# 60 GHz Millimetre wave/ 10 Gbps Transmission for Super Broadband Wi-Fi Network

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***Abstract*** —The combination of both Fibre and Wireless (Fi-Wi) offer super bandwidth for bolstering the future services of wireless access points. Optical fibre communication is becoming one of the infrastructure media for providing vast bandwidth for both mobile and fixed users to support video in internet applications. This can be realised by substituting the electrical components of a traditional network with optical ones. Radio over Fibre (RoF) technology is considered a reliable and cost-effective tool for distributing simple and small Remote Antenna Units (RAUs) in wireless access networks. The central operation can achieve a dynamic resource allocation to small cells. In this paper, a new radio/millimetre over fibre link is proposed using Single Mode Fibre (SMF). The simulation model is built in MATLAB environment, With the performance being reported for various lengths of SMF and wireless channel distances. The system transports 10 Gbit/s of pseudo random sequence data modulated on a 60 GHz carrier using Amplitude Shift Keying (ASK); with the result being modulated by an electro optic modulator based on a 1550 nm coherent optical carrier. The Quality of Service (QoS) of the system relies on attenuation impairments and chromatic dispersion of SMF.

***Index Terms***—Radio over Fibre, 60 GHz band, Wi-Fi, optical communication, Fi-Wi and wireless communication.

## I. Introduction

The user demands for higher capacity for the next generation of mobile networks at 1 Gbit/s and upwards are exponentially increasing, while there is a limited radio spectrum. In order to locate newer mobile subscribers in the network, this requires allocating more bandwidth places in the present Radio Frequency (RF) band, which in turn, causes a congested band with a higher level of interference. However, the customers require a reliable system with cost-effective technology and upcoming generation must be a scalable system to incorporate new multimedia services. The millimetre-wave (mm-wave) is one of the promising technologies for 5G, which can provision multi-Gbit/s as a data rate for mobile devices, because it operates over very high frequency ranges from 30 GHz to 300 GHz, that can correspond to wavelengths from 1 mm to 10 mm. A 60 GHz band has 7 GHz of wide channel ranges 57-64 GHz, this unlicensed band has been considered by Federal Communications Commission (FCC) in 2001. This band is an idle spectrum and free to use. It has been found that a 60 GHz system has excellent benefits, with superior power consumption and data rate for upcoming super broadband services. The current trend is for wireless cellular systems using a small cell size with a mm-wave for both fixed and mobile users, which can accommodate more consumers with a lower level of congestion. This requires an enormous number of Base Stations (BSs) in order to cover the user area. The success key of 5G is to make a simple and cost-effective remote base station. The system architecture must be developed in terms of functionality regarding such as signal processing/routing, frequency allocation and handover. These processes are carried out in the Central Station (CS) instead of BSs. However, links between the CS and many BSs are undertaken via an optical network to take advantage of all the merit provided by optical fibre, such as a broad bandwidth, low loss and being immune to Electromagnetic Interference (EMI) as well as Radio Frequency Interference (RFI) [1]. The RoF link is depicted in Fig. 1.

The technique that enables to modulate radio frequency onto an optical fibre is known as "Radio over Fibre" (RoF). RoF technology is considered as being a reliable solution and cost-effective for 5G. With its links used to connect the CS to many remote BSs. In downlink, RF signals distribute from the CS to many remote BSs, whilst in uplink, the receiving RF signals from the BSs are sent back to the CS through optic fibre. The main benefits of RoF technology are as follows: (1) The possibility of centralised operation. (2) Simple and small BSs are required; (3) Wire and wireless standards can be supported; (4) Low loss and (5) Bandwidth and modulation techniques are transparent. However, such a technique has many challenges in terms of implementation, such as the initial installing cost for the optic network and the nonlinear condition for its components. Recently, many researchers have been interested in discovering and evolving new techniques to solve these challenges [1], [3].

The centralised work arrangement can keep all the sensitive and expensive equipment in the same place, which can be easily shared among the BSs this can reduce Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) expenses. The suggested generation of a cellular system with smaller cell size can reduce the

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transmitted power to users as well as eliminating the need for mobile transceivers and power amplifiers at the BSs. This enable more power saving, thus a longer battery life for lighter and simpler mobile devices. Low power consumption means a low health effect and low cost for both consumers and operators [4].

