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REVIEW ARTICLE

A comprehensive review of Millimeter wave based radio over fiber for 5G front haul transmissions

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Abstract

Objectives: To find out how fiber distribution system could be utilized for 5G based futuristic higher capacity and lower latency front haul transmission system. **Findings:** Integrating the transmission of Millimeter wave (Mm wave) signals over the Radio over Fiber (RoF) system i.e. Mm-RoF can be seen as a promising candidate that would satisfy the requirement imposed by 5G wireless system. Further, optical generation of Mm wave signals is a major concern that needs to be taken care of and some appropriate hybrid photonic generation methods should be employed for Mm wave signal distribution over the RoF system that incur lower installation cost and higher transmission performance. **Applications:** This will enrich the researchers with valuable content on single platform and motivate them to undertake the research work towards the advancement in the photonic generation of Mm wave signals over the RoF network for 5G applications with reduced system cost and complexity.

Keywords: Radio over Fiber; Mm-wave technology; 5G networks; optical signal generation; Mm wave based RoF etc

1 Introduction

Due to the rapid rise in data traffic for portable devices and its global expectation will grow about eight times by the end of the year 2023 as new multimedia applications for instance ultra high definition (UHD) video streaming, virtual and augmented reality (AR) and evolving industrial use etc. involve higher bandwidth, higher capability and reduced latency around 1 ms enabling the researchers to look for new spectrum beyond 4G standard, therefore giving rise to the transition towards the new generation i.e. 5G cellular network[(1)].

Further, 5G would push through other technologies to a next level such as the Internet of Things (IoTs), games, smart city, smart home, self-driving cars, remote operations, machine learning etc.[(2)]. So, there are challenges prevailing in the path of the wireless service providers to provide a more efficient technology that would provide higher data rates in order to tackle the worldwide bandwidth shortage so as to efficiently utilize the electromagnetic spectrum. This cellular technology transition is almost instantaneously opening up a new world of linked applications[(3)]. To accomplish this kind of performance, the network will probably require a lot of small coverage cells and greater bandwidth spectrum [4]. The technology roadmap now expands to the LTE-advanced (LTE-Adv.) network to satisfy the requirement of maximum throughput levels exceeding 1 Gb/s. This LTE-Adv. heterogeneous networks cover macro, micro and Pico cellular architecture. The backbone network design of this generation will help in migrating from coaxial cable to optical fiber to mm wave wireless links [1] [3].

RoF in 5G system comes out to be promising solution in this fast growing communication field for delivering high speed radio signal transmission in the Mm wave band as the existing microwave band being overcrowded by improving the accessibility and system performance; providing low latency transmission system which optically transmits radio signal to cover long distances. In order to use functionally simple base stations and a cost effective structure; Mm-wave signal distribution with RoF system is a considerably significant transmission system for the 5G networks as presented by D. Kamissoko et al. [3] [4].

1.1 Recent developments

Several research work have been currently being reported over this system for the 5G front haul transmission system such as low cost remote radio frontend based on silicon photonics consisting of Mach Zehnder Modulator (MZM) integrated with micro-ring modulator [5], analog photonic link based on dual parallel phase modulators with wavelength division multiplexing suppressing third order inter-modulation distortion and enhancing the spurious free dynamic range (SFDR) [6], bias free silicon based Optical single sideband (OSSB) modulator based on Dual drive MZM (DD-MZM) and silicon photonics eliminating bias drifting problem and the requirement for bias control and tracking circuits [7]. Miao Kong et al. simultaneously generated wired and wireless signal by utilizing dual-polarized MZM reducing the power penalty by placing an interleaver [8]. D. Kamissoko et al. proposed a W-band Mm wave RoF system using a 64 Quadrature Amplitude Modulation with Orthogonal frequency division multiplexing (QAM-OFDM) scheme based on optical heterodyne generation and self homodyne detection resulting in a cost effective and suitable for long haul transmission with error vector magnitude (EVM) falling within forward error correction limit [9]. Yu tian et al. experimentally compared ROF fronthaul links lying in the Mm wave band using double sideband suppressed carrier (DSB-SC) and Optical single sideband (OSSB) scheme and found that OSSB scheme has better receiver sensitivity [10]. Jalal Ameen et al. introduced a dispersion compensation scheme based on fiber bragg grating (FBG) providing high data rate for 5G fronthaul transmission [11]. Ahmed et al. utilized cascaded dual parallel polarization modulators for generating a frequency-12 tupled optical signal with an Optical Sideband Suppression ratio of 25.1 dB and radio frequency sideband suppression ratio of 19.1 dB [12]. M. Baskaran et al. generated a 160 GHz Mm wave signal through frequency 16 tupling based on the polarization property of phase modulators and obtained OSSR of 61 dB and RFSSR of 51 dB [13]. Aasif et al. generated a frequency 16 tupled signal through cascaded connection of two parallel MZM and found that OSSR along with RFSSR are independent of extinction ratio of MZM [14]. Dongfei Wang et al. generated 160 GHz Mm wave signal using optical attenuator and two MZM biasing at maximum transmission point (MTP) and obtained OSSR of 31.35 dB and RFSSR of 24.11 dB [15].

The present work provides a broad view of RoF for 5G explaining its key technologies, types, applications, signal generation in detail. The paper organization is done as follows. Section 2 describes the RoF technology explaining its features, operating principle, types, applications, modulation techniques and fiber nonlinearities. The Mm wave based RoF for 5G with its optical generation techniques are presented in section 3 followed by discussing different performance improvement and cost reduction strategies in section 4 with conclusion of paper in section 5 and future scope in section 6.

2 Radio over Fiber (RoF) technology

With increasing data rates and network capacity demands, transmitting the radio signals over the optical fiber network (OFN) in 5G comes out to be a cost effective solution for delivering high speed radio signal transmission in the Mm wave band.

