Radio over Fiber (RoF) Technology an Integration of Microwave and Optical Network for Wireless Access

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ABSTRACT
Radio-over-Fiber (RoF) technology is an integration of microwave and optical networks. It has emerged as a potential solution for increasing capacity and mobility as well as decreasing costs in the broadband access network. The concept of RoF means to transport information over optical fiber by modulating light with radio frequency signal (RF) or at the intermediate frequency (IF) to take advantage of the low loss characteristic of an optical fiber. RoF system is very cost effective because the localization of signal processing takes place in central station where electrical to optical conversion, advanced modulation formats and multiplexing techniques are used, whereas a simple base station where only optical to electrical conversion takes place and the electrical signal is transmitted wirelessly through remote antenna units (RAUs). It acts as a back-end technology to the wireless network access system where there is a need for high data rate along with mobility is increasing day by day.

General Terms
WDM based Radio-over-Fiber systems, frequency up and down conversion in Radio-over-Fiber systems, Multiplexing techniques in RoF, Intensity modulation and direct detection IM-DD, Hetero-junction bipolar transistor (HBT) electronic mixer.

Keywords
Radio-over-Fiber; Sub-carrier multiplexing (SCM); IF-over-Fiber; RF-over-Fiber; BB-over-Fiber; Advantages of RoF; Wavelength-division multiplexing (WDM); Heterojunction-bipolar transistor (HBT) electronic mixer; Orthogonal-frequency-division multiplexing (OFDM).

1. INTRODUCTION
In today's era of ubiquitous connectivity or "communication anytime, anywhere and with anything". The demand to have broadband capacity wirelessly has put pressure on wireless communication systems to increase both their transmission capacity, as well as their coverage [1]. Research on millimeter waves has gained attention recently. High frequencies in the range of GHz have more bandwidth, hence their data carrying capacity are more, but they encounter more losses when they are transmitted wirelessly hence they cannot be transmitted long distances whereas the low frequency signals encounters less losses hence they can travel long distances. At high frequency associated losses are high. Hence, there is a need for a waveguide to carry these waves. The medium is nothing but optical fiber due to the low loss offered by them (0.2 dB/km) in 1550nm band which is much smaller than any other medium can provide. In order to meet the ever increasing demand for larger transmission bandwidth. Wireless network based on radio over-fiber technologies is a very beneficial solution. It acts as a back-end technology for the transportation of microwave and millimeter waves [1].

RoF is a well-established technique for the distribution of wireless communication systems due to the larger bandwidth offered by optical fiber and the add drop facility offered by the WDM systems makes it suitable to add and drop any channels simultaneously during transmission through Optical add-drop multiplexers (OADMs) [5].RoF makes it possible to centralize the RF signal processing functions in one shared location (Central office), and then to use optical fiber to distribute the RF signals to the remote base stations (BS) from there they are transmitted wirelessly through the remote antenna units (RAUs), as shown in figure 1. By doing so, RAUs are simplified significantly, as they only need to perform optoelectronic conversion and amplification functions. The need for increased capacity per unit area leads to higher frequencies per unit area leads to higher operating frequencies, smaller radio cells and large no of BS. Therefore, cost-effective BS development is a key success to the market.

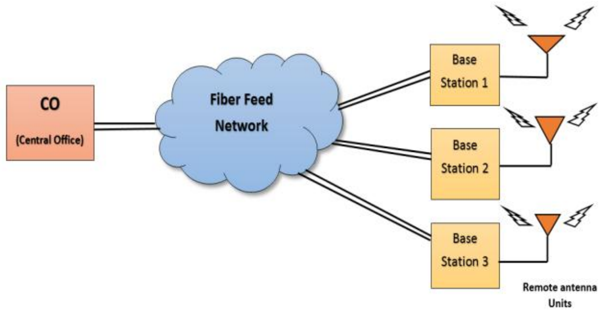


Figure 1: Radio-over-Fiber System [1].