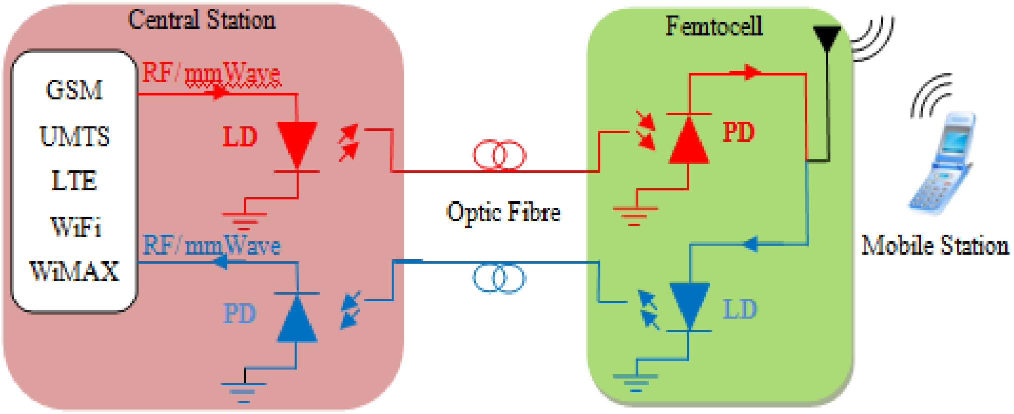


Fig. 1. Schematic diagram of bidirectional RoF technology based on direct modulation and photo diode detection.

For our research, we draw on recent work on RoF, where the authors proposed a Photonic Analogue to Digital Converter (PADC) for digital radio over fibre link to cope with the challenges of traditional ADC and Electronic ADC (EADC) using high frequency [5]. A full duplex RoF system transfers 10 Gbit/s pseudo random sequence, which is OFDM modulated with 4-QAM mapping over a 60 GHz RF carrier. The RoF signal was transmitted over 1.5 km of Multi-Mode Fibre (MMF) [2]. Other authors have suggested all-photonic Digital Radio over Fibre (DRoF) for an integrated transportation system to transfer distinct kinds of baseband, digital and analogue signals over single mode fibre. The proposed integrated system transports 1 Gbit/s pseudo-random data mapped in an ASK modulator with a 5 GHz RF carrier to be transmitted over a integrated link [6].

This paper is focused on proposing and investigating a new mm-wave over fibre architecture for using an unlicensed spectrum for small cells. This technique can overcome the current problems of the RF spectrum, for 60 GHz is a relatively idle spectrum with less of interference. This combination supports higher bandwidth compared with conventional RoF, thereby accommodating a considerably greater number of new users and supporting more services. With the proposed model, femtocell transports a 10 Gbit/s Bernoulli binary generator over a 60 GHz carrier modulated by ASK modulation to be transmitted on SMF.

The reminder of this paper is organised as follows: Section 2 introduces the RF/mm-wave over fibre system using either direct or indirect modulation principles. Section 3 provides our proposed system architecture and its analysis. The simulation results are presented in section 4. Finally, section 5 summarises the paper.

## II. Radio Over Fibre System

Analogue RoF (ARoF) technology is also known as RoF and the best solution for distributing an RF signal over an optical network. That is, this technique is considered cost-effective and reliable technology for ongoing wireless access networks. An RoF link consists from an optical source, modulator, optical channel, optical filter, optical amplifier and optical receiver. RoF works to modulate the sub-carrier (RF or mm-wave) onto an optical fibre network by applying either direct intensity modulation or indirect external modulation.

### A. *Direct Moduation*

The light source that is generated by a laser diode is directly modulated by the RF signal. The direct modulation uses a semiconductor laser to convert the RF current into emitted photons, which is varied according to the data to be transmitted. The output optical power is dependent on the injected current through the laser diode. The transfer function is represented in Eq. (1).

$$\boldsymbol{P_{opt}} = \frac{\boldsymbol{hf}}{\boldsymbol{e}}\eta_L(\boldsymbol{I} - \boldsymbol{I_{th}}) \qquad (1)$$

where, $I$ denotes as the input current of the RF signal with DC bias, $\boldsymbol{I_{th}}$ is the threshold value of the diode current, $\eta_L$ is the laser quantum efficiency, $f$ is the frequency (Hz), $h$and $e$ are Planck constant and charge of an electron, respectively[7]-[8].

