IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 2, July 2024

Energy-Efficient Transmission Strategies for Fiber-Wireless Networks: A Performance Evaluation

Rakesh Kumar Singh[1] and Dr. Shiv Prakash[2]
Research Scholar, Department of Physics[1]
Research Guide, Department of Physics[2]
NIILM University, Kaithal, Haryana, India

Abstract: *Research on fiber-wireless technology as a possible option for next-generation broadband wireless signal delivery is ongoing. The adoption and commercial implementation of this hybrid system are hindered by several technical issues, notwithstanding its popularity. In today's telecommunications infrastructure, one of the fundamental problems is the transmission of wireless signals via a mostly digital optical network. Numerous strategies have been presented and shown to function, with digital radio frequency transfer of wireless communications being the best suitable for the current optical fiber networks. In order to overcome the inherent problems with analog transport in fiber-wireless networks, we discuss our work in the field of digitized RF transport in this article. We also evaluate the energy economy and transmission performance of the various transport schemes*

Keywords: Fiber-Wireless (Fi-Wi) Networks, Transmission Performance

I. INTRODUCTION

Over the past 20 years, fiber-wireless technology has become increasingly popular as the "last mile connectivity" to meet the growing demand for higher capacity and faster transmission speeds, which has been fueled by the widespread use of reasonably priced smart phones and tablets with data-intensive multimedia apps. Additionally, by using the existing optical fiber infrastructure, this hybrid solution may handle both wired and wireless services by utilizing a single backhaul network to unify the telecommunications backhaul infrastructure. A typical fiber-wireless system's architecture is shown in Figure 1, where a central office (CO) serves many base stations (BSs) linked by high-speed optical fiber-based backhaul, while the BSs provide wireless service to end customers. It is well known that centralized control in fiber-wireless systems, where the majority of hardware intelligence is centralized, allows for the widespread deployment of low-cost, basic antenna base stations.

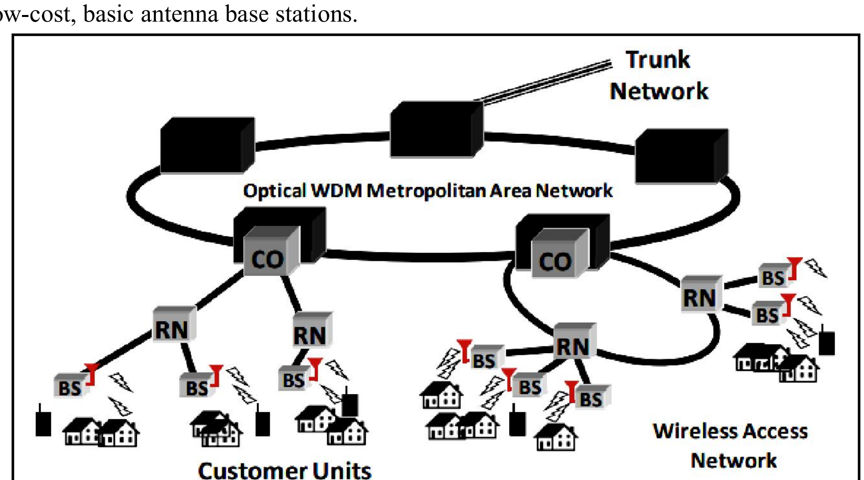


Figure: Fiber-wireless network

IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.53

Volume 4, Issue 2, July 2024

Analog optical distribution of wireless communications at wireless carrier frequencies may concentrate control. Despite the beauty of hybrid fiber-wireless infrastructure, analog optical connection qualities restrict performance. Many techniques have been proposed to improve analog optical links for wireless signal transport, including linearization, predistortion, and modulation depth optimization, but they require complex implementation and precise control, making fiber-wireless scheme less cost-effective.

We previously presented an alternate transport system that digitizes wireless signals using band pass sampling to increase fiber-wireless connection dynamic range and address analog optical link difficulties. This article reviews our efforts on improving the performance, capacity, and energy efficiency of fiber-wireless networks compared to conventional transport methods. The paper's structure follows. Section 2 discusses the roles and base station configurations of fiber-wireless transport schemes, and Section 3 presents experimental results comparing analog optical transport and digitized transport based on band pass sampling for broadband wireless OFDM signal transmission. Energy consumption for alternative transport strategies based on base station site power consumption and wireless cell size is studied and quantified in Section 4.

Wireless Signals Transport Strategies for Fiber-Wireless Link

In order to comprehend the distribution of wireless signals in a fiber-wireless connection, Figure 2 illustrates the various link configurations for a basic point-to-point transmission between an antenna base station (BS) and a CO. Five transport schemes RF-over-fiber (RFoF), IF-over-fiber (IFoF), Baseband-over-fiber (BBoF), Digitized RF-over-fiber (DRFoF), and Digitized IF-over-fiber (DIFoF) can be used to deliver wireless signals regardless of the wireless carrier frequencies, as seen in Figure 2.