1.1 Architecture of RoF
RoF systems are classified into three main categories:

1. RFoF (Radio Frequency over Fiber)
2. IFoF (Intermediate Frequency over Fiber)
3. BBoF (Baseband signal over Fiber)

In RF-over-Fiber architecture, an RF signal (analog waveform) with high frequency (greater than 10 GHz with baseband data embedded in it) can be modulated with light waves.

In IFoF architecture, a data carrying RF signal with frequency (less than 10 GHz) are modulated with light wave using either direct or external modulation before transmission over the optical link. Therefore, before radiation through the air at the remote base station this signal from IF frequency needs to be up-converted to RF level before transmitting them wirelessly through RAUs. IFoF scheme has exhibited a 2dB better sensitivity than RFoF scheme [1].

In BBoF scheme a baseband signal is modulated with light wave and transmitted over optical fiber. Then, at the receiver end this baseband signal is detected and up-converted to RF level by up-conversion techniques. BBoF scheme exhibits better sensitivity than an IFoF scheme by 4dB [1]. A general architecture of radio over fiber architecture is shown in figure 3 optical fiber is used to transmit data between central office and remote base station. Optical fiber is used for both downlink and uplink operations due to its enormous bandwidth offered by it. During the downlink operation in the central office electrical to optical (E/O) conversion takes place, whereas in the remote base station optical to electrical (O/E) conversion takes place using a photo-detector. Similarly, during uplink transmission E/O conversion takes place in remote base station using an external modulator and O/E conversion takes place in the Central office where this signal is further processed to receive the base band data.

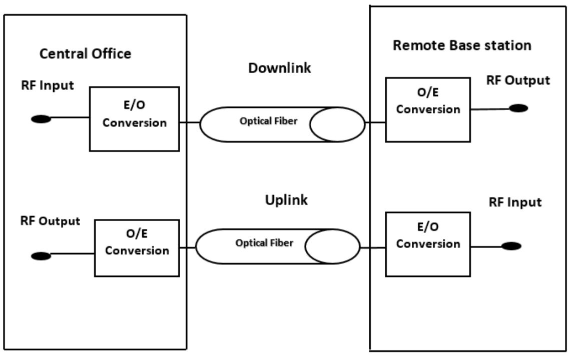


Figure 3: Radio-over-Fiber Architecture [3].

1.2 Advantages of RoF

Some of the advantages and benefits of the RoF technology compared with electronic signal distribution are given below : (i) Low Attenuation loss: optical fiber offers very low loss hence RoF technology can be used as a backbone for transporting microwave or millimeter waves from central station to base stations (ii) Large Bandwidth: Optical fibers offer enormous bandwidth however, todays state-of-the art commercial systems utilize only a fraction of this capacity (iii) Low RF power remote antenna units (RAUs) has many benefits such as Increased battery life of mobile terminals, Low generated interference, Easier frequency/network planning and relaxed human health issues (iv) Dynamic resource allocation: For instance in a RoF distribution system for GSM traffic, more capacity can be allocated to an area during busy hours and then re-allocated to others areas. (v) Centralized upgrading: As most of the signal processing operations take place in central station the remote base station is simpler. (vi) Line of sight (LOS) operation (multipath fading effects are minimized) as the signals are carried out by optical fiber the losses that occur during wireless transmission systems are avoided to a greater extend. (vii) Immunity to Radio Frequency Interference: is a very attractive property of the optical fiber, which also provides privacy and security [1, 2].

1.3 Applications of RoF

RoF technology has its applications in many areas. In which the use of RoF in WPAN (Wireless personal area network) and in Mobile communication network has gained more importance recently.

1.3.1 Wireless personal area networks

For in-building applications such as Wireless personal area network (WPAN), the cell size should be small due to high losses through walls. Hence, high frequency signals can be used due to reduced cell size in WPAN networks. Millimeter waves, such as 60 GHz (unlicensed band) have gained attention recently which can be used for such WPAN applications. Millimeter waves can transmit data rate greater than 1.25Gbps at 60 GHz. These waves are compatible with fiber optic networks at 60 GHz hence, they can be used in WPAN applications. Due to the reduced cell size, frequency is reused between adjacent cells.

