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Zaid Al-Husseini

Channel characterization in wireless mm-wave communication and radio over fibre systems

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Channel characterization in wireless mm-wave communication and radio over fibre systems

Zaid AL-HUSSEINI

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Abstract

In the past decades, there has been a paramount evolution in multimedia services as well as in internet usages. At the same time, the motivation of solution providers to integrate different access network devices in one mobile platform leads to exploring a new technology which converges between wire and wireless services by satisfying the increasing demands of bandwidths required by such applications. Radio over Fiber (RoF) is expected to be one of the most promising broadband communication technologies for the current and next decades. The hybrid use of fiber-optic as wired medium and millimeter wave as wireless medium allows to integrate the superabundant bandwidth provisioned by fiber and mobility feature provided by wireless link in one platform. There are some impacts due to the inherent nature of the fiber cable itself. Chromatic dispersion (CD) is considered as one of the most important effects, which affects the distance that can be reached as well as the quality of the received signal. The scope of the thesis focuses on two main pillars: RoF system setup and offline processing applied to the received data signal to recover the carrier in terms of phase shift and frequency offset. Regarding for the RoF setup, a set of simulations and measurements have been performed to optimize the setup, characterize the generated 60 GHz carrier, applying advanced modulation format like QPSK , and investigating optical modulation options (optical single sideband (OSSB) / optical double sideband (ODSB)). Phase and frequency estimator algorithms that can be realized in DSP or FPGA have been comprehensively studied analytically, in simulations and experiments. Finally, the offline processing module is represented as a cascade of a frequency estimator, which works as coarse compensator followed by an adapted Viterbi & Viterbi algorithm as a fine compensator to remove the residuals.

Kurzfassung

In den vergangenen Jahrzehnten gab es eine vorrangige Entwicklung sowohl in Multimediadiensten als auch in der Nutzung des Internets. Gleichzeitig führt die Motivation der technischen Lösungsanbieter, die unterschiedlichen Zugangsnetzgeräte in eine mobile Plattform zu integrieren, zur Erforschung einer neuen Technologie, die Konvergenz zwischen leitungsgebundenen und drahtlosen Diensten herstellt und damit die steigenden Bandbreitenanforderung oben genannter Anwendungen erfüllt. Radio over Fiber (RoF) ist erwartungsgemäß einer der vielversprechendsten Breitbandkommunikationstechnologien der aktuellen und nächsten Dekaden. Die hybride Nutzung von Faseroptik als leitungsgebundenes Medium und Millimeterwellen als Funkmedium erlaubt, die in Faser überreichlich vorhandene Bandbreite und die Mobilitätseigenschaften von Drahtlosverbindungen in einer Plattform zu integrieren. Es gibt einige Einflüsse aufgrund der Faser als Medium zu betrachten. Chromatische Dispersion (CD) wird als einer der wichtigsten Effekte betrachtet, der die erreichbare Übertragungsreichweite und die Qualität des empfangenen signals beeinflusst. Der Hauptinhalt dieser Arbeit ruht auf zwei Pfeilern: Aufbau des RoF-Systems und Offline-Datenverarbeitung, die auf das empfangene Signal angewandt wird, um den Träger in Bezug auf Phasenverschiebung und Frequenzoffset zurückzugewinnen. Für den Aufbau des RoF-Systems wurden eine Anzahl von Simulationen und Messungen durchgeführt, um das Setup zu optimieren, den generierten 60 GHz Träger zu charakterisieren, moderne Modulationsformate wie QPSK einzusetzen sowie die Möglichkeiten der optischen Modulation (optische Einseitenbandmodulation (OSSB) oder optische Doppelseitenbandmodulation (ODSB)) zu untersuchen. Phasen- und Frequenzschätzalgorithmen, die in DSP oder FPGA realisiert werden können, wurden umfassend betrachtet – analytisch, in Simulationen und mit Experimenten. Schließlich besteht das Offline-Processing-Modul aus einer Kaskade aus Frequenz-Schätzer, der zur Grobkompensation dient und einem folgenden angepassten Viterbi & Viterbi-Algorithmus, der die Feinkompensation vornimmt und den Restoffset entfernt.

