Baseband Radio over Fiber Aided Millimeter-Wave Distributed Antenna for Optical/Wireless Integration

Varghese Antony Thomas, Salman Ghafoor, Mohammed El-Hajjar, and Lajos Hanzo

***Abstract*—A Baseband Radio Over Fiber (BROF) architecture is proposed, where upto four Radio Frequency (RF) carriers can be generated, while using the heterodyne photo-detection of only two optical signals. This proposed BROF architecture has a star-like structure and it is composed of six Radio Access Units (RAUs), where data is transmitted from the Central Unit (CU) to the Base Station (BS) and from the BS to the RAU over a distance of 20 Km and 0.3 Km, respectively, at a rate of 768 Mbps. The performance of the system supporting four carrier frequencies drops by at most 1dB, at a BER of 10^{-9}, compared to conventional heterodyne photo-detection.**

***Index Terms*—Radio over fiber, distributed antenna system, heterodyne detection, time division duplexing.**

I. INTRODUCTION

THE past decade has seen a huge increase in the number of wireless communication subscribers and the development of high-bandwidth services. Radio Over Fiber (ROF) is expected to constitute the backbone of future wireless communication systems. Baseband ROF (BROF) [1] and Analogue ROF (AROF)[2] are commonly employed optical transmission techniques in ROF communication. The ROF optical signals are transmitted over an optical network that utilises either Wavelength Division Multiplexing (WDM)[3] or Time Division Multiplexing (TDM)[4] to serve multiple Radio Access Units (RAUs). Unlike WDM, TDM requires fewer semiconductor lasers, but its employement is limited to digital optical links. The detection of these optical signals can be direct [2] or heterodyne [2],[3]. AROF employs an analogue optical link. Hence the achievable data-rates and fiber-lengths are severely limited by fiber dispersion and the optical link's non-linearity [2]. In contrast to AROF, BROF utilises a more robust digital optical link [1]. However, unlike AROF, the RAU in a BROF-based architecture performs more complex signal processing and up-conversion to Radio Frequency (RF). The need to have up-convertors in a BROF RAU can be relaxed through the use of heterodyne photo-detection [2]. However, conventional heterodyne photo-detection of two optical signals is capable of generating a signal only at a single RF carrier at the difference of the two optical frequencies [2]. In this treatise, we propose a system to overcome this limitation. We propose a Distributed Antenna System (DAS) constituted by RAUs that are fed using BROF techniques in the star-like network topology of Fig. 1d. The RAUs of each cell are connected to a Central Unit (CU) via a BS. This contribution is the outcome of the second phase of a two-stage project, which is aimed at designing a multi-cellular fiber-based DAS, which is capable of significantly increasing the throughput at the cell-edges for a given transmit power, without reducing the cell-center's throughput. This involved the twin challenges of designing an efficient technique for the wireless communication over the wireless channel as well as designing a robust optical backhaul. A wireless link was designed in [5] using the architecture of Fig. 1d, where the cluster of cells was operated at four carrier frequencies. Our study used VPITransmissionMaker 8.6 (www.vpiphotonics.com) - a commercial optical simulation software.

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V. A. Thomas, M. El-Hajjar, and L. Hanzo are with the School of ECS, University of Southampton, SO17 1BJ, United Kingdom (e-mail: {vat1g10, meh, lh}@ecs.soton.ac.uk).