Non-linear behavior occurs when the injected current is above the threshold current and the input to output relationship can be written as

$$\boldsymbol{P_{opt}} = \boldsymbol{a} + \boldsymbol{b}(\boldsymbol{I} - \boldsymbol{I_{th}}) + \boldsymbol{c}(\boldsymbol{I} - \boldsymbol{I_{th}})^2 + \boldsymbol{d}(\boldsymbol{I} - \boldsymbol{I_{th}})^3 \qquad (2)$$

where, $a$, $b$, $c$ and $d$ are constants. This makes the direct modulation having limited modulation bandwidth, chirp and extinction ratio. Thus, indirect modulation has better performance with high data rate transmission [8]-[10].

### B. *Indirect Modulation*

This is also known as external modulation and uses an electro-optical modulator defined as a Mach-Zehnder Modulator (MZM) in order to modulate the RF signal onto an optical signal coming from the laser diode. The MZM is classified as an amplitude modulator, as shown in Fig. 2.

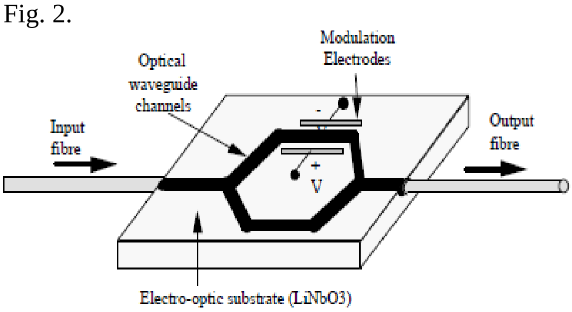


Fig. 2. MZM [11].

It is clearly seen that the light signal is equally divided into two paths by the Y-junction of the substrate. When the voltage of the RF signal is not applied at the electrodes, the two separated signals are in-phase and are integrated at the second Y-junction. When the voltage of the RF signal is applied at the electrodes, the refractive index is varied due to the electro-optical effects of the Lithium Niobate (LiNBO3) substrate. As a result, the phase of the optical signal for the first arm is advanced compared to the other arm and the two signals are out of phase when they are combined at the second Y-junction. Consequently, the resultant optical signal from the MZM is considered as being a modulated signal with optical and electrical elements. Moreover, it has a balanced power ratio regarding the two arms of the MZM. The relationship between the output of the MZM to the input is written as

$$\boldsymbol{E_{out}(t) = E_{in} cos\left(\frac{V(t).\pi}{2\,V_\pi}\right)} \qquad (3)$$

where, $E_{out}(t)$ denotes the electrical field of the modulated signal at the output of the MZM, $E_{in}$ is the electrical field of the input optical carrier, $V(t)$ is the voltage of the input RF signal and $V_\pi$ is the applied bias voltage at the electrodes, which generates $\pi$ radians phase difference between the two arms of the optical signals of the MZM [1]. However, the optical signal that is launched into the MZM, as generated by the laser diode, is represented by:

$$\boldsymbol{E_{in}(t) = E_o \cos(w_0 t)} \qquad (4)$$

where, $w_0$ and $E_o$ denote the angular frequency and amplitude of input optical carrier, respectively. It can also depict the input RF signal as an ASK carrier signal in the complex form by:

$$\boldsymbol{S(t) = A_c m(t) e^{j[w_c t + \varphi_c]}} \qquad (5)$$

The actual signal is considered the real part of the ASK signal, where $A_c$ and $\varphi_c$ are the amplitude and phase of the ASK signal, which are constants; and $m(t)$ is the bit sequence of the binary information that changes through a symbol-by-symbol rule. The ASK signal is composed of N bits and so, the complex signal $S_s(t)$ can be symbolised via:

$$\boldsymbol{S_s(t) = \sum_{n=0}^{N-1} A_c m_n(t) e^{j[w_c t + \varphi_c]}} \qquad (6)$$

