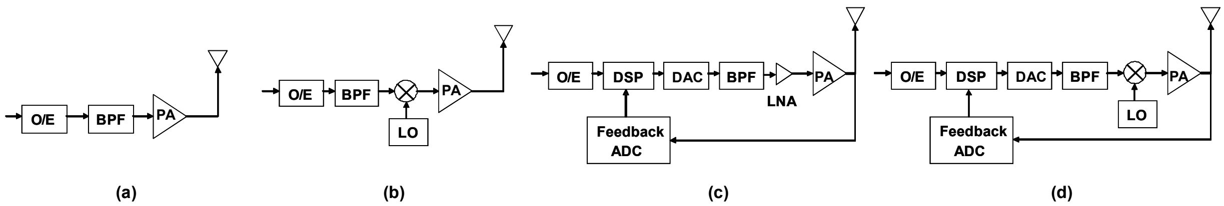
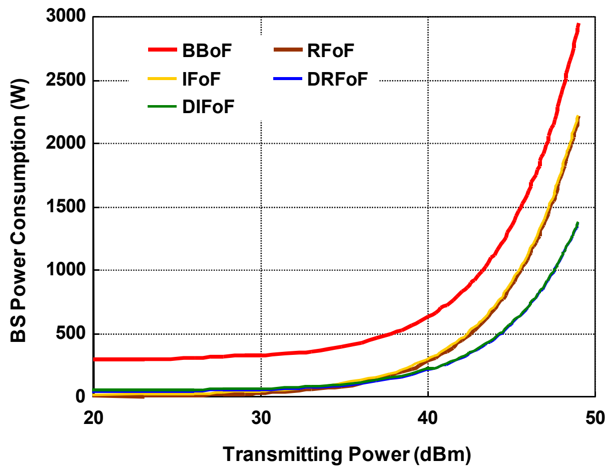


Figure 8. Base station power consumption as a function of transmitting power for the five different transport schemes investigated.



4.2. Energy Consumption per Unit Coverage

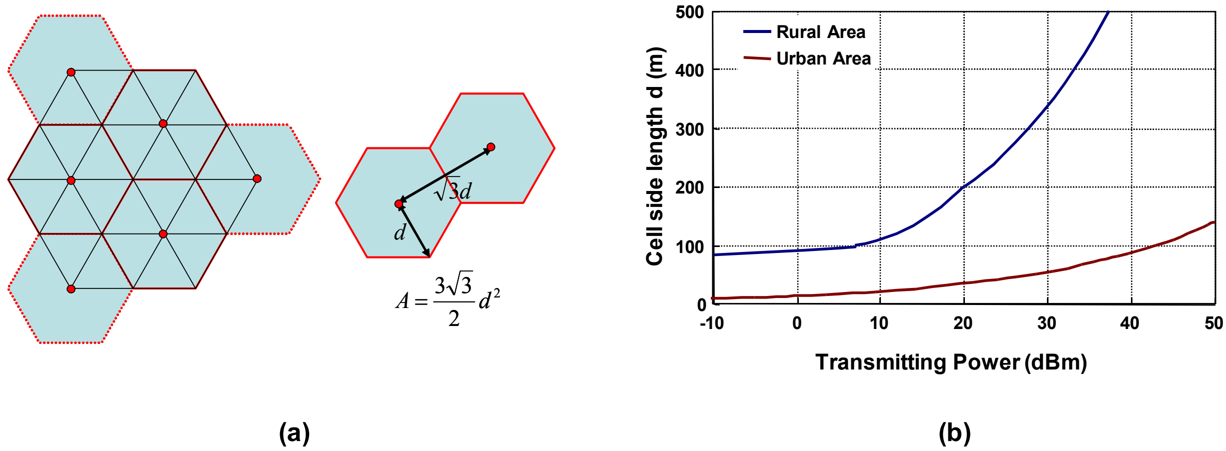
To establish a more realistic and practical evaluation on power consumption for fiber-wireless network, we have also studied the energy consumption per base station coverage [41]. Here we model the mobile wireless network as an infinite regular grid of sites characterized by the size distance, generating equally sized hexagonal cell structures of side length *d* as shown in Figure 9a. Each hexagonal cell represents the coverage of a base station which is located in the center of the cell at a distance of $3\sqrt{3}/2d^2$. To ensure that the entire cell is covered, the transmitting power (P_{TX}) has to be greater than the customer's receiver sensitivity (P_{RX}) after taking into account the propagation loss (*PL*) over a distance of *d*. The *PL* quantifies the wireless signal deterioration due to path loss, shadowing and multipath fading which can be formulated into Equation (2) [42]. The value is dependent on man-made structures [42,43] and hence, is different for different areas. Using the estimated parameters in [44] and Equation (2), we are able to estimate the propagation losses for rural and urban areas which are quantified by Equations (3) and (4). Figure 9b shows the maximum cell side lengths (d) at different transmitting power in both rural and urban areas for a typical receiver sensitivity of −120 dBm. It is obvious that the cell size is much larger for rural area compared to urban area for the same base station transmitting power. Since the propagation models are different for urban and rural areas, we will investigate the power consumption per square meter as a function of cell size for both rural and urban areas separately.