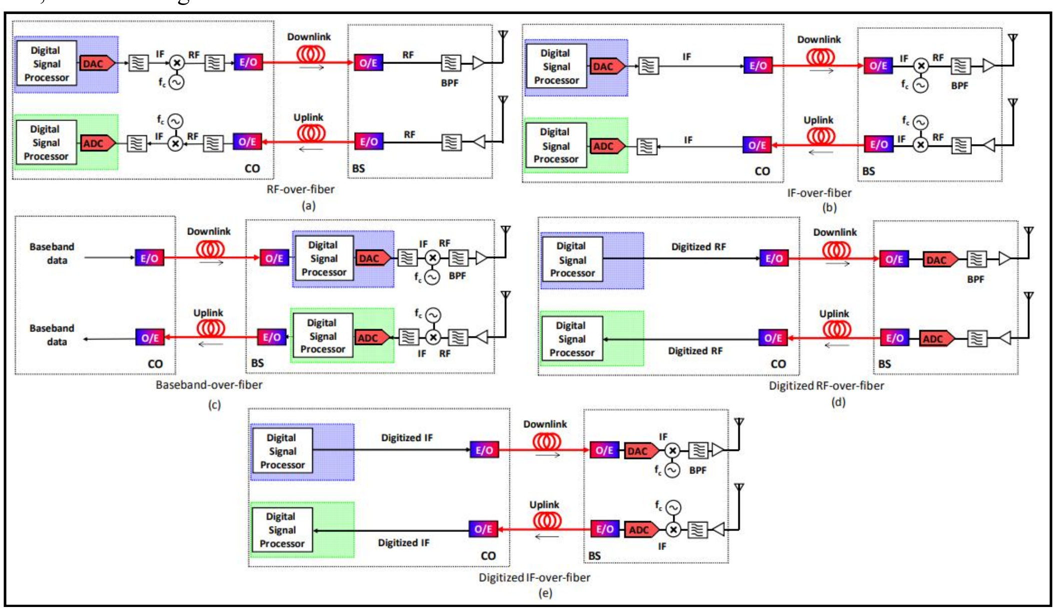


Figure: Schematic showing the transport scheme for (a) RF-over-Fiber (RFoF) (b) IF-over-Fiber (IFoF) (c) Baseband-over-Fiber (BBoF) (d) Digitized RF-over-Fiber (DRFoF) (e) Digitized IF-over-Fiber (DIFoF).

The fastest way to deliver wireless signals over an optical fiber backhaul network is RF-over-fiber transmission at the wireless carrier frequency without base station frequency processing (Figure 2a). Modulated optical carriers provide wireless messages analogly across optical links. Multi-band wireless, simplified base station architecture, centralized management, and wireless signal transparency are RF-over-fiber benefits. Wireless communications outside microwave bands need challenging carrier frequency-matching optical equipment. In optically modulated wireless communications, fiber chromatic dispersion reduces RF power and transmission distance.

IF-over-fiber transmission uses the optical platform to send wireless signals at a lower intermediate frequency (IF) to circumvent high-speed optoelectronic hardware restrictions (Figure 2b). Fiber chromatic dispersion decreases with IF signal optical distribution. Stable local oscillators (LO) and frequency translation mixers limit antenna BS design.

Fiber-based baseband transmission handles wireless signals at antenna BS (Figure 2c). Digital optical networks help transport. Although optically simple, baseband-over-transport antenna BSs need electronics to manage wireless signals, reducing connection transparency. Fiber-wireless transport systems use enhanced digital optical lines with BS architecture after wireless signal digitalization. Baseband-over-fiber transport handles wireless signals in the antenna BS, whereas digitized wireless transport processes them before optical transfer. Digital wireless transport uses RF/IF-over-fiber.

Digital RF-over-fiber serially samples wireless signal data to change the optical source (Figure 2d). Wireless communications without analog difficulties are possible with digital photonic links. Wireless communications are digital, therefore optical connection dynamic range is independent of fiber transmission distance until link sensitivity is exceeded. The CO processes complicated signals whereas the antenna BS employs ADC and DAC converters. The BS does not control wireless signals, therefore the connection is clear. The system employs ADC/DAC. To digitize wireless communications, ADC analog bandwidth must surpass carrier frequency, sample rate, and resolution. Wireless communications above microwave frequencies are restricted by this standard. To bypass ADC restrictions, digitized IF-over-fiber converts wireless communications to IF frequencies. Figure 2e shows the method.

Wireless base station interface standards CPRI and OBSAI allow open cellular networks. Figure 3a shows OBSAI and CPRI's digital IF-over-fiber base stations. A photo detector (PD) recovers and analyzes the optical digital data stream in the downlink before a DAC reconstructs the analog signal at an IF frequency. Two frequency up conversions generate wireless signals. The wireless signal uplink is down converted by two frequency translation operations before digitizing, processing, and modulating the IF signal into an optical carrier for CO delivery

Band pass sampling may reduce ADC technology requirements for most wireless applications since information bandwidth is a tiny fraction of wireless carrier frequency. Like wireless information bandwidth, band pass sampling samples wireless signals below the carrier frequency. Wireless signal images are duplicated endlessly. Local picture noise aliasing is reduced by smart sampling frequency. Band pass filters can recover wireless signals since limitless picture clones are made. Thus, frequency translation is possible without LO or mixers. Figure 3b shows the BS architecture of a fiber-wireless connection using band pass sampling-based digitized IF-over-fiber transmission. Uplink frequency translation is removed via band pass sampling, simplifying base station installation.

