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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Radio-over-fibre (RoF) technologies and their applications

ITU-T G-series Recommendations – Supplement 55

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Supplement 55 to ITU-T G-series Recommendations

Radio-over-fibre (RoF) technologies and their applications

Summary

Supplement 55 to ITU-T G-series Recommendations provides general information on radio-over-fibre (RoF) technologies and their applications in optical access networks.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G Suppl. 55	2015-07-03	15	11.1002/1000/12575

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

FOREWORD

NOTE

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Radio-over-fibre (RoF) technologies and their applications

1 Scope

The purpose of this Supplement is to introduce the general radio-over-fibre (RoF) technology types and their applications in optical access networks. In general, RoF technologies can be classified into two categories, which are analogue RoF and digital RoF. It is noted that the RoF concept shown in this Supplement can be commonly used for both analogue RoF and digital RoF. The description of RoF network models is also considered for analogue RoF and digital RoF.

2 References

[ITU-T G.982] Recommendation ITU-T G.982 (1996), *Optical access networks to support services up to the ISDN primary rate or equivalent bit rates.*

[ITU-T G.989.1] Recommendation ITU-T G.989.1 (2013), *40-Gigabit-capable passive optical networks (NG-PON2): General requirements*.

[ITU-R M.1035] Recommendation ITU-R M.1035 (1994), *Framework for the radio interface(s) and radio sub-systems functionality for international mobile telecommunications-2000 (IMT-2000).*

[ITU-R M.1224-1] Recommendation ITU-R M.1224-1 (2012), *Vocabulary of terms for International Mobile Telecommunications (IMT).*

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following term defined elsewhere:

3.1.1 diplex working [ITU-T G.982]: Bidirectional communication using a different wavelength for each direction of transmission over a single fibre.

3.1.2 micro cell [ITU-R M.1224-1]: Outdoor cell with a large cell radius, typically several 10s of kilometres (radius of 35 km).

NOTE – Further details are given in ITU-R M.1035.

3.1.3 macro cell [ITU-R M.1224-1]: Cell with low antenna sites, predominantly in urban areas, with a typical cell radius of up to 1 km.

NOTE – Further details are given in ITU-R M.1035.

3.1.4 small cell [b-SCF030.03.03]: An umbrella term for low-powered radio access nodes that operate in licensed spectrum and unlicensed carrier-grade Wi-Fi, with a range of 10 m up to several hundred meters. These contrast with a typical mobile macrocell that might have a range of up to several tens of kilometers. The term covers femtocells, picocells, microcells and metrocells.

NOTE – A unanimous definition of a small cell deployment is hard to agree within the industry. As an example, according to [b-3GPP TS 25.104], cell types are classified based on the "minimum coupling loss" between cell site and user device, thus originating four classes of cells. Other available definitions consider the radius of the cell, the number of connected users, the deployment options and so on. See [b-NGMN small cell].

3.1.5 pico cell [ITU-R M.1224-1]: Small cell with a typical cell radius of less than 50 m that is predominantly situated indoors.

NOTE – Further details are given in ITU-R M.1035.

3.2 Terms defined in this Supplement

This Supplement defines the following term:

3.2.1 radio over fibre (RoF): Fibre-optic transmission of waveform for radiocommunication services.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

AC Asymmetric Clipping

ACC Automatic Current Control

A/D Analog to Digital

ADC A/D Converter

APD Avalanche PhotoDdode

ASE Amplified Spontaneous Emission

AWG Arbitrary Waveform Generator

BB Baseband Block

BB M/dMP Baseband Modulation and demodulation Processor

BBU Baseband Unit

BEP/FEP Back-End Processor and Front-End Processor

BER Bit Error Ratio

BPF Bandpass Filter

BS Base Station

BtB Back-to-Back

CA Carrier Aggregation

CDMA Code Division Multiple Access

C-RAN Centralized Radio Access Network

CWDM Coarse Wavelength Division Multiplexing

D/A Digital to Analog

DAC D/A Converter

DC Direct Current

DCO Down-Converter-Offset OFDM

DEMUX Demultiplexer

DFB-LD Distributed Feedback Laser Diode

DML Directly Modulated Laser

DMT Discrete Multi-Tone

D-RoF Digitized Radio over Fibre

DSP Digital Signal Processing

DWDM Dense Wavelength Division Multiplexing

E-BTB Electrical Back-To-Back

EDFA Erbium-Doped Fibre Amplifier

E/O Electrical to Optical

E-UTRA Evolved Universal Terrestrial Radio Access

EVM	Error Vector Magnitude
FA	Frequency Assignment
FCP	Frequency Conversion Processor
FDC	Frequency-Down-Converter
FUC	Frequency-Up-Converter
FDM	Frequency Division Multiplexing
GSM	Global System for Mobile communications
IF	Intermediate Frequency
IM/DD	Intensity Modulation with Direct Detection
I/Q	In-phase and Quadrature-phase
iRoF-BB	Radio over Fibre Baseband interface
iRoF-IF	Radio over Fibre Intermediate Frequency band interface
iRoF-RF	Radio over Fibre Radio Frequency band interface
LD	Laser Diode
LNA	Low Noise Amplifier
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
M/dMP	Modulation and demodulation Processor
MFH	Mobile Front-Haul
MIMO	Multi-Input Multi-Output
M-QAM	*M*ary Quadrature Amplitude Modulation
MUX	Multiplexer
MWP	Microwave Photonics
OAN	Optical Access Network
OBPF	Optical Bandpass Filter
ODN	Optical Distribution Network
O/E	Optical to Electrical
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
OMI	Optical Modulation Index
ONU	Optical Network Unit
OOK	On-Off Keying
PA	Post-Amplifier; RF-band Power Amplifier
PD	Photodetector
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QSC	Quadratic Soft Clipping
RAN	Radio Access Network
RF	Radio Frequency
RoF	Radio over Fibre

RRH	Remote Radio Head
RRU	Remote Radio Unit
R/S	Reference point at the interface of the ONU and the ODN
Rx	Receiver
SA	Signal Analyser
SC	Soft Clipping
SCM	Subcarrier Multiplexing
SG	Signal Generator
SMF	Single-Mode Fibre
SNI	Service Network Interface
SNR	Signal-to-Noise Ratio
S/R	Reference point at the interface of the OLT and the ODN
SSMF	Standard Single-Mode Fibre
TDM	Time Division Multiplexing
Tx	Transmitter
TWDM	Time Wavelength Division Multiplexing
UNI	User Network Interface
VEA	Variable Electrical Attenuator
VOA	Variable Optical Attenuator
VSA	Vector Signal Analyser
VSG	Vector Signal Generator
W-CDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WM	Wavelength Multiplexer

5 General concept

The current deployment of radiocommunication services shows a tendency towards higher bit rates with higher radio carrier frequencies, compared to those in the legacy radiocommunication services, in order to satisfy customer demands for broadband access. To realize such radiocommunication services, a cell size covered by one radio access point must be smaller from the physical viewpoint, leading to drastic increases in the number of antennas serving as radio access points. In addition, there exist many areas inaccessible to radio waves ("radio shadow" areas), such as underground spaces (subterranean structures), tunnels, areas behind buildings, upper stories of skyscrapers, dips below ground level in metropolitan areas and within mountainous regions. To support small cell radio communications and radio shadow countermeasures, many RoF technologies have been actively studied and deployed in the research and development of microwave photonics (MWP). The current implementations of RoF technologies are described in [b-APT/ASTAP/REPT-03] and [b-APT/ASTAP/REPT-11].

Figure 5-1 shows the basic concept of an RoF system. In this Supplement, RoF is defined as the fibre-optic transmission of a waveform for radiocommunication services without any intentional essential change to that waveform during fibre-optic transmission. The waveform includes the essential physical information for radiocommunication services, such as the format of the radio wave and payload. Note that the carrier frequency of the radio signal will not affect processing at the baseband, and is thus considered nonessential here. Therefore, the RoF signal should be regarded as an analogue signal carrying the same radio signal when viewed from the optical domain, although the radio-frequency (RF) carrier frequency of the RoF signal may be different from that of the original radio signal. As shown in Figure 5-1, the RoF system consists of components for electrical-to-optical (E/O) and optical-to-electrical (O/E) conversions and of an optical fibre for transmission. RoF has two major features as follows.

– Preservation of the waveform: the waveform of the radio signal is essentially preserved during the fibre-optic transmission under ideal or close-to-ideal conditions.
– Tolerance to electromagnetic interference: RoF signals in the fibre are not affected by frequency interference from the proximate radiocommunication signals.

From the technical point of view, a distribution technology for legacy RF video is considered to be a type of RoF technology, but one which possesses only a downlink function. Since the RoF system should be generally treated as an analogue transmission system, the overall signal-to-noise power ratio and the overall dynamic range should be increased to maximize the potential of the two RoF features listed above by properly managing the noise figure and nonlinearity of the system.

An alternative method of transmission is digital fibre-optic transmission. Digitized radio over fibre (D-RoF) is a kind of digital RoF as explained in clause 6.2. The D-RoF technology is an alternative attractive candidate for transmitting the waveform, especially in cases where both distortion and poor sensitivity hamper analogue transmission under conditions of higher noise figure and nonlinearity. Here, we have to pay attention to the fact that its realization strongly depends on the performance of the digital signal processing (DSP) function, which is influenced by performance of analogue-to-digital converters (ADCs) and digital-to-analogue converters (DACs). It is also difficult to remove quantization noise due to digitization, which itself causes distortion in the radio waveform. Furthermore, each time domain sample is digitized to many quantized bits for binary transmission in D-RoF, so the bandwidth efficiency of D-RoF can be much lower than that of analogue RoF. Digital interfaces for mobile base stations, such as the Common Public Radio Interface [b-CPRI] and Open Base Station Architecture Initiative [b-OBSAI], make good use of the concept of D-RoF technology.

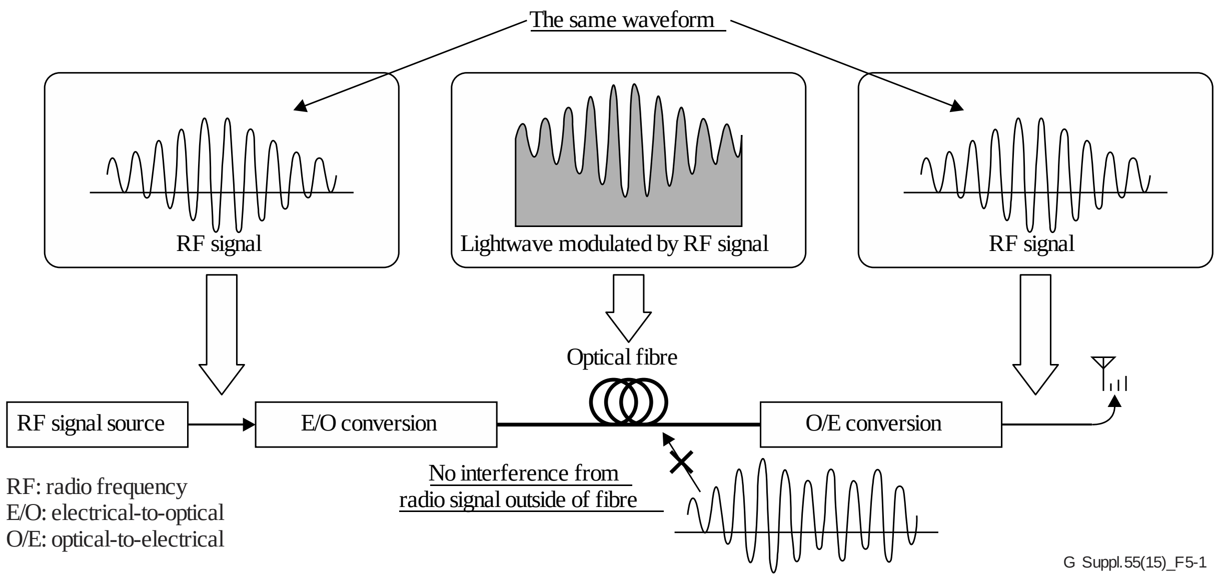


Figure 5-1 – Basic concept of a RoF system

6 System architectures

Based on the RoF concept, various system architectures are considered. When a system consisting of one base station (BS) and many remote antenna sites, which is a typical model of RoF systems, is considered, it falls into one of two categories that differ in the types of signal transmitted over the fibre-optic link. One is a system for transmitting subcarrier signal(s), and the other is a system for transmitting equivalent low-pass signal(s). In addition, system architectures for relay transmission are important for radio shadow countermeasure applications. Their system architectures and their features are explained here in detail. Here, it is noted that the system architectures shown in this clause are typical examples and that other system architectures are conceivable.

6.1 Analogue RoF system

6.1.1 Subcarrier signal(s) transmission

Figure 6-1 illustrates general and fundamental architectures for transmitting subcarrier signal(s), such as RF-band subcarrier, intermediate-frequency-band (IF-band) subcarrier, and reference frequency signals. In Figure 6-1, it is assumed that equipment on the left side of the fibre-optic link is located in the local office and equipment on the right side is located at the remote antenna.

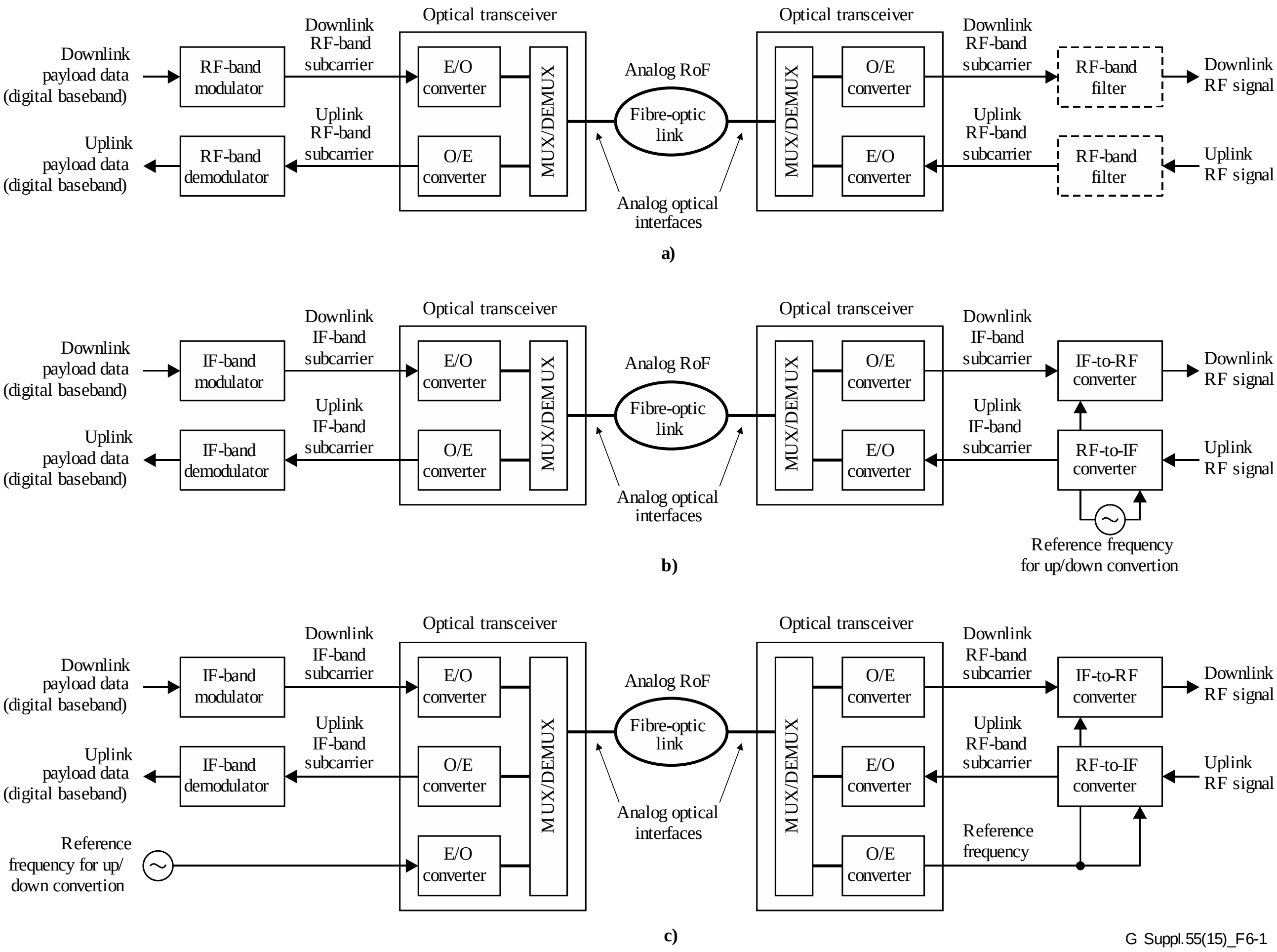


Figure 6-1 – Configuration examples for transmitting subcarrier signal(s): a) RF-band; b) only IF-band signal; and c) IF-band signal and reference frequency

In an RF-band RoF transmission scheme such as that shown in Figure 6-1-a, the system consists of an RF-band modulator, an RF-band demodulator, a pair of optical transceivers, a fibre-optic link, and two RF-band filters. The RF-band filters may be used if the need arises in order to obey the Radio Regulation. For the downlink, the RF-band carrier is modulated by downlink payload data using the RF-band modulator at the local office end. The generated downlink RF-band subcarrier signal modulates an optical carrier using an E/O converter in the optical transceiver. The generated downlink analogue RoF signal is transmitted over the fibre-optic link. At the remote antenna end, the received downlink RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating RF-band subcarrier signal, becomes the desired downlink RF signal. For the uplink, a received uplink RF signal modulates an optical carrier using another E/O converter in the optical transceiver. The generated uplink analogue RoF signal is transmitted over the fibre-optic link. At the local office end, the received uplink RoF signal is optically detected using another O/E converter in the optical transceiver. The detected electrical signal, which is the same as the uplink RF-band subcarrier signal, is demodulated with the RF-band demodulator to recover the uplink payload data.

In an IF-band RoF transmission scheme such as that shown in Figure 6-1-b, the system consists of an IF-band modulator, an IF-band demodulator, a pair of optical transceivers, a fibre-optic link, an IF-to-RF up-converter, an RF-to-IF down-converter, and a reference frequency generator. Because the IF is typically much lower that the RF, the IF-band RoF transmission scheme offers a much improved optical bandwidth efficiency compared to the RF-band RoF transmission scheme. For the downlink, an IF-band carrier is modulated by downlink payload data using the IF-band modulator at the local office end. The generated downlink IF-band subcarrier signal modulates an optical carrier using an E/O converter in the optical transceiver. The generated downlink analogue RoF signal is transmitted over the fibre-optic link. At the remote antenna end, the received downlink RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating IF-band subcarrier signal, is frequency up-converted using the IF-to-RF up-converter and a reference frequency to the desired downlink RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. For the uplink, a received uplink RF signal is frequency down-converted using the RF-to-IF down-converter to an IF-band subcarrier signal. The generated uplink IF-band subcarrier signal modulates an optical carrier using another E/O converter in the optical transceiver. The generated uplink analogue RoF signal is transmitted over the fibre-optic link. At the local office end, the received uplink RoF signal is optically detected using another O/E converter in the optical transceiver. The detected electrical signal, which is the same as the uplink IF-band subcarrier signal, is demodulated using the IF-band demodulator to recover the uplink payload data. In an IF-band RoF and reference frequency transmission scheme, such as that shown in Figure 6-1-c, the system configuration is the same as that of the IF-band RoF transmission scheme shown in Figure 6-1-b, except that the reference frequency is provided from the local office end and is delivered to the remote antenna site.

Since the main parts of the radio transceiver, such as electrical modulator and demodulator, can be located at the local office end, the configuration of each equipment at the remote end becomes simpler. In some cases (for example, those involving no change in the frequency band of interest), this architecture can easily offer an upgrade to the latest radiocommunication service without any change of configuration at the antenna site. Since the main part of the radio transceiver is located at the operator's site, it is also easy to repair or renew the unit. This also offers a step towards a future optical access network (OAN), which can realize higher-speed transmission and provide multi-granular bandwidth resources, such as an OAN based on orthogonal frequency division multiplexing (OFDM). In the configurations shown in Figures 6-1-a and 6-1-c, no reference frequency generator is required at the remote end, resulting in a simpler configuration of remote equipment. In the configurations shown in Figure 6-1-b and -c, the reference frequency value can be also decreased if a sub-harmonic mixing technique is used in the IF-to-RF and RF-to-IF converters.

6.1.2 Equivalent low-pass (equivalent baseband) signal(s) transmission

Figure 6-2 illustrates general and fundamental architectures for transmitting orthogonal equivalent low-pass (equivalent baseband) signals, such as (non-binary) in-phase and quadrature-phase (I/Q) baseband signals. In Figure 6-2, it is assumed that equipment on the left side of the fibre-optic link is located in the local office and equipment on the right side is located at the remote antenna.

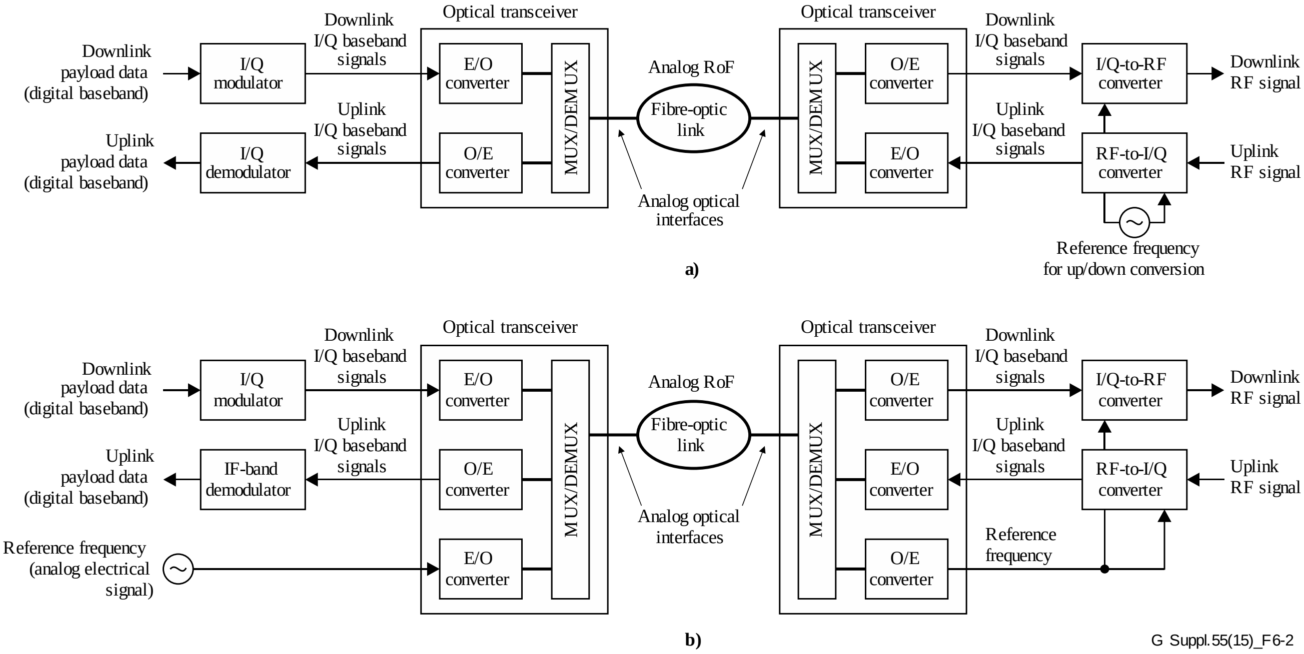


Figure 6-2 – Configuration examples for transmitting equivalent low-pass signal(s): a) only I/Q baseband signals; and b) I/Q baseband signals and reference frequency

In an I/Q baseband signals transmission scheme such as that shown in Figure 6-2-a, the system consists of an I/Q modulator, an I/Q demodulator, a pair of optical transceivers, a fibre-optic link, an I/Q-to-RF up-converter, an RF-to-I/Q down-converter, and a reference frequency generator. For the downlink, the I/Q modulator generates I/Q baseband signals from the downlink payload data at the local office end. The generated downlink I/Q baseband signals modulate an optical carrier using an E/O converter in the optical transceiver. The generated downlink multi-level or analogue baseband signals, which are a form of analogue RoF signal, are transmitted over the fibre-optic link. At the remote antenna end, the received downlink optical signals are optically detected using an O/E converter in the optical transceiver. The detected electrical signals, which are the same as the modulating I/Q baseband signal, are frequency up-converted with the I/Q-to-RF up-converter and a reference frequency to the desired downlink RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. The generated uplink I/Q baseband signals modulate an optical carrier using another E/O converter in the optical transceiver. The generated uplink multi-level or analogue baseband signals are transmitted over the fibre-optic link. At the local office end, the received uplink optical signals are optically detected using another O/E converter in the optical transceiver. The detected electrical signals, which are also a type of analogue RoF signal, and are the same as the uplink I/Q baseband signals, are demodulated with the I/Q demodulator to recover the uplink payload data.