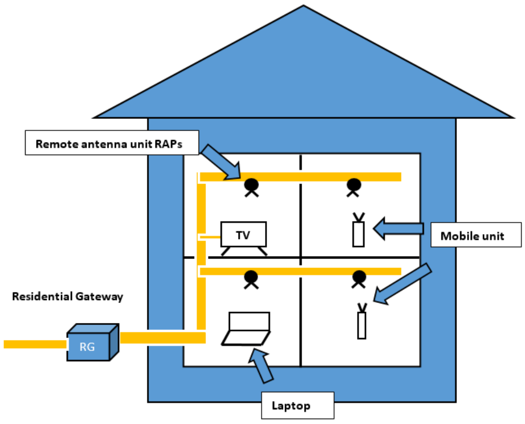


Figure 4: Wireless personal area network [1].

1.3.2 Mobile communication systems

The goals of the microcellular mobile communication systems is to provide service availability for the high percentage of user environments and to provide a combination of services such as voice, data and multimedia. To provide such enhanced services at high quality level we require a large density of expensive remote antenna (base station) per square kilometer. To make these base stations simple and cost-effective RoF technique acts as a fiber feeder network for this microcellular systems. In RoF all the signal processing functions is done in the central station, which has control over all its remote base stations. As shown in figure 5 fiber carrying radio signals from central unit (CU) is distributed among microcells (formed by cell splitting the original cell) whose range is less than 2 kilometers. These microcells provide better coverage, high data throughput, seamless handover, and high capacity.

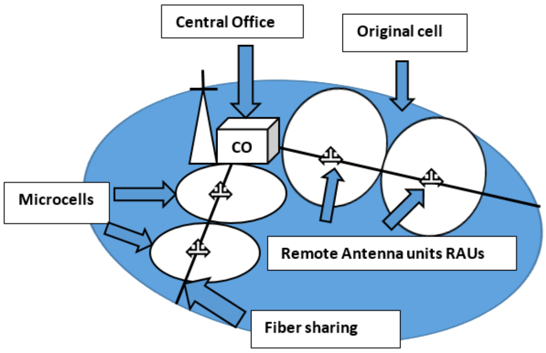


Figure 5: Mobile communication systems [2].

1.4 Technical issues and challenges of RoF

There are several technical issues such as i) Multipath interference ii) Echo iii) Coupling issues iv) Propagation delay v) Optical issues with shared architecture vi) Frequency up and down conversion issues which has to be resolved and taken into consideration while designing a future next generation RoF system [14]. Apart from technical issues there are several challenges also which has to be overcome in RoF based systems.

The first challenge to address is the current access and in house network evolution, which tend to use a single protocol (e.g. Internet protocol) to deliver different services. The second challenge for RoF in access networks come from the necessary mutualisation of the optical infrastructure between the different network types which may have different evolutions. The extension and fusion between the Access and Metro networks is being planned today. A scenario for using RoF over current Access Network architectures must be defined, but, on top of this, a scenario for the introduction of RoF over Metro-Access networks must be prepared. The challenge is then to demonstrate the cost savings that will be realized today by using RoF to deploy Mobile and Wireless Access over current optical infrastructures, but as well how these cost savings will evolve when the access networks evolve.

The third challenge we can identify is the lack of standardization for RoF. Some very preliminary work has started to establish and maintain the standard specifying measurement methods for microwave and millimeter-wave to optical convertor, which are used in RoF communication systems. At present, the techniques and architectures used in RoF are very diverse and the adequate solutions must be identified collegially between the different actors in this sector (operators, system suppliers and component manufacturers) in order to push for the most adapted solutions and increase the deployment opportunities [15].