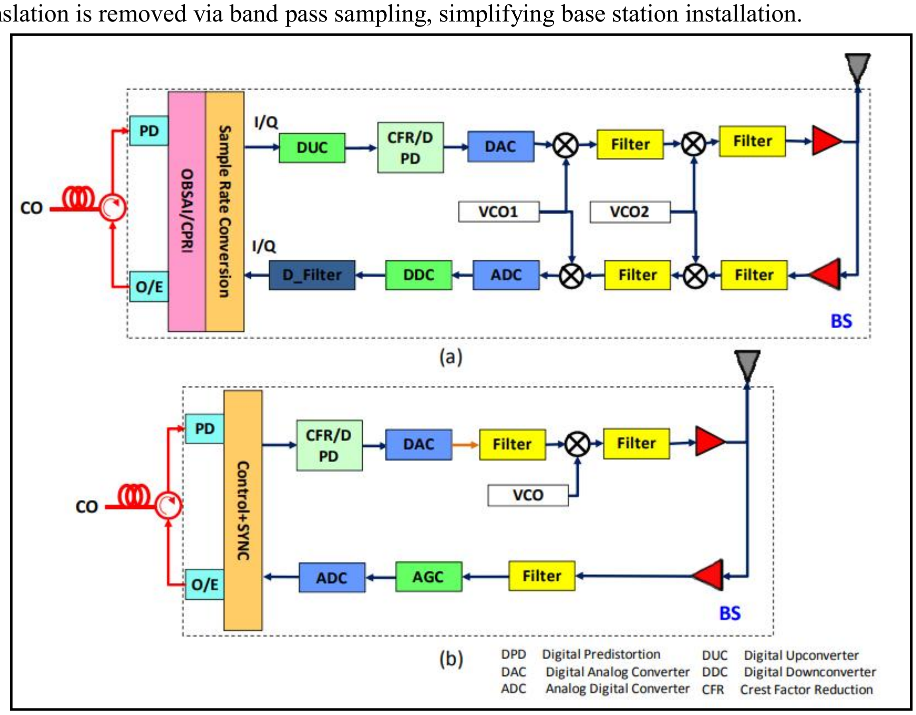


Figure: Possible base station configuration for (a) digitized IF-over-Fiber transport and (b) digitized IF-over-Fiber transport incorporating bandpass sampling technique.

IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.53

Volume 4, Issue 2, July 2024

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

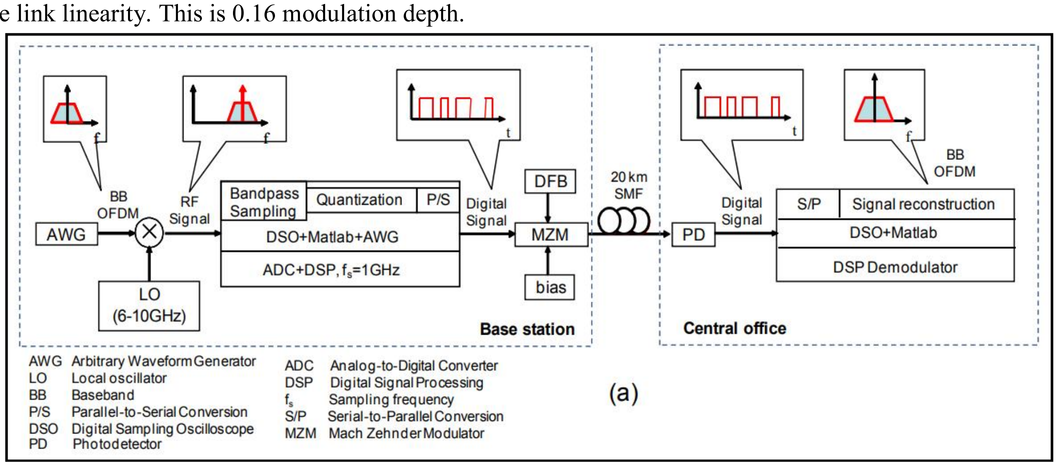
Transmission demonstrations for varied transport methods have increased transmission capacity, link dynamic range, and transmission distance to test fiber-wireless link performance. Optimizing wireless bandwidth using advanced modulation format and broadband orthogonal frequency-division-multiplexing may increase transmission capacity. Transmission capacity is rising due to bandwidth-intensive activities like real-time HD video streaming and graphic-intensive online gaming.

OFDM is chosen for 3GPP Long Term Evolution (LTE) to personal area network ultra-wideband because to its spectrum efficiency, multipath fading resistance, and dispersion tolerance. OFDM's multi-carrier nature necessitates a linear transmission link that can handle high peak-to-average power. Wideband (>1 GHz) communications have greater requirements. Analog optical transport has distributed OFDM signals across fiber-wireless networks in several instances, however linearity demands low modulation depth, which consumes photo detector DC power. Avoiding nonlinearity, digitized transport may be ideal for broadband OFDM signal distribution in fiber-wireless networks. High-speed ADC and DAC and high optical information rate after digitization may make digitized transport unattractive. Our previous experiment investigated the dispersion of a 1 GHz OFDM signal using analog and digital RF-over-fiber transport methods, considering their pros and cons.