In an I/Q baseband signals and reference frequency transmission scheme, such as that shown in Figure 6-2-b, the system configuration is the same as that of the I/Q baseband RoF signal transmission scheme shown in Figure 6-2-a, except that the reference frequency is provided from the local office end and is delivered to the antenna site.

In addition to the merits mentioned in clause 6.1, the required optical transmission bandwidth for transporting radio format information is minimized. In the configurations shown in Figure 6-2-b, no reference frequency generator is required at the remote end, resulting in a simpler configuration of remote equipment. The reference frequency value can be also decreased if sub-harmonic mixing technique is used in the IQ-to-RF and RF-to-I/Q converters.

6.2 Digital RoF system

6.2.1 Digital radio signal(s) transmission

Figure 6-3 illustrates general and fundamental architectures for transmitting digital radio signals. RF-band pulse(s), such as impulse radio signal(s), is a typical example of the digital radio signal(s). In Figure 6.3, it is assumed that equipment on the left side of the fibre-optic link is located in the local office and equipment on the right side is located at the remote antenna.

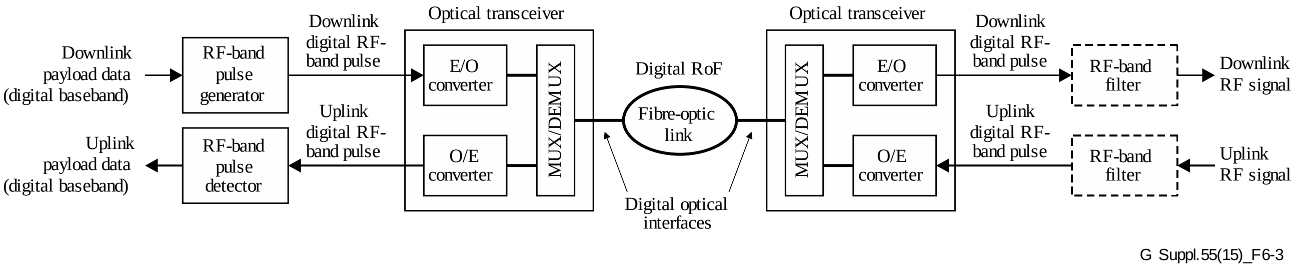


Figure 6-3 – Configuration examples for transmitting digital signal(s): RF-band pulse

In a RF-band pulse transmission scheme, such as that shown in Figure 6-3, the system consists of an RF-band pulse generator, a RF-band pulse detector, a pair of optical transceivers, a fibre-optic link, and two RF-band filters. The RF-band filters may be used if the need arises in order to obey the Radio Regulation. For the downlink, an RF-band pulse is generated with downlink payload data using the RF-band pulse generator at the local office end. The generated downlink RF-band pulse modulates an optical carrier using an E/O converter in the optical transceiver. The generated downlink digital RoF signal is transmitted over the fibre-optic link. It is noted that, although an optical interface of the fibre-optic link is treated as digital, the nature of the interface may be close to analogue. This is because the intensity of optical signal may have analogue value, such as monocycle pulse, doublet pulse and so on. At the remote end, the received downlink RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating RF-band pulse, becomes the desired downlink RF signal. For the uplink, a received uplink RF signal, which corresponds to an uplink RF-band pulse, modulates an optical carrier using another E/O converter in the optical transceiver. The generated uplink digital RoF signal is transmitted over the fibre-optic link. At the local office end, the received uplink RoF signal is optically detected using another O/E converter in the optical transceiver. The detected electrical signal, which is the same as the uplink RF-band pulse, is demodulated with the RF-band pulse detector to recover the uplink payload data.

6.2.2 Digitized radio signal(s) transmission

Figure 6-4 illustrates general and fundamental architectures for transmitting digitized radio signals, such as digitized RF-band subcarrier, digitized IF-band subcarrier, and digitized I/Q baseband signals. In Figure 6-4, it is assumed that equipment on the left side of the fibre-optic link is located in the local office and equipment on the right side is located at the remote antenna.

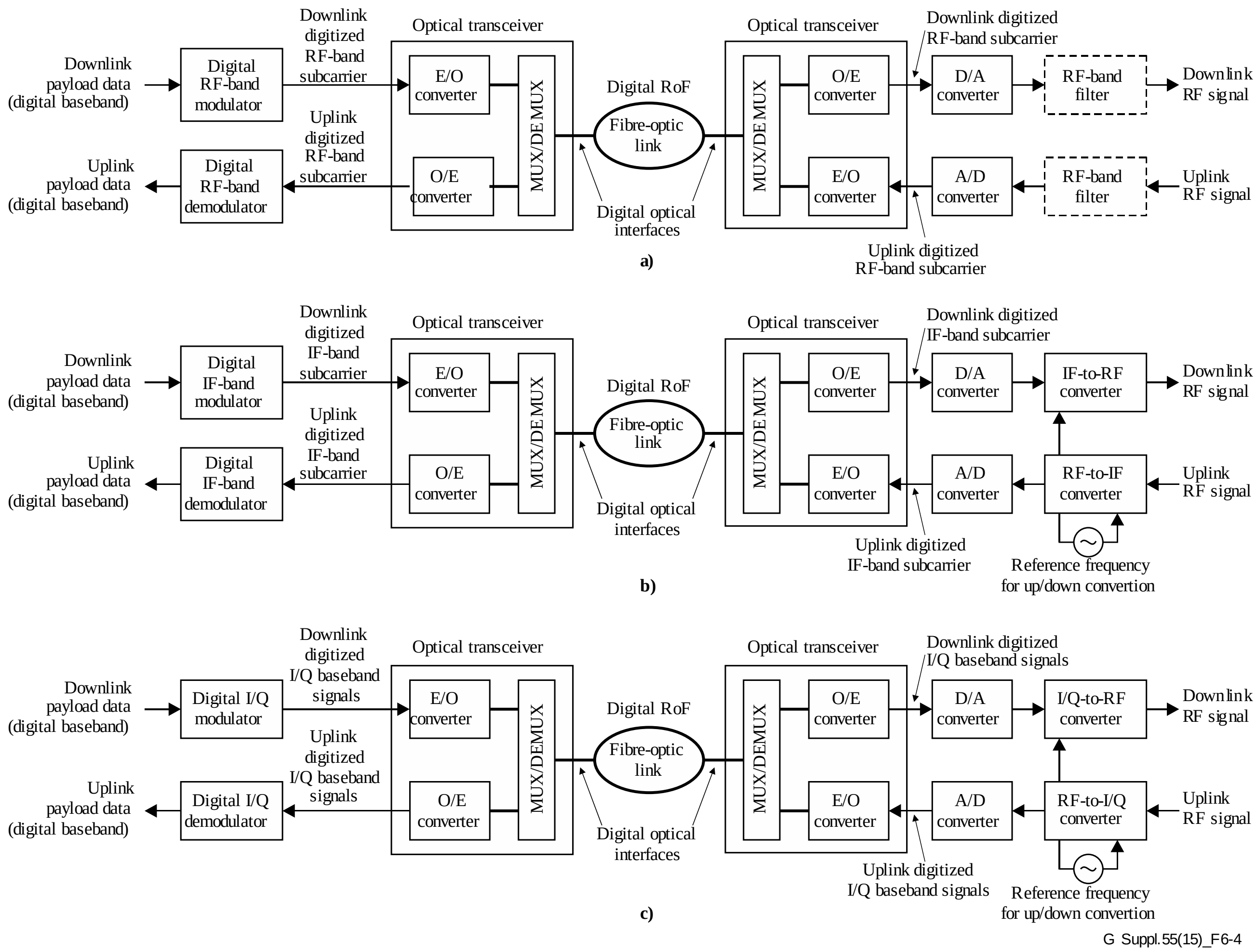


Figure 6-4 – Configuration examples for transmitting digitized signal(s): a) digitized RF-band signal(s); b) digitized IF-band signal(s); and c) digitized I/Q baseband signal(s)

In a digitized RF-band RoF transmission scheme such as that shown in Figure 6-4-a, the system consists of a digital RF-band modulator, a digital RF-band demodulator, a pair of optical transceivers, a fibre-optic link, a DAC, an ADC, and two RF-band filters. The RF-band filters may be used if the need arises in order to obey the Radio Regulation. For the downlink, a digitized RF-band subcarrier is digitally generated with downlink payload data using the digital RF-band modulator at the local office end. The generated downlink digitized RF-band subcarrier signal modulates an optical carrier using an E/O converter in the optical transceiver. The generated downlink RF-band D-RoF signal is transmitted over the fibre-optic link. At the remote end, the received downlink D-RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating digitized RF-band subcarrier signal, is digital to analogue (D/A) converted to generate the desired downlink RF signal. For the uplink, a received uplink RF signal is A/D converted, and then the uplink digitized RF-band subcarrier signal modulates an optical carrier using another E/O converter in the optical transceiver. The generated uplink RF-band D-RoF signal is transmitted over the fibre-optic link. At the local office end, the received uplink D-RoF signal is optically detected using another O/E converter in the optical transceiver. The detected electrical signal, which is the same as the uplink digitized RF-band subcarrier signal, is digitally demodulated with the digital RF-band demodulator to recover the uplink payload data.

In a digitized IF-band RoF transmission scheme, such as that shown in Figure 6-4-b, the system consists of a digital IF-band modulator, a digital IF-band demodulator, a pair of optical transceivers, a fibre-optic link, a DAC, an ADC, an IF-to-RF up-converter, an RF-to-IF down-converter, and a reference frequency generator. For the downlink, a digitized IF-band subcarrier is digitally generated with downlink payload data using the digital IF-band modulator at the local office end. The generated downlink IF-band D-RoF signal is transmitted over the fibre-optic link. At the remote end, the received downlink D-RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating digitized IF-band subcarrier signal, is D/A converted to generate the desired downlink IF signal. Then, the downlink IF-band signal is frequency up-converted using the IF-to-RF up-converter and a reference frequency to the desired downlink RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. For the uplink, a received uplink RF signal is frequency down-converted using the RF-to-IF down-converter to an IF-band subcarrier signal. The generated uplink IF-band subcarrier signal is A/D converted and then the generated digitized IF-band subcarrier signal modulates an optical carrier using another E/O converter in the optical transceiver. The generated uplink IF-band D-RoF signal is transmitted over the fibre-optic link. At the local office end, the received uplink D-RoF signal is optically detected using another O/E converter in the optical transceiver. The detected electrical signal, which is the same as the uplink digitized IF-band subcarrier signal, is digitally demodulated using the digital IF-band demodulator to recover the uplink payload data.

In a digitized I/Q baseband signals transmission scheme such as that shown in Figure 6-4-c, the system basically consists of a digital I/Q modulator, a digital I/Q demodulator, a pair of optical transceivers, a fibre-optic link, a DAC, an ADC, an I/Q-to-RF up-converter, an RF-to-I/Q down-converter, and a reference frequency generator. For the downlink, the digital I/Q modulator generates digitized I/Q baseband signals from the downlink payload data at the local office end. The generated downlink digitized I/Q baseband signals modulate an optical carrier using an E/O converter in the optical transceiver. The generated downlink baseband D-RoF signals are transmitted over the fibre-optic link. At the remote end, the received downlink D-RoF signals are optically detected using an O/E converter in the optical transceiver. The detected electrical signals, which are the same as the modulating digitized I/Q baseband signal, are D/A converted to generate the desired downlink I/Q baseband signals. Then, the downlink I/Q baseband signals are frequency up-converted with the I/Q-to-RF up-converter and a reference frequency to the desired downlink RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. For the uplink, a received uplink RF signal is frequency down-converted using the RF-to-I/Q down-converter to an I/Q baseband signals. The generated uplink I/Q baseband signals are A/D converted and then the generated digitized I/Q baseband signals modulate an optical carrier using another E/O converter in the optical transceiver. The generated uplink D-RoF signals are transmitted over the fibre-optic link. At the local office end, the received uplink optical signals are optically detected using another O/E converter in the optical transceiver. The detected electrical signals, which are the same as the uplink digitized I/Q baseband signals, are digitally demodulated with the digital I/Q demodulator to recover the uplink payload data.

From the above, these digitized radio signal(s) (D-RoF) transmissions require DACs and ADCs.

6.3 Relay transmission (repeater)

Figures 6-5 and 6-6 illustrate general and fundamental architectures for relay transmission (repeater) for analogue and digital RoF systems, respectively. Both subcarrier and equivalent low-pass signal transmission are possible as the relaying signal over a fibre-optic link. In Figures 6-5 and 6-6, it is assumed that equipments at both ends of the system are equivalent and play the same role for both directions of transmission of the RF signals.

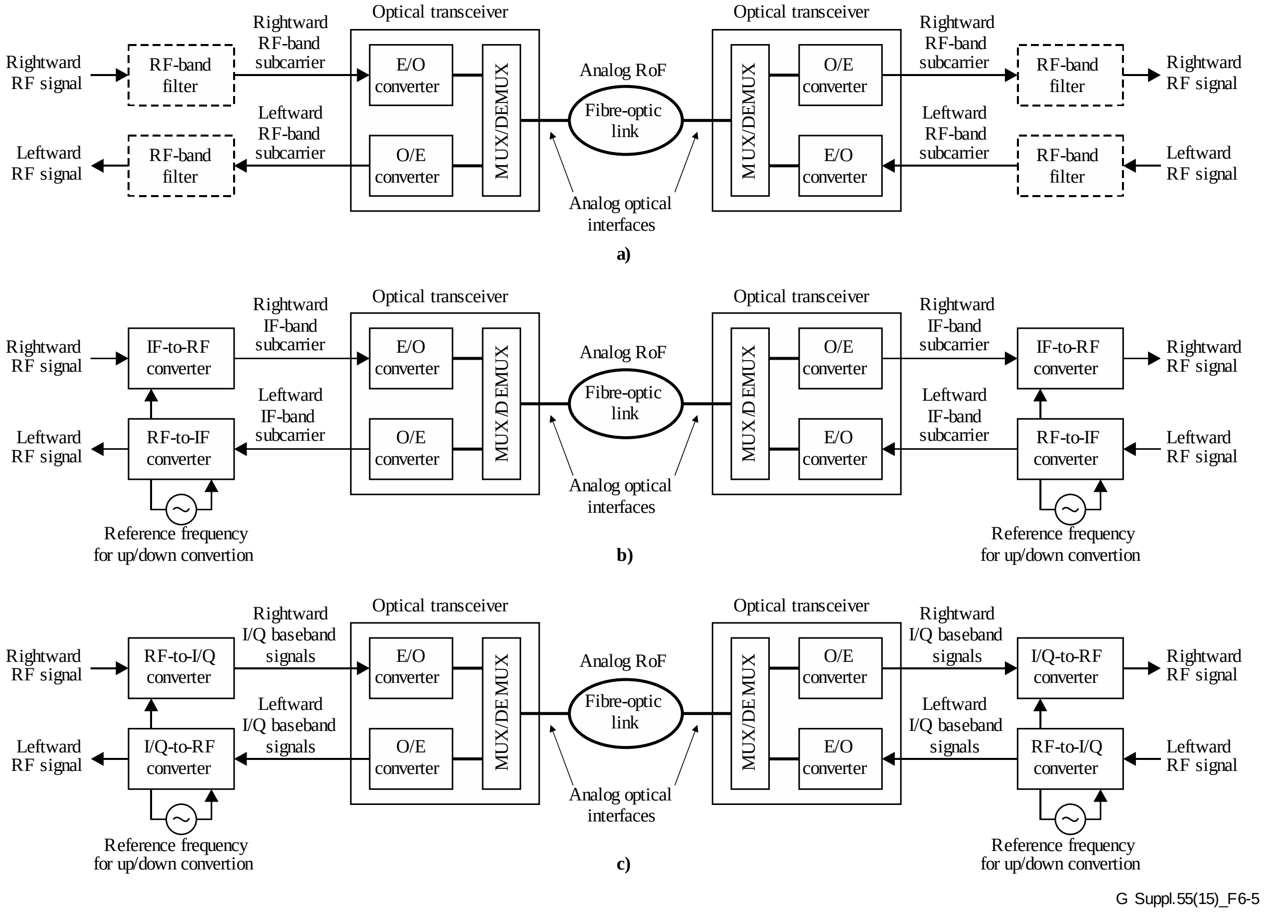


Figure 6-5 – Configuration examples for analogue relay transmission: a) RF-band signal(s); b) IF-band signal(s); and c) I/Q baseband signals

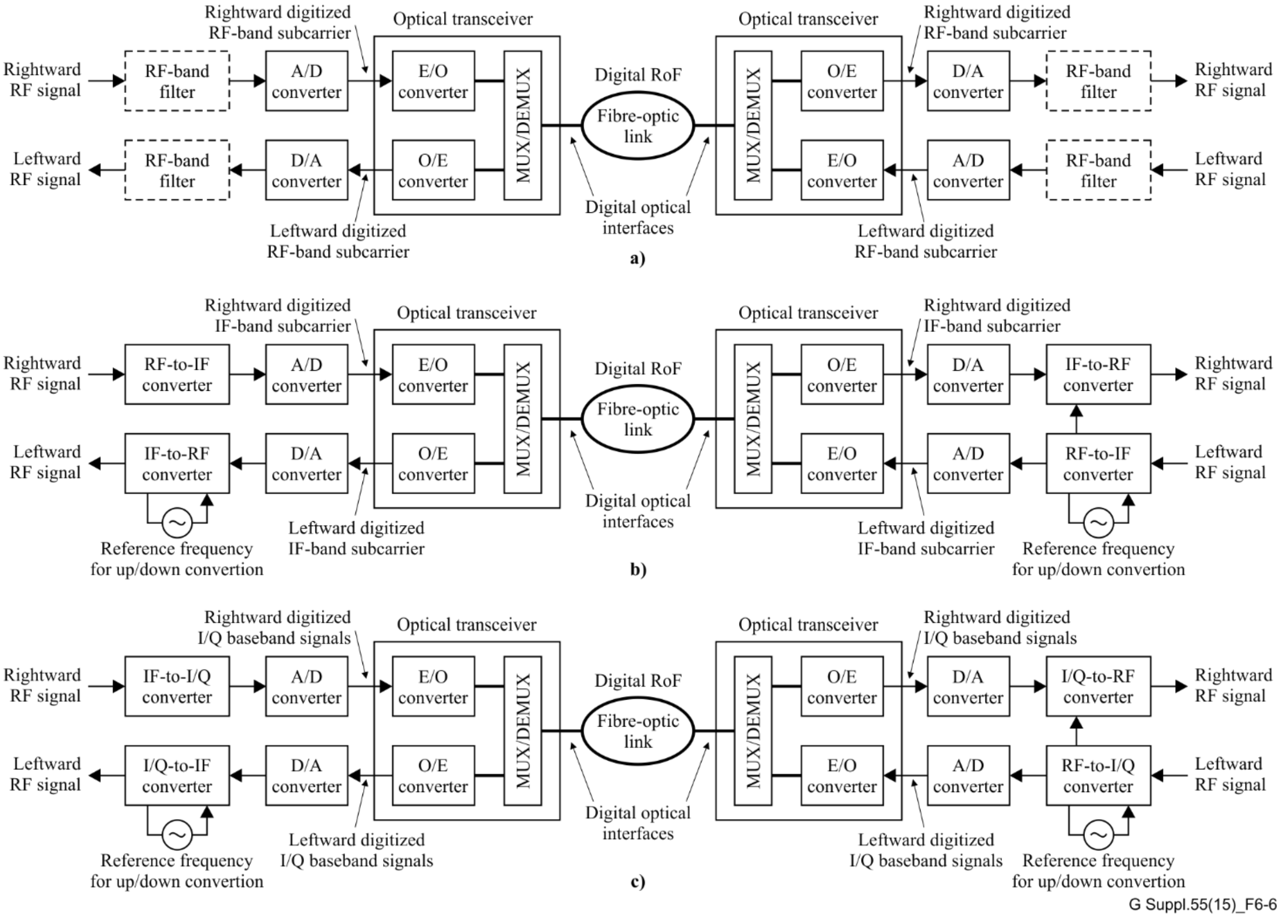


Figure 6-6 – Configuration examples for digital relay transmission: a) digitized RF-band signal(s); b) digitized IF-band signal(s); and c) digitized I/Q baseband signals

In an RF-band RoF relay transmission scheme such as that shown in Figures 6-5-a and 6-6-a, the system consists of two pairs of RF-band filters, a pair of optical transceivers, and a fibre-optic link. For digital RoF, moreover, an ADC and DAC pair is required. On the transmitter side, a received RF signal modulates an optical carrier using an E/O converter in the optical transceiver. The generated analogue RoF signal is transmitted over the fibre-optic link. On the receiver side, the received uplink RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating RF-band subcarrier signal, becomes the desired RF signal. In this way, RF signals in both directions are repeated through the fibre-optic link.

In an IF-band RoF relay transmission scheme such as that shown in Figures 6-5-b and 6-6-b, the system consists of two pairs of RF-to-IF and IF-to-RF converters, two reference frequency generators, a pair of optical transceivers, and a fibre-optic link. For digital RoF, moreover, an ADC and DAC pair is required. On the transmitter side, a received RF signal is frequency down-converted using the RF-to-IF down-converter to an IF-band subcarrier signal. The generated IF-band subcarrier signal modulates an optical carrier using an E/O converter in the optical transceiver. The generated analogue RoF signal is transmitted over the fibre-optic link. On the receiver side, the received RoF signal is optically detected using an O/E converter in the optical transceiver. The detected electrical signal, which is the same as the modulating IF-band subcarrier signal, is frequency up-converted using the IF-to-RF up-converter and a reference frequency to the desired RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. In this way, both directions of RF signal transmission are repeated through the fibre-optic link.