2. RoF LINK DESIGN ISSUES

The major issues affecting the performance and design of RoF links that are required for wireless communications systems are discussed below:

2.1 Carrier Frequency

This is very important parameter for RoF links. The radio carrier frequency determines the type of optoelectronic components that can be used. Low cost semiconductor lasers are readily available with an upper modulation frequency limit of around 3GHz beyond that, semiconductor lasers become more and more expensive, up to around 20 GHz, after which they are no longer commercially available. Thus, above 20GHz, the use of external optical modulators becomes essential, but these external modulators much expensive. Wireless systems are likely to use bands below 6 GHz, where radio propagation characteristics are suitable for low cost network deployments. Whereas, high frequencies such as mm-wave bands are preferred for WPAN where very high dynamic range is not required due to the greater spectrum availability. An attractive solution to this problem is to use frequency translation, where the signals are carried over the RoF link at a much lower frequency, or intermediate frequency (IF). It allows multiple channels to be transmitted over a single link at the same radio carrier frequency, for example, to carry multiple MIMO channels. These advantages make IF transmission a compelling choice for situations where the radio carrier frequency is higher than 3 GHz or where several radio channels must be transported simultaneously over a single link [5]. These IF signals are up-converted using suitable frequency conversion techniques. Some of the frequency conversion techniques which are used in RoF based systems are discussed in the next section.

2.2 Frequency conversion techniques

Frequency up and down conversion is a technique where instead of RF signal IF signal is transmitted over optical fiber. The transmitted IF signal is free from the fiber dispersion effect. There are many reported frequency conversion techniques using an external modulator, optical heterodyne, optical transceiver, using nonlinear effects such as Four-wave mixing (FWM), using mixers such as Heterojunction bi-polar transistor (HBT), High electron mobility transistor (HEMT), Avalanche photodiodes etc.

2.2.1 Frequency conversion using Mixers

Electronic mixers such as Si-Ge based HBTs are used on the receiver side where the frequency is up-converted before transmitting wirelessly to the end users. The optical signal is first demodulated using photo-detector in the receiver end and then it is up-converted to the required radio frequency level. Any device used as a mixer must have strong non-linearity, low noise, low distortion and adequate frequency response. An electrical mixer consists of two input port and one output port as shown in figure 6. In which one input is given as IF input signal and the other input port is given a pump waveform which is known as local oscillator (LO) port is required to pump the mixer. LO signal is the strongest and hence it is used to transform IF signal to RF during downlink and RF to IF signal during uplink [10].

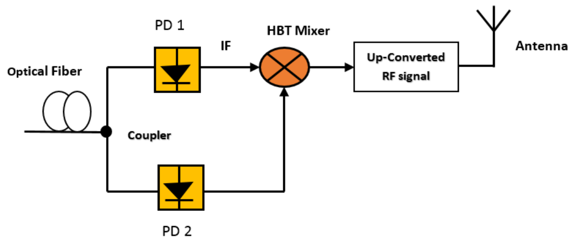


Figure 6: Frequency up-conversion at receiver side using an HBT mixer [10].

2.2.2 Frequency conversion using Stimulated Brillouin Scattering (SBS)

A frequency up and down conversion based on SBS has been used for RoF system. The up conversion is based on the 1st Stokes of Brillouin fiber laser in True-wave reach fiber (TWF) and the down conversion is based on 1st Anti-Stokes of Brillouin fiber laser in Dispersion compensating fiber (DCF). Frequency up conversion from 2GHz to 12.5GHz and Frequency down conversion from 12.5GHz to 1.8GHz with the largest IF power of -32dBm has been demonstrated successfully [11].

2.2.3 Frequency conversion using non-linear effects

Frequency conversion techniques utilizing the non-linear effects have gained importance recently. Various all-optical frequency up-conversion schemes, using cross gain modulation (XGM) and cross phase modulation (XPM) in a semiconductor optical amplifier (SOA) and SOA Mach-

Zehnder interferometer have been reported [11]. The all optical frequencies down-conversion using an XPM effect in a Semiconductor optical amplifier Mach-Zehnder inferometer (SOA-MZI) has been experimentally demonstrated for WDM based RoF systems. The maximum frequency of the optical, RF signal that can be down-converted by SOA-MZI was limited by the bandwidth of SOA-MZI which is determined by the minority carrier lifetime. An all optical frequency down-conversion using a FWM effect in a single SOA for WDM RoF applications has been used. The maximum frequency of the all-optical frequency down-conversion using an FWM effect in SOA can be extended to several hundreds of gigahertz which is much higher than using an XPM effect in SOA-MZI [9].