The real part of the given signal in equation (6) is represented by:

$$\boldsymbol{V(t) = \sum_{n=0}^{N-1} A_c m_n(t).\cos(w_c t + \varphi_c)} \qquad (7)$$

Eq. (7) and Eq. (4) can be substituted into in Eq. (3) in order to get the electrical field of the output optical modulated signal at the output of the MZM as follows:

$$\boldsymbol{E_{out}(t) = E_o \left\{ cos(w_c t) . cos\left( \mathrm{U} \sum_{n=0}^{N-1} [m_n(t). cos(w_c t + \varphi_c)] \right) \right\}} \qquad (8)$$

where, U denotes the modulation index that can be expressed by:

$$\boldsymbol{\mathrm{U} = \frac{(A_c.\pi)}{2.V_\pi}} \qquad (9)$$

In order to expand the elements in Eq. (8), Bessel function is employed [12] and Eq. (8) can be reformed as:

$$\boldsymbol{E_{out}(t) = E_o \cos(w_c t) \times \left[ \mathrm{J_0(U)} + 2\left( \sum_{k=1}^{\infty} -1^k \mathrm{J_{2k}(U)} \sum_{n=0}^{N-1} [m_n(t). cos(w_c t + \varphi_c)] \right) \right]} \qquad (10)$$

where, $\mathrm{J_k(U)}$ is the Bessel function for any integer k and written as:

$$\boldsymbol{\mathrm{J_k(U)} = \frac{1}{\pi} \int_0^{\pi} cos(\mathrm{U}.sin\theta - K\theta) d\theta} \qquad (11)$$

Finally, Eq. (10) can be rewritten as:

$$\boldsymbol{E_{out}(t) = E_o J_0(U) \cos(w_0 t) + E_o \sum_{k=1}^{\infty} \left\{ (-1)^k J_{2k}(U). \sum_{n=0}^{N-1} m_n(t) \times [cos((w_0 + w_c)t + \varphi_c) + cos((w_0 + w_c)t - \varphi_c)] \right\}} \qquad (12)$$

Eq. (12) shows that the optical carrier is represented in the first term, and the mm-wave or sidebands of the RF are covered in the second term. According to Eq. (12), the nonlinear behaviour of the MZM generates infinite terms that produce spurious bands, which in turn, affects the overall performance of the RoF system [1]. In our scheme, the indirect modulation with a single laser diode with 1550 nm wavelength is used as a cost-effective solution in terms of processing and complexity.

## III. The Proposed System Architecture

In this section, the proposed optical-wireless link is simulated via MATLAB platform. The bandpass signal is generated in the central base station to be transfered to the RAU across the optical network, which used the indirect optical modulation. Then, the RAU propagates the RF signal throughout the wireless channel.

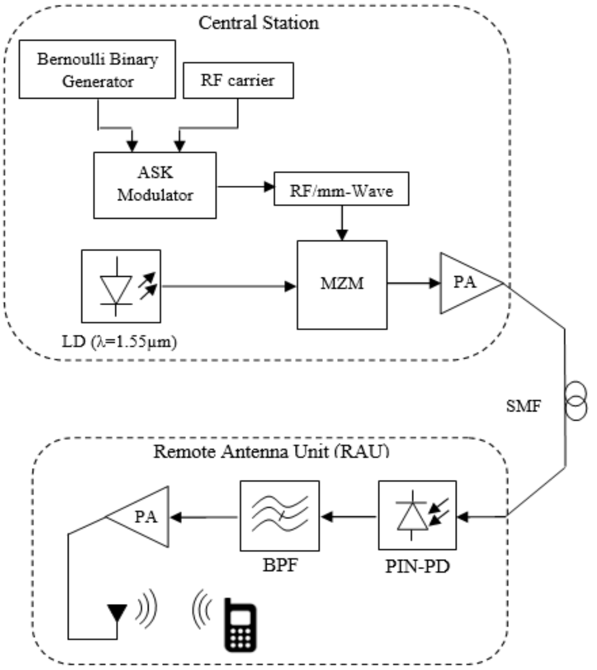


Fig. 3. The simulation model of FTTH network.