S. Ghafoor is with the National University of Sciences and Technology, Pakistan (e-mail: salman.ghafoor@seecs.edu.pk).

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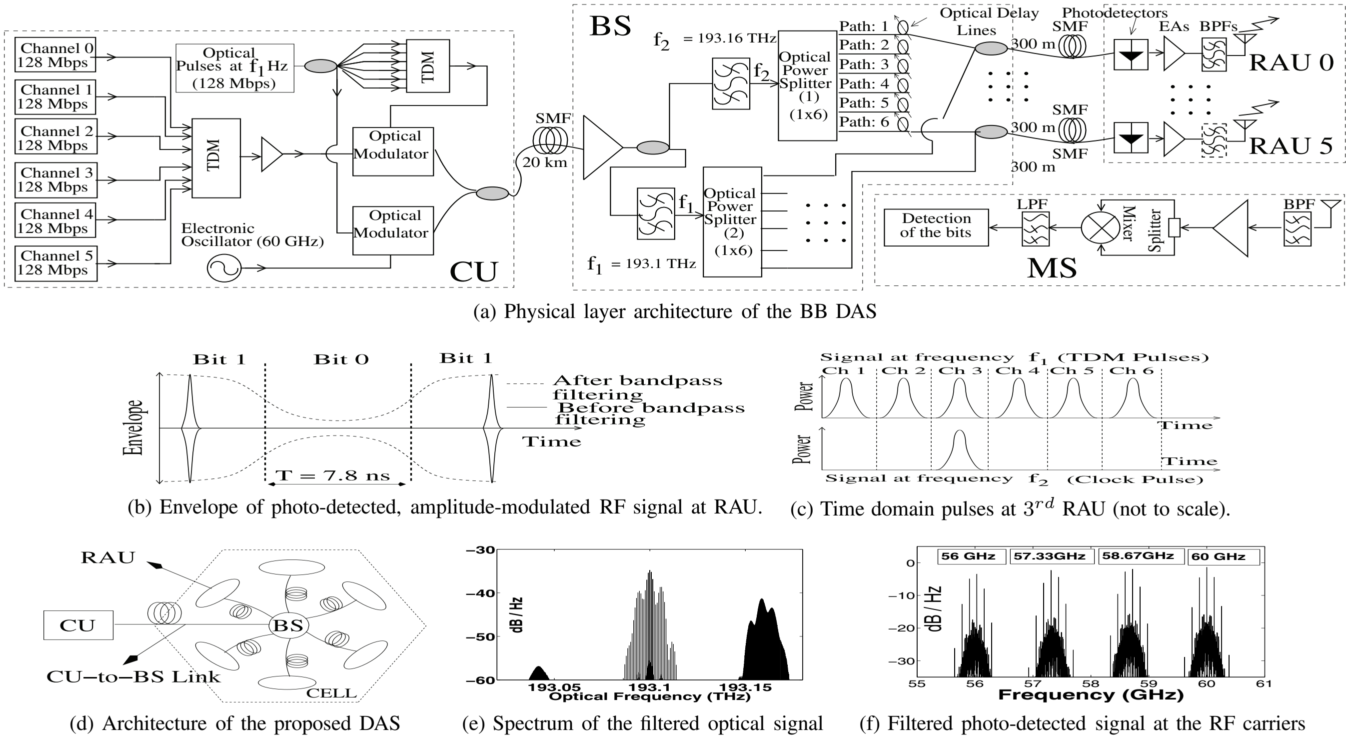
We propose an optical fiber back-bone that is based on our novel technique that generates wireless signals at multiple RF carriers, while retaining the ability to use a digital optical link and a single optical source. Against this background, the new contributions of this paper are:

1) The proposed sytem is capable of transmiting signals at multiple RF carriers, while using heterodyne detection of only two optical signals and without any significant change of hardware components. The extent of overlap between the pulses in the two optical signals was varied, using optical delay lines, for the sake of generating multiple RF carriers.
2) The proposed system is capable of simultaneously performing photo-detection and conversion from optical-TDM to wireless Frequency Division Multiplexing (FDM). The conversion is achieved by varying the optical delay.
3) We propose the heterodyning of two pulsed optical signals that are generated from a single pulsed semiconductor laser.

Experimental proof of a similar concept was provided in [12], where an unbalanced optical modulator was used with no heterodyne detection. The proposed technique draws its motivation from optical serrodyne modulation [13], [14], which uses modulation-induced chirp for optical frequency translation.