2.3 Radio Channel Bandwidth

Channel bandwidths of up to 100 MHz are being investigated for next generation wireless systems to meet the user data-rate requirements. Channel noise changes directly with bandwidth, which means that higher signal power is needed to maintain the minimum carrier to noise ratio (CNR) required for successful demodulation. The increased channel noise leads to reduced receiver sensitivity and therefore the radio range is also reduced.

This is true for the wireless system which wirelessly connects the remote base stations and antennas without RoF. RoF links must be capable of supporting the required CNR in the face of higher channel noise, so must have good performance. The SFDR (Spurious free dynamic range) of the RoF link varies inversely with channel bandwidth by a factor of 2/3, so increasing the bandwidth from 10 MHz to 100 MHz results in an SFDR reduction of 6.7 dB [5].

2.4 Modulation techniques

RoF link undergoes two types of modulation one in the electrical domain and the other in the optical domain.

2.4.1 Baseband-RF Modulation

It is an electrical side modulation typical wireless modulation schemes such as QPSK (Quadrature phase shift keying), GMSK (Gaussian minimum shift keying), and QAM (Quadrature amplitude modulation) can be used. It is decided by the wireless operator [13]. As the modulation complexity increases the requirement for minimum CNR requirement also increases. For example, minimum CNR required for a 16-QAM and 64-QAM is 14.4 dB and 20 dB in a Ricean channel with coding rate 5/6 after Reed-Solomon decoding. A high CNR requirement leads to a reduction in radio range due to desensitization of the radio receiver. This is a feature of the wireless system and is not directly related to the performance of the RoF link as long as the link has sufficient CNR at its output [5].

2.4.2 RF-Optical Modulation

It is an optical side modulation a RoF engineer has control over it. It can be either direct or external modulation. In Direct modulation a RF signal is superimposed on the bias current this bias current continuously modulates the light wave involves directly modulating the laser diode. Such type of modulation cannot be used for high data rate systems. Hence, the second option is to use an external modulator to modulate the RF over optical carrier. This system is used for high data rate systems, but they are more expensive due to the use of modulators such as Mach-Zehnder modulator (MZM) and Electro-absorption modulator (EAM) [13].

2.5 Multiplexing techniques

Multiplexing techniques play an important role in achieving high spectral efficiency hence, to select an appropriate multiplexing technique with high spectral efficiency, enhanced performance and lower complex is a necessity for RoF systems. Some of the multiplexing techniques used in RoF systems are discussed below:

2.5.1 Sub-carrier multiplexing (SCM)

Optical Sub-carrier multiplexing (SCM) is a scheme where multiple signals are multiplexed in the radio frequency domain and transmitted by a single wavelength in the optical domain. In SCM system's frequency spacing between adjacent RF channels is much narrower than that in a conventional DWDM system. To minimize the impact of chromatic dispersion and to increase optical bandwidth efficiency Optical single sideband (OSSB) modulation is used. However chromatic dispersion is not a limiting factor in SCM systems, Polarization mode dispersion (PMD) has a big impact on the system performance if RF coherent detection is used in the receiver. FWM is the dominant source of non-linear crosstalk in SCM optical systems.

A significant advantage of SCM is that microwave devices are more mature than optical devices; the stability of a microwave oscillator and the frequency selectivity of a microwave filter are much better than their optical counterparts. In addition, the low phase noise of RF oscillators makes coherent detection in the RF domain easier than optical coherent detection and advanced modulation formats can be applied easily. A popular application of SCM technology in fiber optic systems is analog cable television [4, 6].

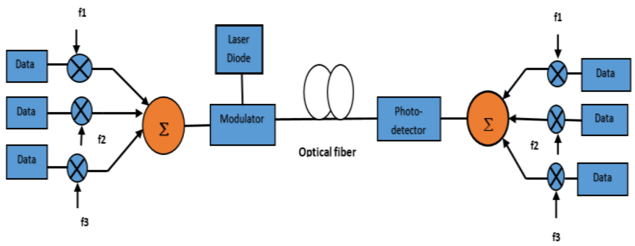


Figure 7: Sub-carrier multiplexing [6].