In an I/Q baseband signals relay transmission scheme such as that shown in Figures 6-5-c and 6-6-c, the system consists of two pairs of RF-to-I/Q and I/Q-to-RF converters, two reference frequency generators, a pair of optical transceivers, and a fibre-optic link. For digital RoF, moreover, an ADC and DAC pair is required. On the transmitter side, a received RF signal is frequency down-converted using the RF-to-I/Q down-converter to I/Q baseband signals. The generated I/Q baseband signals modulate an optical carrier using an E/O converter in the optical transceiver. The generated multi-level or analogue baseband signals, which are a form of analogue RoF signal, are transmitted over the fibre-optic link. On the receiver side, the received optical signals are optically detected using an O/E converter in the optical transceiver. The detected electrical signals, which are the same as the modulating I/Q baseband signals, are frequency up-converted using the I/Q-to-RF up-converter and a reference frequency to the desired RF signal. The characteristics of the reference frequency should be designed to be satisfied with the frequency stability of the downlink RF signal. In this way, both directions of RF signal transmission are repeated through the fibre-optic link.

It is obvious that the RF-band RoF relay transmission scheme can achieve the simplest system architecture, compared with system architectures for the other schemes. With the IF-band RoF relay transmission scheme, the requirement on the frequency response of E/O and O/E converters can be reduced, and the optical bandwidth efficiency of the analogue RoF system can be improved. Moreover, the I/Q baseband signals relay transmission scheme has the advantage that the optical transmission bandwidth required for repeating a radio waveform is minimized, while this relay transmission will increase the optical complexity because optical I/Q modulation and optical coherent detection will be required. These schemes should be adequately selected according to system requirements and installation conditions.

7 Fundamental technologies

7.1 Electrical-to-optical conversion

7.1.1 Direct modulation

Direct modulation is an optical modulation scheme of obtaining a desired optical signal (RoF signal) by applying a modulating electrical signal to the driving signal of light source, as shown in Figure 7-1. Figures 7-1-a and 7-1-b represent the direct modulation schemes for subcarrier signal(s) transmission, and for equivalent low-pass (baseband) signal(s) or digital signal(s) transmission, respectively. If needed, a bias current or voltage may be added to the modulating electrical signal for a linear operation. In Figure 7-1, f_{ele} and f_{opt} are the central frequencies of modulating electrical signal and optical carrier, respectively. In most cases, the power of optical carrier is modulated in proportion to the waveform of modulating electrical signal. In some cases, the frequency of optical carrier can be modulated. In general, direct modulation is the simplest, most cost-effective way to obtain the modulated optical signal because the required optical device is just a laser source. However, some intrinsic characteristics of the light source, such as nonlinear input-output relationship, limited driver bandwidth, relaxation oscillation, chirping, pattern effect and so on, may often cause the distortion of modulated optical signal. To prevent this, a light source capable of producing the desired system performance should be used.

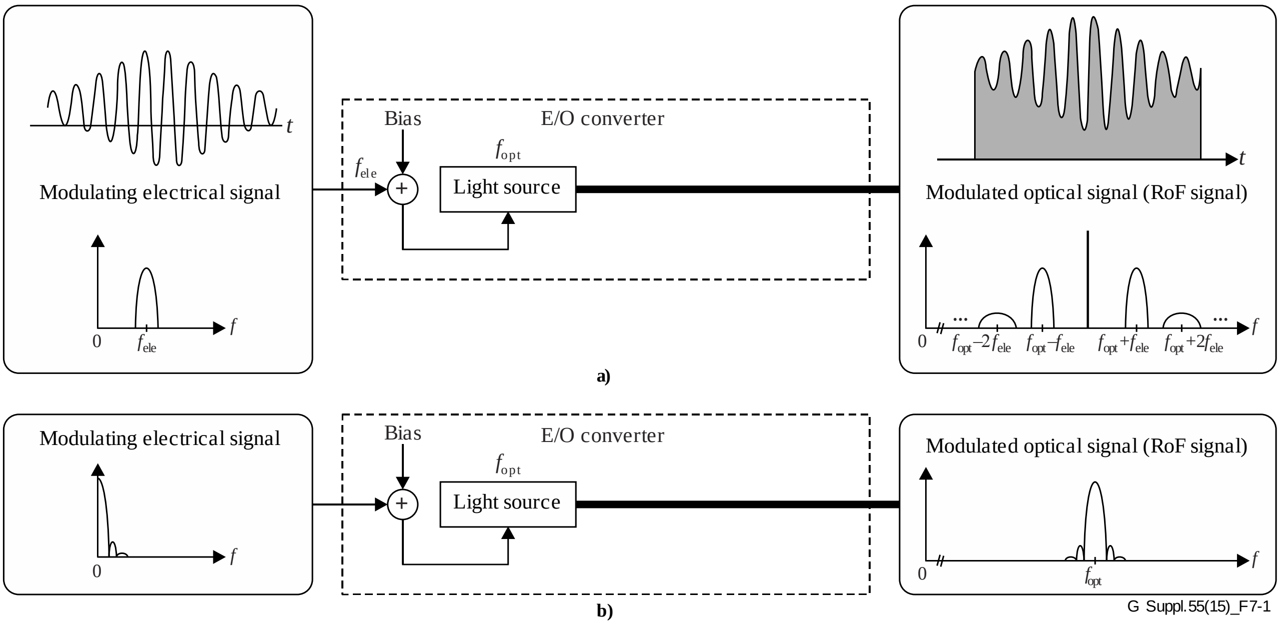


Figure 7-1 – Schematic block diagram of direct modulation: a) for subcarrier signal(s) transmission; and b) for equivalent low-pass (baseband) signal(s) or digital signal(s) transmission

7.1.2 External modulation

External modulation creates the desired optical signal (RoF signal) using an external modulator coupled with a CW light source, as shown in Figure 7-2. Figure 7-2-a and -b represent the external modulation schemes for subcarrier signal(s) transmission and for equivalent low-pass (baseband) signal(s) or digital signal(s) transmission, respectively. Once again, a bias current or voltage may be added to the modulating electrical signal for a linear operation if needed. The power, phase, frequency or state-of-polarization of optical carrier can be modulated in proportion to the waveform of modulating electrical signal. Although this scheme requires an external modulator in addition to the light source, the modulated optical signal will be of higher quality, because the intrinsic imperfections of the light source are avoided.

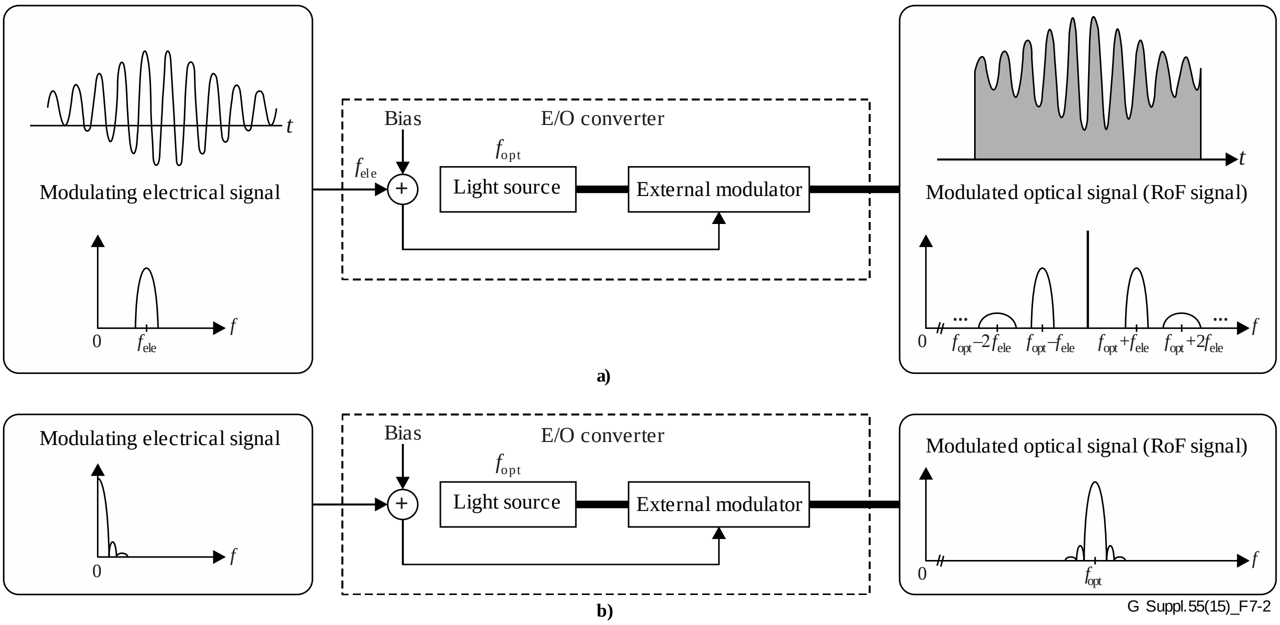


Figure 7-2 – Schematic block diagram of external modulation: a) for subcarrier signal(s) transmission; and b) for equivalent low-pass (baseband) signal(s) or digital signal(s) transmission

7.2 Optical-to-electrical conversion

7.2.1 Optical incoherent detection

Optical incoherent detection is a power detection scheme. The square-law function of photodetector is used for detecting the envelope of received optical signal (RoF signal), which corresponds to the power of optical signal. Therefore, if the optical signal power is modulated in proportion to the modulating signal, then incoherent detection can recover the original signal, as shown in Figure 7-3. Figure 7-3-a and -b represent the optical incoherent detection schemes for subcarrier signal(s) transmission and for digital signal(s) transmission, respectively. In most cases, a bias voltage should be added to the output port of photodetector for a linear operation. An electrical filter is used to extract only a desired electrical signal.

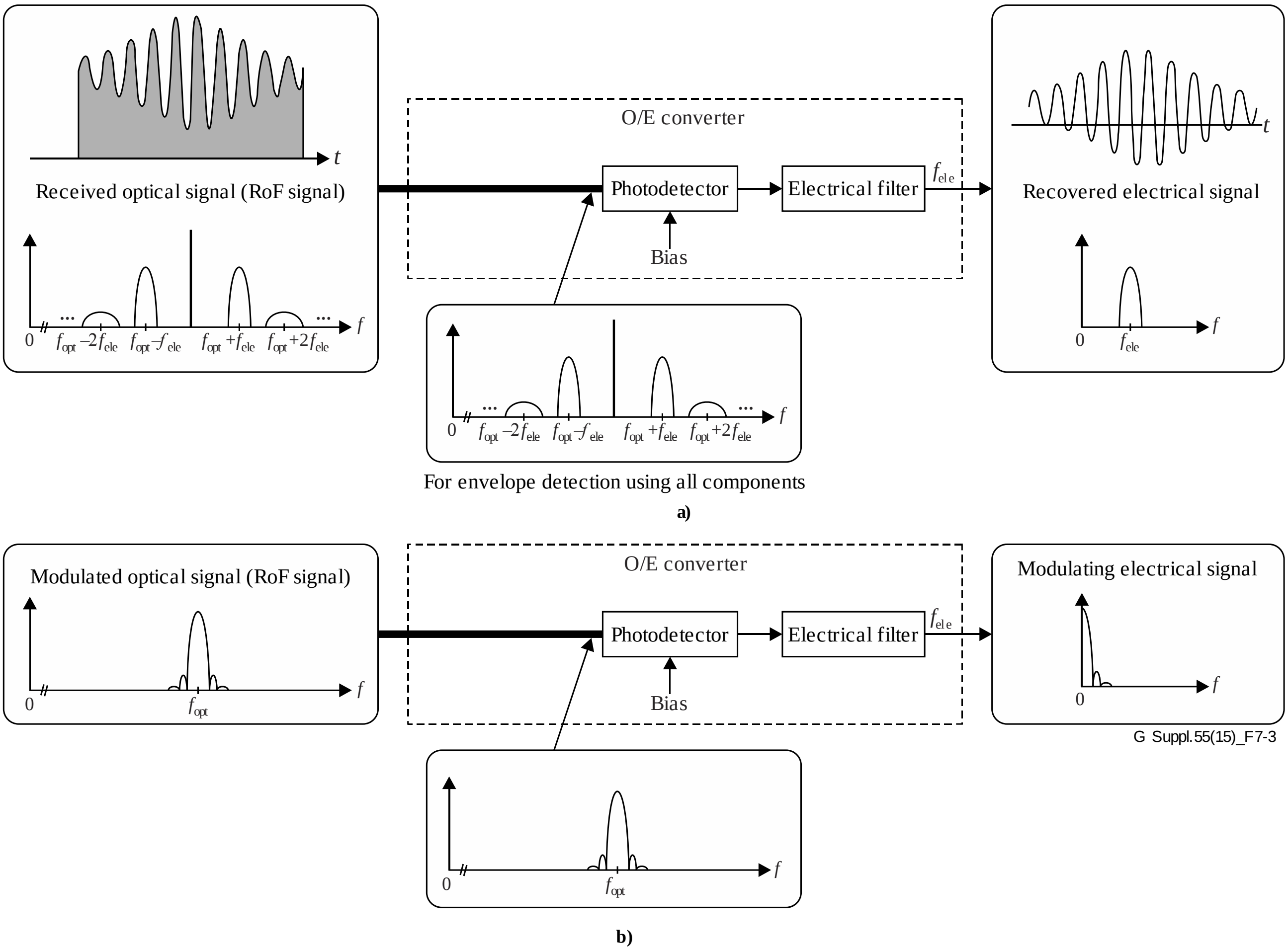


Figure 7-3 – Schematic block diagram of optical incoherent detection: a) for subcarrier signal(s) transmission; and b) for digital signal(s) transmission

7.2.2 Optical coherent detection

Optical coherent detection is a detection scheme that allows the measurement of the electric field of the signal. In this case, the square-law mixing function of photodetector is used to beat two or more optical components, where one of optical components is a reference signal. The reference signal may be modulated or not.

As an example, Figure 7-4 is a schematic block diagram of optical coherent detection. In Figure 7-4-a, which is an example of optical self-heterodyne detection, a received optical signal (RoF signal) put into an optical filter to extract, for example, the modulated optical component at $f_{opt} + f_{ele}$ and the reference optical component at f_{opt}. It is noted that the optical filter in the O/E converter may be able to be omitted if only the modulated optical component and the reference optical component are received at the O/E converter. The extracted optical components are photodetected to recover the original electrical signal with the photodetector. In most cases, a bias voltage should be added to the output port of photodetector for a linear operation. An electrical filter is used to extract only a desired electrical signal. Figure 7-4-b is an example of optical homodyne detection with an independent local light source, which is used for detecting an equivalent low-pass (equivalent bandpass) signal shown in Figures 6-2 and 6-5-c.

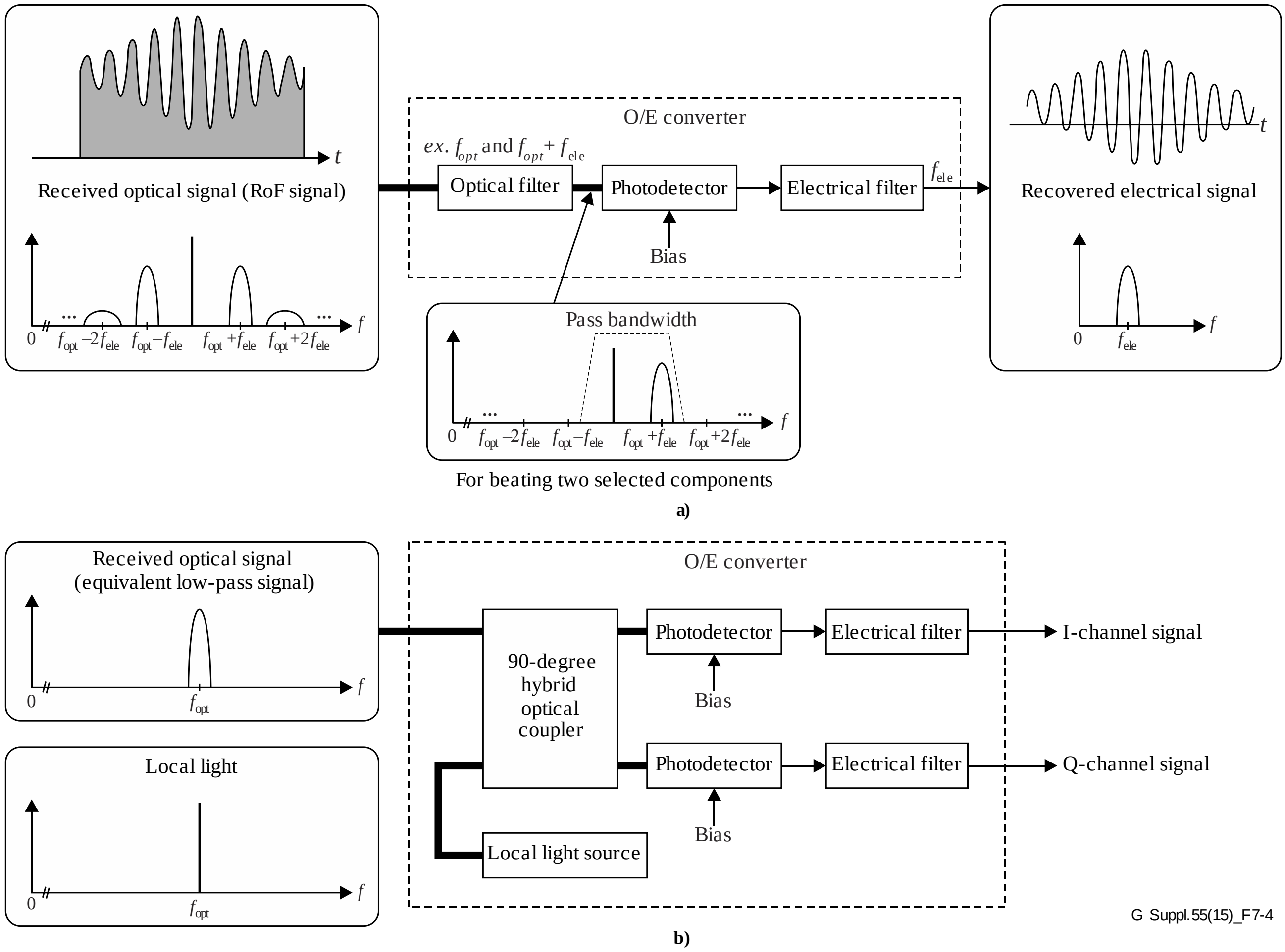


Figure 7-4 – Schematic block diagram of optical coherent detection: a) for subcarrier signal(s) transmission; and b) for equivalent low-pass (equivalent baseband) signal(s) transmission

7.3 High-spectral-efficient transmission

7.3.1 Subcarrier multiplexing transmission

7.3.1.1 Analogue aggregation

Subcarrier multiplexing (SCM) is an electrical multiplexing scheme of obtaining a desired driving signal for optical modulation by combining several electrical bandpass signals with different central frequencies. Therefore, it is a kind of frequency division multiplexing (FDM) in the electrical domain. Figure 7-5 is a schematic block diagram of SCM transmission, where f_{en} (n = 1, 2, …, N) and f_{opt} are the central frequencies of modulating electrical bandpass signals and optical carrier, respectively. At first, the electrical bandpass signals with different central frequencies are combined with an electrical frequency multiplexer (MUX) to generate an SCM signal. The SCM signal modulates an optical carrier with an E/O converter to generate an SCM RoF signal. The received SCM RoF signal is photodetected with an O/E converter to regenerate the original SCM signal. The recovered SCM signal is put into an electrical frequency demultiplexer (DEMUX) to be divided into N original modulating electrical signals.

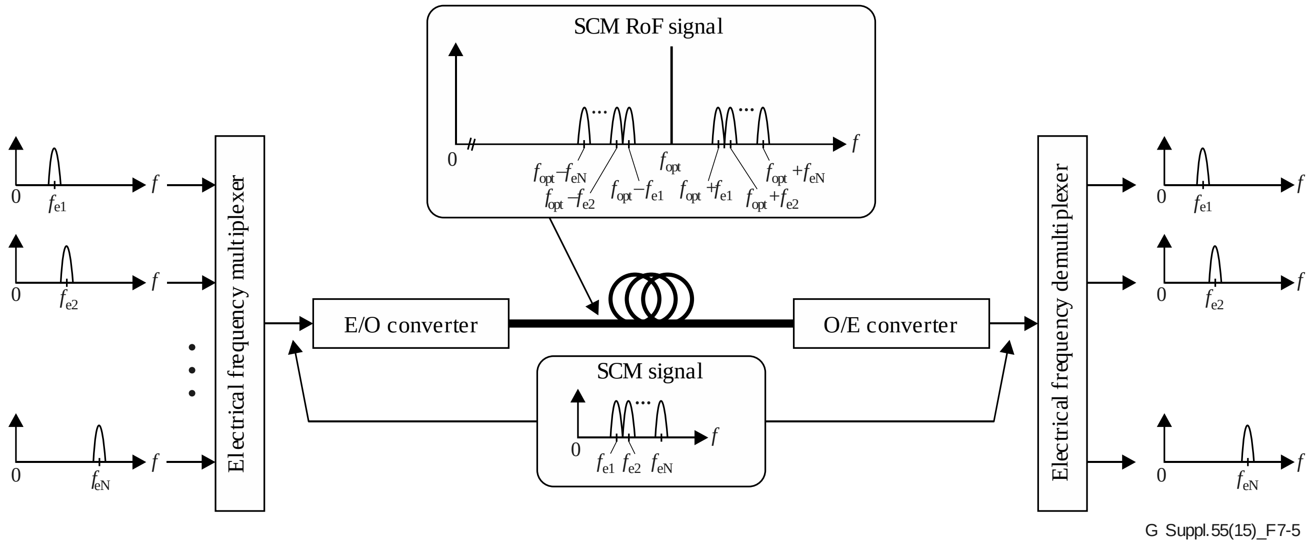


Figure 7-5 – Schematic block diagram of SCM transmission

7.3.1.2 Digital aggregation

The principle of aggregated analogue RoF is to aggregate wireless channels to/from multiple remote radio heads (RRHs) so that they can be transported together in a single optical wavelength channel in a mobile front-haul (MFH) system. By sharing the same optical hardware among multiple wireless channels, the cost of the needed optical access components may be much reduced.

Figure 7-6 is a schematic diagram of an aggregated analogue RoF based MFH system. Multiple RRHs may share the same optical fibre link to reduce overall cost. No baseband processing may be needed at the remote radio unit (RRU), making the implementation energy-efficient. Also, the optical signal transmitted over the optical fibre link may contain all the aggregated wireless channels with their bandwidths unchanged (untouched). This means that this approach may be optical bandwidth efficient. The optical bandwidth efficiency of this approach may be seen from the fact that the transmitted optical signal may be viewed essentially as an analogue optical signal rather than as a binary on-off keying (OOK) optical signal typically used with the Common Public Radio Interface [b-CPRI] or D-RoF.