Experimental Demonstration

Figure 4a shows the experimental setup for uplink broadband wireless OFDM signal transmission via a fiber-wireless connection with digitized RF-over-fiber transport. This Matlab-programmed baseband (BB) OFDM was physically created using an arbitrary waveform. We create frequency components conjugate complex to guarantee Q is always zero to prevent high-speed I/Q mixers. With 128 carriers and 80 4-QAM modulated carriers, the signal bandwidth was 1 GHz and the data throughput was 1.25 Gb/s. A local oscillator (LO) up converted the OFDM signal to 10 GHz to create the broadband OFDM wireless signal. An 8-bit, 1 G Sample/s ADC in a digital sampling oscilloscope band pass sampled the 10 GHz OFDM signal in the BS. Quantize, serialize, and process the samples offline after band pass sampling before generating digital data with an AWG. A 10 GHz OFDM signal was transformed to an 8 Gbps digital data stream. A DFB laser and Mach-Zehnder (MZM) modulated the digital data stream onto an optical carrier before transporting it across 20 kilometers of standard fiber (SMF) for this demonstration. A PIN photo detector detected the optical signal in the CO, and the digital data stream was processed offline.

Figure 4b shows experiments employing analog RF-over-fiber transport to disseminate the identical 10 GHz OFDM signal. The up converted OFDM signal was externally modulated into the optical carrier using a MZM and carried across 20 kilometers of SMF. At the CO, 10 GHz OFDM was down converted to baseband and processed offline. The peak-to-peak driving voltage of the RF signal entering the MZM was set at one hundredth of the switching voltage to preserve link linearity. This is 0.16 modulation depth.



IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 2, July 2024

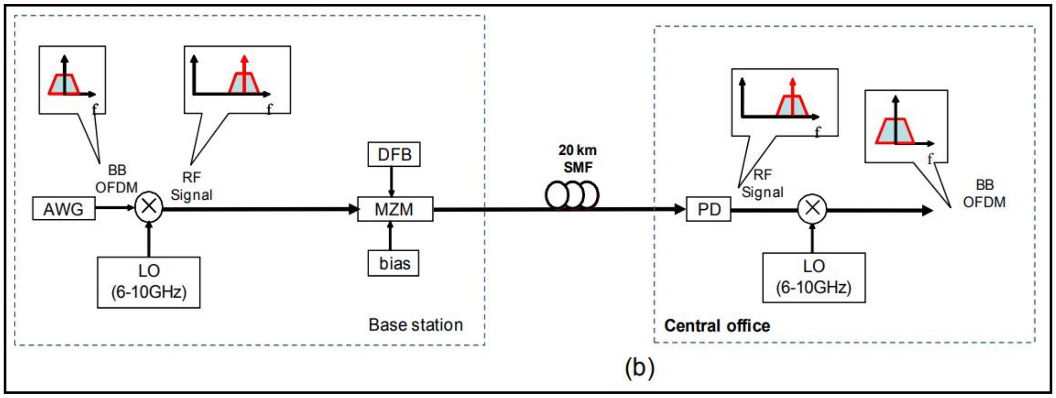


Figure: Experimental setup for (a) digitized RF-over-fiber transport and (b) analog RF-over-fiber transport of wideband OFDM signal

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 5a shows the observed error vector magnitude (EVM) as a function of received optical power (dBm) for digitized RF-over-transport over 20 km of SMF with 8-bit bit resolution. ADC 4 and 6 bit resolution results. A dotted line shows error-free reception for 4-QAM transmissions with a bit-error-rate of 10−12. Once received optical power exceeds link sensitivity, it drastically lowers connection performance. Received optical power must be −13 dBm for error-free transmission with a 4-bit resolution. Both 6-bit and 8-bit resolutions improved EVM performance and lowered optical power consumption (−13.5 and −15 dBm).

EVM for analog RF-over-fiber OFDM signal transmission across 0, 10, and 20 km SMF is shown in FIGURE 5b. As transmission distance and optical power decrease, analog link performance drops. For error-free reception over 20 km of SMF, analogue RF-over-fiber requires more optical power (>−10 dBm) than digital transmission (−15 dBm for 8-bit resolution). Digital RF-over-fiber connections beat analog links with the identical OFDM signal at 10 GHz and −10 dBm optical power, despite a 4-bit ADC resolution, 4 Gb/s optical bit rate, and −13 dB

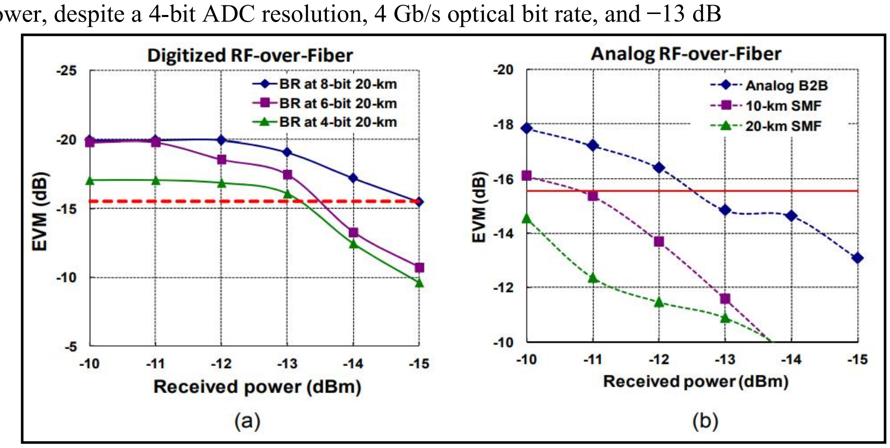


Figure: Error vector magnitude measured for (a) digitized RF-over-fiber transport and (b) analog RF-over-fiber transport over 20 km of fiber.