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Abbreviations

3GPP	**3rd** **G**eneration **P**artnership **P**roject
A/D	**A**nalog to **D**igital
AML	**A**ctive **M**ode **L**ocking
AMPS	**A**dvance **M**obile **P**hone Service
ASE	**A**mplified **S**pontaneous **E**mission
ASK	**A**mplitude **S**hift **K**eying
AWG	**A**rrayed **W**aveguide **G**rating
AWGN	**A**dditive **W**hite **G**aussian **N**oise
BER	**B**it **E**rror **R**ate
BS	**B**ase **S**tation
CAGR	**C**ompound **A**nnual **G**rowth **R**ate
CAPEX	**CA**pital **EX**penditure
CD	**C**hromatic **D**ispersion
CDMA	**C**ode **D**ivision **M**ultiple **A**ccess
CFSK	**C**ontentious **F**requency **S**hift **K**eying
CNR	**C**arrier to **N**oise **R**atio
CRLB	**C**ramer **R**ao **L**ower **B**ound
CU	**C**enter **U**nit
CW	**C**ontentious **W**ave
D/A	**D**igital to **A**nalog
DA	**D**ata **A**ided
DBR	**D**istributed **B**ragg **R**eflector
DEMZM	**D**ual **E**lectrode **Mach** **Z**ehnder **M**odulator
DFB	**D**istributed **F**eed**B**ack
DFT	**D**iscrete **F**ourier **T**ransform
DGD	**D**ifferential **G**roup **D**elay
DFE	**D**igital **F**eedback **E**qualizer
DMA	**D**elay **M**ultiply and **A**verage
DPMZM	**D**ual **P**arallel **M**ach **Z**ehnder **M**odulator
DSP	**D**igital **S**ignal **P**rocess
EAM	**E**lectro **A**bsorption **M**odulator
ECL	**E**xternal **C**avity **L**aser
EDFA	**E**rbium **D**oped **F**iber **A**mplifier
EDGE	**E**nhanced **D**ate rates for **GSM** **E**volution
E/O	**E**lectrical to **O**ptical
EVM	**E**rror **V**ector **M**easurements
FBG	**F**iber **B**rag **G**rating
FCC	**F**deral **C**ommunications **C**ommission

FDMA	**F**requency **D**ivision **M**ultiple **A**ccess
FFT	**F**ast **F**ourier **T**ransform
FIR	**F**inite **I**mpulse **R**esponse
FLM	**F**iber **L**oop **M**irror
FP	**F**abry **P**erot
FSR	**F**ree **S**pectral **R**ange
FWM	**F**our **W**ave **M**ixing
GPIB	**G**eneral **P**urpose **I**nterface **B**us
GPRS	**G**eneral **P**acket **R**adio **S**ervice
GSM	**G**lobal **S**ystem for **M**obile communication
GSL	**G**ain **S**witching **L**aser
GVD	**G**roup **V**elocity **D**ispersion
HSPA	**H**igh **S**peed **P**acket Access
ICI	**I**nter **C**hannel **I**nterference
IMT2000	**I**nternational **M**obile **T**elecommunications 2000
IP	**I**nternet **P**rotocol
ISI	**I**nter **S**ymbol **I**nterference
LD	**L**aser **D**iode
LED	**L**ight **E**mitting **D**iode
LO	**L**ocal **O**scillator
LOS	**L**ine **O**f **s**ight
LR	**L**uise **R**egiannini
LSE	**L**east **S**quare **E**stimation
LTE	**L**ong **T**erm **E**volution
LUT	**L**ook **U**p **T**able
MCRLB	**M**odified **CRLB**
MIMO	**M**ulti **I**nput **M**ulti **O**utput
ML	**M**aximum **L**ikelihood
MLL	**M**ulti-mode **L**ocking **L**aser
MLSE	**M**aximum **L**ikelihood **S**equence **E**stimation
MMF	**Multi** **M**ode **L**aser
MS	**M**obile **S**tation
MSC	**M**obile **S**witching **C**enter
MSE	**M**ean **S**quare **E**rror
MTC	**M**achine **T**ype **C**ommunications
MU	**M**obile **U**nit
MVUE	**M**inimum **V**ariance **U**nbiased **E**stimator
MZI	**M**ach **Z**ehnder **I**nterferometer
MZM	**M**ach **Z**ehnder **M**odulator
NDA	**N**on**D**ata **A**ided
NLSE	**N**on**L**inear **S**chrödinger **E**quation
NMT	**N**ordic **M**obile **T**elephone
NRZ	**N**on **R**eturn to **Z**ero
OCM	**O**ptical **C**lock **M**ultiplier
ODSB	**O**ptical **D**ouble **S**ide **B**and
O/E	**O**ptical to **E**lectrical
OFDM	**O**rthogonal **F**requency **D**ivision
OFL	**O**ptical **F**requency **L**ocking
OIL	**O**ptical **I**njection **Locking**