II. PHYSICAL LAYER OF THE BASEBAND DAS

a) ***Control Unit**:* The DL signal transmitted to each of the six RAUs has a bit-rate of $R_{DL} = 128$ Mbps, where the RAUs are represented by the index k ($k = 0, 1, ..5$) in Fig. 1a. They are multiplexed using TDM, resulting in a total



(a) Physical layer architecture of the BB DAS

(b) Envelope of photo-detected, amplitude-modulated RF signal at RAU.

(c) Time domain pulses at 3^{rd} RAU (not to scale).

(d) Architecture of the proposed DAS

(e) Spectrum of the filtered optical signal

(f) Filtered photo-detected signal at the RF carriers

Fig. 1. System architecture and functioning.

bit-rate of $R_{TDM} = (6 \times 128)$ Mbps. The baseband TDM data is modulated onto a (6×128) Mbps pulse stream. This pulse stream is generated by time-multiplexing the output of a 128 Mbps pulsed semiconductor laser that operates at a frequency of $f_1 = 193.1$ THz and has a pulse Full Width at Half Maximum (FWHM) $T_{FWHM} = 40$ ps. Simultaneously, as shown in Fig. 1a, clock pulses are generated by modulating a 60 GHz electronic oscillator signal onto one of the 128 Mbps pulsed outputs from the laser. The outputs of the two optical modulators are multiplexed and transmitted to the BS over a 20 km Single Mode Fiber (SMF) link. This multiplexed optical signal consists of a (6×128) Mbps On Off Keying (OOK) signal at 193.1 THz and of 128 Mbps clock pulse streams at the pair of frequencies of $193.1\ THz \pm 60\ GHz$. The use of a single laser reduces complexity and cost.

b) ***Base Station****:* At the BS of Fig 1a, the incoming optical signal is amplified by an amplifier having a noise figure of 6 dB and then split into two paths. Optical filters having center frequencies of $f_1 = 193.1\ THz$ and $f_2 = 193.1\ THz + 60\ GHz = 193.16\ THz$ are used in each path for isolating the pulsed TDM signal and one of the two pulsed clock signals, respectively. These are transmitted to the RAUs through a 0.3 km fiber link. The six paths carrying the pulsed clock signal, as shown in Fig. 1a, include Delay Lines (DLs) to perform demultiplexing and up-conversion. The DLs ensure the selection of a particular TDM channel by ensuring that its pulses overlap with the pulses in the 128 Mbps clock channel. The DL also controls the extent of overlap between the pulses in the clock channel and the selected channel. This in turn decides the up-converted frequency after photo-detection. Optical DLs have been widely used for time-synchronization [6] and optical signal processing [7]. Furthermore, efficient synchronization, coherent heterodyne photo-detection and up-conversion has been made possible by the availability of variable optical DLs with femtosecond sensitivity as well as by the use of a single pulsed optical source at the CU. Polarization control and time-domain overlap has been reported for optical pulses that are significantly shorter than the ones used in this paper [10], [11] , with the intention of using Cross-Phase Modulation (XPM).

c) ***Radio Access Unit****:* The photo-detected RF signal consists of up-converted impulses whose temporal width equals that of the optical pulses. As shown in Fig 1a, the RF signals are amplified and then band-limited by the transmit-filtering using a Band Pass Filter (BPF) with 256 MHz bandwidth and a Gaussian shaped time-domain response. As seen from Fig. 1b, bandpass filtering broadens these impulses. This signal is then transmitted to the Mobile Station (MS), where it is filtered, amplified and down-converted to baseband, without an oscillator, through self-mixing [8], as shown in Fig 1a. The signal is then Low Pass Filtered (LPF) and decoded.

d) ***Uplink Communication****:* The uplink (UL) RF signal is down-converted to baseband by self-mixing [8]. The 193.16 THz clock pulses do not carry OOK data and can be reused at the RAU to carry the UL baseband signal, thereby reducing the RAU complexity just like in [16]. The UL optical signals from the RAUs are sent to the BS, where they are time-multiplexed and then sent to the CU, for direct photo-detection. Heterodyne photo-detection is not needed, since there is no up-conversion at the CU. The narrow photo-detected pulses are low-pass filtered (thereby broadening them), Time Division Demultiplexed and used for bit detection.