Energy Consumption of Different Transport Schemes

Digitized transport is more dynamic than analog, yet energy consumption is higher. ICT energy usage is high, with wireless access networks releasing the highest CO_2. Wireless base stations produce two-thirds of CO_2, therefore improving their energy utilization is vital to decreasing their carbon footprint. However, smart devices have strained mobile networks. Cell size reduction and mobile base stations are the simplest changes. Base station energy use will

IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 2, July 2024

grow, exacerbating the energy situation. Problem solved by fiber-wireless technology with optical fiber backhauling small cells with highest processing power in one region. A compact, energy-efficient base station is created.

Single Base Station Energy Consumption for Different Transport Schemes

We calculate the fiber-wireless network's energy consumption per square meter for the transport systems in Section 2 to quantify its energy consumption. We previously published a generalized power consumption model for fiber-wireless base stations that supports many wireless transmission techniques. Traditional base station design using baseband-over-fiber transmission is shown in Figure 6. BBU, Data Converter Unit, RF unit, Power Amplifier, Feeder, Clock Management, Power Supply, Battery Backup, and Cooling System are included. Table 1 illustrates the power consumption of each unit estimated using commercial components for this base station using Equation (1).

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

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

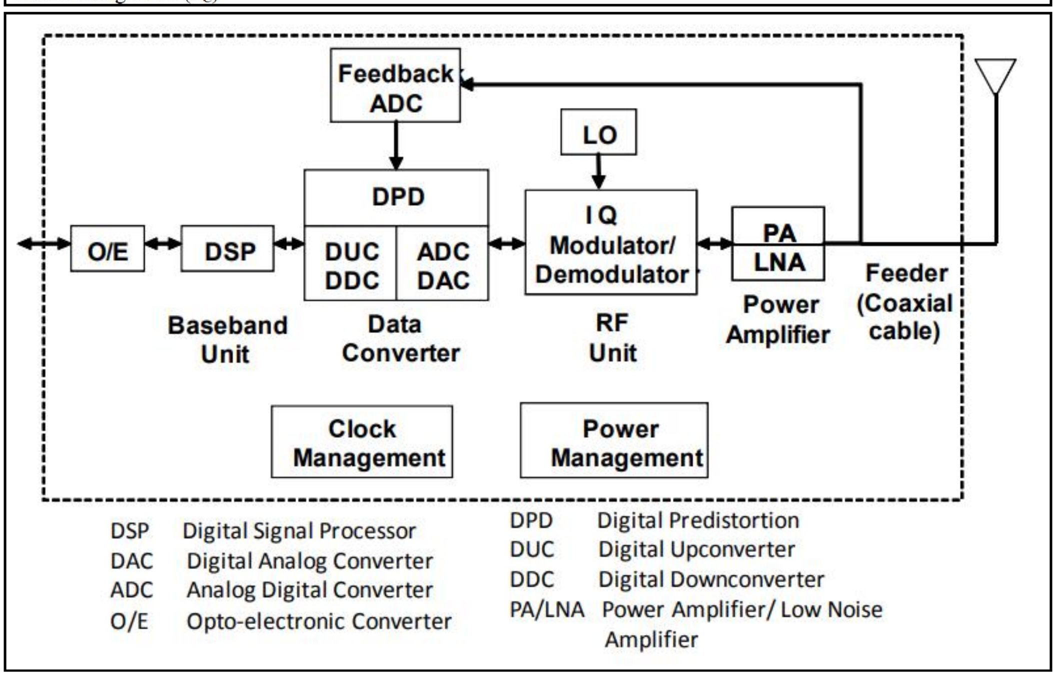


Figure 6: Conventional base station architecture incorporating BBoF transport scheme

IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 2, July 2024

The model may be used to analog RF-over-fiber, analog IF-over-fiber, digital RF, and IF-over-fiber schemes since the power for each unit stays the same regardless of the transport method. Figure 7a–d shows the comprehensive base station layouts. This research also employed the identical ADC/DAC specs for DRFoF and DIFoF. ADC/DAC power consumption is mostly affected by bit resolution, which is the same for DRFoF and DIFoF in this research.

In Figure 8, base station power consumption varies with transmitting power for several fiber-wireless transport systems. The findings show that baseband-over-fiber transport uses the maximum power for a single base station, whereas digitized RF/IF transport saves energy, particularly at high transmitting power.