RoF constitutes the best tool for distributing wireless signals in remote antenna units for future radio/mm-wave access networks. As Fig. 3 shows, the downlink RF/mm-wave signals are distributed from the central station to a femtocell RF/mm-wave wireless access point across SMF. RoF is a technique that modulates the RF/mm-wave onto the optical fibre in order to achieve huge bandwidth, thereby accommodating more new users and applications. The simulation model has been built in MATLAB environment, with the laser source being assumed as 1550 nm at 10 mW, and the MZM loss is 0.5 dB. The proposed system transfers a half-duplex 10 Gbit/s Bernoulli binary generator that is Amplitude Shift Keying (ASK) modulated with 60 GHz sub-carrier frequency, which is modulated on a CW laser using an electro-optic modulator to transmit onto SMF. The photo diode responsivity and resistance are 0.8 and 50 ohms, respectively, whilst the transmitter antenna gain (G_T) and receiver antenna gain (G_R) of the wireless channel are 8 dB and 0.5 dB, respectively. A free space model and an Additive White Gaussian Noise (AWGN) channel have been supposed for the wireless environment. Therefore, our proposed simulation can make the remote base station as a simple as possible to reduce the cost and complexity. It can replace the RAU by using the photonic antenna as a single element.

## IV. Simulation Result and Discussion

In this section, the simulation results of proposed model are presented. The Bit Error Rate (BER) is measured at a mobile station and we simulate the system for different wireless channel distances, as illustrated in Fig. 6. The BER increases in conjunction with Tx-Rx separation, because free space pathloss is in direct proportion to the squared frequency and distance, which is defined as in the Friis equation below:

$$\boldsymbol{Pathloss} = \left(\frac{\boldsymbol{4\pi f \times distance}}{\boldsymbol{c}}\right)^{\boldsymbol{2}} \tag{13}$$

where, $f$ and $c$ denote the frequency and speed of light, respectively. According to Eq. (13), the mm-waves suffer from high pathloss losses for long distances and hence, the mm-waves should be used for short distances to support very high data transmission. The received carrier to noise ratio ($C/N$) is given as in Eq. (14).

$$\frac{\boldsymbol{C}}{\boldsymbol{N}} = \frac{(\boldsymbol{P_T G_T})}{\boldsymbol{Pathloss}} . \left(\frac{\boldsymbol{G_R}}{\boldsymbol{T_s}}\right) . \frac{\boldsymbol{1}}{\boldsymbol{K.B}} \tag{14}$$

where, $P_T G_T$ is called the Equivalent Isotropic Radiated Power (EIRP), $\left(\frac{G_R}{T_s}\right)$ is the receiver characterisation, known as figure of merit, whilst $K$, $B$ and $T_s$ are Boltzman's constant, noise bandwidth and the receiving system temperature, respectively [16]. The received carrier to noise ratio can be rewritten in dB form as follows:

$$\left(\frac{C}{N}\right)_{\boldsymbol{dB}} = \boldsymbol{EIRP_{dB}} - \boldsymbol{Pathloss_{dB}} + \left(\frac{G_R}{T_s}\right)_{\boldsymbol{dB}} - \left(\frac{1}{K.B}\right)_{\boldsymbol{dB}} \tag{15}$$

In this system simulation, the filter and mixer losses are 0.275 dB and the noise in the mobile station is $4 \times 10^{-12} dBW$. From Eq. (15), it has been shown that the received signal power dramatically decreases with distance. The remaining parameters have been chosen in the designing stage. The BER depends on the received power level, which is inversely proportional to the square of the distance, according to the pathloss, as given by Eq. (14).

Fig. 4 shows the received RF signal in the time domain with 60 GHz at the mobile station. It is clearly seen that the RF signal has been attenuated by the noisy channel. After ASK demodulation and low pass filter, we will get the received baseband signal, as visualised in Fig. 5. The detected signal is also distorted and attenuated by noise to be added in the AWGN channel.

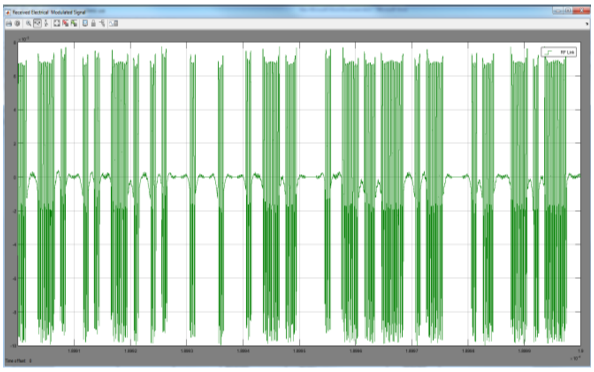

Fig. 4. Downlink received modulated signal with 60 GHz at the mobile station.