Figure 7-7 is an illustration of the principle of channel aggregation through shifting the centre frequencies of the input wireless channels and combining of frequency-shifted channels. The channel aggregation may be implemented with relatively simple DSP. The reverse process can be applied to realize channel de-aggregation.

Wireless channels typically have well-defined channel bandwidths and channel sampling rates, as shown in Table 7-1 for the evolved universal terrestrial radio access (E-UTRA). In the long-term evolution advanced (LTE-A) standard, carrier aggregation (CA) is specified such that the effective bandwidth of a wireless channel may be increased beyond 20 MHz, e.g., to 100 MHz. The proposed channel aggregation method may be overlaid on CA, but it does not touch (or change) each carrier-aggregated wireless channel in terms of its bandwidth and baseband payload data.

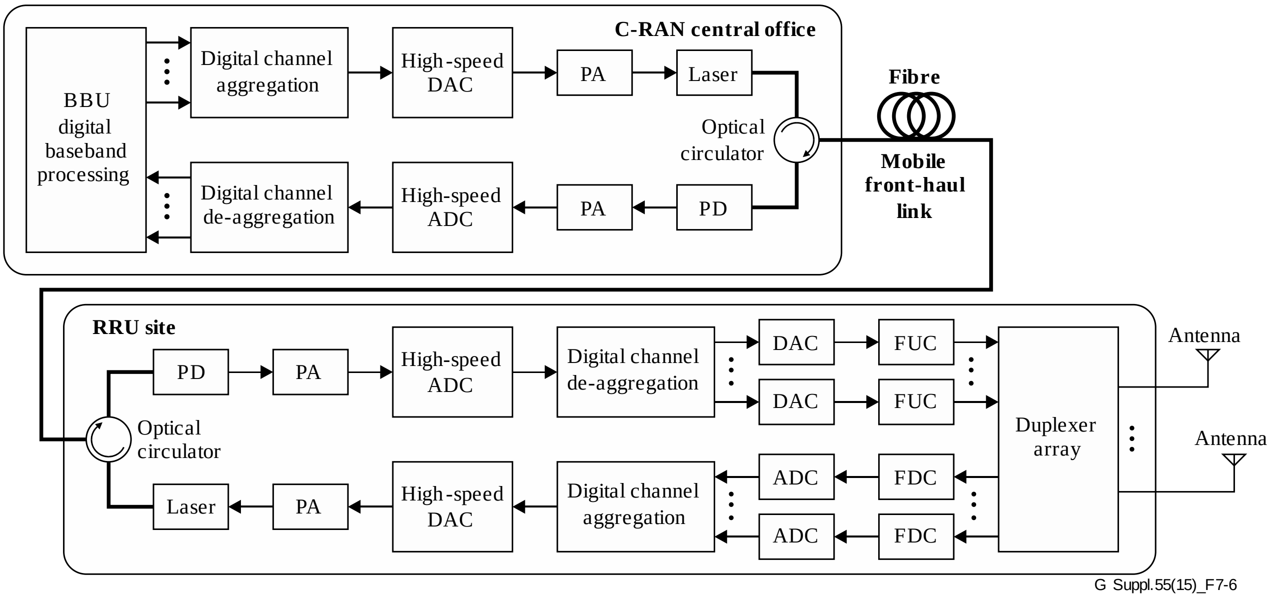


Figure 7-6 – Schematic diagram of an aggregated analogue RoF based MFH system. C-RAN: centralized radio access network; BBU: baseband unit; DSP: digital signal processing; DAC: D/A converter; ADC: A/D converter; PA: RF-band power amplifier; PD: photodetector; RRU: remote radio unit; FUC: frequency-up-converter; FDC: frequency-down-converter

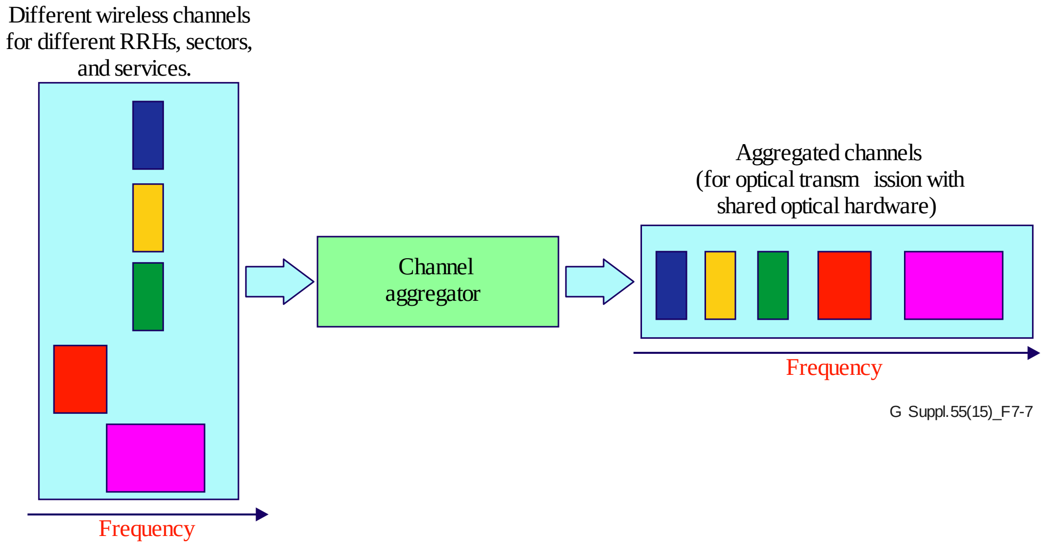


Figure 7-7 – Illustration of the channel aggregation principle

Table 7-1 – Typical channel bandwidth and sampling rates for E-UTRA

Channel bandwidth (MHz)	1.4	3	5	10	15	20
FFT size	128	256	512	1 024	1 536	2 048
Sampling rate (MHz)	1.92	3.84	7.68	15.36	23.04	30.72

The analogue RoF technology can be extended to allow the use of modest DSP for channel aggregation and de-aggregation. This would achieve high bandwidth efficiency and flexibility. In addition, the analogue RoF technology can be backward-compatible with CPRI-based D-RoF, e.g., by separately transmitting the I/Q data and the CPRI control words.

7.3.2 Wavelength division multiplexing transmission

Wavelength division multiplexing (WDM) is an optical multiplexing scheme of obtaining a desired optical signal by combining several modulated optical signals with different central frequencies. Therefore, it is a kind of FDM in the optical domain. Figure 7-8-a is a schematic block diagram of WDM transmission for subcarrier signal(s) transmission, where f_{ele} and f_{on} ($n = 1, 2, \ldots, N$) are the central frequencies of modulating electrical signal and optical carriers, respectively. Here, f_{ele} may be different for different modulating electrical signal. Figure 7-8-b is a schematic block diagram of WDM transmission for equivalent low-pass (equivalent baseband) signal(s) or digital signal(s) transmission. At first, for both cases, an electrical signal modulates an optical carrier with an individual E/O converter to generate a modulated optical signal (RoF signal). The generated RoF signals with different central frequency are combined with a wavelength MUX to generate a WDM RoF signal. The received WDM RoF signal is put into a wavelength DEMUX to be divided into *N* original RoF signals. Each RoF signal is photodetected with an individual O/E converter to regenerate the original electrical signal.

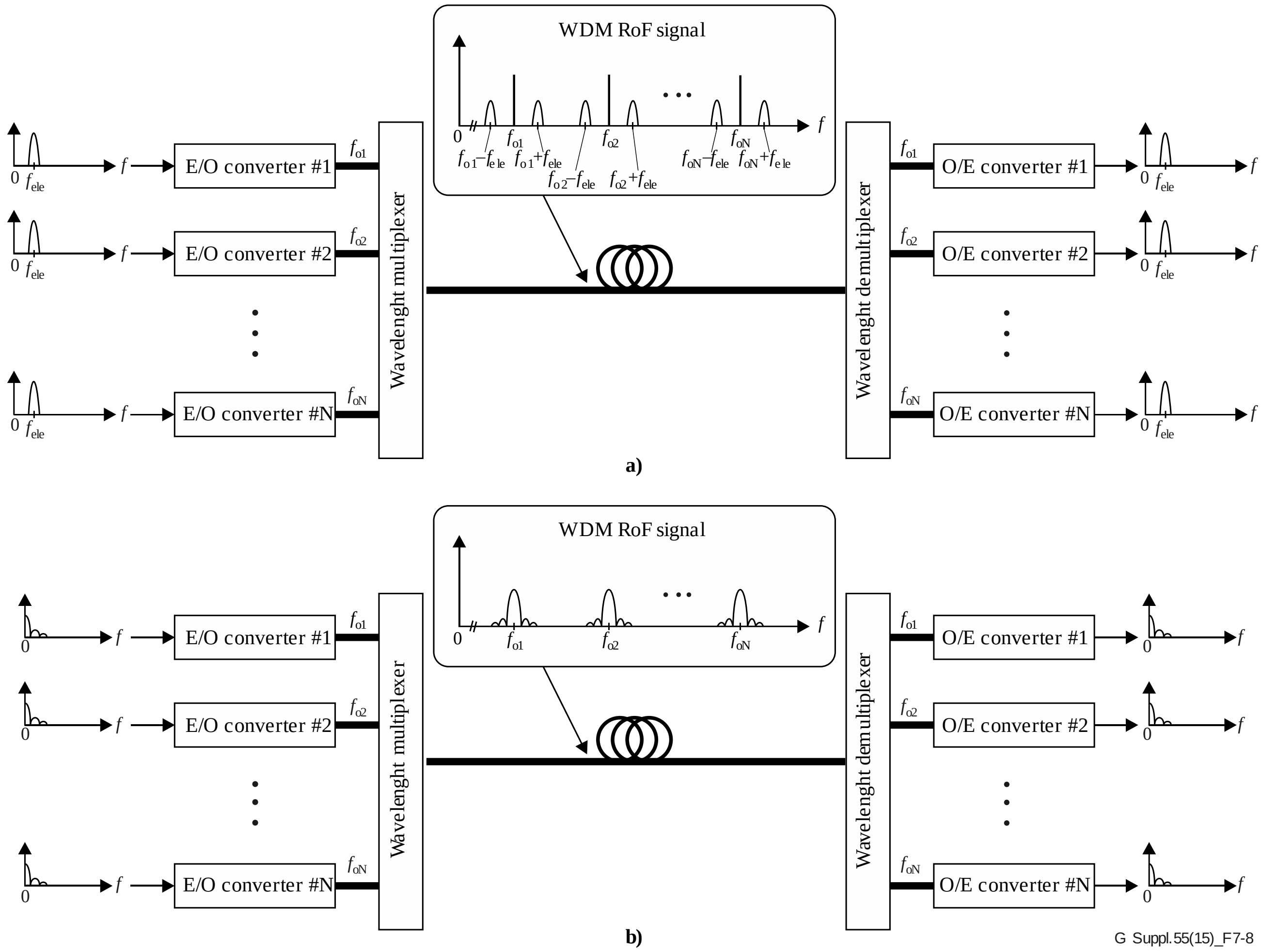


Figure 7-8 – Schematic block diagram of WDM transmission: a) for subcarrier signal(s) transmission; and b) for equivalent low-pass (equivalent baseband) signal(s) or digital signal(s) transmission

7.3.3 Multi-level modulation

There are many multi-level modulation schemes, for example, quadrature phase shift keying (QPSK), *M*-ary quadrature amplitude modulation (M-QAM), discrete multi-tone (DMT), OFDM and so on. They serve to increase the transmission capacity of a single channel provided that the signal-to-noise ratio (SNR) is high enough. For an RoF signal, it is considered that multi-level modulation can be generally performed in both the electrical domain and the optical domain.

In the electrical scheme, multi-level modulation is carried out when a modulating electrical signal is generated. Figure 7-9 shows an example of multi-level modulation performed in the electrical domain. As shown in Figure 7-9, at first, serial binary data is converted to parallel data for multi-level modulation with a binary-to-multi-level converter. The converted data modulates an electrical carrier at f_{ele} with an electrical I/Q modulator to generate a modulating electrical signal. The modulating electrical signal is put into an E/O converter, shown in Figures 7-1 and 7-2, to generate a desired RoF signal as shown in Figure 7-9-a and -b, respectively.

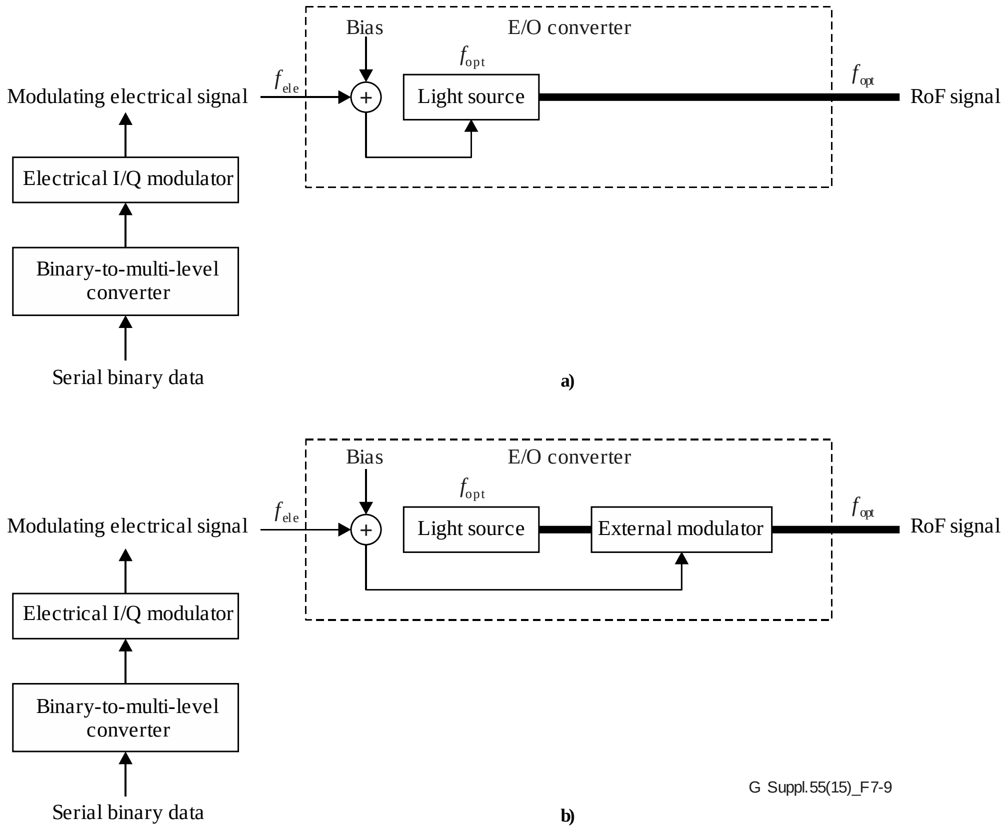


Figure 7-9 – Schematic block diagram of multi-level modulation performed in the electrical domain: a) with direct modulation; and b) with external modulation

In the optical scheme, multi-level modulation is carried out with an optical I/Q modulator. Figure 7-10 shows an example of multi-level modulation performed in the optical domain. As shown in Figure 7-10, at first, two-tone or multi-tone light is generated with a reference frequency of $f_{ele}/2$. A DEMUX extracts two optical frequency components at f_{opt}-$f_{ele}/2$ and f_{opt}+$f_{ele}/2$, where f_{opt} is the central frequency of optical carrier. On the other hand, serial binary data is converted to In-phase (I) data and quadrature-phase (Q) data for multi-level modulation with a binary-to-multi-level converter. The converted data modulates one optical frequency component at f_{opt}+$f_{ele}/2$ with an optical I/Q modulator. The modulated optical component at f_{opt}+$f_{ele}/2$ is combined with the other optical unmodulated component at f_{opt}-$f_{ele}/2$ via a MUX to generate a desired RoF signal.

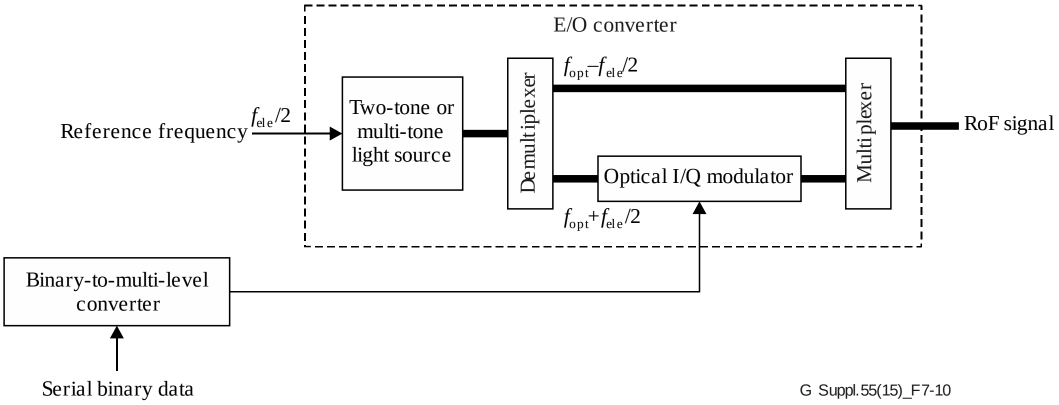


Figure 7-10 – Schematic block diagram of multi-level modulation performed in the optical domain

7.4 Digital-signal-processing-assisted (DSP-assisted) analogue RoF techniques

Figure 7-11-a and -b show typical configurations of an analogue RoF system and a D-RoF system, respectively. They are based on system architectures shown in clause 6. DACs and ADCs are used for the conversion between an analogue signal and a digitized signal. Frequency converters are used if necessary. An RF-band back-end processor and front-end processor (BEP/FEP) is assumed to be mainly an air-interface function, such as a radio antenna, which may include general functions for compensating any signal distortions, such as amplifications, bandpass filtering, equalizations, signal monitoring and so on. As mentioned in clause 5, the D-RoF system is an alternative candidate for transmitting the waveform, especially in cases where both distortion and poor sensitivity hamper analogue transmission under conditions of higher noise figure and nonlinearity. However, in general, the D-RoF system requires much wider optical bandwidth than that of the analogue RoF system, which sometimes gives inefficient use of the optical link.

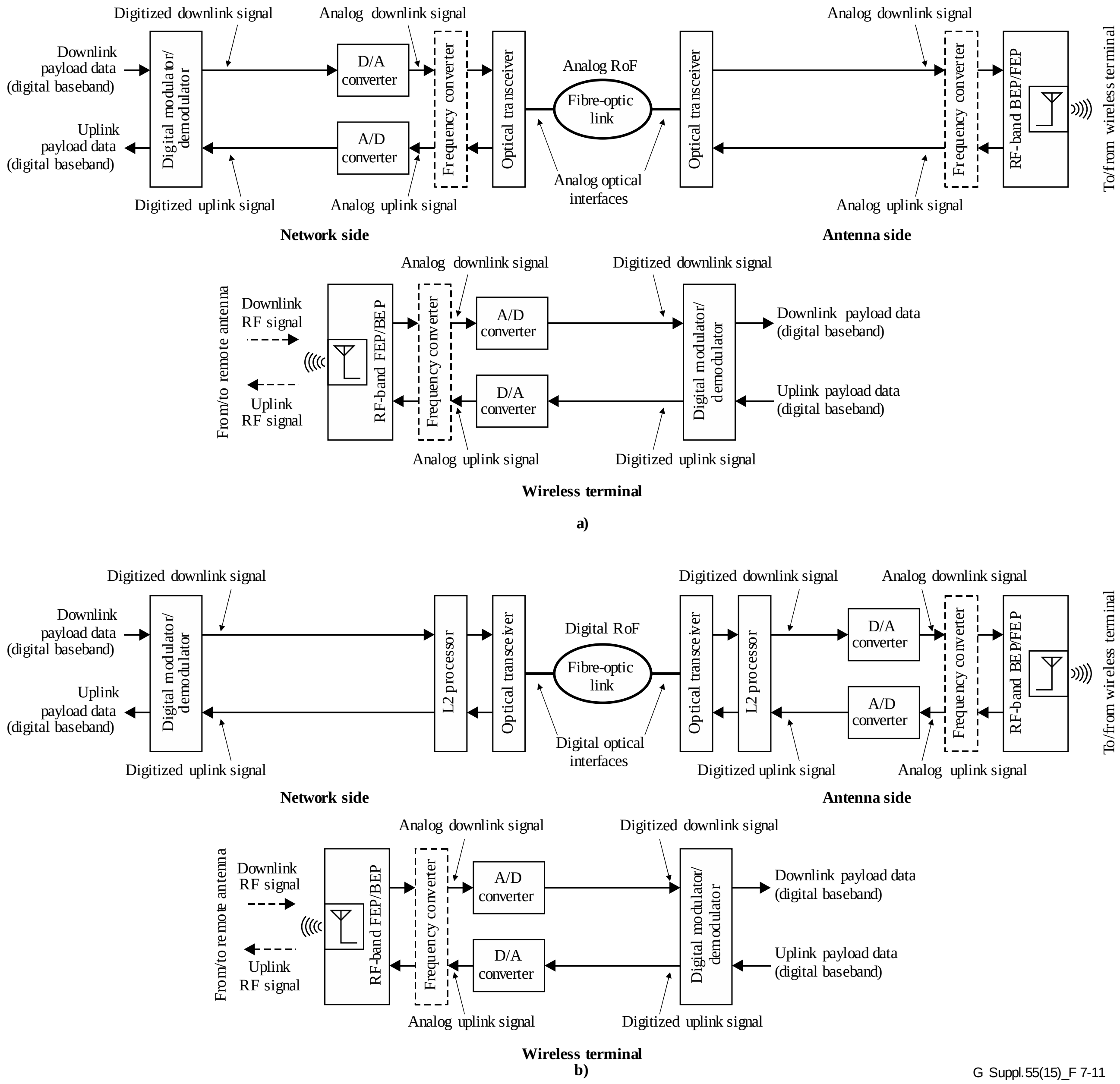
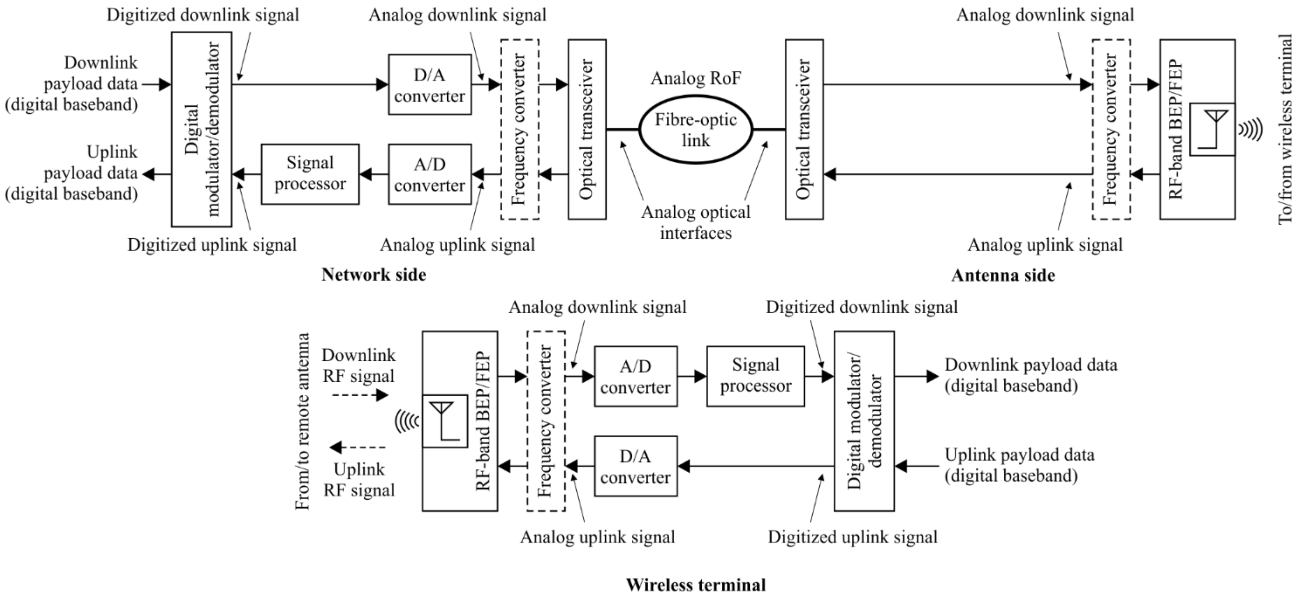