OOK	**O**N **O**FF **K**eying
OPEX	**OP**erational **EX**penditure
OPL	**O**ptical **P**hase **L**ocking
OPLL	**O**ptical **P**hase **L**ock **L**oop
OSA	**O**ptical **S**pectrum **A**nalyzer
OSSB	**O**ptical **S**ingle **S**ide **B**and
PDF	**P**robability **D**ensity **F**unction
PE	**P**hase **E**stimation
PLL	**P**hase **L**ock **L**oop
PMD	**P**olarization **M**ode **D**ispersion
PML	**P**assive **M**ode **L**ocking
PRBS	**P**seudo **R**andom **B**it **S**equence
QPSK	**Q**uadrature **P**hase **S**hift **K**eying
RAP	**R**adio **A**ccess **P**oint
RAU	**R**emote **A**ccess **U**nit
RBLS	**R**ao **B**lackwell **L**echman **S**cheffe
RIN	**R**elative **I**ntensity **N**oise
RoF	**R**adio over **F**iber
SCM	**S**ubscriber **M**ultiplexing
SMF	**S**ingle **M**ode **F**iber
SMS	**S**hort **M**essage **S**ervice
SOA	**S**emiconductor **O**ptical **A**mplifier
SPM	**S**elf **P**hase **M**odulation
TDMA	**T**ime **D**ivision **M**ultiple **A**ccess
UMTS	**U**niversal **M**obile **T**elecommunications **S**ystem
WDM	**W**avelength **D**ivision **M**ultiplexing
UWB	**U**ltra **W**ide **B**and
VCSEL	**V**ertical **C**avity **S**urface **E**mitting **L**aser
VCO	**V**oltage **C**ontrol **O**scillator
VLSI	**V**ery **L**arge **S**cale **I**ntegration
VNA	**V**ector **N**etwork **A**nalyzer
V&V	**V**iterbi and **V**iterbi
WLAN	**W**ireless **L**ocal **A**rea **N**etwork
WPAN	**W**ireless **P**ersonal **A**rea **N**etwork
WIMAX	**W**orldwide **I**nteroperability for **M**icrowave **A**ccess
XPM	**C**ross **P**hase **M**odulation

Physical Constants

Speed of Light	$c = 2.997\,924 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Planck's constant	$h = 6.62 \times 10^{-34}\,\mathrm{W\,s^{2}}$
Boltzmann constant	$K_B = 1.3807 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
Electron charge	$q = 1.6022 \times 10^{-19}\mathrm{As}$

Symbols

m_a	Amplitude modulation index
ω	Angular frequency
I_D	Average dark current
I_p	Average photo current
I	Current
D	Chromatic dispersion parameter
V_{DC}	DC bias voltage
i_{dark}	Dark current
S	Dispersion slope
B_e	Effective bandwidth
CS_el	Electrical carrier suppression
ϑ	Estimated parameter
R_k	Estimated autocorrelation
A_{eff}	Effective area of the optical waveguide
Δf	Frequency separation
Δw	Frequency offset
I_ϑ	Fisher Information
n_L	Group refractive index
v_g	Group velocity
V_π	Half wave voltage
$p_i(t)$	Instantaneous optical power signal
γ	Kerr nonlinear coefficient
f	Laser frequency
η_L	Laser quantum efficiency
L	Length
n_L	Linear refractive index
P_L	Linear polarization
R_L	Load resistance
L_c	length of the cavity
A_0	Magnitude of the original harmonic
A_n	Magnitude of the n$^{\text{th}}$ harmonic
ρ_n	Magnitude of the complex symbol
ϵ	Mean square error
P_{NL}	Nonlinear polarization
n_{NL}	Nonlinear refractive index
$w(t)$	Noise contribution
E	Optical field
α	Optical attenuation parameter