The technique utilized for modulating the RF signal on the light (optical) signal over an optical fiber link is termed as "Radio over Fiber" (RoF) technology, introduced in 1990 for cordless telephone service. It consists of a central station (CS) where all the signal processing and frequency distribution operations are executed and an optical fiber network for interconnecting CS to several base stations (BSs) before radiating through air as fiber offers lower optical losses, wider bandwidth, immunity towards noise and electro-magnetic interference (EMI) [16] [17]. The BS transform light to electrical signals and electrical to light signals via E/O and O/E converters. Each base station communicates with at least one user mobile station (MS) in its range via radio connection as presented in Figure 1 .

The modulated RF signal which is to be transmitted over the fiber can be generated by varying the output power from optical source which can be achieved by either directly modulating the laser source or by externally modulating through intensity modulator such as MZM, Electro Absorption Modulator (EAM) or Phase modulator. Based on the frequency of the transported radio signal, the radio communication over fiber is broadly categorized into two main categories as: RF-over-Fiber (RoF) and

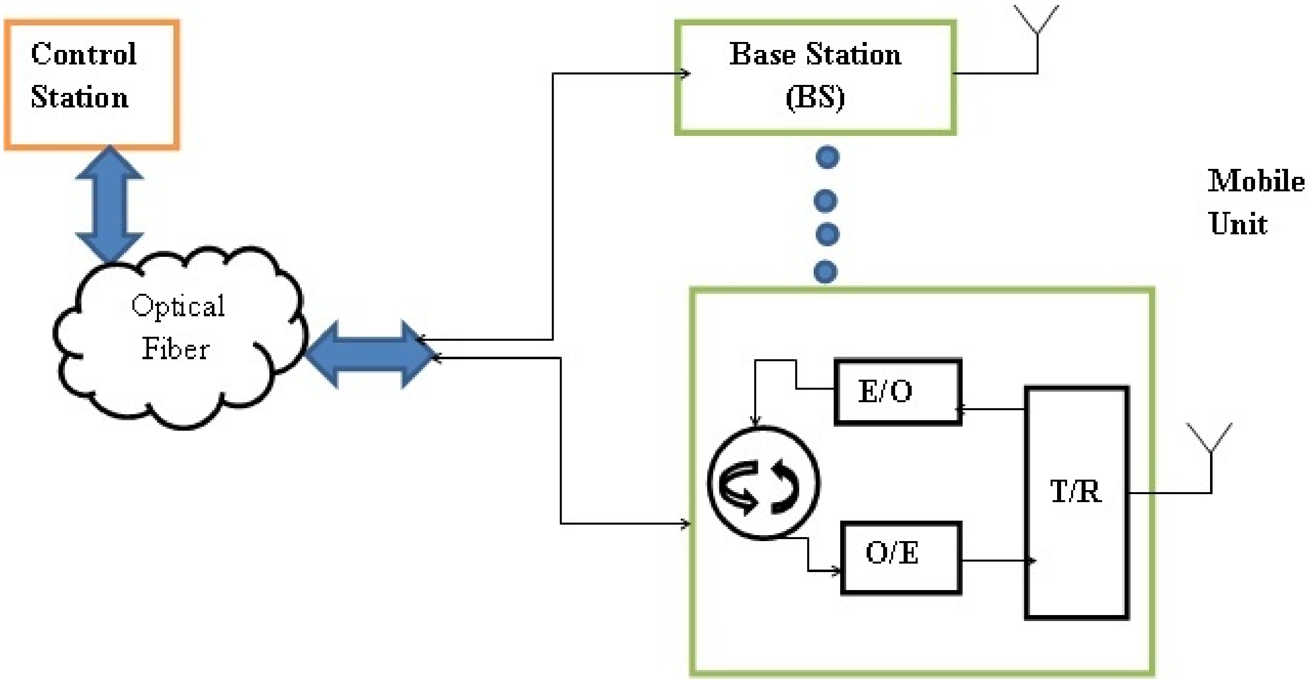

Fig 1. General Radio-Over-Fiber network

IF-over-Fiber (IoF).

In RoF scheme, a high frequency (RF) signal bearing information (f_{rf} >10 GHz) is superimposed on an optical carrier before transporting via the optical fiber connection. As high frequency signal is used therefore, there is no need for frequency up/down conversion at base stations which results in easy and cost-effective application of circuitry at base stations. For IoF scheme, an intermediate frequency (IF) signal (f_{if} < 10 GHz) is used to modulate the light signal and then carry the modulated signal through the fiber optic connection. Signal processing is therefore needed at the base station, such as frequency up conversion and amplification circuitry[18].

RoF being a hybrid technology provides benefits of both optical and wireless communication stated as lower fiber attenuation, larger bandwidth, improved cellular coverage and power efficiency[19]. Meanwhile, this technology would satisfy the requirement imposed by 5G wireless systems as small cells and multi input multi output (MIMO) schemes reported to be used in the 5G network can also be easily and economically implemented through ROF technology[20]. A few of applications areas for RoF technology are described:

- *Communication purpose*: For multiple applications ranging from the transmission of mobile radio signals for wireless access (*i.e.* 3G, 4G, 5G, Wi-Fi), cable TV (CATV) signals transmission, L-Band frequency signals (950 MHz to 2150 MHz) transmission for satellite communication, radio transmission over fiber is used. But the term "RoF" mostly pertains to wireless access.
- *Access dead areas*: It also provides wireless access to dead zones (i.e. where it is not feasible to provide backhaul connection). These regions can be places within a framework for example an underpass, mountain sites, jungles, building areas etc.
- *FTTA:* By using fiber to the antenna (FTTA) a direct optical link is made with the antenna that helps in gaining immunity towards lightening strikes/ electric discharges, lower the transmission line losses and decreasing the complexity of base station by directly attaching optical to electrical converter to the antenna.