Figure 7-11 – Typical configurations: a) of an analogue RoF system; and b) of a D-RoF system

To overcome these problems, a DSP can be used in the analogue RoF system to compensate for signal distortion during the transmission, the so-called DSP-assisted analogue RoF technique. Typical examples of system configurations with the DSP-assisted analogue RoF technique are shown in Figure 7-12. Note that their combination and the other configurations are also possible as the DSP-assisted analogue RoF system. In Figure 7-12-a, the distortion compensation-like post-compensation method is performed at the edge of the link. For the downlink, a signal processor and a demodulator in a wireless terminal compensate for the signal distortions in both the optical and radio links. For the uplink, a signal processor and a demodulator on the network side compensate for them. In Figure 7-12-b, the distortion compensation, such as the pre-distortion method, can also be performed at the edge of the link. For the downlink, a signal processor on the network side pre-compensates for the signal distortions in both the optical and radio links. For the uplink, a signal processor on a wireless terminal side also compensates for them. In Figure 7-12-c, multiple distortion compensations are also performed at the edge of the link, which is a combination of distortion compensations shown in Figures 7-12-a and 7-12-b. For the downlink, a signal processor on the network side pre-compensates for the signal distortions in the optical links. In addition, a signal processor in a wireless terminal compensates for the signal distortion in the radio links. For the uplink, another signal processor in a wireless terminal pre-compensates for the signal distortion in the radio links and a signal processor on the network side also compensates for the signal distortions in the optical links. In these three cases, the equipment on the antenna side is the simplest. In Figure 7-12-d, the distortion compensation is performed in the middle of link. For the downlink, a signal processor on the antenna side compensates for the signal distortion in the optical link. For the uplink, another signal processor on the antenna side compensates for the signal distortion in the radio link. In this case, the equipment in the wireless terminal is basically in the same configuration as that in the typical RoF systems shown in Figure 7-11. Therefore, it is possible to continuously use the wireless terminal even if the equipment on the antenna side is changed.



a)

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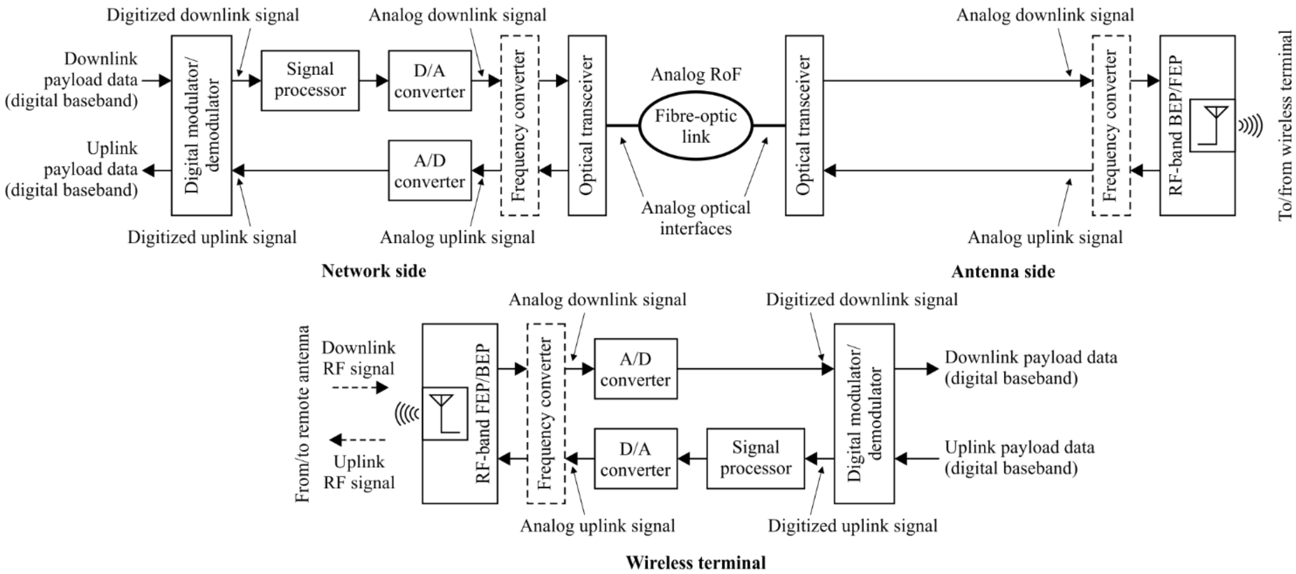

b)

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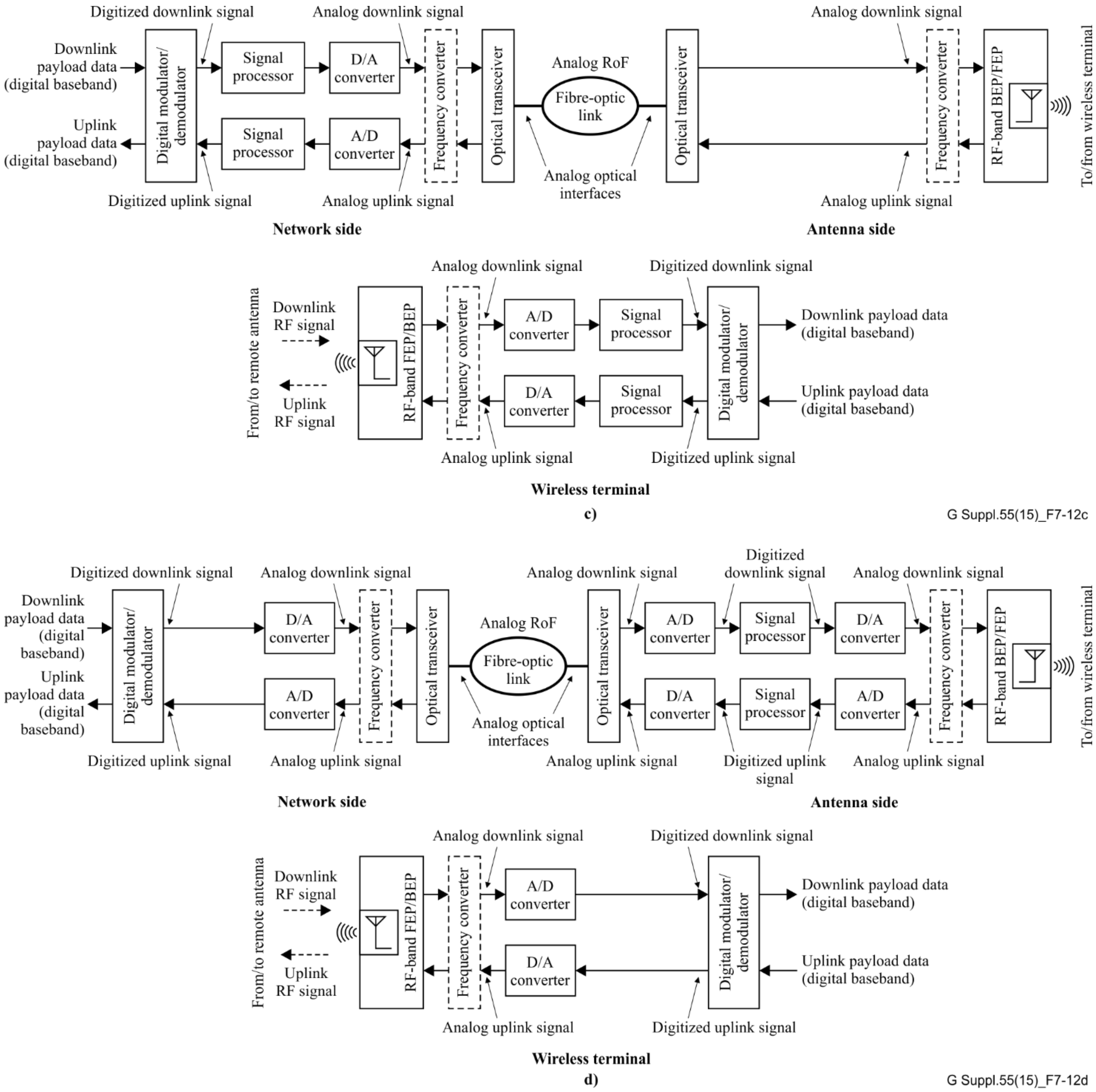


Figure 7-12 – Example configurations of DSP-assisted analogue RoF systems: a) with DSP at the edge of the link for post-compensation; b) with DSP at the edge of the link for pre-compensation; c) with DSP at the edge of the link for both post-compensation and pre-compensation; and d) with DSP in the middle of link

8 Network models

In radio access networks (RANs), macro cells are generally deployed to provide seamless coverage for outdoor and partial indoor environments, micro cells are deployed for street, hotspot and deep indoor coverage with a distributed antenna system, and small cells are used for dead spot or hotspot and local deployment.

The total number of RoF signals is considered in order to categorize RANs into types, taking fibre assets and fibre topologies of optical distribution network (ODN) into account. First, the existing definitions of three RAN scenarios as a function of cell structure and coverage are as follows.

A macro cell (see definition in clause 3.1.3) is compliant with the Third Generation Partnership Project (3GPP) standard, a few 10s of watts RF output power level, several radio technologies and several cells sectors to achieve a large coverage.

A micro cell (see definition in clause 3.1.2) is compliant with the 3GPP standard, a few 10s of watts RF output power level, several radio technologies and typically one cell sector to achieve a specific coverage area.

A pico cell (see definition in clause 3.1.5) can be one flavor configuration of small cell.

For our RoF topic, the small cell (3.1.4) is compliant with the 3GPP standard, low-power RF transmission (with varying output power ranging from 0.5 W to a few watts), one or several radio technologies and one cell sector to achieve a specific coverage area.

These three radio configuration descriptions allow it to be understood that several RF combinations could be implemented for each scenario. In order to achieve a classification for RoF applications, the parameters required for counting the number of RoF signals are clarified. There are four parameters.

The number of radio technologies (N^{RT}): This corresponds to the kind of radio (especially mobile) communication standards and their generations, such as the global system for mobile communications (GSM), wideband code division multiple access (W-CDMA), code division multiple access-2000 (CDMA-2000), long term evolution (LTE), LTE-A, worldwide interoperability for microwave access (WiMAX) and WiMAX2.

The number of RF bands allocated in one radio technology (N^{RFB}, where RFB denotes radio frequency block): W-CDMA (FDD) and LTE have many RF bands, which are defined in [b-3GPP TS 25.101] and [b-3GPP TS 36.101], such as band 1 (2 100 MHz band), band 2 (1 900 MHz band), band 5 (850 MHz band) and band 8 (900 MHz band).

The number of radio sectors (N^{RS}): This is applicable only for cells with sector antennas.

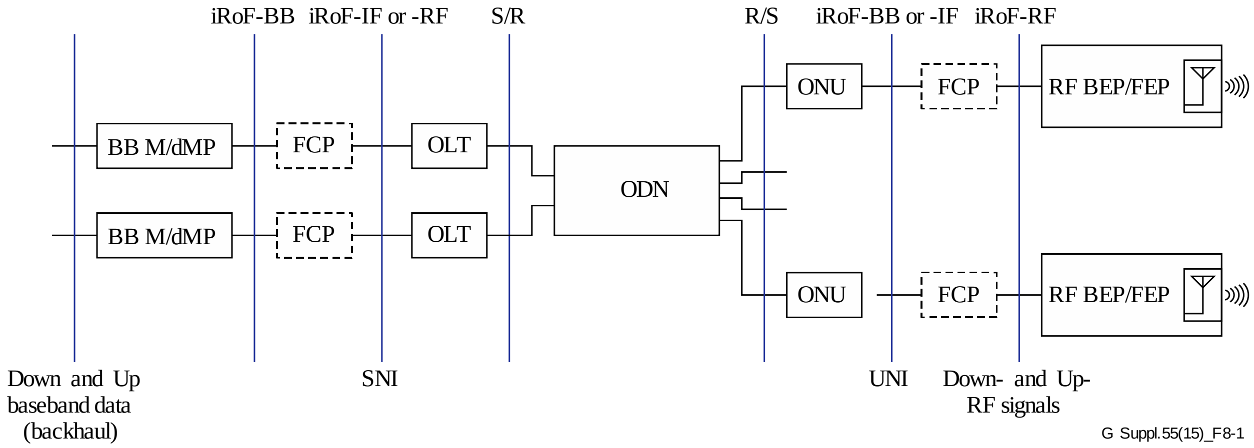
The number of multi-input multi-output (MIMO) signals (N^{MIMO}): In LTE and LTE-A systems, the MIMO technology must be supported. In the specific case of digital RoF, the present implementation supports the processing of all the MIMO signals in a single RoF signal ($N^{MIMO} = 1$).

These two descriptive ways of RANs are used to understand the applicability of proposed ODNs, network interface and transmission mechanisms for RoF signals.

In clauses 8.1 to 8.5, unless stated otherwise, the expression "RoF signal" concerns analogue and digital RoF.

8.1 Reference points

Figure 8-1 shows a set of reference points that are defined in this Supplement.



iRoF-BB Radio over fibre baseband interface
iRoF-IF Radio over fibre intermediate frequency band interface
iRoF-RF Radio over fibre radio frequency band interface

Figure 8-1 – Reference configuration for a RoF over ODN

The ODN offers one or more optical paths between one or more optical line terminals (OLTs) and one or more optical network units (ONUs). Each optical path is defined between reference points S and R in a specific wavelength window.

This system consists of OLT, ONU and fibre cable, which has an ODN configuration with passive optical devices (e.g., optical power splitter, optical wavelength MUX/DEMUX).

The RoF signal transmission in downstream and upstream directions can take place on an ODN with same fibre and components (duplex/diplex working) or on separate fibres and components (simplex working). We have to consider ODN architecture including the following.

One local (e.g., central office) hosting several baseband stations to one antenna site hosting several remote antennas with optional protection scheme.

One local (e.g., central office) hosting several baseband stations to several antenna sites hosting several remote antennas with optional protection scheme.

Multiple access techniques should be considered to achieve a limited number of fibres in the ODN and optical interfaces. The multiplexing technologies are as follows.

Time division multiple access should be used for digital (preferred) and analogue (potential) RoF signals.

For digital RoF, we have to consider two levels of time multiplexing, as follows.

The first concerns the capability to time multiplex several digital RoF signals in the electrical domain and transmit the result as one wavelength channel. In other words, the time multiplexing here means the capability to aggregate different links with smaller data rate into one link with much higher data rate. Then, the high data rate link could be mapped to one wavelength channel pair. One example of this capability is the aggregation of four 2.5 Gbps CPRI links into one 10 Gbps CPRI link.

The second concerns the capability to address several ONUs (several RF BEP/FEPs) connected to the same ODN and a single OLT port connected to several baseband modulation and demodulation (BB M/dMP) processors. Time division multiple access is used to achieve a transmission technique involving the multiplexing of many digital RoF inside time slots onto the same time payload.

For analogue RoF, optical pulses modulated by different radio signals with different timing are multiplexed in the optical domain, where the amplitude of optical pulse is an analogue value proportional to the sampled value of radio signal.

Wavelength division multiple access should be used for analogue and digital RoF. Each RoF interface is colourized.

Subcarrier multiple access should be used for analogue (preferred) and digital (potential) RoF. This multiplexing technique concerns the RF domain and not the optical domain. For analogue RoF, this multiplexing method allows optoelectronic emitter and receiver to be shared between several RF signals. For digital RoF, each subcarrier can transport partially or totally a digitized RoF signal with the help of specific processing.

8.2 Service

Such an RoF over ODN system could provide the complete range of all currently known and new mobile services being discussed for RAN including an existing or green field optical network segment. These services include the analogue and digital RoF signals. Some common features are listed below:

As the services evolve and newer services are introduced, the number of interfaces, bit rate for D-RoF and bandwidth for analogue RoF and management requirements will increase. This requires the RoF to be flexible and easily upgradable.

The overlay of several RoF generations of independent RAN is required.

The ability to re-use existing ODN plant for a RoF service is an option and must be done by either operating in usable spectrum not occupied by legacy passive optical networks (PONs) in a particular deployment or re-using the legacy PON interfaces.

8.3 Optical distribution network

The ODN consists of passive optical elements based on single mode optical fibre. This ODN has to support the following.

Maximum fibre distance between the reference point at the interface of the OLT and the ODN (S/R) and the reference point at the interface of the ONU and the ODN (R/S):

- 50 km for digital RoF signals due to the maximum 500 µs round trip time between BB M/dMP to RF BEP/FEP to BB M/dMP. A more stringent fibre distance requirement could be needed in function of mobile equipment performances and latency of digital RoF interface.
- 60 km for analogue RoF signals based on the maximum supporting distance defined in [ITU-T G.989.1].

Transmission in downstream and upstream directions can take place on the same fibre core and components (duplex/diplex working) or on separate fibre core and components (simplex working). The ODN offers one or more optical paths between one or more OLTs and one or more ONUs. Each optical path is defined between reference points in a specific wavelength window.

Optical passive devices to achieve optical wavelength multiplexing/de-multiplexing or optical power splitting/combining purposes are considered.

The two directions for optical transmission in the ODN are identified as follows.

Downstream direction for signals travelling from the OLT(s) to the ONU(s).

Upstream direction for signals travelling from the ONU(s) to the OLT(s).

8.4 Possible RoF over ODN configurations and characteristics

There can be several types of configurations as a function of the use of optical wavelength or power passive devices.

The wavelength based ODN is described in Figures 8-2-a and 8-2-b and comprises an optical head end, connecting to the ODN through one- or two-fibre links. The optical head end houses a set of optical transmitters and receivers based on dense wavelength division multiplexing (DWDM) or coarse wavelength division multiplexing (CWDM). The DWDM and CWDM characteristics have also to be considered for the passive wavelength multiplexer (WM). Two fibre ODN could be considered for CWDM and DWDM in absence of wavelength diplex definition. One fibre and DWDM colourless transceiver is considered as the target solution for the ONU and OLT.

Figures 8-2-a and 8-2-b present two examples of configuration authorizing a link between a base band pool and one or several antenna sites with high number of RoF signals ($N^{RT} \times N^{RFB} \times N^{RS} \times N^{MIMO}$) based only on the use of wavelength division multiplexing. These ODN scenarios could be typical use cases for macro and micro cell applications.

Figures 8-2-c and 8-2-d present two examples of configuration with optical power splitter and wavelength MUX and DEMUX based ODN. The optical splitter allows time division multiplexing (TDM) and time wavelength division multiplexing (TWDM) techniques to be used for RoF application. The WM also allows WDM technics to be used for RoF applications in coexistence with TDM and TWDM interfaces. One-fibre ODN is only considered in these scenarios based on diplex technology. We could consider that the use of the existing ODN splitter reduces the number of potential number of RoF ONUs available (cf. ODN end faces, wavelength spectrum allocation) and so one or several antenna sites with a limited number of RoF signals in comparison with the two previous scenarios could be used. These ODN scenarios could be typical use cases for micro and small cell applications.

Concerning Figure 8-2-c for Digital RoF, TDM or TWDM PON interface should require adaption of the PON interfaces (e.g., fixed bandwidth allocation algorithm) to allow a transmission of a continuous traffic with controlled latency and jitter.

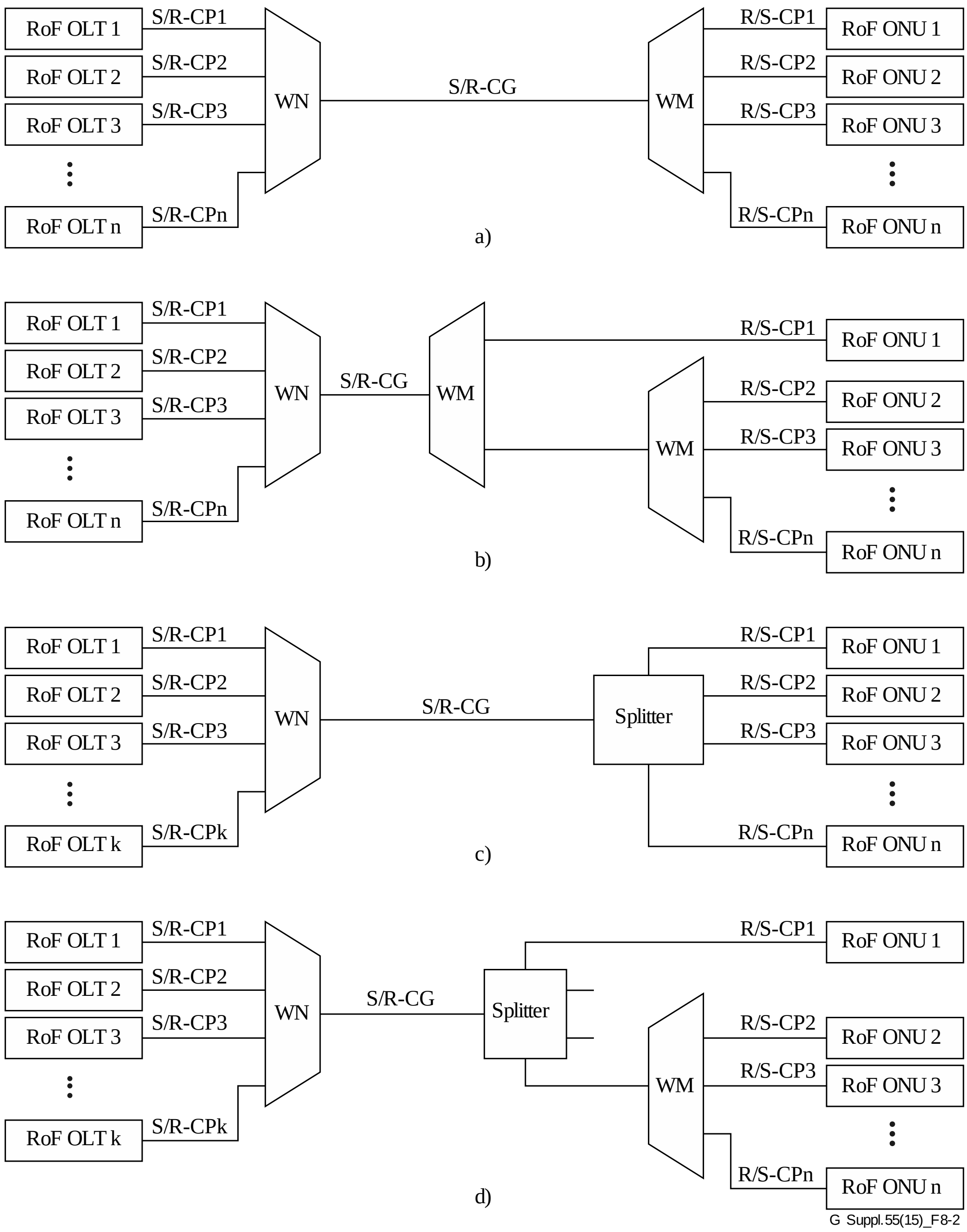


Figure 8-2 – Possible RoF over ODN configurations for a RoF based PON. WM: wavelength multiplexer/demultiplexer

8.5 Possible RoF over ODN survivability and characteristics

RoF over ODN should provide 1:1 or 1 + 1 backup mechanism in case of ODN failure.