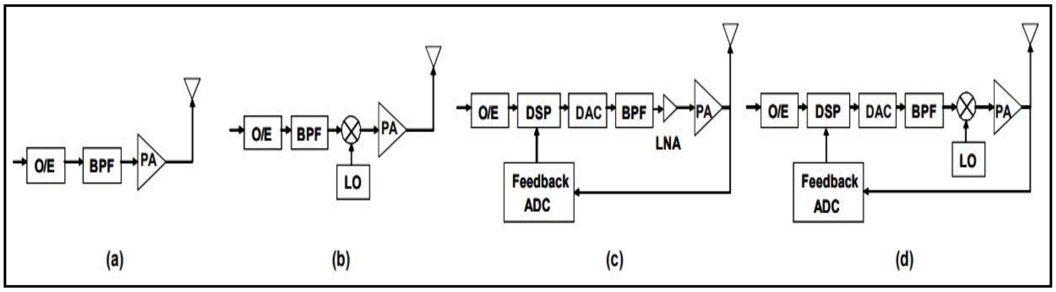


Figure 7: Base station architectures for (a) Analog RF-over-fiber (RFoF) (b) Analog IF-over-fiber (IFoF) (c) Digitized RF-over-fiber (DRFoF) and (d) Digitized IF-over-fiber (DIFoF)

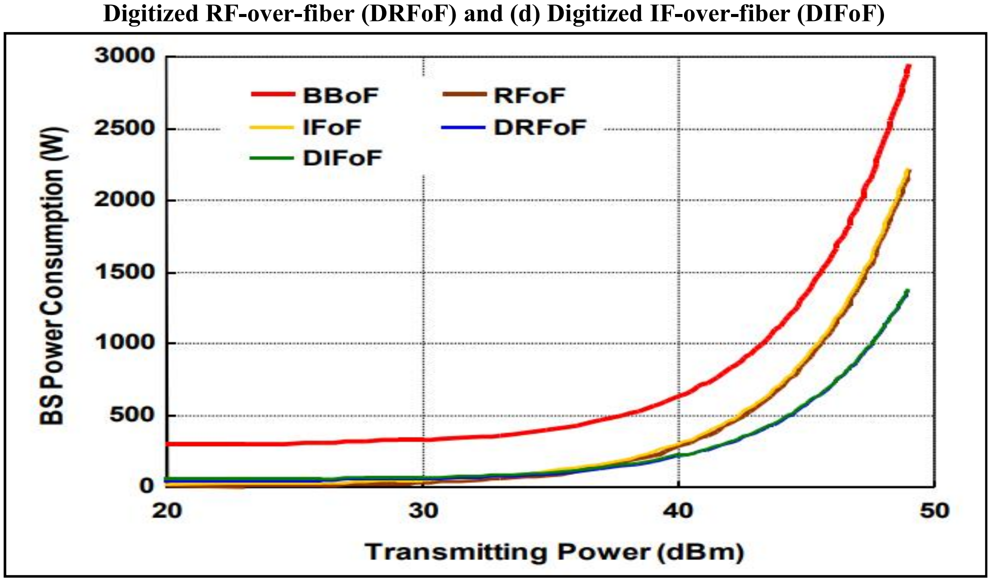


Figure 8: Base station power consumption as a function of transmitting power for the five different transport schemes investigated

Energy Consumption per Unit Coverage

Energy utilization per base station coverage was also evaluated to measure fiber-wireless network power consumption. The mobile wireless network is an endless regular grid of sites determined by size distance, resulting in equally sized hexagonal cell structures of side length d (Figure 9a). To reach the whole cell, PTX must surpass PRX after accounting for propagation loss (PL) across d. Equation (2) uses the PL to predict wireless signal deterioration from route loss, shadowing, and multipath fading. Value depends on location and man-made constructions. We may use Equation (2) values to estimate rural and urban propagation losses in Equations (3) and (4). Figure 9b shows maximum cell side lengths (d) for different transmitting strengths in rural and urban areas, assuming −120 dBm receiver sensitivity. Per base station transmission power, rural cells are larger than urban cells. Since propagation models vary, we will study rural and urban power consumption per square meter as a function of cell size separately.

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

IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.53

Volume 4, Issue 2, July 2024

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

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

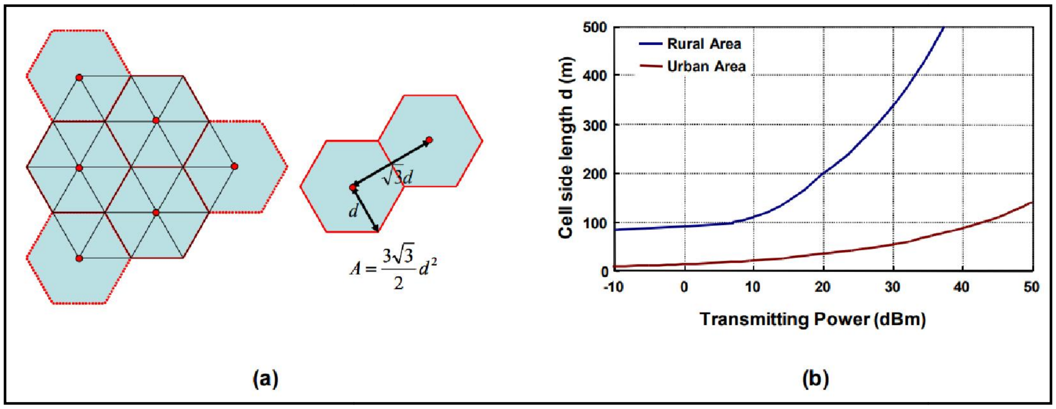


Figure 9: (a) Hexagonal cell coverage and the corresponding length measurement (b) Calculated cell side length versus transmitting power for rural and urban areas (With kind permission from Springer Science and Business Media).