However, this modulated RF signal when propagates through the optical fiber channel is subjected towards a number of impairments due to the fiber characteristics such as attenuation, dispersion and fiber nonlinearities which degrades the overall system performance. Attenuation tends to reduce the power of the optical signal while propagating through the fiber and helps in determining the maximum transmission length of optical signal. Whereas, widening of pulse duration while travelling along the fiber is known as dispersion. As per this expansion the pulses slowly begin to overlap with each other and thus produce inter-symbol interference (ISI). The pulses barely stay distinguishable after some range and if the signal propagates further, the pulses lose their identity and the information is lost [21].

Meanwhile, the optical fiber acts as a linear medium for low power level and non-linear for high power level thereby impacting the optical fiber with non-linear effects which deteriorates the system performance [22]. These nonlinear effects are more prominent in single-mode fibers and at high input powers. There are two general categories of fiber nonlinearities: The first type of nonlinearity stems from modulating the silica refractive index (RI) through modifications in the signal's optical intensity (Kerr effect). This results in different nonlinearities as per the shape of the input field such as Self Phase Modulation (SPM, single channel), Cross Phase Modulation (CPM, multi channel) and Four Wave Mixing (FWM, multi channel). The second type of nonlinearity rises due to the inelastic scattering process. For high power, this scattering process leads to stimulated effects such as Stimulated Brillouin Scattering (SBS, single channel) and Stimulated Raman Scattering (SRS, multi channel) [23]. Light intensity due to these effects increases exponentially when the power of incident signal crosses a certain limit.

The next section will present a detailed description of why millimeter wave technology needs to be linked with RoF network with its challenges regarding the various generation techniques.

3 Millimeter wave based RoF

In order to support the growing data services and traffic demands for high speed indoor communication in 5G networks, it is required to move on the frequency spectrum to the high frequency Mm wave band ranging from 30-300 GHz. The Mm frequency spectrum apart from providing huge transmission bandwidth suffers from significant propagation losses (higher frequency signals will have more collisions with obstacles in the air tending to lose their energy more quickly) such as path loss, diffraction, atmospheric losses, rain attenuation, and foliage losses [21] [22] which tends to reduce its transmission distance. This communication can be put to use by reducing the size of the cell which is covered by a single BS resulting in the small cell or micro cell or pico cell technology. This small cell being very small in size covering up to few meters would require large no. of BSs for providing service to broader area and this would in turn increases the frequency reuse factor [23] and enhances the system cost and complexity. However, RoF technology can overcome these drawbacks associated with the signal propagation as it offers cost-effective simple structure with centralization of signaling operations, lowering operational cost and reduces latency. Thus, Mm wave based RoF forming the integration of optical and wireless communication utilizing is the most viable solution with providing numerous capabilities required for the 5G networks as:

1. Mm wave is a new and less used band.
2. Higher frequency waves carry much more data than lower frequency wave.
3. It would be able to provide reduced latency due to cellular size reduction for Mm wave signal transmission.
4. It would offer cost effective simple structure as the signal processing operations would be centralized and performed by CS rather than BS due to radio over fiber distribution.
5. Spectral efficiency could be enhanced by incorporating massive multi-input-multi-output scheme.
6. Operational cost could be cut down due to the fiber distribution network.
7. Greater frequency reuse due to small size of cellular transmission enabling better connectivity for high speed applications.

One of the major issues related to Mm wave based RoF system to be implemented for 5G applications is its generation and transmission. The generation of the high frequency Mm wave signals can be performed in electrical as well as optical domain [24]. The electrical generation method is quite challenging and troublesome process therefore photonic/optical generation methods of Mm wave signal with RoF transmission are a matter of concern and therefore discussed in the succeeding subsections and thereafter the recent developments taken place in the last few years have been reported.

3.1 Optical Mm wave signal generation

The Mm wave carriers may be generated through RF local oscillators but this is applicable for only low frequencies as the efficiency decreases with high frequencies. However, the optical generation of Mm wave signal above 40 GHz is limited by the frequency response of MZM or phase modulator [25]. Therefore, optical generation of signals beyond 40 GHz is the area of interest. There are several techniques for the generation of Mm wave signal in optical domain e.g. techniques based on fiber nonlinearities, optical heterodyning, phase locked loop, injection locking, external modulation, up-conversion etc as categorized in Figure 2.

The photonic Mm wave generation techniques such as Direct Modulation, External Modulation, Optical Heterodyning and Optical Up/Down conversion are described in next sub sections.