$$PL = PL(d_0, f) + 10n\log(d/d_0) \quad (2)$$

$$PL_{rural}(dB) = 49 + 43.5\log(d) \quad (3)$$

$$PL_{urban}(dB) = 77 + 48\log(d) \quad (4)$$

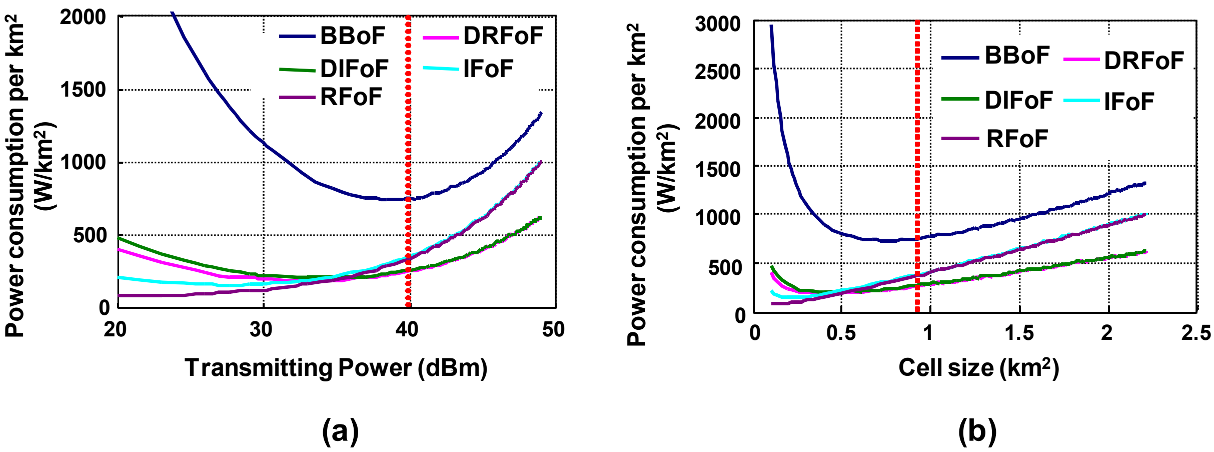
Figure 9. (**a**) Hexagonal cell coverage and the corresponding length measurement (**b**) Calculated cell side length *versus* transmitting power for rural and urban areas (With kind permission from Springer Science and Business Media).



4.2.1. Rural Area

Figure 10a,b show the power consumption per square km plotted as a function of base station transmission power (Figure 10a) and cell size (Figure 10b) for the five fiber-wireless transport schemes investigated [41]. The power consumption per square km for the five transport schemes investigated follows the same trend, where it first reduces and then increases with transmitting power (increasing cell size). There is an optimal transmitting power (cell size) associate with each transport scheme to achieve the lowest energy consumption. The optimal transmitting power for baseband-over-fiber transport scheme is ~40 dBm; for digitized RF/IF-over-fiber is ~33 dBm; and for analog RF/IF-over-fiber is ~22 dBm. Both results show that baseband-over-fiber transport scheme consumes the most power with regards to every square km. The power consumption per square km for the digitized and analog transport crosses at a transmitting power of ~34 dBm, which indicates that analog RF/IF-over-fiber transport scheme is more energy-efficient when the base station transmitting power is <34 dBm and digitized RF/IF-over-fiber is more efficient for transmitting power >34 dBm. This can be attributed to the additional power required for digital signal processing for digitized transport which is regardless of the base station transmitting power. For current macro base station used in rural areas, the transmitting power is at least 40 dBm [45] and this is indicated by the red line in Figure 10a,b. Hence for the cell size used in the rural area at present, the digitized RF/IF-over-fiber transport schemes are the most energy-efficient to service the rural area.

