Analysis and impact of digital modulation techniques on LTE over fibre for 5G systems applications.

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Abstract- The impact of digital modulation techniques used in Long Term Evolution (LTE) when applied to radio over fibre for fifth-generation systems has been analysed and evaluated in this paper. The analyses are based on the measured BER and the observed eye-diagram with quality factors for the different modulation techniques such as QPSK, 16 QAM, 64 QAM, and 256 QAM. A fibre length between 5 km and 100 km is adopted to showcase the best configuration at a particular length that can support 5G systems. Huge bandwidth and low latency with high spectral efficiency are needed to accommodate 5G applications in areas of critical surgery, home automation, smart transportation, security, and smart cities via IoT among others. Recent researches are focusing on a synergy between the wireless systems and optical network systems to enhance the transmission of RF signals from a central location to a separate unit of the radio element known as the remote radio head (radio over fibre). This technology merges the optical networks and microwaves to provide a possible solution to increase channel capacity, mobility, and reduced the cost of the access network for customers' comfort. The whole system link is simulated using a commercial optical simulator Optisystem 17.

Keywords: Digital Modulation; Long term evolution (LTE); Radio over fibre (RoF), Fifth generation (5G); Optisystem 17

1. Introduction

Modulation is the process of the transmitting baseband signal (information) over the band-pass medium by adjusting the properties of the sinusoidal wave. Modulation could either be through analog signal over an analog medium often referred to as analog modulation or digital modulation whereby digital bit-streams from the transmitter to the receiver(s) over the analog information channel (medium). Nearly all wireless communication links are associated with modulation techniques. Modern-day transmissions have been digitized and available spectrum limited. Hence, adopting modulation schemes is significant to fully utilize the available bandwidth for good quality of service.

The evolution of analog to digital modulation has many advantages such as enlarged capacity, compatible digital data services, secured data rate, improved quality communications skills, and high-speed system accessibility [1]. In digital modulation, the amplitude-shift keying (ASK) is referred to as a message mapped with the carrier amplitude. However, when the message is linked to the carrier frequency (fc), such modulation is termed the frequency-shift keying (FSK). Modifying the phase of the carrier in accordance with the message gives rise to phase-shift keying (PSK). Utilizing both the amplitude and phase component of the carrier wave is considered quadrature amplitude modulation
Bit error rate (BER) which is a determining factor of the behavior of digital modulation has for long been the measurement primarily used to assess digital link performance. ITU-T Recommendation G.821 recommends that if the BER is too high, the system is declared to have either failed or unavailable [2]. The sporadic growth of multimedia controlled application has awakened an unquenchable desire for vast data rate, which has in turn put more demand on mobile network operators and vendors to adopt advanced technology with the robust transmission, and efficient spectrum utilization. This is necessary since the existing Long Term Evolution (LTE) structure has not been able to meet the humongous bandwidth requirement of the fifth-generation (5G) that is about 10 Gb/s, compared to less than 1 Gb/s provided by the LTE structure [3]. The new 5G has the capacity for enhanced data mobility, robust connectivity, scalability, and energy optimization. The 5G networks will build on the existing technology, Radio-over-Fibre (RoF) link in conjunction with millimeter-wave (mMW). The mMM bands have the advantage of broad bandwidth when compared with the microwave front haul. The spectrum window (30-300 GHz) of mMW is a good tool for the next phase of wireless technology [4, 5]. Furthermore, the spectrum window of mMW carriers will enhance a robust data rate compared with RF carriers in the microwave frequencies band [6, 7]. Although the transmission link of MWW is a factor of the fc and atmospheric conditions, this can be annihilated using an optical fibre between the central station (CS) and the base station (BS). In doing so, a cloud base-band unit (C-BBU) in the core station (which consists of a central pool of resources) is physically connected to several remote radio heads (RRH). The C-BBU is part of a cloud radio access network (C-RAN) that comprises of software-defined network (SDN) controller, hypervisor, virtual BBU (vBBU), and the evolved packet core. This setup reduces the complexity of the small cell front-haul (5G) which in turn reduces the cost of deployment, expansion, and maintenance. Transporting 5G services with RoF offers the benefits that include security and high bit-rate transmission which will in turn offer assistance in inbuilt sight and sound, voice, video, internet, and other broadband management activities [5]. Integrating wireless access with optical links is achievable and has led to more robust data communication services. More so, 5G utilizes microcells as a result of the MMW propagation characteristics which are different from the microwave band. The mMW is associated with propagation problems like path loss, diffraction and blockage, rain attenuation, and foliage loss behaviors; which in turn limits the transmission distance. Also, the placement of antenna needs to be closer to targeted areas causing a vast amount of antennas to be deployed in line with densification. However, the deployment of fiber optics does not require license and has very high interference immunity and poses no radiation concerns. Hence the need for the use of fiber optics for 5G deployment.