Rural Area Figures 10a,b demonstrate the five fiber-wireless transport technologies' power consumption per square kilometer by base station transmission power and cell size. In the five conveyance modalities evaluated, energy consumption per square kilometer drops and then increases with transmitting power (cell size). Each transport system has an appropriate transmission power (cell size) to save energy. The optimal transmission power for baseband-over-fiber is ~40 dBm, whereas digital and analog variations are ~33 and ~22 dBm. Both statistics show baseband-over-fiber transmission consumes the most per-km2 power. Since power consumption per square kilometer is the same, analog RF/IF-over-fiber transmission is more energy-efficient than digital transport when the base station transmits 34 dBm. Digitized transmission requires more power for digital signal processing, not base station transmitting power. The red line in Figure 10a,b shows rural macro base stations emit at least 40 dBm. For rural cell sizes, digitized RF/IF-over-fiber transmission is most energy-efficient.

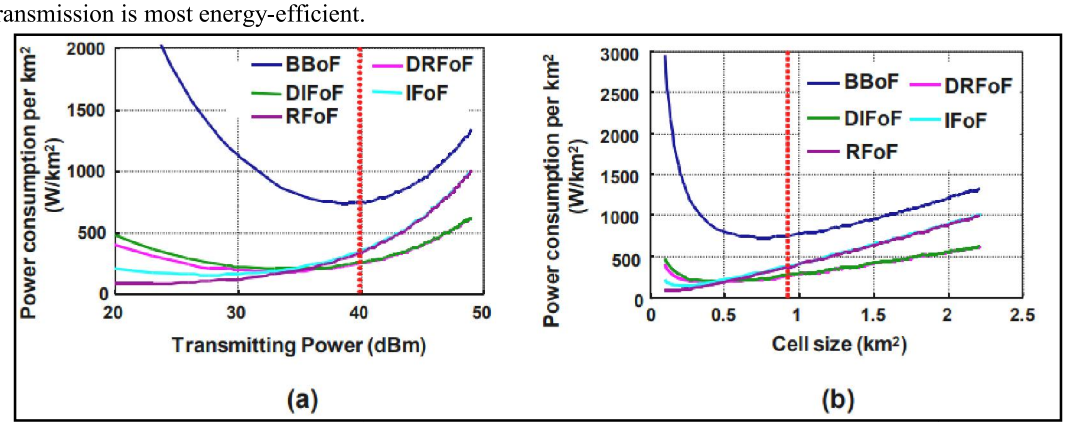


Figure 10: Power consumption per square km coverage for rural area for the five different transport schemes plotted as a function of (a) base station transmitting power and (b) cell size (With kind permission from Springer Science and Business Media).

Urban Area Urban electricity usage per square kilometer is shown in Figure 11a,b. Even though they trend similarly, the findings are dramatically different from Figure 10a,b. Baseband-over-fiber is still the least energy-efficient urban design. High mobile user density in urban areas leads to the deployment of micro base stations with fewer cells and lower transmitting power (<25 dBm). This is on the left of Figure 11a,b's red dashed line (transmitting power = 25 dBm). In dense metropolitan settings with microcells, analog transport schemes are more energy-efficient than digital transport, with analog RF-over-fiber being the most energy-efficient of the five schemes tested.

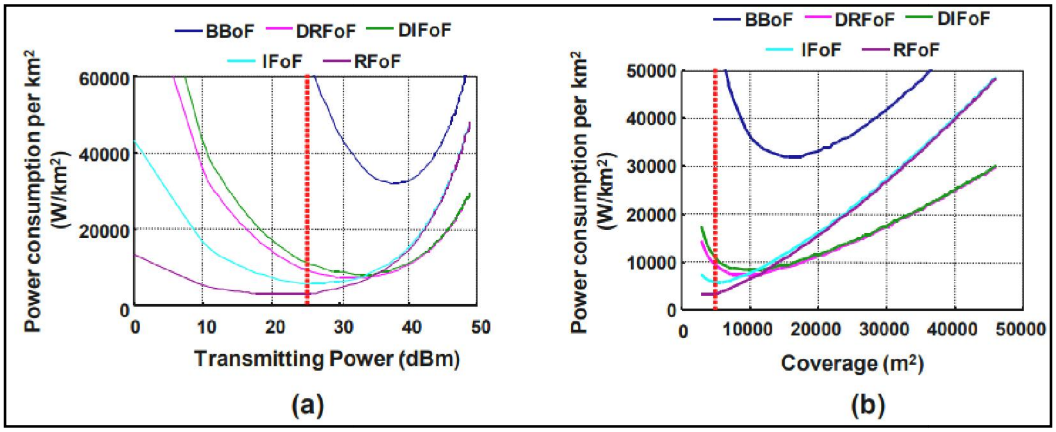


Figure 11: Power consumption per square km coverage for urban area for the five different transport schemes plotted as a function of (a) base station transmitting power and (b) cell size (With kind permission from Springer Science and Business Media).