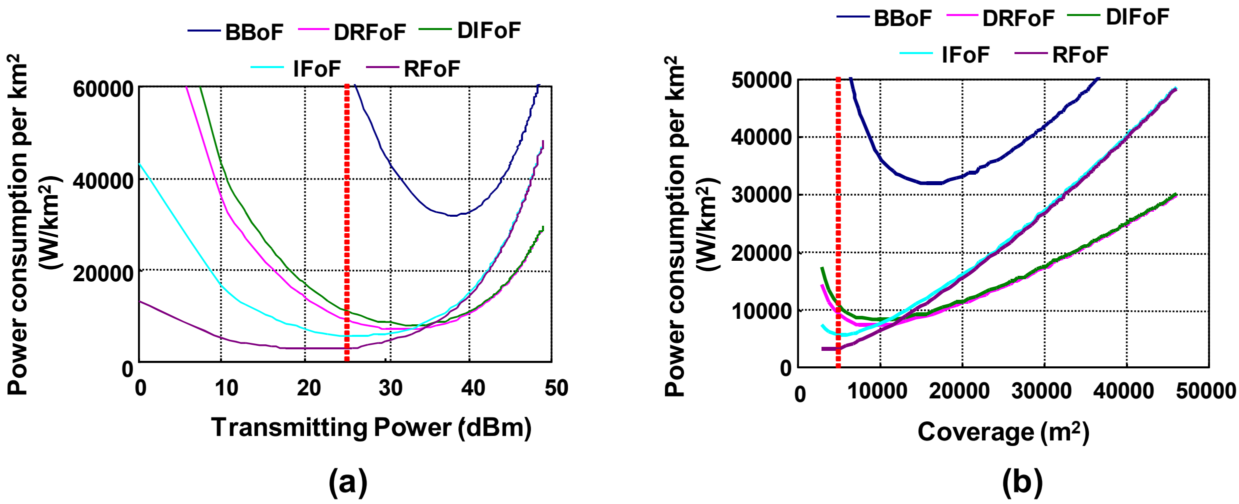
Figure 10. Power consumption per square km coverage for rural area for the five different transport schemes plotted as a function of (**a**) base station transmitting power and (**b**) cell size (With kind permission from Springer Science and Business Media).



4.2.2. Urban Area

Figure 11a,b show the power consumption per square km for the urban areas. Compared to Figure 10a,b, the results are significantly different even though they follow a similar trend. In the urban areas, the baseband-over-fiber scheme is still the most energy inefficient. Due to the high density of mobile users in the urban areas, micro base stations are commonly used with smaller cell size and lower transmitting power (<25 dBm) [45]. This falls on the left side of the red dashed line (transmitting power = 25 dBm) in Figure 11a,b. Therefore for the more dense urban areas where microcells are used, analog transport schemes are more energy-efficient compared to digitized transport; with analog RF-over-fiber being the most energy-efficient among the five schemes investigated.

Figure 11. Power consumption per square km coverage for urban area for the five different transport schemes plotted as a function of (**a**) base station transmitting power and (**b**) cell size (With kind permission from Springer Science and Business Media).


BBoF
DRFoF
DIFoF
IFoF
RFoF
Power consumption per km²
(W/km²)
Transmitting Power (dBm)
0
10
20
30
40
50
0
20000
40000
60000
(a)
Coverage (m²)
0
10000
20000
30000
40000
50000
(b)

5. Conclusions

This paper provides a comprehensive summary and review of some of the research that has been carried out by our research group in the area of fiber-wireless systems; in particular focusing on wireless signal transport schemes and power consumption. The main focus of these research activities has been directed towards the realization of high-performance and energy-efficient fiber-wireless links. The study shows that digitized transport scheme based on bandpass sampling has the potential to simplify the base station architecture while maintaining high link performance. We have demonstrated the transport of 1 GHz bandwidth OFDM signal at 6–10 GHz RF frequency via digitized transport. Error-free reception was achieved even at 4-bit ADC resolution and it outperformed the analog transport counterpart. We have also investigated the power consumption of the base station under different transport schemes for both rural and urban coverage. The study showed that although a digitized transport scheme resulted in better link performance, analog transport is more energy-efficient for urban areas using micro base stations with a transmitting power of <25 dBm. Digitized transport is more energy-efficient for rural environments with a transmitting power of >40 dBm.

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Authors Contributions

This review article was jointly written and proof-read by Christina Lim, Yizhuo Yang and Ampalavapillai Nirmalathas. The experimental results and modelling work were carried out by Yizhuo Yang who is the postdoctoral research staff employed with full supervision from Christina Lim and Ampalavanapillai Nirmalathas who are the chief investigators for this project. Christina Lim and Ampalavanapillai Nirmalathas are responsible for the progress of this project.

Conflicts of Interest

The authors declare no conflict of interest.

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