2.5.2 Wavelength division multiplexing (WDM)

In WDM systems light is modulated with the data directly or using an external modulator and carried into an optical fiber as wavelengths. In WDM systems, each wavelength is treated as an individual channel and carries different data. WDM multiplexer is a passive devices that combine light signals with different wavelengths, into a single fiber. The use of WDM for the distribution of RoF signals has gained importance recently. WDM enables the effective exploitation of the fiber bandwidth. Selectivity of optical filters and limitations in wavelength stability of semiconductor lasers, and the minimum channel spacing in current commercial WDM is ~50 GHz. The channel spacing in WDM can be decreased to 50 GHz or even to 25 GHz and in this way, it is possible to use hundreds of channels. But, if the channel spacing is dropped to 50 GHz instead of 100 GHz, it will become much harder to upgrade the systems to operate at 40 Gbps due to the nonlinear effects [6]. Carriers modulated with mm-waves are dropped from and added to a fiber ring using

Optical Add-Drop Multiplexers (OADM). The OADM is placed at base stations and tuned to select the desired optical carriers to drop [7].

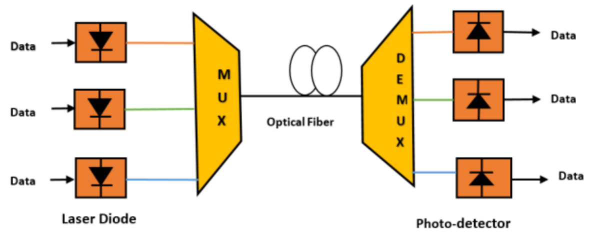
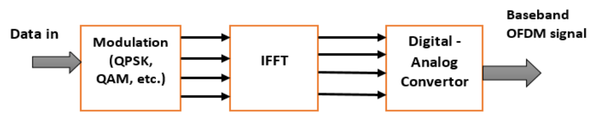


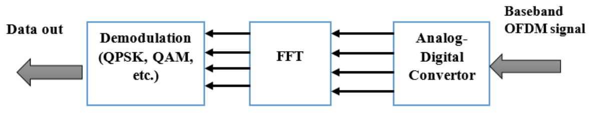
Figure 8: Wavelength division multiplexing [1].

2.5.3 Orthogonal frequency division multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) system is a multicarrier (parallel) communication system with orthogonal subcarriers. OFDM uses a variety of subcarriers to transmit low rate data streams in parallel. The subcarriers are themselves modulated by using PSK (Phase Shift Keying) or QAM (Quadrature Amplitude Modulation). OFDM is similar to FDM (Frequency Division Multiplexing) except for the stringent requirement of orthogonality between the subcarriers. Combining OFDM modulation system to RoF transmission link is a new technology for high-speed wireless communication that covers a wide area. OFDM signal is formed using the Inverse Fast Fourier Transform (IFFT), adding a cyclic extension and performing windowing to get a steeper spectral roll off. While in the receiver, the subcarriers are demodulated using Fast Fourier Transformation (FFT). Thus, the requirement in OFDM system for the intensive computations accounts for the complexity of OFDM transmitters and receivers. Figure 9a and Figure 9b show the block diagrams of the basic OFDM transmitter and receiver. OFDM systems are much more sensitive to frequency offset and phase noise. Furthermore, OFDM has a relatively large peak-to-average power ratio (PAPR), which can reduce the power efficiency of the RF amplifier [16].



(a)



(b)

Figure 9: (a) OFDM transmitter (b) OFDM Receiver [16].