III. CONCLUSION

This study summarizes and reviews our research on fiber-wireless systems, concentrating on wireless signal transport techniques and power usage. These research efforts have focused on high-performance, energy-efficient fiber-wireless connections. The research indicates that bandpass sampling-based digital transport schemes may simplify base station design while retaining connection performance. Digitized transmission of 1 GHz bandwidth OFDM signal at 6–10 GHz RF frequency was shown. Even at 4-bit ADC resolution, it outperformed analog transmission with error-free reception. Our base station power consumption under alternative transit methods for rural and urban coverage was also examined. Digitized transport had greater connection performance, while analog transport was more energy-efficient for urban areas employing 40 dBm tiny base stations.

REFERENCES

[1]. Chowdhury, P.; Tornatore, M.; Sarkar, S.; Mukherjee. (2010). "B. Building a green wireless-optical broadband access network (WOBAN)." *IEEE J. Lightw. Technol*. 2010, 28, 2219–2229.

[2]. Kurniawan, T.; Nirmalathas, A.; Lim, C.; Novak, D.; Waterhouse, R. Performance analysis of optimized millimeter-wave fiber radio links. *IEEE Trans. Microw*. Theory Tech. 2006, 54, 921–928.

[3]. Ismail, T.; Liu, C.-P.; Mitchell, J.E.; Seeds, A.J. High-dynamic-range wireless-over-fiber link using feedforward linearization. *IEEE J. Lightw. Technol*. 2007, 25, 3274–3282.

[4]. Lee, S.H.; Kang, J.M.; Won, Y.Y.; Kwon, H.C.; Han, S.K. Linearization of RoF optical source by using light-injected gain modulation. *Proc. Microw. Photonics* 2005, doi:10.1109/MWP.2005. 203590.

[5]. Novak, D.; Clark, T.; O'Connor, S.; Oursler, D.; Waterhouse, R. High performance, compact RF photonic transmitter with feedforward linearization. In Proceedings of Military Communication Conference 2010 (Milcom2010), San Jose, CA, USA, 31 October–3 November 2010; pp. 880–884.

[6]. Shah, A.R.; Jalali, B. Adaptive equalisation for broadband predistortion linearisation of optical transmitters. *IEEE Proc. Optoelectron*. 2005, 152, 16–32.

[7]. Djupsjobacka, A. A linearization concept for integrated-optic modulators. *IEEE Photonics Technol. Lett.* 1992, 4, 869–872.

[8]. Kanno, A.; Inagaki, K.; Morohashi, I.; Sakamoto, T.; Kuri, T.; Hosako, I.; Kawanishi, T.; Yoshida, Y.; Kitayama, K. 40 Gb/s W-band (75–110 GHz) 16-QAM radio-over-fiber signal generation and its wireless transmission. *Opt. Exp*. 2011, 19, B56–B63.

[9]. Zibar, D.; Sambaraju, R.; Caballero, A.; Herrera, J.; Westergren, U.; Walber, A.; Jensen, J.B.; Marti, J.; Monroy, I.T. High-capacity wireless signal generation and demodulation in 75- to 110-GHz band employing all-optical OFDM. *IEEE Photonics Technol. Lett*. 2011, 23, 810–812.

[10]. Zhang, J.; Yu, J.; Chi, N.; Dong, Z.; Li, X.; Chang, G.K. Multichannel 120 Gb/s data transmission over 2x2 MIMO fiber-wireless link at W-band. *IEEE Photonics Technol. Lett.* 2013, 25, 780–783.

[11]. Ng'oma, A.; Shih, P.-T.; George, J.; Annunziata, F.; Sauer, M.; Lin, C.-T.; Jiang, W.-J.; Chen, J.; Chi, S. 21 Gbps OFDM wireless signal transmission at 60 GHz using a simple IMDD radio-over-fiber system. *In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA*, 21–25 March 2010.

[12]. Hraimel, B.; Zhang, X.; Liu, T.; Xu, T.; Nie, Q.; Shen, D. Performance enhancement of an OFDM ultra-wideband transmission-over-fiber link using a linearized mixed-polarization single-drive x-cut mach-zehnder modulator. *IEEE Trans. Microw. Theory Tech*. 2012, 60, 3328–3338.

[13]. Lebedev, A.; Pang, X.; Vegas Olmos, J.J.; Beltran, M.; Llorente, R.; Forchhammer, S.; Tafur Monroy, I. Feasibility study and experimental verification of simplified fiber-supported 60-GHz picocell mobile backhaul links. *IEEE Photonics* J. 2013, doi:10.1109/JPHOT. 2013.2277011.

[14]. Chowdhury, P.; Tornatore, M.; Sarkar, S.; Mukherjee, B. Building a green wireless-optical broadband access network (WOBAN). *IEEE J. Lightw. Technol*. 2010, 28, 2219–2229.

[15]. Yang, Y.; Lim, C.; Nirmalathas, A. Comparison of energy consumption of integrated optical-wireless access networks. *In Proceedings of the Optical Fiber Communication Conference, Los Angeles, CA, USA*, 6–10 March 2011.