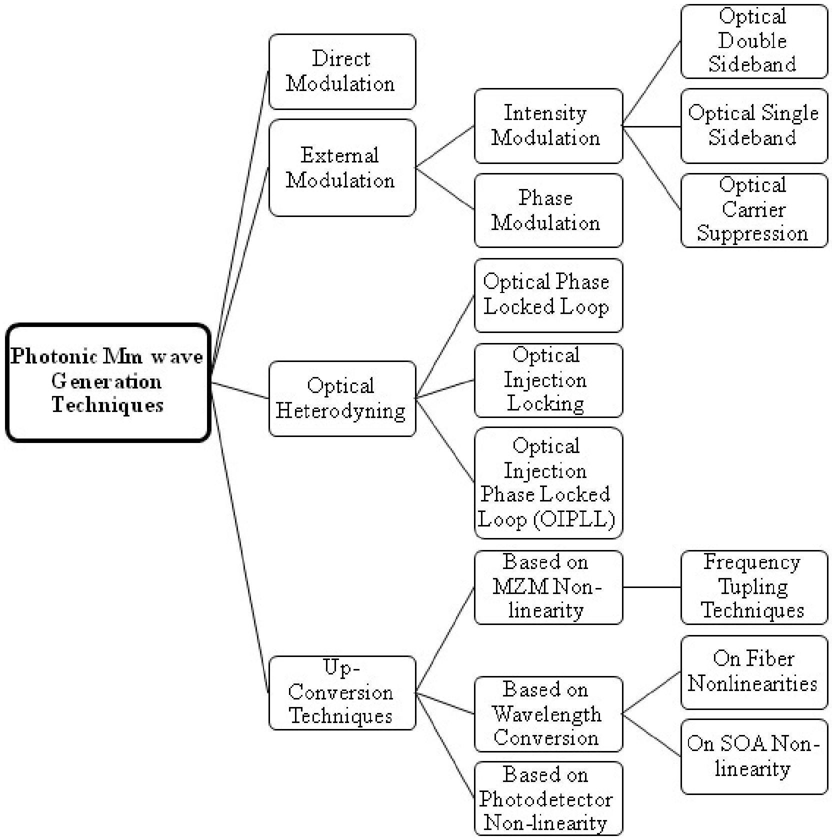

Fig 2. Photonic 3Mm wave generation technique

3.1.1 Direct intensity modulation

Direct Intensity Modulation is the cheapest and oldest method employed for mm wave signal generation as it directly modulates the semiconductor laser and the generated mm wave signal is recovered with the help of photodetector as shown in Figure 3. Although this method is simple in configuration but it is applicable only for generating low frequency signals as the modulating signal is restricted by the modulation bandwidth of laser (i.e. 40 GHz) above which this method tends to produce unwanted noise, frequency chirp and exhibit nonlinear characteristics resulting in lesser stable output[18]. These limitations can be overcome by externally modulating the laser for generating high frequency signals.

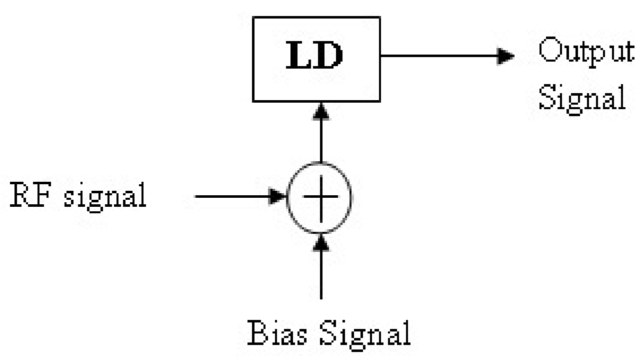

Fig 3. Direct modulation technique (LD: Laser diode, RF: Radio frequency).

3.1.2 Optical heterodyning

Optical heterodyning technique is based on the principle of heterodyning two or more than two optical signals with frequencies ω_1 and ω_2 to produce a beat signal at the output of the photodetector whose frequency is equal to the frequency difference between two optical signals $\omega_1 - \omega_2$ as shown in Figure 4 . This technique is useful for generating high frequency signals with higher link gain and carrier to noise ratio (CNR). It also makes the system less sensitive towards chromatic dispersion when only one out of the two optical carriers is modulated with data [26]. Apart from these advantages this technique suffers from laser phase noise as the phases of the two optical signals are not correlated. This sensitivity towards phase noise could be reduced using techniques such as optical phase locked loop (OPLL), optical Injection Locking (OIL) and combination of OPLL and OIL i.e. Optical Injection Phase Locked Loop (OIPLL) improves the signal quality [27].

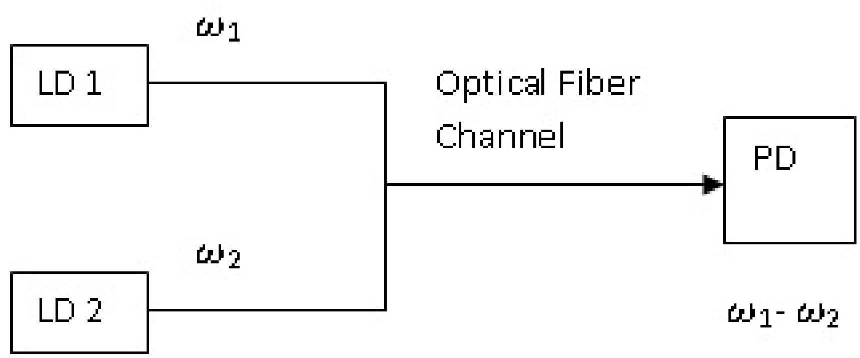

Fig 4. Optical heterodyne technique (LD 1: Laser diode 1, LD 2: Laser diode 2, PD: Photodetector).

3.1.3 External Modulation

In this technique, light carrier generated from laser is modulated with the help of external intensity modulator such as MZM, EAM or external phase modulator (EPM) to generate high frequency Mm wave signal as shown in Figure 5. The basic working principle for this method depends on the higher order harmonic generation resulting from the modulator nonlinearities in transmission [28]. The power of harmonics is regulated from the bias voltage and modulation index while the amplitude can be adjusted by the LO drive voltage [29]. This minimizes the bandwidth requirement and helps in generating high frequency signal from low drive signal reducing the system cost [30]. Depending on the type of modulator employed this method leads to further two modulation approaches: External Intensity Modulation and Phase Intensity Modulation.

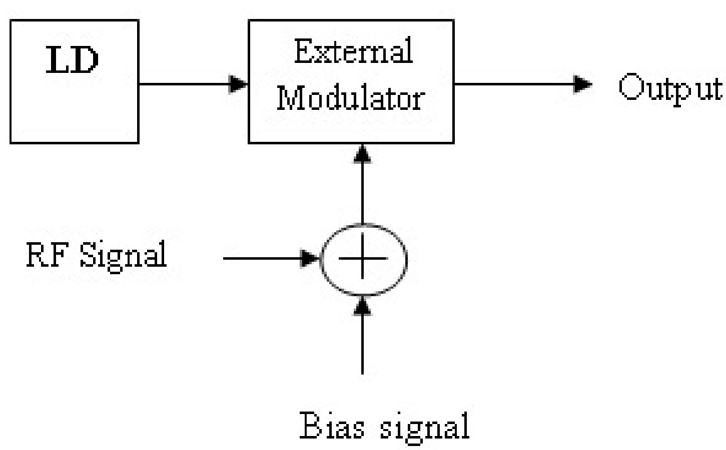

Fig 5. Block diagram for external modulation (LD: Laser Diode, RF: Radio Frequency).