The familiar BER which is defined as the ratio of false bits to the total number of received bits is not the only determinant of the behavior of an RoF link. The Q-factor is also a strong factor. It dictates how good an analog transmission signal is based on its signal-to-noise ratio (SNR). The SNR, in turn, determines the cause of the signal fading such as noise, non-linear effects among others. The implication is that high Q-factor leads to better SNR, and lower occurrence of the BER. Thus, for long-distance transmission, a low BER and high Q-factor must be ensured. The International Telecommunication Union (ITU) recommended $>10^{-9}$ as the minimum value of the BER of an RoF system, and a Q-factor value of more than 6 to obtain a very good performance at the receiver [8]. The BER can be related to Q-Factor based on:

$$BER = \frac{1}{2} erf c\left(\frac{Q_{BER}}{\sqrt{2}}\right) \tag{1}$$

where:

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du \tag{2}$$
$Q_{\text{BER}}$ is the minimum Q-factor required for a given BER and $\text{erfc}(x)$ in equation (2) is the complementary error function that allows the formulation of an analytical expression that is simple for the BER in equation (1). A typical RoF setup is illustrated in Figure 1.

![Basic diagram of RoF technology](image)

**Figure 1.** Basic diagram of RoF technology.

### 2. Methodology

The simulated system consists of a transmitter (Tx) and a receiver (Rx) end. At the transmitter stage, the input data signal which is a bit rate of 10 Gbps is modulated using the various modulation schemes applied in LTE by a Pseudo-Random Bit Sequence (PRBS) generator for 60 GHz and 5 GHz. The incoming signal is passed through the Optical Band Pass Bessel filter (OBPF) having cut off frequency of 10 GHz for modulating an optical carrier of frequency 193.1 THz using a Mach-Zehnder Modulator (MZM). The MZM is a high-speed external modulator for modulating the intensity or phase of the source of light. The light source is kept ON while it acts as a shutter that is controlled by the conveyed information. The modulated signal is passed through a single-mode fibre mostly used at 1310 nm and 1550 nm and is amplified using an optical amplifier. At the Rx, the amplified optical signal is fed to OBPF to filter the upper sideband (USB) of the optical signal which is subsequently applied to the PIN photo-detector. This photo-detector demodulates the filtered optical signal and converts it directly into a baseband signal that is an electrical signal. The output of the LPF is seen using a BER analyzer and an eye-diagram analyzer. Besides, the same amount of data that was initially transmitted is received at the output of the LPF. The parameters used in the simulation are itemized in Table 1 while the remaining ones are assigned by default using the Optisystem software.

| Component                      | Specification                      |
|--------------------------------|------------------------------------|
| Number of radio Transmitter    | 2 base Stations                    |
| Radio signal Bite Rate         | 10 Gbps                            |
| Laser frequency(EO)            | 1 THz                              |
| Fibre optical mode             | Single mode fibre                  |
| Fibre length                   | 5 km up to 100 km                  |
| Optical amplifier gain         | 20 dB                              |
| Photo-detector(OE)             | PIN photo-detector                 |
| Photo-detector responsivity    | 1 A/W                              |
| Wavelength                     | 1310 nm, 1510 nm                   |

The Optisystem is a simulation package developed for optical communication for optimization, designing, running, and designing virtually different kinds of optical links in the physical layer of a
board spectrum of the optical network. The system designed for analysis is illustrated in Figures 2 and 3.