In the digital RoF case, the baseband interface could be equipped with two digital radio over fibre baseband interface (iRoF-BB) ports. Each iRoF-BB port could be used to achieve protection on a separate ODN.

When protection is needed between ONU and OLT, a type B single and dual parenting configuration is proposed.

Although in this Supplement the compatibility of RoF with any existing optical access system is not discussed, the issue should be addressed in future work.

9 System design for supporting a radio access system over an optical access network

9.1 Measurement test model for mobile front-hauling over an optical distribution network

Figure 9-1 shows a general test model for physical-level quality measurement of RF signal in MFH with the RoF technology, which is based on the RF-band subcarrier signals transmission shown in Figure 6-1-a. As shown in Figure 9-1-a, the measurement set-up basically consists of two radio signal generators (SGs), two radio signal analysers (SAs), two E/O converters, two O/E converters, two MUXs/DEMUXs, a standard single-mode optical fibre (SMF), and a variable optical attenuator (VOA). Here, thin and thick lines represent electrical and optical wirings, respectively. In this model, it is assumed that the OAN under test corresponds to a link between service network interface (SNI) and user network interface (UNI). The output of radio SG is input into the OAN under test and the output of the OAN under test is input into the radio SA. Their signals, which should be radio signals, are delivered via the SNI or the UNI. For the purpose of transmitting a RoF signal, a set of one E/O converter, one O/E converter, and one MUX/DEMUX at the network side corresponds to an OLT, and another set of one E/O converter, one O/E converter, and one MUX/DEMUX at the user side corresponds to an ONU. An ODN consists of the SMF and the VOA, where the VOA emulates a splitting loss of splitters and the other excess losses between the OLT and the ONU, except for the SMF transmission loss. Figure 9-1-b and -c show the general configurations of E/O converter for direct modulation and O/E converter for incoherent detection, respectively. In each converter, an electrical amplifier, an electrical bandpass filter (BPF), an optical amplifier, and an optical BPF are optional components, which may be selectively used to meet the physical requirement at the point of SNI and UNI.

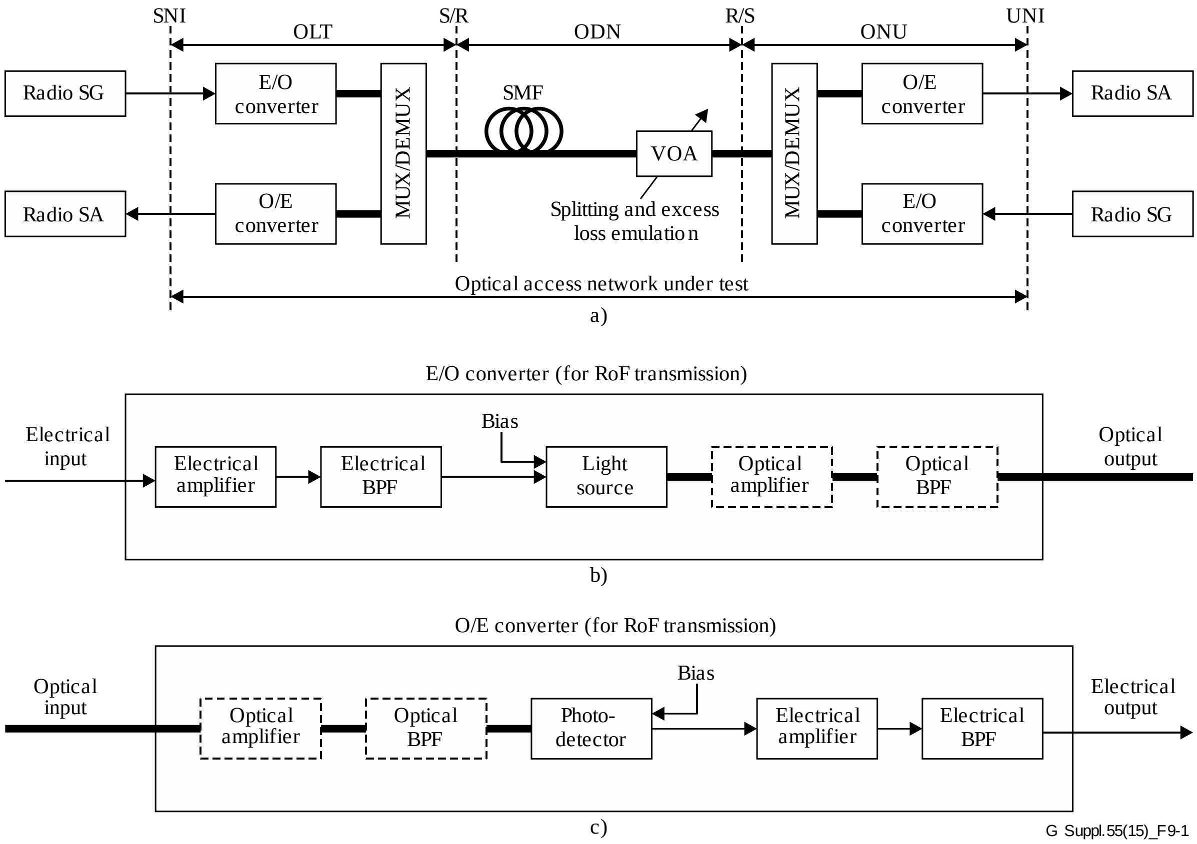


Figure 9-1 – General test model for RoF transmission over ODN: a) block diagram of measurement set-up; b) general configuration of E/O converter for direct modulation; and c) general configuration of O/E converter for incoherent detection

9.2 Example of system performance evaluation

In this clause, the following conditions are assumed as an example model.

Wireless service: Cellular mobile communication

BS class (see [b-3GPP TS 36.104]): Local Area BS

RF signal: LTE or LTE-A

Length of SMF in ODN: 20 or 40 km

9.2.1 Single downlink signal transmission

Figure 9-2 shows the typical experimental set-up for measuring the transmission quality of a typical LTE signal. It consists of an LTE vector signal generator (LTE VSG), an RoF transmitter (RoF Tx), three standard SMFs, a VOA, an erbium-doped fibre amplifier (EDFA), an optical bandpass filter (OBPF), an RoF receiver (RoF Rx), and an LTE signal analyser (LTE SA). The LTE VSG generated a typical LTE signal with the radio carrier frequency of 2.68 GHz, the bandwidth of 20 MHz, and the power of 0 dBm, in which the LTE band #7 was assumed (see [b-3GPP TS 36.101]). In this measurement, QPSK, 16 quadrature amplitude modulation (QAM), and 64-QAM were tested as a modulation format of the OFDM subcarrier. To generate a desired RoF signal, the generated LTE signal was input into the RoF Tx, which corresponded to an OLT. The generated RoF signal with a centre wavelength of 1 549.5 nm and a power of about 6 dBm was transmitted over 25 km, 5 km, and 15 km cascaded SMFs (total: 40 km) and the VOA to an ONU. The VOA emulates a passive optical power splitter. In the ONU, the received RoF signal was amplified with the EDFA followed by the OBPF. The EDFA was driven with an auto-current control and the OBPF with a 3 dB bandwidth of 1 nm was used to eliminate undesired amplified spontaneous emission (ASE) noise from the EDFA. The optically amplified RoF signal was detected with the RoF Rx to regenerate the LTE signal. Finally, the error vector magnitude (EVM) and the electrical spectrum of regenerated LTE signal were measured with the LTE SA.

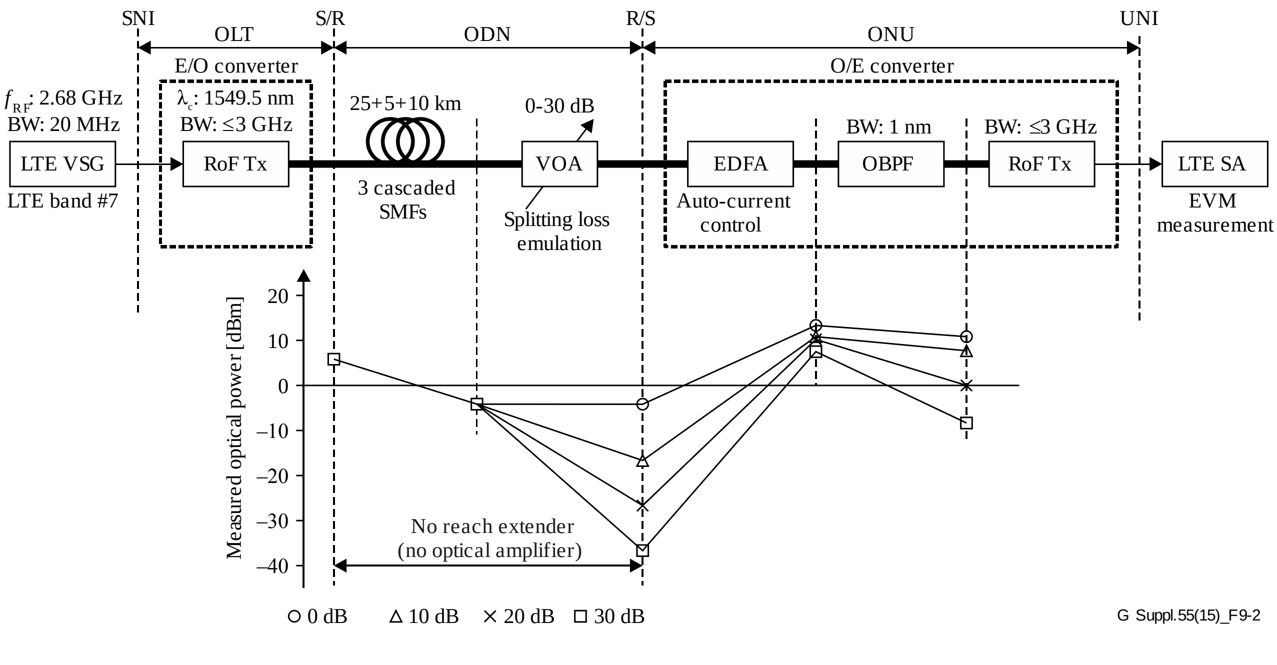


Figure 9-2 – Typical experimental set-up (upper) and optical power level diagram (lower)

The measured optical power level diagrams for 0, 10, 20, and 30 dB attenuation of the VOA are shown in Figure 9-2. As shown in Figure 9-2, the total insertion loss of SMFs was about 10 dB. In addition, the insertion loss of VOA itself was about 2 dB. It was observed that the gain of EDFA was dependent on the power of the received RoF signal input into the EDFA. For 0 dB attenuation, the gain of EDFA was saturated due to the large input power. For 30 dB attenuation, on the other hand, the ASE noise from EDFA was dominant due to the small input power. As a result for the latter, the effect of OBPF was well observed for 30 dB attenuation.

Figure 9-3 shows the measured symbol constellation and electrical spectra of regenerated LTE signals for the transmission before transmission and after transmission with a total optical path loss of 32 dB. From the electrical spectra, the SNR decreased due to the optical loss, compared with that for the optical transmission signal. However, it can be seen that all symbol constellations were clearly apparent for all modulation formats, even when the total optical path loss was 20 dB.

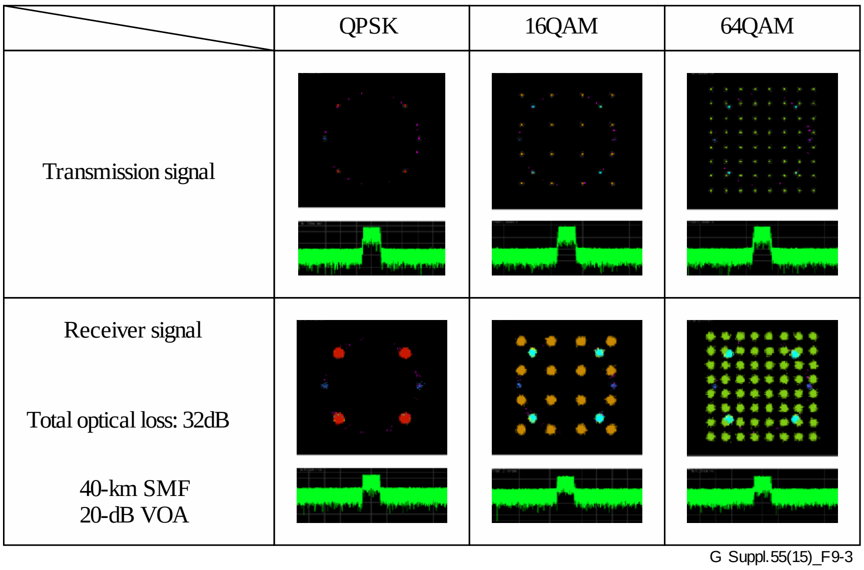


Figure 9-3 – Measured symbol constellations and electrical spectra

The measured EVM as a function of an additional loss after a 40 km-long SMF transmission is shown in Figure 9-4. According to "LTE; E-UTRA; BS radio transmission and reception" [b-3GPP TS 36.104], required EVMs of LTE transmitted signal at the BS for the modulation formats of QPSK, 16-QAM, and 64-QAM are ≤17.5, ≤12.5 and ≤8.0% r.m.s., respectively. From the measured EVMs and the requirements, it can be seen that 30 dB optical path loss, corresponding to 64 split, are acceptable, which has a margin of 7 dB for 64-QAM. For the modulation format of 64-QAM, the EVM at the optical path loss of 42 dB was degraded so much due to small power, which caused loss of synchronization. In the low additional loss region, the degradation of EVM was also observed. This is because nonlinearity of an electrical amplifier in the RoF Rx causes signal distortion of the received RoF signal. However, it is expected that these problems should be easily overcome by means of a power control of the received RoF signal, which is in general a common technique of optical transmission. From the above, it can be concluded that analogue RoF transmission over a typical ODN is feasible.

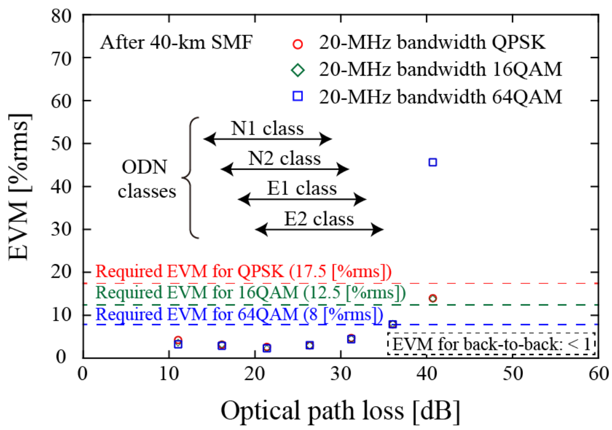


Figure 9-4 – Measured EVMs vs. optical path loss

9.2.2 Single uplink signal transmission

Figure 9-5 shows the typical experimental set-up for measuring the transmission quality of a typical LTE signal. It consists of an LTE VSG, a variable electrical attenuator (VEA), an RoF Tx, three SMFs, a VOA, an EDFA, an OBPF, an RoF Rx, and an LTE SA. The LTE VSG generated a typical uplink LTE signal with the radio carrier frequency of 2.535 GHz, the bandwidth of 1.4 to 20 MHz, and the power of −10 dBm, in which the LTE band #7 was assumed (see [b-3GPP TS 36.101]). To emulate a free-space propagation loss, the generated LTE signal was manually attenuated by 50 to 90 dB with the VEA. To generate a desired RoF signal, the LTE signal was input into the RoF Tx, which corresponded to an ONU. In the RoF Tx, the LTE signal was electrically amplified by 52 dB with a low noise amplifier (LNA) and then was converted with a laser diode (LD) to an optical signal. The generated RoF signal with a centre wavelength of 1 551.7 nm and a power of about 10 dBm was transmitted over 25 km, 5 km, and 15 km cascaded SMFs (total: 40 km) and the VOA to an OLT. The VOA emulates an additional optical path loss. In the OLT, the received RoF signal was amplified with the EDFA followed by the OBPF. The gain of EDFA was fixed to 20 dB and the OBPF with the 3 dB bandwidth of 1 nm was used to eliminate undesired ASE noise from the EDFA. The optically amplified RoF signal was detected with the RoF Rx to regenerate the LTE signal, where the RoF Rx consisted of a photodetector (PD) and a post-amplifier (PA) with the variable gain of 25 to 40 dB. Finally, the EVM and the electrical spectrum of regenerated LTE signal were measured with the LTE SA.

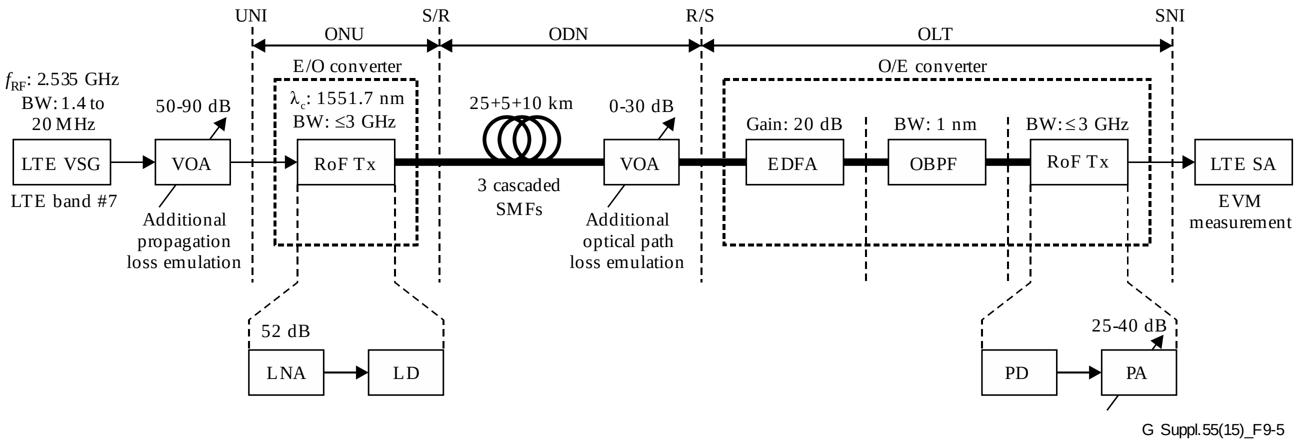


Figure 9-5 – Typical experimental set-up

Figure 9-6 shows the measured EVM as a function of optical path loss to evaluate the available dynamic range of optical path loss. The measurement was done when the input RF power to the RoF

Tx was –65 dBm. For an optical path loss ranging from 10 to 40 dB, the observed EVMs appear to be constant at approximately 3% for both a 20 MHz-bandwidth 64-QAM signal (which provides the maximum bit rate) and a 1.4 MHz-bandwidth QPSK signal (which provides the minimum bit rate). They were within the required EVM for a 64-QAM of 8% and QPSK of 17.5%, respectively (see [b-3GPP TS 36.104]). From this measurement, the available dynamic range of optical path loss was larger than 16 dB at least. These results show that the uplink transmission of an LTE signal over a fibre-optic link can be applicable to all the ODN classes specified in the ITU-T G.98x series under the condition of relatively high modulation index.

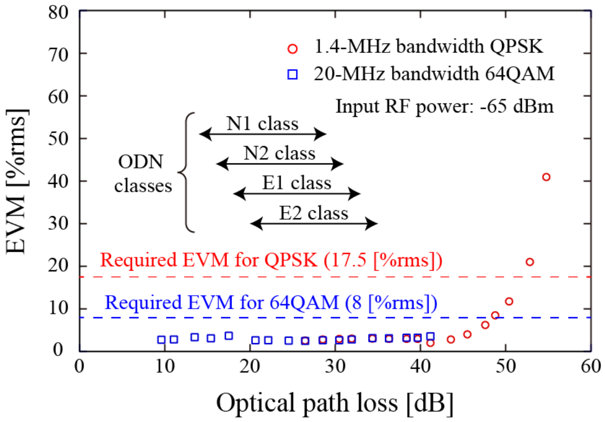


Figure 9-6 – Measured EVMs vs. optical path loss

Figure 9-7 shows the measured EVM as a function of input RF power to evaluate the minimum input RF power. In the case of electrical back-to-back (E-BtB), in which the LNA in the RoF Tx was directly connected to the LTE vector signal analyser (VSA), it is estimated that the EVM of 17.5% was obtained when the input RF power was about −100 dBm. Also in the case of RoF BtB, in which the RoF Tx was directly connected to the RoF Rx without any optical amplifier, almost the same result was observed. Thus, no significant degradation of the signal quality due to the introduction of the RoF Tx and Rx was observed. In the case of 36 dB optical path loss, it is estimated that the EVMs of 17.5% for 1.4 and 20 MHz-bandwidth QPSKs were obtained at the input RF powers of less than −92 and −85 dBm, respectively. From this result, it can be seen that the RoF transmission of uplink LTE signal over an ODN specified in the ITU-T G.98x series is feasible under the condition of input RF power of more than −92 dBm. Hence, it is considered that the power penalties are generally caused by the increase of total noise figure. However, the noise figure and the operational power range of the whole system can be optimized.

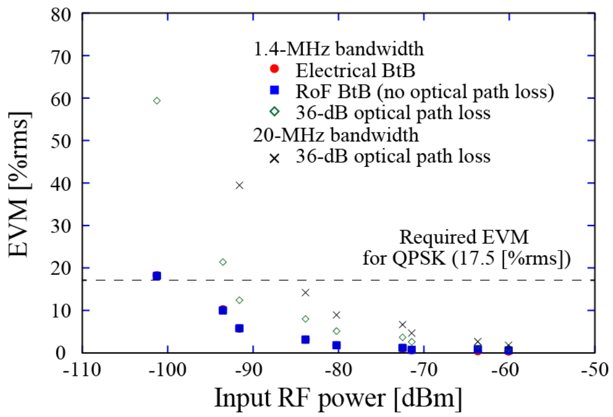


Figure 9-7 – Measured EVMs vs. input RF power

9.2.3 Multiple downlink signals transmission

9.2.3.1 IF-band SCM RoF system with an analogue aggregation technique in ONU

Figure 9-8 shows the typical experimental set-up for measuring the transmission performances of typical multiple LTE signals based on IF-band SCM RoF transmission scheme. This is a kind of IF-band SCM RoF system with an analogue aggregation technique in ONU. It consists of an arbitrary waveform generator (AWG) to generate multiple LTE signals, an RoF Tx, standard SMF of 20 km, a VOA, an EDFA, an ASE rejection filter, an RoF Rx, a BPF, a frequency-up-converter (FUC), high power amplifier (HPA), antenna and an LTE VSA. The AWG generated typical multiple LTE signals at the intermediate carrier frequency from 160 to 820 MHz with 60 MHz spacing. The bandwidth of each IF-band carrier was 20 MHz. The total summed RF power for all IF carriers was about 0 dBm to obtain a proper optical modulation index (OMI) for better transmission performance. In this measurement, a 64-QAM was employed as a modulation format of the OFDM subcarrier. To generate a desired RoF signal, the generated LTE signals were input into the RoF Tx, which corresponded to an OLT.