3.1.3.1 External Intensity Modulation (EIM).

In the External Intensity Modulation, the intensity of the signal being the square of the amplitude of the signal is modulated as per the baseband signal and this can be accomplished by MZM or EAM. An EAM requires less driving power and can be easily combined with the optical laser source than MZM [31]. This technique eliminates the requirement for complex circuitry with providing large bandwidth and long haul transmission without any amplifier. Although this technique is simple but it suffers from high insertion loss, fiber dispersion effects, distortion due to intrinsic nonlinearity of modulators. Further, there are three different variants to this method employing MZM or EAM: Optical Double Sideband, Optical Single Sideband and Optical Carrier Suppression Modulation as discussed in succeeding sub sections.

3.1.3.1.1 Optical double sideband modulation (ODSB).

An optical double sideband consists of two sidebands i.e. upper and lower centered at the optical carrier frequency, f_c, such that the separation between the carrier frequency and one of the sidebands is equal to the frequency of the modulating RF signal. It can be generated by directly modulating laser or by using external modulators such as single or dual drive MZM or EAM. While using a dual-drive MZM, a π phase difference should be maintained between the RF signals for generating the Mm wave signal with no frequency chirps [25]. However, when this signal is transmitted through fiber, phase shift occurs between the spectral components due to fiber chromatic dispersion effects, these effects can be eliminated by using dispersion compensation fibers or equalizers [32] or with dispersion tolerant schemes by either suppressing one of the sidebands (i.e. SSB) or by suppressing the carrier signal (i.e. OCS).

3.1.3.1.2 Optical single sideband modulation (OSSB).

The Optical single sideband signal consists of a carrier and one of the sideband with a separation of the RF signal frequency. This type of modulation can be achieved by employing Fiber Bragg Gratings (FBGs) filters after generating an ODSB signal so that one of the sideband can be eliminated. Additionally, it can also be generated with the help of quadrature biased dual drive MZM with a phase shift of $\pi/2$. Eamonn Martin, et al. experimentally demonstrated a 60 GHz RoF system based on a gain switched laser modulated with a single sideband sub carrier multiplexed quadrature phase shift keying (SSB SCM QPSK) modulation employing a self heterodyne method and Wavelength Selective Switch (WSS) for filtering comb lines over 25 km of SSMF. It provided an error-free transmission using Dispersion Compensation Module [33] [34].

3.1.3.1.3 Optical carrier suppression modulation (OCS).

An Optical carrier suppression modulated signal consists of two sidebands located at frequency $f_c \pm f_{rf}$ Hz where f_{rf} is the modulating signal frequency. For obtaining the OCS signal with the frequency of $2f_{rf}$ Hz, MZM is biased at $V_\pi \pm m2V_\pi$. It was reported that this modulation scheme provides the highest receiver sensitivity, spectral efficiency, the lowest spectral occupancy, the lowest bandwidth requirement for RF signal, amplifier and optical modulator with lower power penalty for long distance.

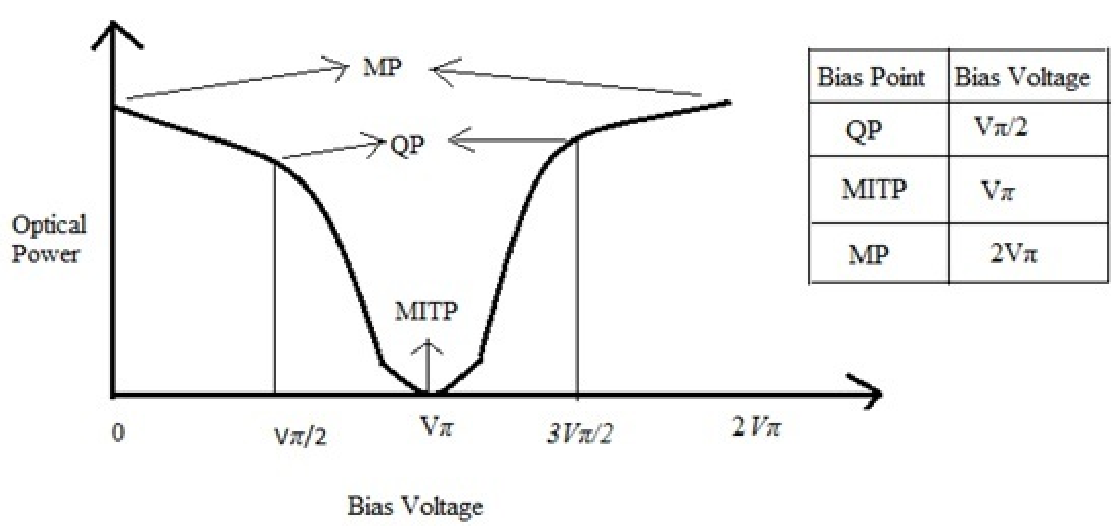

Fig 6. Different MZM Biasing points

There are three biasing points used for MZM: Quadrature Point (QP), Maximum Point (MP) and Minimum Point (MITP) as shown in Figure 6 with corresponding voltages. QP generates both even and odd order harmonics, while MITP produces odd order and MP produces even order harmonics as reported by V. Thomas et al.[25]. For suppressing the optical sidebands, MZM should be biased at maximum or minimum transfer function point (MTP), which tends to cause bias drifting problem leading poor system robustness and requirement for control circuitry to minimize this issue thereby increasing the cost and complexity of the system. This can be overcome by replacing MZM by Phase Modulators[24].