III. Theoretical Analysis

*a) **Time Division Demultiplexing (TDD)**:* Let $x_k(t)$ be the envelope of the pulsed optical signal for the k^{th} RAU. Then, the TDM optical signal, $x_{tdm}(t)$, that is received at the RAUs and is centred at an optical frequency of f_1, can be represented as:

$$x_{tdm}(t) = \sum_{k=0}^{5} x_k(t - kt_{bit}) \cos[2\pi f_{inst1}\{t - kt_{bit}\}(t - kt_{bit})]$$

where $f_{inst1}\{t\}$ is the instantaneous frequency, while $t_{bit} = 1/R_{TDM}$ is the multiplexing delay. The clock signal, at an optical frequency of f_2 is $x_{clock}(t) = c(t)\cos(2\pi f_{inst2}\{t\}t)$, where $c(t)$ is the envelope of the pulsed clock signal, while $f_{inst2}\{t\}$ is the instantaneous frequency. As seen from Fig. 1c, channel selection is achieved by delaying the clock pulse by kt_{bit} seconds to ensure that the pulses in the clock signal overlap with the pulses in the desired TDM channel. Mathematically, this is expressed as follows:

$$\begin{aligned} &x_{clock}(t - kt_{bit} - t_{od}) \cdot x_{tdm}(t) = c(t - kt_{bit} - t_{od}) \cdot \\ &x_k(t - kt_{bit}) \cdot \cos[2\pi f_{inst1}\{t - kt_{bit}\}(t - kt_{bit})] \cdot \\ &\cos[2\pi f_{inst2}\{t - kt_{bit} - t_{od}\}(t - kt_{bit} - t_{od})], \qquad (1) \end{aligned}$$

where $t_{od},\ with\ |t_{od}| \ll t_{bit}$, is the additional delay applied for variable up-conversion. Note that the actual delay applied to the clock would vary slightly from the theoretically calculated value, in order to account for the difference in the optical pulse propogation velocities at frequencies of f_1 and f_2.

*b) **Variable Up-conversion**:* The instantaneous frequencies $f_{inst1}\{t\}$ and $f_{inst2}\{t\}$ of the optical TDM signal and the clock signal are as follows:

$$f_{inst1}\{t\} = f_1 + \Delta f\{t\},\ f_{inst2}\{t\} \ = f_2 + \Delta f\{t\}. \qquad (2)$$

where $\Delta f\{t\}$ is the linear frequency chirp. This chirp is introduced by either one or both of the following factors - 1) Linear chirp due to fiber dispersion [9], 2) Additional linear-chirp may be obtained by employing pulsed optical sources that are chirped. If τ is the time normalised by the bit-period in the n^{th} bit duration ($n = 0, 1, 2...$), then $\tau = -\frac{t_{bit}}{2} + t - nt_{bit}$. Hence $-\frac{t_{bit}}{2} \leq \tau < \frac{t_{bit}}{2},\ \forall\ t$. Now, $\Delta f\{t\} = M\tau$, where $M = [C/(2\pi T_0^2)]$ [9], [15]. Here C is the chirp parameter and $T_0 = T_{FWHM}/1.665$. Additionally, M can be adjusted by employing chirped optical sources and by varying the chirp parameter of the generated pulses. Thus, as seen in Fig. 2, the instantaneous frequency changes linearly across each pulse and it is centred around the optical carrier frequency. Hence the spectra of these optical signals are centred around the frequencies f_1 and f_2, which is also seen from Fig. 1e. The spectra become wider as the optical pulses become narrower. Time instances, which are separated by integer multiples of the bit period have the same normalised time instant. Hence we have,

$$\Delta f\{t - kt_{bit}\} = \Delta f\{t\} = M\tau. \qquad (3)$$

In addition to the delay that is applied to perform channel selection, an additional overlap delay, $t_{od} \ll t_{bit}$, is applied to the clock signal. This results in a slight overlap mismatch between the clock pulse and the pulse in the selected channel. The chirp in the delayed clock signal is as follows:

$$\Delta f\{t - kt_{bit} - t_{od}\} = \Delta f\{t - t_{od}\} = M(\tau - t_{od}). \qquad (4)$$