2.5.4 A combination of both SCM based WDM RoF systems

In order to take advantage of both the multiplexing techniques a combination of SCM based WDM systems are used. SCM systems are more mature hence, RF modulation, filtering can be done in the electrical domain whereas WDM systems provides enormous bandwidth. As shown in figure 10 SCM is used as electrical side multiplexing whereas WDM is used as an optical side multiplexing. On the receiver side the optical WDM systems are de-multiplexed and detected by a photo-detector to respective wavelengths which are further de-multiplexed into respective RF as shown in figure 11. The combination of SCM based WDM systems may provide a flexible platform for high-speed optical transport networks with high optical bandwidth efficiency and high dispersion tolerance [4, 6].

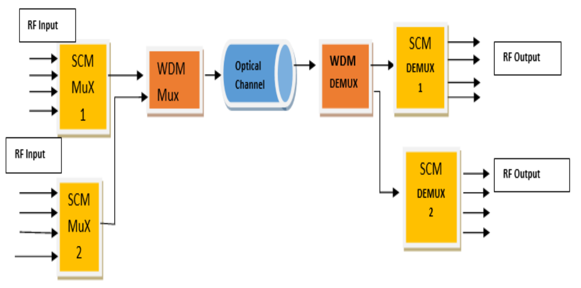


Figure 10: A combination of SCM-WDM RoF systems [4].

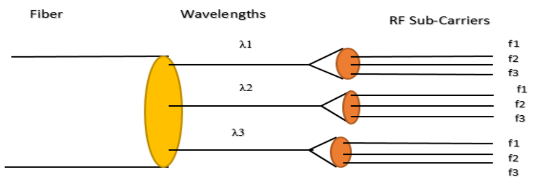


Figure 11: De-multiplexing of WDM and SCM in the receiver side of RoF systems [2].

2.5.5 The combination of OFDM based WDM RoF system

The combination of OFDM in WDM-RoF access networks can improve the spectral efficiency of the wireless access system, also support the seamless integration between air and optical transmission. The OFDM is a promising technology, which has a very high spectrum efficiency and robust dispersion tolerance. It is specially designed to improve the system capability and transmission distance over fiber and air links. In order to maximize the bandwidth usage and prevent on crosstalk in a single fiber optic, the Wavelength-Division Multiplexing (WDM) is positioned to the access networks. Our main goal of RoF systems is to design remote base station simple and less complex, but in OFDM system's computational complexity is there in both transmitters (i.e. Central station) and the receiver (i.e. Remote base station). To maintain orthogonality between the carriers is also a challenge for long distance OFDM based RoF systems [16].

3. CONCLUSION

RoF is a technique which acts as a back-end technology for high data rate wireless access systems. The main aim of RoF systems is to design a less complex base stations where only the opto-electronic conversion takes place. The central station is highly complex. Three types of architecture of RoF architectures are designed in which IF over fiber provides 2dB better sensitivity than RF over fiber scheme, but it requires up-conversion in the receiver base station before transmitting them wirelessly. RoF system offers numerous advantages such as Low attenuation, large bandwidth, Dynamic resource allocation, low RF power remote antenna unit, and simpler base stations which makes them suitable for different applications such as WPANs, Mobile cellular networks. Lack of standardization is the major challenge faced by RoF systems.

Different types of link design issues have been studied such as carrier frequency, modulation techniques, multiplexing techniques, frequency conversion techniques. Frequency conversion using an electronic mixer such as HBT makes the base station simple their conversion gain is also better than other mixers based on unipolar devices. Of all the multiplexing techniques used for RoF systems, SCM based WDM systems provide high spectral efficiency and less complex receiver base station as shown in table 1.

Table 1: Comparison of different multiplexing techniques [17]

	SCM	WDM	OFDM	SCM-WDM	OFDM-WDM
Spectral Efficiency	**Medium**	**Low**	**Medium**	**High**	**High**
Transmitter side Electrical Complexity	**Medium**	**Low**	**High**	**Medium**	**High**
Transmitter side Optical Complexity	**Low**	**Medium**	**Medium**	**Medium**	**Medium**
Receiver side Electrical Complexity	**Low**	**Low**	**Medium**	**Low**	**High**
Receiver side Optical Complexity	**Low**	**Low**	**Medium**	**Low**	**Medium**

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