3.1.3.2 External phase modulation (EPM).

In the external phase modulation, the phase of the carrier signal is modulated as per the light signal through phase modulators. Phase modulators have an added advantage over MZM that they do not need dc biasing due to which they are free from bias drifting problem and thus provides a stable output[26]. An approach for generating a tunable mm wave signal at 54, 90 and 126 GHz was demonstrated by the authors in 2003[27]. This method was based on the spectrum slicing of the phase modulator and used Fabry Perot filter for sideband suppression. The tunable filter adds complexity which can be eliminated by using alternate fixed optical filter. In 2005, G. Qi et al. demonstrated the generation of two tuned Mm wave signal band ranging from 37.6-50 GHz and 75.2-100 GHz from drive signal of 18.8-25 GHz using FBG fixed notch filter for carrier suppression and phase modulator over 60 km SSMF producing a stable and narrow linewidth output[35].

3.1.4 Optical up conversion

In the up conversion method, an intermediate frequency (IF) signal is transmitted to the BS with the help of optical fiber. This IF signal is then up converted to RF signal and Mm wave carrier signal is generated through local oscillator at the BS. There are broadly three main methods categorized for achieving optical up conversion: (a) wavelength conversion (b) using photodetector non-linearity and (c) MZM non-linearity. The up-conversion techniques relying on wavelength conversion depends on non-linearities residing in ROF link components and can be accomplished with optical switching[21]. However, MZM based up-conversion techniques varies the transmitted signal frequency without altering LO frequency and generates wavelength division multiplexed (WDM) signal through a single modulator thus reducing cost of the system.

3.1.4.1 Optical up-conversion based on MZM Non-linearity.

The transmittance of MZM showing non-linear characteristics tends to generate harmonics and inter-modulation products. These harmonics and inter-modulation products are utilized for optical up conversion through optical K-tupling technique. In the optical K-tupling technique, the frequency of the photo detected output signal is K^{th} harmonic of the local oscillator frequency. This technique can be achieved in a single step employing a single upconversion through MZM or by two-step process where IF modulation is followed by up conversion through MZM and obtaining the RF signal having frequency, f_{RF}, given by the Equation 2, both the methods employ optical filter to remove unwanted sidebands.

$$f_{RF} = Kf_{LO} + f_{IF}$$

Another optical K-tupling technique which is robust towards dispersion is Optical Frequency Multiplication (OFM), in which the laser output is frequency/phase modulated through RF signal rather than intensity modulated and the resulting harmonics are then converted to intensity modulation through frequency/phase discriminator.

In optical K-tupling techniques, there are various implementations discussed by the researchers by putting on different K values such as K=2,3,4,5,6,8,12 etc. leading to doubling, tripling, quadrupling, quintupling, six-tupling, octupling and 12-tupling. A brief description of various up conversion optical k-tupling techniques presented by authors is tabulated in Table 1.

Table 1. Literature review of various optical K-Tupling techniques

Optical K-Tupling	Author with references	Technique	Findings
Doubling	Yichao Teng et al. [32]	Based on Opto electronic oscillator with two MZM in cascaded connection.	• Systems Phase noise performance has been improved by utilizing high Q frequency response.
	X. Li et al. [33]	Generated 40 GHz frequency doubled QPSK modulated signal through single DML and wavelength selective switch.	• Avoided the need of external modulator for vector Mm wave generation, thus reduces system cost. • Reduces Bandwidth requirement.
Tripling	Jie Liu et al. [35]	On the basis of frequency tripling through directly modulated Fabry Perot Laser (FPL) with external injection	• Using FPL with external injection requires less optical injection power. • Observed negligible power penalty of around 3 dB at 10^{-9} BER.
	Z. Jia et al. [36]	Based on vestigial sideband filtering (VSB) with OCS.	• Provided high dispersion tolerant transmission by employing VSB with OCS.
Quadrupling	Muthu et al. [37]	Based on dual parallel MZM configurarion where MZM is biased at MTP	• Obtained Optical sideband suppression ratio (OSSR) of 57.2 dB • Radio frequency sideband suppression ratio of 53 dB achieved.
	Zhao et al. [38]	Utilizing integrated nested MZM, electrical phase modulator and electrical gain	• Overcome the fading effects caused by fiber chromatic dispersion. • Less than 1 dB power penalty achieved upto 40 km transmission
	Nael et al. [39]	Employed parallel configuration of two MZM by biasing them at MITP and an optical coupler	• OSSR of 42.07 dB • RFSSR of 36 dB
	Chung Ting Lin et al. [40]	Employing single integrated MZM without using any optical filter.	• Fast frequency tuning achieved. • Harmonic distortion suppression ratio more than 36 dB.
Quintupling	L. Zhang et al. [41]	Employing two cascaded single drive MZM with optical filter and driving the first MZM with a sub carrier multiplexed (SCM) signal.	• Driving the MZM with SCM signal eliminates the need of phase control between two RF signals.
12-Tupling	Y. Han et al. [42]	Employing parallel phase modulators	• High Power output achieved • No Dc biasing required • Filterless technique
	Zihang Zhu et al. [43]	Using nested MZM over 60 km to overcome chromatic dispersion.	• No fading and Bit walk-off effect caused by chromatic dispersion. • BER is not sensitive towards variations in modulator extinction ratio and RF LO voltage.

These upconversion techniques discussed in Table 1 based on the optical harmonics are assuming ideal conditions of extinction ratio. However, for non-ideal conditions these techniques would not be able to perfectly suppress the unwanted harmonics. Uncontrolled optical and RF sideband affects the signal purity Additionally, for larger value of frequency tupling coefficient (K), MZM driving higher powers is needed. Meanwhile, the OFM techniques come out to be with greater flexibility of generating wireless signal with any multiple of LO signal.

3.1.4.2 Frequency up-conversion based on wavelength conversion.

The techniques based on the wavelength conversion deals with the non-linearity of optical fiber, Semiconductor Optical Amplifier (SOA) and photo detector. There are several techniques based on these nonlinearities studied and discussed below.