Figure 2. QPSK based RoF system design

Figure 3. QAM based ROF system design.
3. Result and Discussion.

The performances of the simulated system shown in Figures 2 and 3 have been investigated in terms of BER, Q-factor, and eye diagram. The eye diagram analyzer block of the software displays multiple traces of a modified signal to construct an eye diagram. In telecommunication systems, an eye pattern often referred to as an eye diagram, is regarded as an oscilloscope whereby a digital data signal from a Rx is sampled at length and applied to the vertical input, while the data rate is used to trigger the horizontal sweep [9]. An open eye pattern correlates to the least signal distortion. The distortion of the signal waveform arises due to the inter-symbol interference (ISI) and noise which displays as encasement of the eye-diagram. The classical optical link operates at 1310 nm/1550 nm in order to increase its data transmission capacity [10]. The simulation results for the different modulation schemes are illustrated for the QPSK, 16 QAM, 64 QAM, and 256 QAM modulation schemes at an operating wavelength of 1550 nm and 1310 nm using eye diagrams as performance matrix. The output result presented in Figure 4 indicates the BER, Q-Factor, and eye-diagram of the system at 5 km of single-mode fibre applying QPSK modulation at 1550 nm and 1310 nm wavelength. For both wavelengths, very good eye-opening is observed with a nearly perfect eye-crossing symmetry and a good BER value. At 100 km with QPSK modulation (Figure 5) shows a fair eye-opening and BER value with an asymmetric eye-crossing for 1550 nm wavelength, no eye-opening was seen at a wavelength of 1310 nm. Applying the 16 QAM modulation at 5 km it is observed from Figure 6 that both 1550 nm and 1310 nm have a good eye-opening, asymmetric eye-crossing, good BER value but scattered 0’s bit-stream. However, applying the same modulation at 100 km an eye-opening is observed with a fair BER value and an asymmetric eye-crossing for 1550 nm wavelength as observed from Figure 7. No eye-opening was observed for a wavelength of 1310 nm when the 64 QAM modulation is applied at 5 km. Figure 8 shows a fairly opened eye, not too optimal BER value, and scattered 1’s and 0’s bit-stream for both the 1550 nm and 1310 nm wavelength. When the same 64 QAM modulation applied at 100 km for the 1550 nm wavelength as shown in Figure 9, poor eye-opening, overlapping, and scattered 1’s and 0’s bit-stream with poor BER value was observed, while no opening was observed for the 1310 nm wavelength. The value of BER and the eye-opening are very poor with enormous overlapping and scattered 1’s and 0’s bit-stream as seen from Figure 10 at 5 km for both the 1550 and 1310 nm wavelength. Applying the 256 QAM, with the same modulation scheme at 100 km for the 1550 nm wavelength, an extremely poor BER value is observed with no distinction between the 1’s and 0’s bit-stream. However, at the same optical length for the 1310 nm wavelength, there is no eye-opening as seen in Figure 11.
Figure 4. Simulation results of QPSK at 5 km for (a) 1550 nm and (b) 1310 nm wavelengths.

Figure 5. Simulation results of QPSK at 100 km for 1550 nm wavelength
Figure 6. Simulation Results of 16 QAM at 5 km for (a) 1550 nm and (b) 1310 nm wavelengths.
Figure 7. Simulation Results of 16 QAM at 100 km for 1550 nm wavelength
Figure 8. Simulation results of 64 QAM at 5 km for (a) 1550 nm and (b) 1310 nm wavelengths.