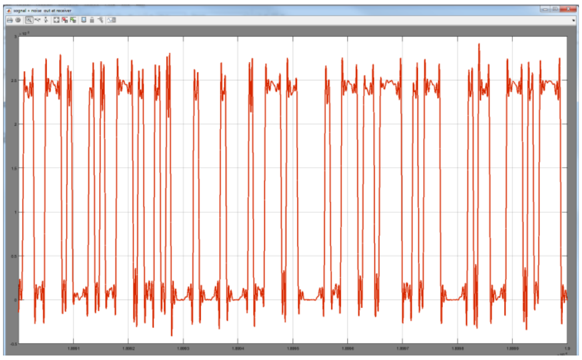

Fig. 5. Downlink received baseband signal by mobile station after low pass filter and ASK demodulation.

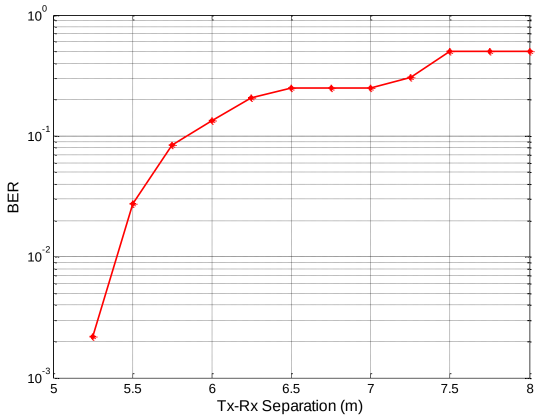


Fig. 6. BER performance of various distances.

ASK modulation is more susceptible to the AWGN channel, which makes the receiver confused in terms of distinguishing between two states (0 and 1) and hence, the BER will increase. Moreover, Fig. 6 shows that the BER of the proposed system model gradually increases with the distance, because the received signal strength dramatically decreases, as clarified in Eq. (15). The simulation results of various fibre lengths are depicted in Fig. 7.

It can clearly be seen that the BER has increased with fibre length resulting from attenuation until it reaches a saturable situation after 21 km. Hence, the performance of the system is dependent on the chromatic dispersion and fibre attenuation.

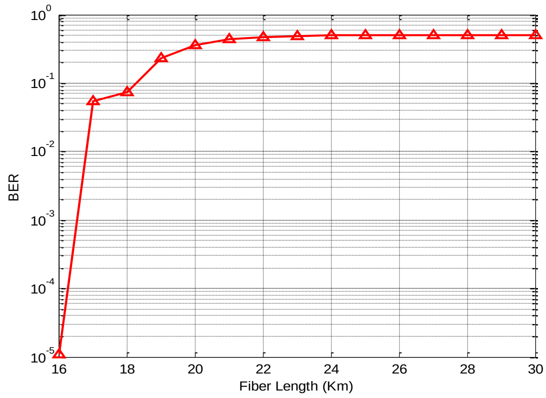


Fig. 7. BER versus SMF length at the mobile station.

## V. Conclusions

In this paper, a proposed model of an RoF downlink for a super broadband femtocell wireless access point has been introduced, where the system is simulated by a MATLAB program. RoF technology is an advanced technique for both mobile and fixed users for the upcoming provision of Wi-Fi and current perspectives regarding cellular systems. The system transports 10 Gbit/s of binary data mapped over a 60 GHz sub-carrier that is modulated with ASK modulation to be transmitted over SMF. The proposed system has been simulated and investigated for different fibre lengths. The QoS of the system depends on the attenuation and dispersion impairment of the optic fibre. Moreover, the system has been tested for various wireless channel distances and the simulation results have shown that the modulation technique used is affected by a noisy channel. Hence, a different modulation type could be used to overcome this noise. In addition, a higher modulation order can be employed in order to increase the spectral efficiency (bit/s/Hz).

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