3.1.4.2.1 Techniques based on fiber nonlinearities.

The fiber refractive index (R.I.) dependence on the optical power results into some non-linearities such as CPM, FWM etc. These fiber non linearities can be utilized for upconversion such as for generating CPM assisted techniques, highly nonlinear dispersion shifted fibers (DSF) are employed up to a certain distance [21]. These fibers exhibit high nonlinear RI when wavelength is shifted from zero dispersion 1300 nm to 1550 nm [22].

Additionally, some architectures are also demonstrated by researchers that exploit FWM for optical upconversion which transfers the modulated signal upconverted spectrum at ω_{FWM} through the DSF. FWM signal strength could be enhanced by employing SRS[23].

3.1.4.2.2 Techniques based on SOA non-linearity.

SOA also suffers from nonlinearities as optical fibers do. They are also affected by gain saturation. So, the phenomenon of CPM, FWM and cross gain modulation (CGM) from SOA can be used for optical upconversion. SOA-MZI is employed to combine the phase modulated signal into intensity modulated signal[44]. Medeiros et al.[45] introduced the RoFnet-Reconfigurable RoF network, which comprises of reflective SOA with optical WDM techniques and found that the grouping of subcarrier multiplexing (SCM) with WDM make the system easier[46]. Authors generated a 12-tupled frequency using dual-parallel MZM along with optical four-wave-mixing utilizing SOA[47].

These wavelength conversion techniques are quite cost-efficient as they reuse wavelength, does not require polarization sensitive MZM and facilitate optical switching while requiring long length DSFs.

3.1.4.2.3 Techniques based on photo-detector nonlinearity.

Photo-detectors also exhibit non-linear behavior which can be exploited for optical upconversion by modulating its bias voltage[18]. A comparative study presented by authors for various optical Mm wave generation techniques along with merits and demerits is tabulated in Table 2.

Table 2. Comparison of various optical Mm wave generation techniques.

Techniques	Merits	Demerits
Direct Modulation[23]	• Simple design. • Low cost BS • Easy implementation	• Limited to Laser's Bandwidth • Suitable for low frequency signals • Performance degradation due to fiber nonlinearities
Optical Heterodyning[25]	• No fiber Dispersion • High CNR • High link gain	• High cost. • High complexity • Phase correlation among carriers.
External Modulation[26] [27] [29]	• Simple structure • For high Frequency signals • Employ DFB Laser. • Flexible configuration providing different variations as ODSB, OSSB, OCS.	• High Driving voltage required • High insertion loss • Frequency chirping • High cost employed for high RF • Fiber chromatic dispersion effects for ODSB modulation
Optical Up/Down conversion[33] [39] [41]	• Free from Fiber chromatic dispersion • IF modulation required. • Lower Phase Noise • Useful with DWDM • Providing broader bandwidth.	• Require additional circuitry for Mixers and LO • High cost and complexity.

After having compared all the generation techniques, however optical up conversion techniques seems to be the most promising techniques as they are free from fiber chromatic dispersion, lowers the phase noise and can generate high frequency signals from a lower frequency signal. But has a disadvantage of additional cost and complexity required for mixers and oscillators which needs to be eliminated for developing an efficient system. So, some hybrid techniques need to be employed for providing Mm wave photonic link in the 5G network. The next section would mention the performance metrics needed to be taken care of and the various integrated mitigation techniques undertaken for improving system performance and cost reduction.

4 Discussion

The various techniques employed for Mm wave signal generation and transportation over the fiber front-haul network as discussed in the previous section are based upon some performance metrics graphically represented in Figure 7.

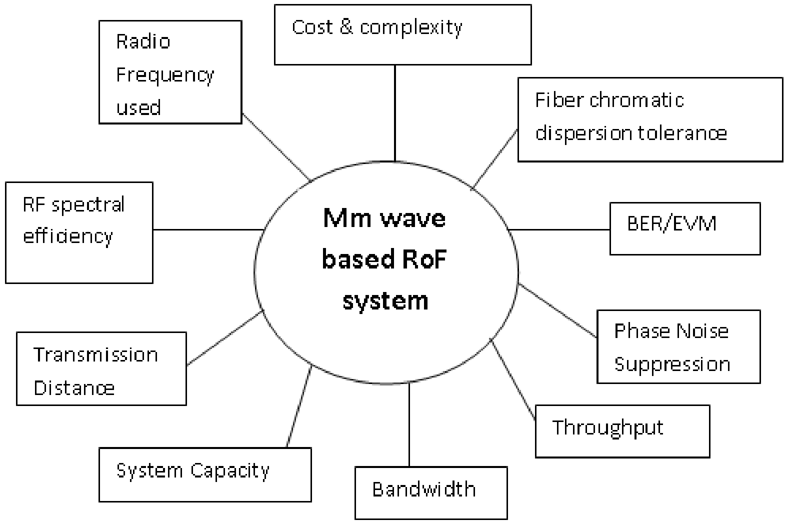

Fig 7. Mm wave based RoF fronthaul network parameters.

These metrics can be categorized into two broad manners as the one that focuses on enhancing the system performance and the other one on reducing the cost and complexity of the chromatic dispersion degrading the BER as discussed in section 3.1, which could be mitigated by employing OSSB or OCS schemes resulting in increasing the system cost by employing additional circuitry and reducing throughput. However, the overall system throughput can be enhanced by incorporating spectrally efficient multiplexing schemes such as DWDM, WDM etc. which would again enhance system cost and complexity. The performance metrics taken into consideration for Mm wave based RoF are listed below in Table 3 with its mitigation strategies and the corresponding impacted parameters.