The generated RoF signal with a centre wavelength of 1 550 nm and an optical power of about 5 dBm was transmitted over the 20 km SMF and the VOA to an ONU. The VOA emulated a passive optical power splitter. The transmitted RoF signal was detected with the RoF Rx to regenerate the LTE signal. The transmitted RoF signal was detected with the RoF Rx to regenerate the LTE signal. This regenerated signal was frequency-up-converted from intermediate frequencies to radio frequencies after passing through the bandpass filter. Frequency-up-converted signal was re-amplified with HPA and inputted to the antenna. Finally, the EVM and the electrical spectrum of the regenerated LTE signal were measured with the LTE VSA. The measured optical power level diagrams for 10, 15, 20 and 25 dB attenuation of the VOA are also shown in Figure 9-8. As shown in Figure 9-8, the total insertion loss of SMF was about 5 dB. In this measurement, the optical amplifier in front of the RoF Rx was not employed in order to take cost-effectiveness of the ONU into account.

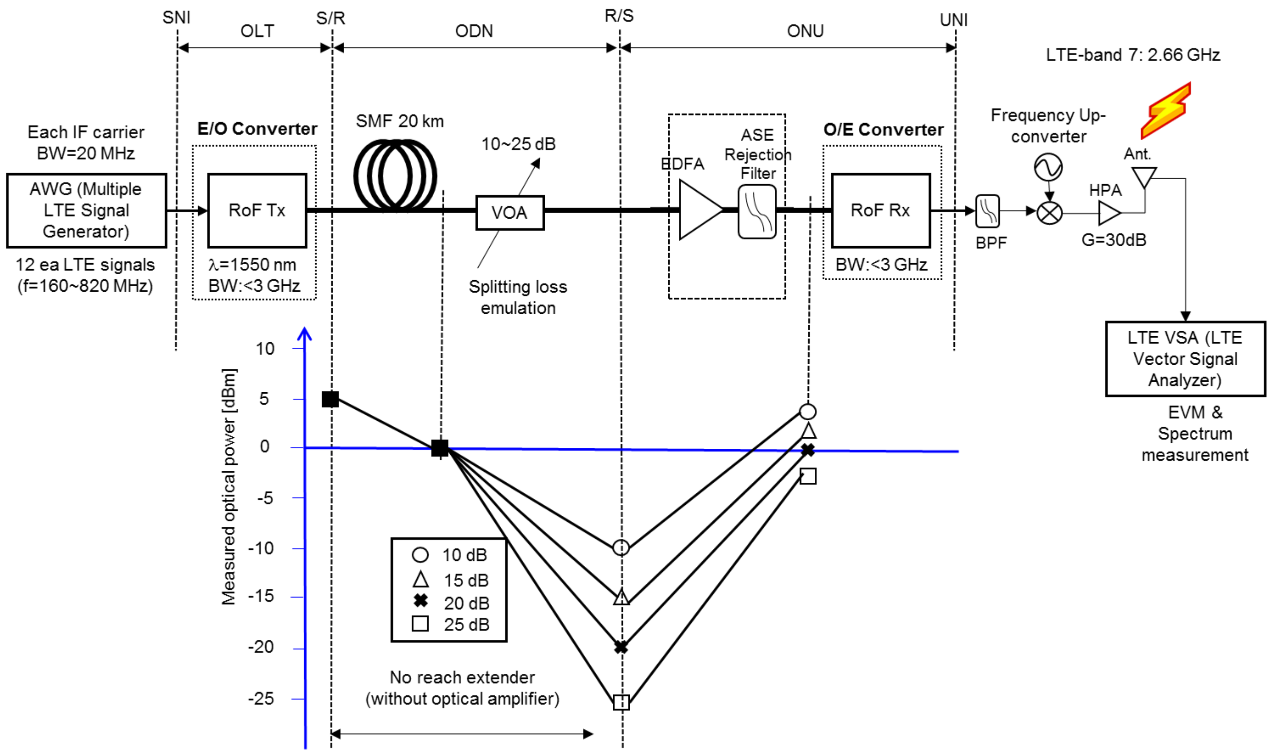


Figure 9-8 – Typical experimental set-up (upper) and optical power level diagram (lower)

In Figure 9-9, measured RF spectra before E/O conversion and after O/E conversion are shown. 12 IF carriers with the 20 MHz bandwidth LTE signal format were successfully obtained with the help of an AWG. Before the 20 km SMF transmission, all generated IF carriers with the LTE signal format had the same power level. However, after the 20 km SMF transmission, there were slight frequency-dependent power variations, which were caused by the uneven frequency response of the RoF Tx.

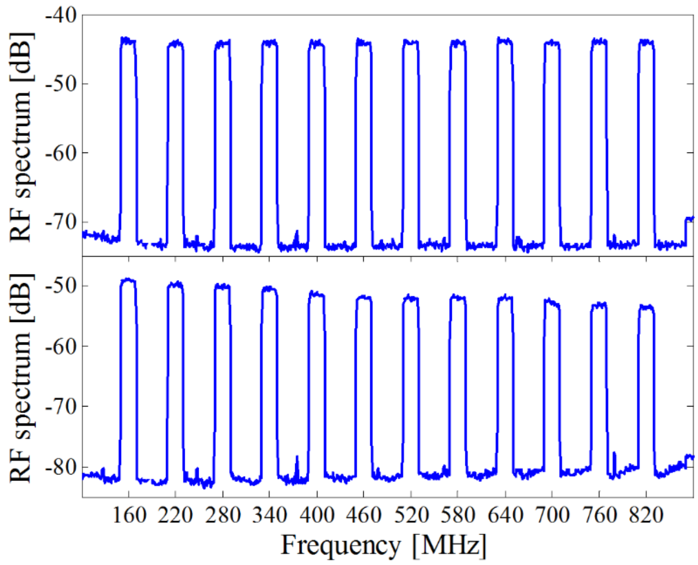


Figure 9-9 – Measured RF spectra before E/O conversion (upper) and after O/E conversion (lower)

The measured EVM as a function of an additional optical link loss after the 20 km SMF transmission is shown in Figure 9-10. We measured the EVMs at the lowest IF carrier frequency of 270 MHz (EVM at RoF-Rx) and the RF carrier (2 660 MHz) frequency (EVM at antenna) to investigate the transmission performance degradations caused by the frequency-up-conversion process. From the measured EVMs and the requirements at the BS (see [b-3GPP TS 36.104]), it can be seen that the optical loss budget can thus be as high as 31 dB, meeting the N1 and N2 loss budget requirements for passive optical networks. From the above, it can be concluded that IF-band SCM RoF transmission scheme is also feasible.

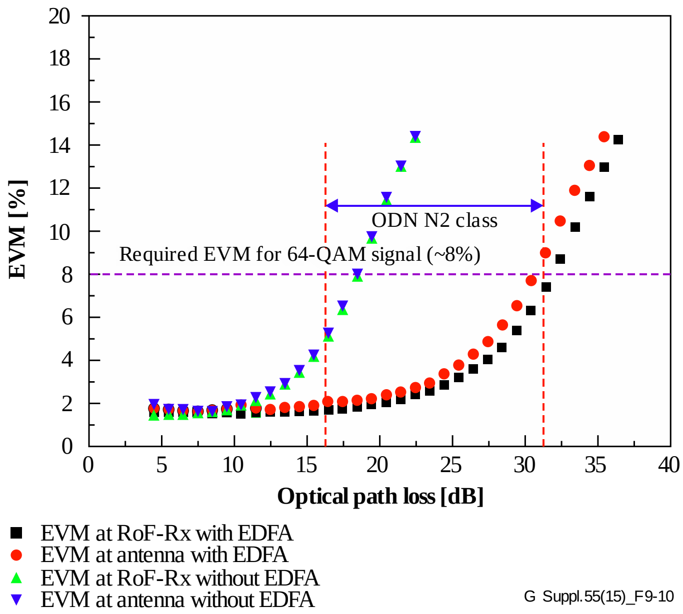


Figure 9-10 – Measured EVM as a function of an additional optical link loss after 20 km-long SMF transmission

9.2.3.2 IF-band SCM RoF system with a digital aggregation technique

Figure 9-11 shows an aggregated analogue RoF system with the 36 LTE channels, consisting of six bandwidth groups each having six channels for 2 × 2 MIMO and three sectors, aggregated in a single optical wavelength. This is a kind of IF-band SCM RoF system with a digital aggregation technique.

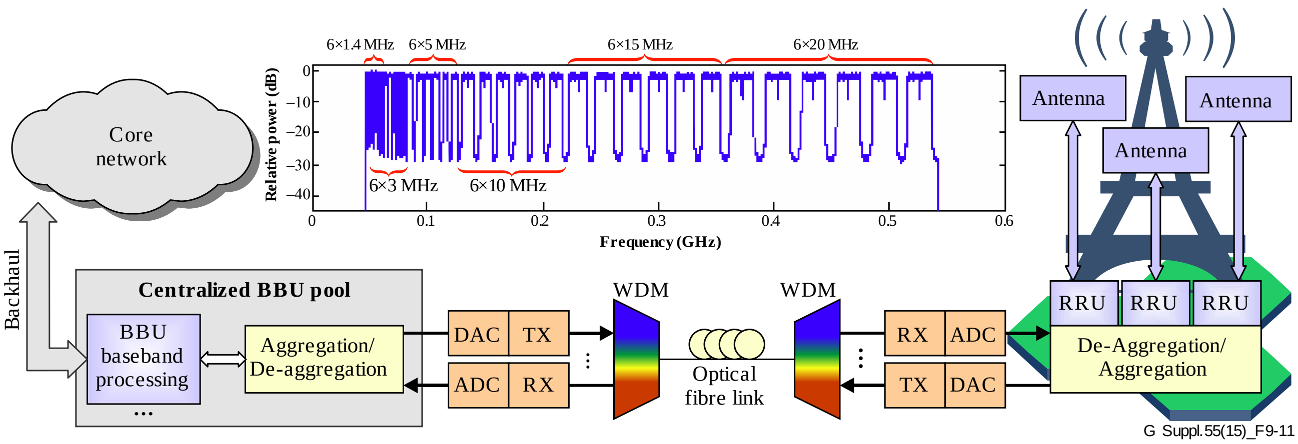


Figure 9-11 – Aggregated analogue RoF system with the 36 LTE channels, aggregated in a single optical wavelength

Figure 9-12-a shows the typical experimental set-up and Figure 9-12-b shows the 64-QAM signal constellations recovered after 20 km transmission over a standard single-mode fibre (SSMF) with −10 dBm received optical power for the six bandwidth groups, corresponding to the LTE bandwidths of 1.4, 3, 5, 10, 15 and 20 MHz. Evidently, the recovered signal constellations show high SNR.

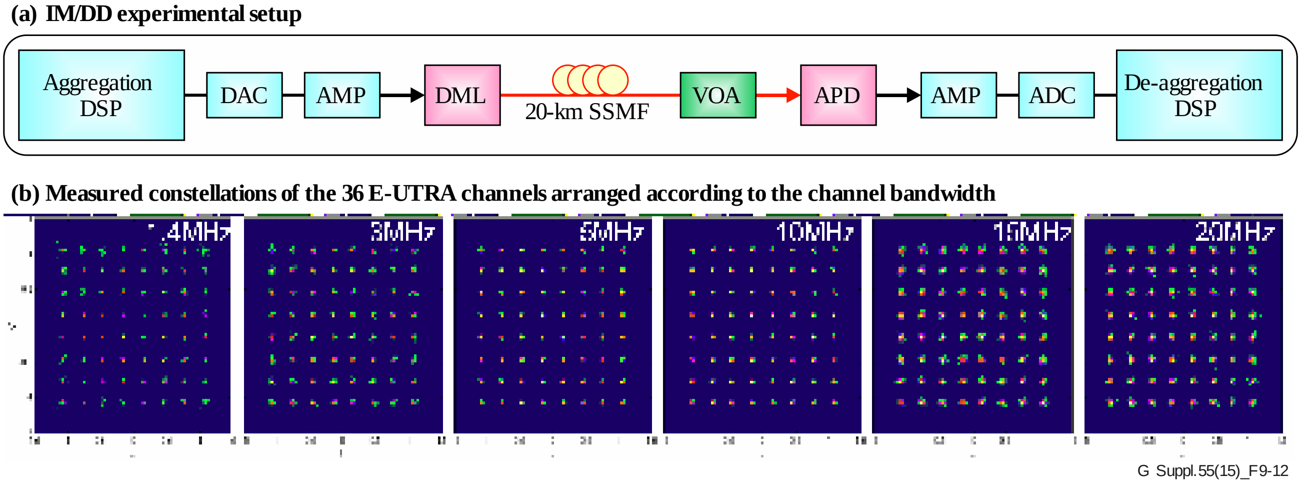


Figure 9-12 – Typical experimental set-up and measurement results. IM/DD: intensity modulation with direct detection

Figure 9-13 shows the measured EVMs of all the 36 LTE channels after transmission through the aggregated analogue RoF system. To achieve an EVM of less than 8% EVM, as required for 64-QAM (see [b-3GPP TS 36.104]), the received optical power needs to be larger than −24 dBm, which corresponds to a link loss budget of 26 dB assuming a typical optical signal power of 2 dBm. This link loss budget can be readily achieved in WDM PONs, indicating the validity of the proposed bandwidth-efficient MFH approach based on aggregated analogue RoF. With the assumption of 8 dBm signal power at the transmitter, the link loss budget can be increased to 32 dB. We expect that with additional performance improvement techniques, the link loss budget may be further increased.

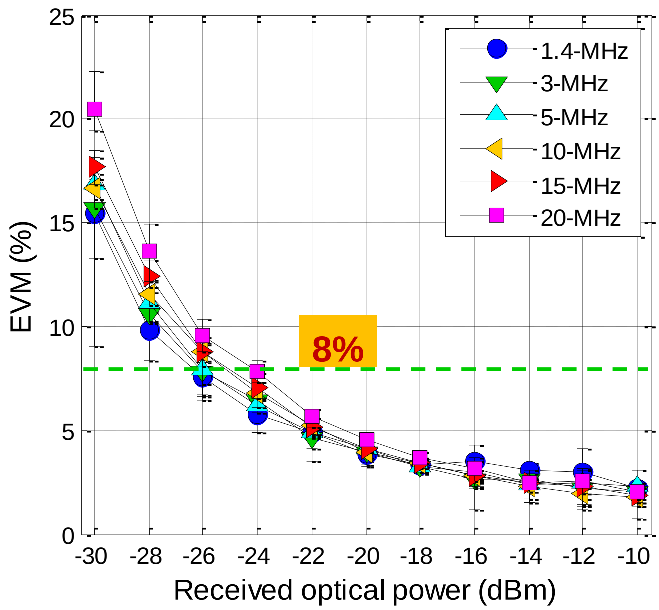


Figure 9-13 – Measured EVMs of all the 36 LTE channels after transmission through the aggregated analogue RoF-based MFH system

Intensity-modulation with direct-detection (IM/DD) is a cost-effective scheme for optical transmission. In conventional IM/DD-based RoF systems, the receiver sensitivity or optical path loss budget is severely limited by the large direct current (DC) offset used. It is desirable to improve the optical path loss budgets of RoF systems, particularly multi-channel RoF systems that contain multiple signals in a single wavelength via FDM or SCM, so that efficient MFH schemes can be readily supported by conventional passive optical networks. We propose the combined use of quadratic soft clipping (QSC) and odd-channel-only mapping in multi-channel RoF to effectively reduce the DC offset without causing signal distortion, therefore increasing optical path loss budget.

The QSC function is expressed as:

$$Y_{QSC} = (X + X_M)^2/(2X_M)$$

where Y_{QSC} is the time-domain output signal, $X + X_M$ is the time-domain input signal that is bounded between 0 and $2X_M$ or $X \in [-X_M, X_M]$, and X_M is the DC offset. This QSC function does not have a discontinuity in its slope, and by its very construction it only has the second order distortion term. A graph of some of these functions and the relative benefit of using the asymmetric clipping (AC) and soft-clipping (SC) schemes is shown in Figure 9-14, as a function of the DC offset (X_M). The AC scheme has constant gain and average level, as it does not have an offset. Both the DC and SC schemes have a nearly constant gain. The DC scheme's average level increases linearly with offset, while the SC scheme increases at a slower rate. As a result, the SC scheme has a benefit of around 2.5 dB at a practical offset of 3, and converges to a benefit of 3 dB in the limit of large offset. The AC scheme has a much larger and ever growing benefit, but at the practical offsets (or practical bias conditions) its benefit is about 5 dB.

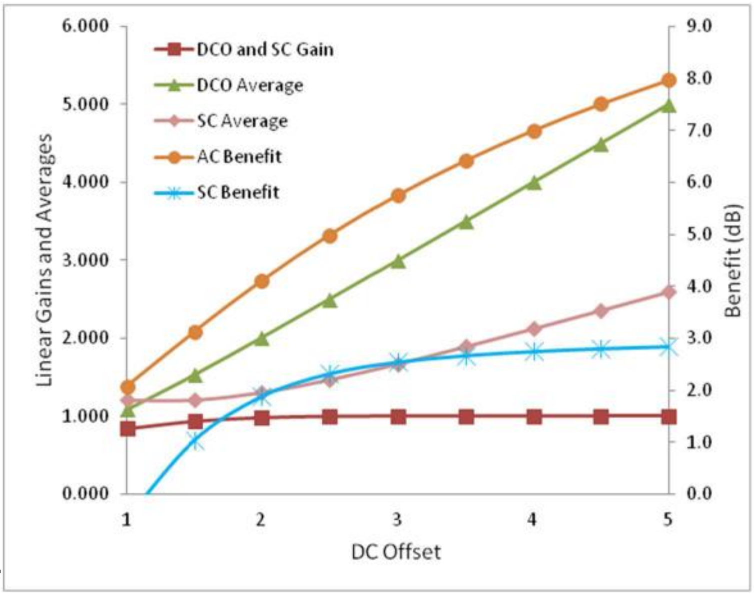


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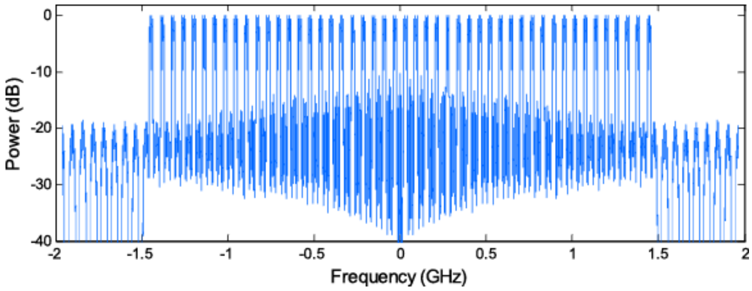
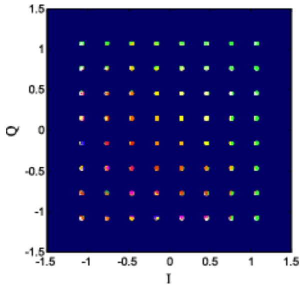
Figure 9-14 – Linear gains, power averages, and power-efficiency gains (benefits) of various OFDM formats. DCO: down-converter-offset OFDM; AC: asymmetrically clipped OFDM; SC: soft-clipped OFDM proposed here

Returning to the channel plan for multi-channel RoF, only the odd channels will be used, and centred at frequencies $(2n - 1)f_0$ where n is a positive integer; however, their bandwidth will be constrained to only 2/3 of the full amount, which is typical for wireless channels. That is, the channel at f_0 will have a band that runs from $(2/3)f_0$ to $(4/3)f_0$. The channel at $3f_0$ has a band that runs from $(8/3)f_0$ to $(10/3)f_0$. Such an arrangement will yield gaps between adjacent channels of $(4/3)f_0$. This will be the spectral width of the second order distortion term. Indeed, all the second order distortions fall exactly in these gaps, leaving the spectrum around the channels to be clear of impairment.

We first perform numerical simulations to verify the analytical results presented above. Figure 9-15-a shows the simulated spectrum of the same aggregated LTE signals under the proposed QSC condition. Evidently, inter-signal mixing only causes distortions in the spectral gaps between signals, avoiding performance degradation to actual signals. Figure 9-15-b shows the recovered constellation of the 24th LTE signal. A low EVM of 0.5% is obtained, confirming that the proposed soft clipping (SC) is viable for multi-channel RoF.



a)



b)

Figure 9-15 – a) Simulated optical spectrum of 24, 20 MHz LTE signals (and their images due to Hermitian symmetry) that are aggregated using the odd-channel-only mapping under the proposed QSC condition; and b) Recovered constellation of the highest-frequency (24th) signal

We then perform experiments to further verify the analytical results. Figure 9-16 shows the typical experimental set-up. At the transmitter, we use offline DSP to generate 24, 20 MHz LTE OFDM signals. The modulation format is OFDM with 64-QAM subcarrier modulation, which is the highest level modulation specified in LTE. The time-domain signal waveform is stored in an AWG and outputted by a 5 GSa/s DAC. This analogue signal is then amplified before driving a 1 550 nm directly modulated laser (DML) with a modulation bandwidth of about 2 GHz. Odd-channel-only mapping is used. The centre frequencies of the signals after aggregation are $(2n - 1) \times 30.72$ MHz, where $n = 1, 2, 3, \dots, 24$, as shown in the measured spectrum in Figure 9-17-a. We compare two bias conditions, the conventional DCO bias condition and the proposed QSC bias condition. The optical signal is launched into a 20 km SSMF. After fibre transmission, a VOA is used to vary the optical power (P_{RX}) received by an avalanche photodiode (APD). The detected signal is digitized by a 10 GSa/s ADC in a real-time sampling scope. The digitized samples are stored in the scope, and later processed by offline DSP for down-sampling, channel de-aggregation, OFDM demodulation, and evaluation of signal EVM and bit error ratio (BER).