CS_opt	Optical carrier suppression
P	power
$S_p(W)$	Power spectral density of the intensity noise
B	Propagation constant
ϕ	Phase
$\Delta\phi$	Phase difference
τ_{ph}	Photon lifetime
v_{ph}	Phase velocity
L_{eff}	Required length to obtain the potential effect of the nonlinearity
R	Responsivity of the photodetector
A	Slowly varying envelope
V_{RF}	RF voltage
n	Refractive index
$R(t)$	Received signal
r	Received symbol
$\Delta\theta$	Static phase shift
τ_{sp}	Spontaneous lifetime
i_{shot}	Shoot noise
T	Temperature
I_{th}	Threshold current
i_{th}	Thermal current
V	Voltage
σ^2	Variance
λ	Wavelength
$\Delta\lambda$	Wavelength spectral width
W_m^F	Weighting coefficient

Dedicated to soul of my beloved father

Chapter 1

Introduction

1.1 Introduction

The number of wireless network users is going to increase significantly due to the paramount evolution in multimedia services as well as in Internet usages. Hence, huge amounts of bandwidth are required. All expectations confirm this trend will keep continuing in the future. The statistics gathered in the year (2014) indicate about half a billion of devices are entered into use. Moreover, the number of devices currently under work overpassed the population of the world [91]. Diverse set of devices such as Machine Type Communication (MTC), wearable devices, smart phones, tablets, laptops, which should be connected at anytime, anywhere, and anyhow changed the legacy lifestyle.

In fact, we are living in what is defined as e-society. Unquestionably, the wireless and mobile traffic load represented by Compound Annual Growth Rate (CAGR) factor is increasing with unprecedented rates as can be seen from Figure 1.1 [91]. Therefore, the motivation of solution providers to integrate the different access network devices in one mobile platform leads to the exploring of a new technology, which converges between wire and wireless services. In order to satisfy the increasing demands of bandwidths required by such applications. It has the capability to cope with the wireless traffic bottleneck of gigabit data rates, which the current wireless technologies can not offer. Extra benefits in terms of cost efficiency, low power consumption, and enhanced spectral efficiency are also obtained.

Radio over Fiber (RoF) is expected to be one of the most promising broadband communication technologies for the current and next decades. The hybrid use of fiber-optics as wired medium and millimeter (mm) wave as wireless medium allows to integrate the superabundant bandwidth provisioned by fiber and mobility feature provided by wireless link in one platform.

There are some impacts due to the inherent nature of the fiber cable itself, as well as, the synchronization establishment of the electrical coherent receiver. Carrier (frequency and phase) recovery plays an important role in electrical coherent receiver systems. Several approaches were applied in order to recover the carrier successfully in different communication systems. Establishing a RoF system working at 60 GHz with IQ data modulation, and realizing carrier recovery techniques suited for RoF systems are the scope of the thesis.

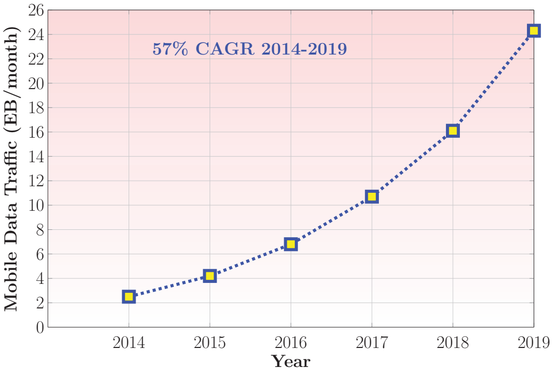

Figure 1.1: Mobile Data Traffic Forecast.