Figure 9. Simulation Results of 64 QAM at 100 km for 1550 nm wavelength.
Figure 10. Simulation Results of 256 QAM at 5 km for (a) 1550 nm and (b) 1310 nm wavelengths
The values of BER and Q-factor obtained from the simulation between 5 km and 100 km have been plotted from figures 12 to 15 for both 1550 nm and 1310 nm wavelengths. Figures 12 illustrate the variation of BER with optical length by comparing the various LTE modulation scheme for 1550 nm and wavelength. The result shows that only the QPSK predicts the best values of BER across the varying optical fiber line which can be associated with sparsely spaced points on the constellation. However, as the length of the optical fibre increases, the BER value degrades in consequences to the losses per km along the optical fibre line. In ITU-T G.652, a single-mode fibre experiences maximum losses (α) in dB/km of 0.42 and 0.28 respectively for 1310 nm and 1550 nm wavelengths [11]. Hence as fiber length increases, BER rapidly increases. It is then observed that the values obtained for the 1550 nm are better than the values obtained at 1310 nm. This is seen by comparing the trend-line of QPSK, 16 QAM, 64 QAM, and 256 QAM in Figures 12 and 13.

Higher-order modulations allow sending of more bits per symbol because of denser points within the constellation amounting to higher throughputs and better spectral efficiencies suited for 5G systems; trades-off exists because the higher modulation schemes are susceptibility to noise and errors. Also, when adopting a modulation technique such as higher-order QAM, an improved Q-factor should be used to avoid any occurrence of interference and ensure a better BER for effective performance. A plot of BER against Q-factor for 1550 nm wavelength in Figure 14 shows improvement in BER value as the value of the Q-factor increases for the various LTE modulation scheme along the regressing optical fiber length which is verifiable by equation (1). A wireless system must be able to adapt its modulation scheme to choose higher-order modulation based on the conditions of the channel. As the link increases, the system should adjust to lower modulations (that is to say, QPSK), but as it moves closer, higher-order modulations like QAM should be adopted for increased throughput. Besides, adaptation allows the system to overcome fading and other interference [12]. 5G requires a higher data rate with a low bit error rate which can be provided by higher modulation schemes such as 256 QAM however, poor BER values were observed from Figure 12 above 5 km optical fiber length at 256 QAM for 1550 nm wavelength. This suggests that the core station should be around 5 km from the base station for effective and increased throughput. Figure 15 shows the worst value of BER in...
correspondence with the lowest value of Q-factor at 256 QAM for 1310 nm pointing out the effect of wavelength in an optical line in the transmission system.

Figure 12: BER against length (km) for 1550 nm wavelength at 10 Gbps

Figure 13: BER against length (km) for 1310 nm wavelength at 10 Gbps
Table 2: Summary of the path length of fibre at which BER begins to fall below ITU standard

| Modulation   | QPSK | 16 QAM | 64 QAM | 256 QAM |
|--------------|------|--------|--------|---------|
| Fibre Length (km) BER |      |        |        |         |
| above $10^{-9}$ at 1510 nm | Above | 90 km  | 40 km  | Below   |
| below 100 km | 100 km |        |        | 5 km    |
| above $10^{-9}$ at 1310 nm | 70 km | 60 km  | 40 km  | Below   |
| below 50 km |        |        |        | 5 km    |

4. Conclusion
This work has been reported based on 10 Gbps of data based on a 60 GHz mWM signal transmitted with the variation of optical fibre length from the central station to base station specifically for 5G applications. The analysis and impact of the simulated modulations applied in LTE for RoF transmission link are successfully evaluated based on Q-factor, BER, and eye diagrams for the 10-Gbps data. Generally, 256 QAM modulation applied in LTE is observed to be suitable for 5G networks but the core station should be around 5 km from the base station to achieve the desired throughput and 1550 nm for an ideal wavelength in the radio over fibre setup. However, the optical fibre length can be increased but the modulation scheme must drop to either 64-QAM or 16-QAM.
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