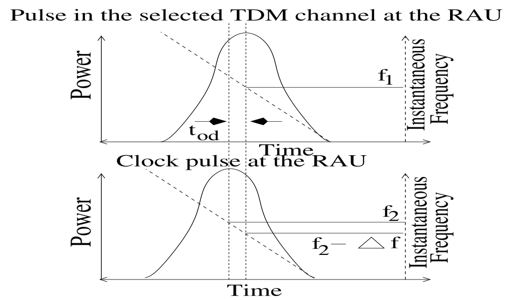


Fig. 2. Pulses at frequencies f_1 and $f_2 (M < 0, t_{od} < 0)$.

The signal generated during the heterodyne photo-detection of the TDM and clock signals at the RAU has a centre frequency, f_{pd}, that is equal to the derivative of the instantaneous phase difference $\Delta\phi(t)$ between the two optical signals, i.e. we have $f_{pd} = (1/(2\pi))(d\Delta\phi(t))/dt)$. Thus:

$$f_{pd} = \frac{d}{dt}\{ \int_0^{t-kt_{bit}-t_{od}} f_{inst2}\{t'\}dt' - \int_0^{t-kt_{bit}} f_{inst1}\{t'\}dt' \},$$

where t' is the integration variable. However, it is known from calculus that for a function $u(x)$, $\frac{d}{dx}\{\int_a^x u(x')\ dx'\} = u(x)$ holds. Hence the above expression of f_{pd} becomes:

$$\begin{aligned} f_{pd} &= f_{inst2}\{t - kt_{bit} - t_{od}\} - f_{inst1}\{t - kt_{bit}\} \\ &= f_2 + \Delta f\{t - kt_{bit} - t_{od}\} - (f_1 + \Delta f\{t - kt_{bit}\}) \\ &= (f_2 - f_1) + (\Delta f\{t - kt_{bit} - t_{od}\} - \Delta f\{t - kt_{bit}\}) \\ &= 60 \times 10^9 - Mt_{od}\ [\ using\ equations\ (3)\ and\ (4)\ ]. \qquad (5) \end{aligned}$$

Hence, the centre frequency of the photo-detected signal can be varied by varying the extent of mismatch. On the other hand, conventional heterodyne detection generates RF signals at a single frequency for a given pair of optical signals.

*c) **TDD & Variable Upconversion via Heterodyne Detection** :* The electronic signal x_{pd}, that is obtained at the RAU by using a photo-detector with responsivity of $r = 0.9$ A/W followed by bandpass filtering is represented as follows:

$$\begin{aligned} x_{pd}(t) &= bpf\{r \cdot |x_{tdm}(t) + x_{clock}(t - kt_{bit} - t_{od})|^2\}, \\ &= bpf\{|r \cdot x_{tdm}^2(t) + r \cdot x_{clock}^2(t - kt_{bit} - t_{od}) \\ &\quad + 2r \cdot x_{tdm}(t) \cdot x_{clock}(t - kt_{bit} - t_{od})|\}, \qquad (6) \end{aligned}$$

where $bpf\{.\}$ is the bandpass filtering function centred at f_{pd} Hz. We use Eq. (1) followed by a trignometric expansion of the third term in Eq. (6). The first 2 terms of Eq. (6) and one of the terms obtained from the trignometric expansion represent spectral components that are removed by the bandpass filter. Hence, the filtered signal can be represented as:

$$\begin{aligned} &x_{pd}(t) = r \cdot c(t - kt_{bit} - t_{od}) \cdot x_k(t - kt_{bit}) \cdot \cos[\Delta\phi(t)] \\ &\approx r \cdot c(t - kt_{bit}) \cdot x_k(t - kt_{bit}) \cdot \cos[\Delta\phi(t)]\ [as\ t_{od} \ll t_{bit}] \\ &\approx r \cdot \tilde{x}_k(t - kt_{bit}) \cdot \cos[\Delta\phi(t)], \qquad (7) \end{aligned}$$

where $\tilde{x}_k(t)$ carries the same OOK information as $x_k(t)$ but consists of approximately squared Gaussian pulses.