1.2 The road towards RoF systems

Back in the 80s of the last century, a first generation of cellular network, which is called Advance Mobile Phone Service (AMPS) was established by Nordic Mobile Telephone (NMT). The system was in analog form using Frequency Division Multiple Access (FDMA) and circuit switching techniques. The channel capacity was 30 kHz and used for voice communication only [30].
The life cycle for every generation is about one decade approximately. Thereby, the second generation was issued in the 90s. The system was developed into digital format but remained depending on the circuit switching technique. The second generation, which is also defined as Global System for Mobile communication (GSM), offered some data services such as Short Message Service (SMS) and emails, in addition to voice communication services. In this generation, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) were used. The data rate is increased up 22.8 kb/s [93]. Two extra developments were carried out to add two new members to generation family. They are: the 2.5G, which uses packet switching in addition to circuit switching and the 2.75G, which is known as Enhanced Data rates for GSM Evolution (EDGE). The main advantage of EDGE is a superset to General Packet Radio Service (GPRS) and can function on any network with GPRS deployed on it.
The third generation system which is called International Mobile Telecommunication (IMT-2000) including Universal Mobile Telecommunication System (UMTS)(2003) of the 3^{rd} Generation Partnership Project (3GPP), is pioneered by high speed mobile access combined with Internet Protocol (IP)-based services. The utilization of a Wideband CDMA and High speed Packet access (HSPA), allowed the system to highly improve the video and audio streaming. The 3G system uses packet switching with high data rates up to 2 Mb/s for indoor applications over 5 MHz channel bandwidth. The frequency band used with this generation is spread over the span $(1.8, 2.5)$ GHz [38].

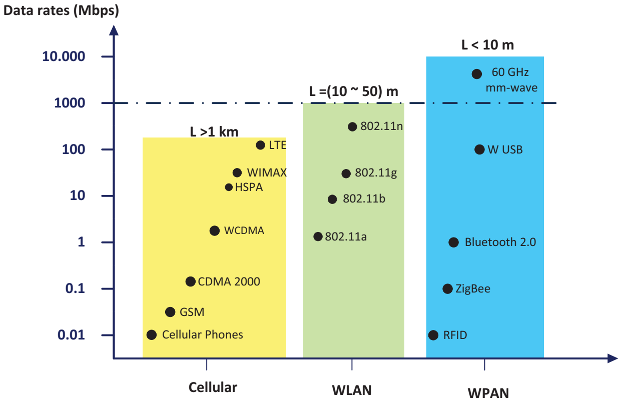

FIGURE 1.2: Wireless technologies development.

It is obvious that with the significant improvement and widely use of smart phones, laptops, and tablets, enforced the communication systems from the 3^{rd} generation to adopt the integration of services for voice communication as well as a wireless data service. Therefore the 3G interface was designed to satisfy the concept of ”to be connected” to Internet wirelessly anywhere, and anytime [38].
ITU is referred IMT-advanced as 4G, while 3GPP is standardized Long Term Evolution (LTE) advanced as 4G also. Skipping the arguments about appellation, the main features that 4G support are: wireless broadband access, video chat, HDTV content, and mobile TV. Since the 4G is designed from the beginning for IP-based packet data, several improvements are carried out to reduce the end-to-end delay [30]. For instance, controlling signal is separated from user data signal to avoid unnecessary processing of data packet in some nodes of the network. An Orthogonal Frequency Division Multiplexing (OFDM) in addition to Multiple Input Multiple Output (MIMO) are considered key technologies to achieve high data rates of 1 Gb/s for low mobility users and 100 Mb/s for high mobility ones [30].
The all projections indicate that traffic load on the cellular network being increased in a dramatic way and the wireless carrier should be prepared to cope with 1000 fold increase in mobile traffic by 2020 [101]. The cooperation between the mobile communication giants and governments to evaluate a new wireless communication technology is more required than any time before. Without doubt, the bottleneck of the wireless bandwidth stands as a key problem for the 5G wireless network.
The development and implementation of 5G will be targeted towards much greater spectrum allocation at untapped mm-wave frequency bands. Besides the benefits, such as high data rate in giga size, several considerations are expected from 5G. These include high number of simultaneously connected devices, higher spectral efficiency, lower battery consumption, lower latency, high reliability, and low infrastructure cost. However, there are some challenges, like a high propagation loss, directivity, sensitivity to blockage which differentiate the mm-wave according to extincting microwave band communication [85]. As the data rate is proportional to

the carrier frequency while the coverage is inversely proportional [101], the concept of small cell access contra to macro cell is introduced. Hereby, for less than 200 m at 60 GHz band and by using directional antenna, multipath effect is not observed. Furthermore, narrow beam receiving antenna and circular polarization assist by suppressing multipath reflection[85]. The tiny wavelengths of mm waves allow to integrate hundreds of antenna elements placed in an array on small size base station. Hereby, an electronically steerable antenna array can be realized and a highly directional beamforming antennas between Base Station (BS) and Mobile Station (MS) can be established.