Table 3. Mitigation strategies of the design challenging parameters

Challenging Parameters	Mitigation strategies working principle	Observation
High Phase Noise Tolerance	Optical heterodyning generation with self homodyne detection	• Increases transmission distance • Reduces system installation cost
Fiber chromatic dispersion tolerance	• OSSB+C (QAM technique) • OCS • External filtering • Fiber non-linearities	• BER degradation
High Transmission distance	OFDM based RoF system	• Increases system installation cost
Low cost and complexity	Filterless frequency k-tupling techniques based on Polarization Modulator [43]	• High OSSR, RFSSR and Extinction ratio • No bias voltage deviation • High frequency multiplication factor (FMF) • Large tunable range
	Filterless frequency quadrupling achieved through two parallel MZM. [41]	
	Optical heterodyning generation with self homodyne detection [9]	• No high speed modulators and local oscillators required at CS and BS • EVM within FEC limit achieved
BER reduction	• Dispersion Compensation Mechanism • Lower Order Modulation Schemes	• Throughput reduced
High transmission efficiency and throughput	• SCM • Spectrally efficient FDM (SEFDM) [42] • Enhancing Spectral efficiency i.e. DWDM	• Bandwidth Compressed
High receiver sensitivity	OSSB	• High Optical Carrier Suppression Ratio (OCSR) tends to high receiver sensitivity
Increasing modulation linearity	• Predistortion scheme • Feedforward linearization scheme • dual parallel IM	• Reduces RF strength • Suppresses non-linear products • Decreases link sensitivity

It can be concluded that the strategies utilized for enhancing the system performance would in turn result in increasing the system cost and complexity. So, there are some other measures that are taken into consideration for reducing cost and complexity as described in Table 4.

Table 4. Techniques undertaken for reducing system cost and complexity

Working Principle		Year	Author with References	Achievements	Applications
Optical heterodyne generation and self homodyne detection		2020	D. Kamissoko et al. [9]	OSSB over the ODSB scheme for the proposed architecture is capable of eliminating chromatic dispersion, phase locking, high speed modulators, oscillators and increasing transmission distance.	FTTH networks for broadband communications
Filterless BS		2013	N. Shareefi et al. [47]	Used OCS+SSB with 2 parallel MZM for achieving frequency quadrupling with no filter thereby reducing system cost.	WDM – RoF system
Wavelength reuse (WR)	Employing single device modulator with photodetector	2008	M. Raza et al. [48]	Utilized SOA-MZI for OCS frequency up-conversion in downlink and the wavelength reuse concept thereby eliminating light source and LO at each BS which in turn reduces the system cost.	Suitable for WDM and non-green filed scenarios
	Carrier reuse	2006	L. Chen et al. [49]	Employed Optical interleaver to generate a frequency doubled signal and reused carrier in UL.	Long distance transmission up to 40 km.
	Optical Remodulation (OR)	2009	H. Kim et al. [50]	Demonstrated OR by phase modulating DL and intensity modulating UL using single optical carrier.	Fixed wireless access network.
Minimising lasers at BS	Multi-mode optical sources	2005	K. Kitayama et al. [51]	Exploited multi mode super-continuum (SC) light source having low phase noise as all modes being phase correlated.	Suitable for multi-user BS in WDM based Mm wave RoF system.
		2006	H. Toda et al. [3]	Applied Photonic up-conversion using single multi wavelength optical source in DWDM for supporting multiple BS.	
		2007	K. Kitayama et al. [52]	Depicted the dynamic channel allocation capability of Mm wave based RoF system using SC source.	
	Modulation harmonics	2009	H. Chien et al. [53]	Simultaneously generated multiband Mm wave using single optical source and a phase modulator utilizing harmonics	
		2013	S. Ghafoor et al. [54]	Utilized DROF for UL and AROF in DL connection with a single laser source for supporting multiple access points.	
Using One Optical Modulator		2007	G. Ellinas et al. [55]	Wired & wireless signals are generated using single IM and SCM.	
Utilizing one optical carrierb		2003	Y. Takahashi et al. [56]	A Single Optical light source after sending in DL to BS is feedback after modulating to CS.	WDM networks
		2007	J. Yu et al. [36]	Demonstrated simultaneous delivery of wired and wireless signals based on wavelength reuse using a single optical source in UL.	Suitable for providing broadband services to both mobile & stationary users
Using Simultaneous modulation		2001	T. Kamisaka et al. [57]	Investigated the simultaneous modulation and transmission of baseband and Mm wave RF signal on a single wavelength using EAM	FTTH networks.

5 Conclusion

RoF in 5G system comes out to be promising solution in fast growing communication field for delivering high speed radio signal transmission in the Mm wave band. This paper covers a detailed study of RoF in 5G explaining its types, applications, signal generation in detail. The Mm wave based RoF system was found to be a prominent solution for transmitting high frequency signal with low drive voltages in the futuristic networks as it has a great potential to support secure, cost effective and high capacity wireless access for broadband and multimedia wireless services. The various different Mm wave optical generation techniques utilized over the past for transmission has also been evaluated and presented and finally some performance improvement parameters with the related techniques employed with reducing cost strategies were also presented and was found that there is a trade off lying between system performance and cost reduction as enhancing the system performance also enhances its cost and complexity. So, some optimum measures need to be undertaken where cost reduction techniques are combined with performance enhancement strategies.

6 Future scope

For the Mm wave based RoF system focus is laid on generating signals in the Mm wave bands for enhancing dispersion tolerance, reducing phase noise, error vector magnitude (EVM) etc. But there are still some opportunities to work upon such as developing a Mm wave based RoF system which is applicable for 5G based networks and focusing on minimizing interference, enhancing robustness, reducing the installation cost and complexity with enhancing system performance. Some potential research areas exist such as laser free BS schemes using reflective EAM, Electro Absorption Transceiver (EAT) helps in avoiding the usage of electrical circuits, using multicore fibers. Yet more research work can be done while developing this integrated system for the 5G based networks over the Optisystem software.

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