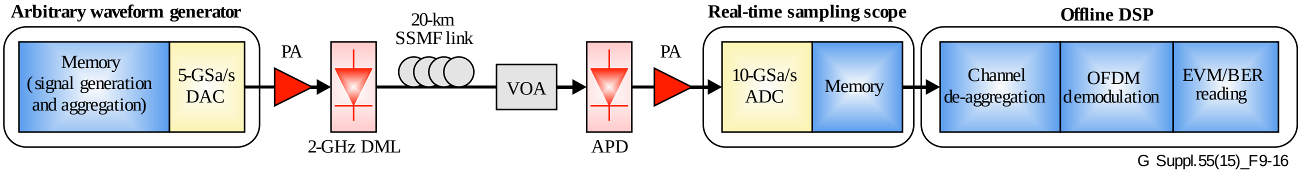
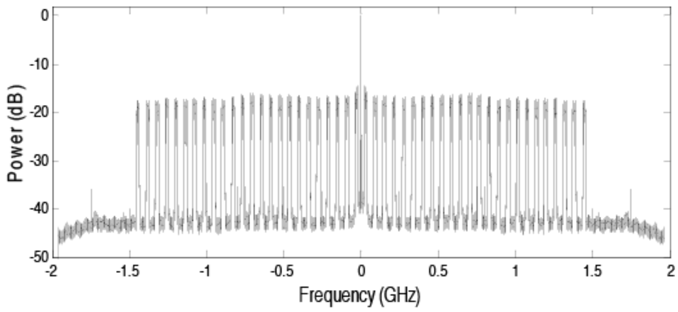


Figure 9-16 – Typical experimental set-up for evaluating the performance of the proposed soft-clipping technique

Figure 9-17 shows the experimentally measured spectrum of the aggregated signals after 20 km SSMF transmission with P_{RX} = –22 dBm (Figure 9-17-a), and the measured EVM as a function of receiver power (Figure 9-17-b), all under the conventional DCO bias condition. The spectral power in Figure 9-17-a is normalized to the power at the centre frequency. For EVM to be less than 5 %, the received power needs to be higher than about –19 dBm. Figure 9-18 shows the experimentally measured spectrum of the aggregated signals after 20 km SSMF transmission with P_{RX} = –22 dBm (Figure 9-17-a), and the measured EVM as a function of receiver power (Figure 9-17-b), all under the proposed QSC bias condition. For EVM to be less than 5%, the received power needs to be higher than about –22 dBm. This means that the QSC method offers a power budget improvement of about 3 dB as compared to the conventional DCO method. It is in good agreement with the analytical results presented above. At the required EVM threshold for 64-QAM of 8% (see [b-3GPP TS 36.104]), the received optical power only needs to be larger than −26 dBm. Given the fact that optical signal power generated by the DML-based transmitter can be as high as 8 dBm, the optical path loss budget can thus be as high as 34 dB, meeting the N1, N2, and E1 loss budget requirements for PONs. We expect that with additional performance improvement techniques, such as optical pre-amplification, the link loss budget can be further increased.



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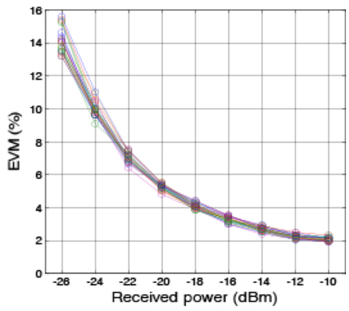
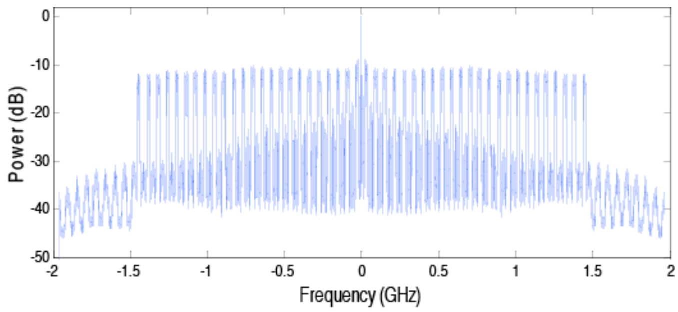
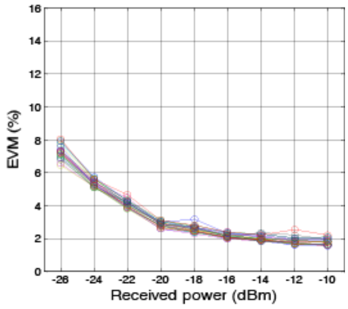


b)

Figure 9-17 – a) Experimentally measured spectrum of the aggregated signals after 20 km SSMF transmission with a received power of –22 dBm and b) Measured EVM vs. received power, all under the DCO condition



a)



b)

Figure 9-18 – a) Experimentally measured spectrum of the aggregated signals after 20 km SSMF transmission with a received power of –22 dBm; and b) Measured EVM vs. receiver power, all under the proposed QSC condition

In LTE-A, MIMO and CA are often used. Assuming a representative macro-cell configuration with 8 × 8 MIMO, CA having two 20 MHz mobile signals, and three directional sectors, there are totally 48, 20 MHz LTE signals. We conducted experiments to investigate the front-haul performance when these 48, 20 MHz LTE signals are aggregated onto one single wavelength channel. To achieve high cost-effectiveness, we used IM/DD with a DML. At the transmitter, we used offline DSP to generate 48, 20 MHz LTE OFDM signals. The modulation format was OFDM with 64-QAM subcarrier modulation, which is the highest level modulation specified in LTE-A. The time-domain signal waveform was stored in an AWG and outputted by a 5 GSa/s DAC. This analogue signal was then amplified before driving a 1 550 nm DML with a modulation bandwidth of no more than 2 GHz. The output power from the DML was about 8 dBm.

To achieve high-capacity MFH with low-bandwidth optics, we used seamless channel mapping. The centre frequencies of the signals after aggregation were $n \times 30.72$ MHz, where $n = 1, 2, 3, ..., 48$. To mitigate the bandwidth-limitation induced power roll-off at high frequencies, a simple digital frequency-domain pre-emphasis was applied at the channel aggregation stage such that $\Delta P(n) = [(n - 1)/47] \times 4$ dB, where $\Delta P(n)$ is the power change of the nth signal in decibels. For high-capacity MFH applications, the distance between the antennas and the baseband processing units (BBUs) can be just a few kilometres. We used a 5 km SSMF to emulate the front-haul link. After fibre transmission, a VOA was used to vary the optical power (P_{RX}) received by an APD. The detected signal was digitized by a 10 GSa/s ADC in a real-time sampling scope. The digitized samples were stored in the scope, and later processed by offline DSP for down-sampling, channel de-aggregation, OFDM demodulation, and evaluation of signal EVM and BER.

Figure 9-19 shows the spectrum of the 48, 20 MHz LTE signals measured after the signals are transmitted over the 5 km SSMF at a received optical power of −6 dBm. Clearly, with the use of the digital frequency-domain pre-emphasis, the power spectrum of the received LTE signals is reasonably uniform.

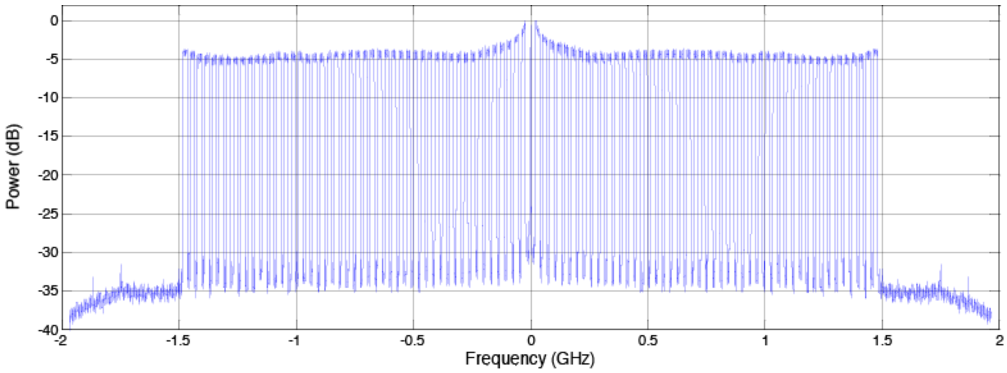


Figure 9-19 – Experimentally measured spectrum of 48, 20 MHz LTE signals (and their images due to Hermitian symmetry) that are aggregated using seamless channel mapping and transmitted over 5 km SSMF. The centre wavelength of the channel is around 1 550 nm. The received signal power is set to −6 dBm

Figure 9-20 shows the EVMs of all the 48 LTE signals measured under three conditions: a) optical BtB (L = 0 km) at P_{RX} = –6 dBm; b) after 5 km SSMF transmission (L = 5 km) at P_{RX} = −6 dBm; and c) after 5 km SSMF transmission (L = 5 km) at P_{RX} = −14 dBm. The first observation is that all the 48 signals have similar EVM values, indicating reasonable performance uniformity in the frequency domain for the multi-channel RoF system. The second observation is that the signal performances obtained after 5 km SSMF transmission are very similar to those obtained at L = 0 km. This indicates negligible fibre dispersion-induced penalty in this scenario. Finally, the signal EVMs after 5 km SSMF transmission with P_{RX} = −14 dBm are about 4%, well below the typical 8% EVM threshold specified for 64-QAM (see [b-3GPP TS 36.104]).

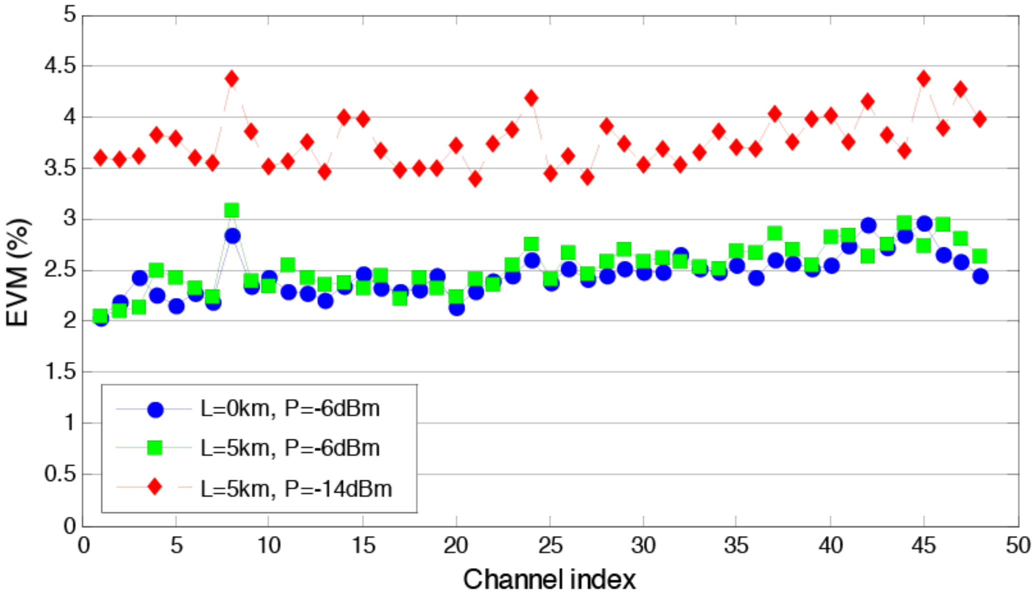
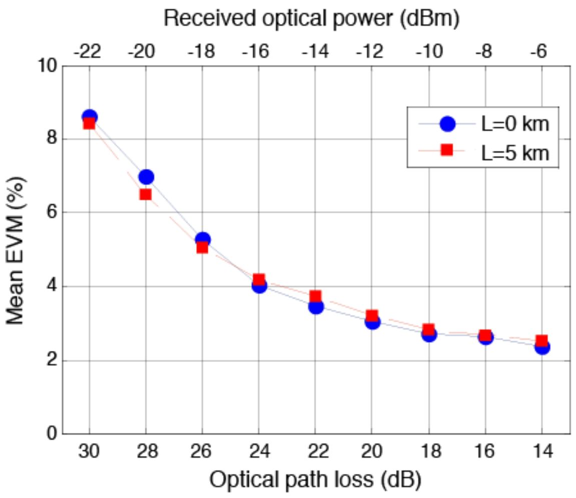
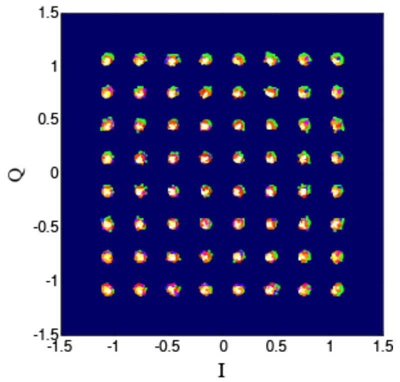


Figure 9-20 – The EVMs of all the 48 LTE signals measured under three conditions: a) optical back-to-back (L = 0 km) at P_{RX} = −6 dBm; b) after 5 km SSMF transmission (L = 5 km) at P_{RX} = −6 dBm; and c) after 5 km SSMF transmission (L = 5 km) at P_{RX} = −14 dBm

Figure 9-21-a shows the mean EVM of all the signals as a function of the optical path loss and the received optical power. Figure 9-21-b shows a typical recovered 64-QAM constellation of one of the 48 LTE signals after 5 km SSMF transmission with P_{RX} = −6 dBm. Evidently, there is no noticeable dispersion-induced penalty in this 5 km MFH system. At the required EVM threshold for 64-QAM of 8% (see [b-3GPP TS 36.104]), the received optical power needs to be larger than −21 dBm. Given the fact that optical signal power generated by the DML-based transmitter is 8 dBm, the optical path loss budget is thus 29 dB, meeting the N1 and N2 loss budget requirements for PONs. We expect that with additional performance improvement techniques, such as optical pre-amplification, the link loss budget can be further increased.



a)



b)

Figure 9-21 – a) The mean EVM of the aggregated LTE signals as a function of optical path loss and received optical power for *L* = 0 km and *L* = 5 km; and b) a typical recovered 64-QAM constellation of one of the 48 LTE signals after 5 km SSMF transmission with P_{RX} = −6 dBm

9.2.4 Multiple uplink signals transmission

Figure 9-22 shows the typical experimental set-up to investigate the transmission performances of typical LTE uplink signals in a normal MIMO antenna configuration. It consists of an LTE VSG, electrical splitter, MIMO antennas, LNAs, frequency-down-converters, BPFs, RF combiner, a VEA, a RoF transmitter, SMF, a VOA, a RoF receiver, and an LTE VSA. EDFA and OBPF are employed in front of RoF receiver as a pre-amplifier to improve the total link power budget. The LTE VSG generated two adjacent uplink LTE channels with the radio carrier frequency of 2.540 and 2.560 GHz to support multi-frequency assignment (FA). The 2 LTE uplink signals generated were employed as incoming signals for the MIMO antennas (Ant-1 and Ant-2). The bandwidth of each uplink signal was 20 MHz, in which the LTE band #7 was assumed (see [b-3GPP TS 36.101]). To emulate a free-space propagation loss, the generated uplink LTE signals were manually attenuated by 50 to 90 dB with the VEA. To configure a desired IF-band RoF transmission scheme, the LTE uplink signals from each antenna were frequency-down converted and bandpass filtered to be suitable for a predefined IF frequencies plan. These uplink signals centred at IF frequencies were combined with RF combiner and then input into the RoF transmitter after being amplified or attenuated to obtain proper OMI for obtaining better transmission performances. As shown in the inset of Figure 9-22, the number of uplink signals was four due to supporting two MIMO antennas and two FAs at the same time. In the RoF transmitter, the uplink LTE signals were optically converted with a directly modulated distributed feedback laser diode (DFB-LD). The generated IF band RoF signal with a centre wavelength of 1548.5 nm and a power of +2.5 dBm was transmitted over SMFs (up to 40 km) and the VOA to an OLT. The VOA emulates an additional optical path loss. In the OLT, the received RoF signal was amplified with the EDFA followed by the OBPF. The driving current of pump LD was fixed to 70 mA to operate the EDFA under the automatic current control (ACC) mode. The OBPF has a 3 dB bandwidth of 0.5 nm and was utilized to eliminate undesired ASE noise from the EDFA. The optically amplified RoF signal was detected by the RoF receiver to regenerate the LTE signals, where the RoF receiver consisted of a PD and a PA with a variable gain of up to 18 dB. Finally, the EVMs and the electrical spectra of regenerated LTE signals were measured by the LTE VSA.

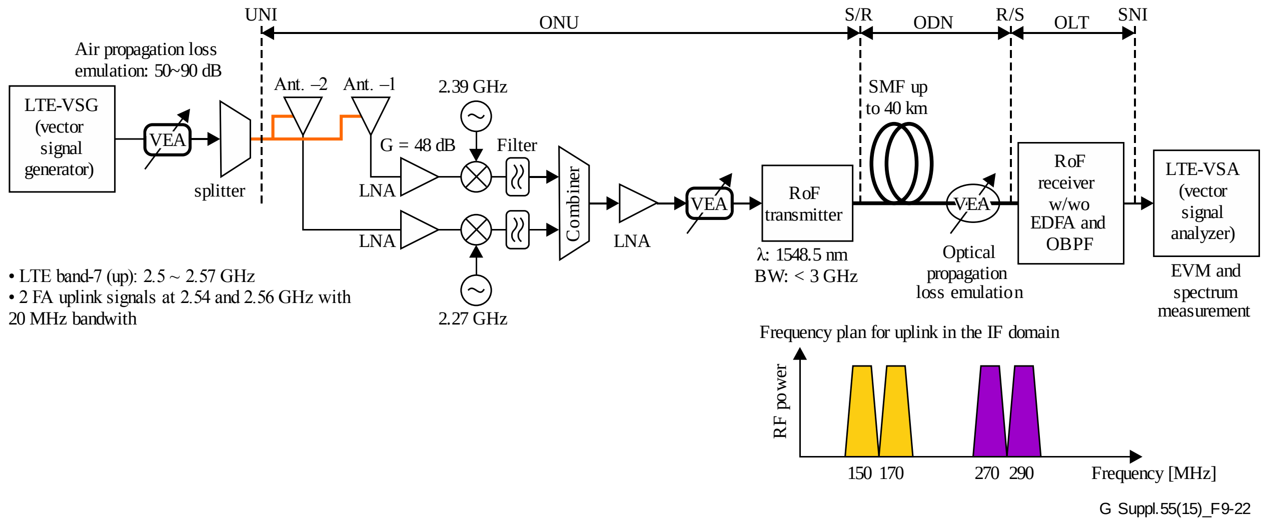


Figure 9-22 – Typical experimental set-up

Figure 9-23 shows the measured EVM as a function of optical path loss to evaluate the available dynamic range of uplink transmission system. EVMs of the uplink signal centered at 270 MHz after receiving LTE signals at OLT were measured. The measurement was done when the input RF power to the RoF transmitter was set to −65 dBm. For an optical path loss ranging from 5 to 15 dB, the observed EVMs appear to be below 3% for a 20 MHz-bandwidth of 64-QAM signal (which provides the maximum bit rate) without using EDFA in front of the RoF receiver. Similarly, for an optical path loss varying from 5 to 30 dB, the observed EVMs appear to be below 4% when using EDFA in front of the RoF receiver. They were well below the required EVM thresholds for 64-QAM of 8%, 16-QAM of 12.5% and QPSK of 17.5% (see [b-3GPP TS 36.104]). From this measurement, the available dynamic range to satisfy the required EVM of 8% was approximately 20 and 36 dB without using EDFA and with EDFA, respectively. It can be seen that the optical path loss budget can thus be as high as 36 dB, meeting the N1, N2, E1 and E2 loss budget requirements for passive optical networks.

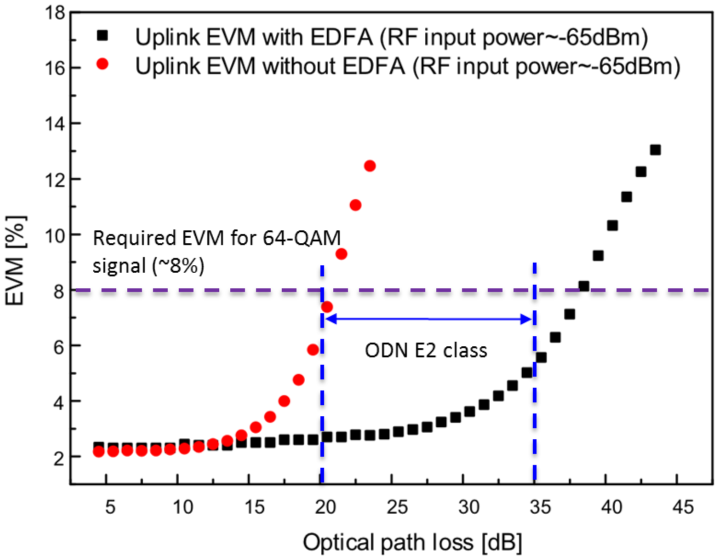


Figure 9-23 – Measured EVM as a function of optical path loss to evaluate the available dynamic range of optical path loss

Figure 9-24 shows the measured EVM as a function of input RF power to evaluate the minimum input RF power. In the cases of E-BTB and E-BTB with LNA, in which the LNA inside the RoF transmitter was directly connected to the LTE VSA, it is estimated that the EVM thresholds of 8 and 12.5% were obtained when the input RF powers were about −76 and −82 dBm, respectively. Also in the case of optical BTB, in which the RoF transmitter was directly connected to the RoF receiver without any optical amplifier (the received optical power was fixed at −10 dBm for the RoF receiver), similar results were observed. As increasing the input RF power level from −62 to −57 dBm, a slight EVM degradation caused by LD clipping was observed. Thus, no significant degradation of the signal quality due to the introduction of the RoF transmitter and receiver was observed in the input RF power range from −85 to −62 dBm. In the case of 36 dB optical path loss, it is estimated that the EVMs of less than 8% for 20 MHz-bandwidth 64-QAM mapped signals were obtained at the input RF powers of more than −67 dBm. Similarly, it is also estimated that the EVMs of less than 12.5% for 20 MHz-bandwidth 16-QAM mapped signals were obtained at the input RF powers of more than −72 dBm. From these results, it is necessary to manage the input RF power level in order to achieve sufficient uplink transmission performance and to reduce overall system degradations.

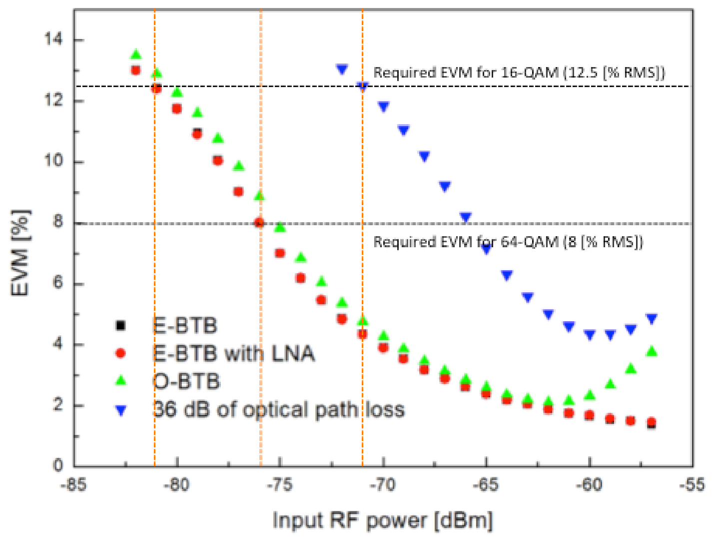


Figure 9-24 – Measured EVM as a function of input RF power to evaluate the minimum input RF power

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