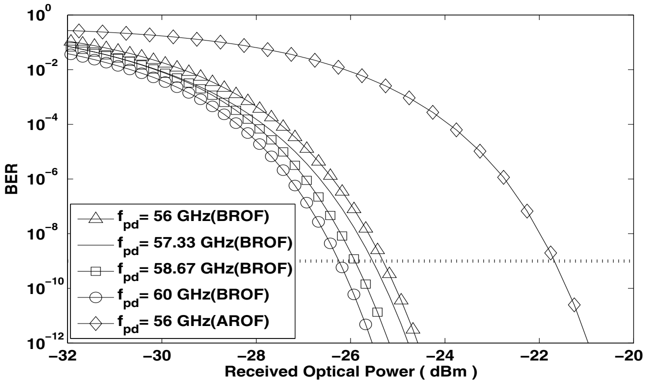


Fig. 3. BER vs. received optical power for the proposed method and AROF.

IV. System Performance

Simulations were carried out by exploiting the fiber-dispersion induced chirp. The cell was operated using signals at RF carriers of 56 GHz, 57.33 GHz, 58.67 GHz and 60 GHz. These are shown in Fig. 1f. The dispersion parameter of single mode fibers at a wavelength of 1550 nm is D= 16 ps/km-nm [15]. Using pulses having $T_{FWHM} = 40ps$ results in a value of $C = -0.9516$ [9], which in turn gives a value of $M = -2.6241 \times 10^{20}$. Hence, from Eq. 5, $t_{od} = 3.8$ ps produces a frequency variation of 1 GHz. The tolerable deviation in the photo-detected signal's frequency from 60 GHz is dictated by the condition that the overlap mismatch should not cause a significant Bit Error Ratio (BER) degradation and receiver sensitivity drop at BER $= 10^{-9}$. The tolerable deviation in the photo-detected signal's frequency from 60 GHz is dictated by the condition that the overlap mismatch should not cause a significant Bit Error Ratio (BER) degradation and receiver sensitivity drop at BER $= 10^{-9}$. The BER of conventional heterodyne photo-detection has been dealt with in chapter ten of [15]. The various factors that cause a BER penalty when compared to conventional heterodyne detection are-

1) Pulse mismatch: The detected signal is down-converted and sampled. Sampling occurs at the bit-center. There is a performance penalty, when a 2^{nd} delayed Gaussian pulse is multipled.
2) Bit boundary mismatch: The difference in the instantaneous optical frequency will not be equal to the target value at the bit boundaries. This, however, is negligible for very small t_{od} because the pulse amplitude at the bit boundary is negligible. Its significance, nevertheless, increases as t_{od} increases.

The performance drop of the system supporting the four RF carriers is within 1dB, at a BER of 10^{-9}, compared to conventional heterodyne photo-detection. Futhermore, the advantage of using a BROF architecture that employs a digital optical link in preference to the more commonly employed AROF architecture can also be seen from Fig. 3. The severity of fiber-dispersion and the consequent sideband-cancellation, increases with the carrier frequency in analogue optical links. The BER performance of 60 GHz-band AROF links is limited by chromatic dispersion.

V. Conclusions

A novel technique was proposed for varying the carrier frequency of the signal, that is generated by heterodyne photo-detection of 2 given optical signals. This technique varies the extent of overlap between the pulses in the 2 optical channels in order to exploit the pulse chirp. Its performance in a BROF architecture, constituted by a star-like DAS of 6 RAUs, was quantified. Also, the BER performance at the 4 RF carriers used in the BROF system was better than that of AROF.

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