The principle of simplifying the complicated cell cites by splitting the digital baseband processing from the Remote Access Units (RAU) is proposed by many operators and vendors [68]. Centralizing of digital baseband units in one pool to share hardware, resources, and management will turn in a significant reduction in Capital Expenditures (CAPEX) and Operational Expenditure (OPEX). Likewise, the mass production of a simplified RAU becomes cost effectively and more reliable to cover numerous number of small cells. The backhaul/fronthaul transport phase occupies an important place in the architecture. The transport medium should be able to transfer multi bands, multi services, multi operators simultaneously and transparency [101]. The convergence of fiber optic and mm wave in order to produce a hybrid system called RoF for indoor (Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN)) and outdoor application is preferable. To this end, the system can be considered the underpinning to establish and implement the 5G systems. Figure 1.2 highlights the different wireless technologies and there classification related to the data rate and coverage size.

1.3 60 GHz Frequency allocation and regulations

Factors, such as high capacity, speed, security, size, and cost, push the communication systems engineers as well the manufacturers far to change their mentality and to depart the currently depleted microwave band into a new band of the spectrum. A small amount of bandwidth is dedicated for unlicensed usage in the conventional microwave band while it is tedious and expensive to obtain a license. Moreover the hungry data rate applications, like video streaming and HDTV, require a gigabit speed in order to satisfy consumer expectations and demands. As this can not be provided by the currently $(2.4, 5.8)$ GHz wireless technologies. Nevertheless, several approaches have been tried by IEEE 802.11, and ever new releases of wireless standards are announced with improvements in the data rate, indoor and outdoor coverage. For instance, a 802.11ac which is an extension of the 802.11n with maximum throughput up to 500 Mb/s for single link centered at 5 GHz.

An Ultra wide band (UWB) is also a considerable candidate for wireless short range communication with unlicensed frequency allocation between $(3.1, 10.6)$ GHz and data rate reaches the level of 1 Gb/s [100]. A strict limitation in the power levels (-41.3) dBm/MHz and the small bandwidth (500) MHz are defined by Federal Communication Commission (FCC) in order to reduce the effect of interference on the existing signals [41].

Millimeter wave is a terminology used to define the electromagnetic waves occupy the spectrum span between $(30, 300)$ GHz. The attention is given for the 60 GHz frequency range application for many different reasons: Firstly, many countries allocate a continuous bandwidth of (9) GHz for unlicensed usage. Secondly, the spectrum allocations change according to the used region, as can be shown in Figure 1.3. However, still there about 3.5 GHz continuous spectrum common among the various regions.

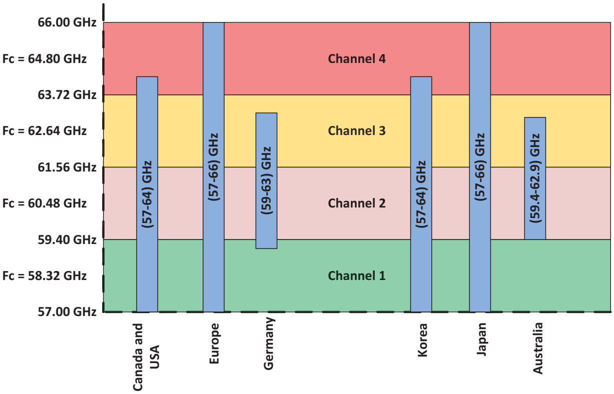

FIGURE 1.3: 60 GHz channel allocation.

Transmission around 60 GHz is suffering from high free path loss compared to 5.8 GHz band. Moreover, the losses folded due to propagation loss through materials and shadowing of human bodies. For more than 100 m wireless transmission length, an extra loss factor limiting the coverage range represented by RF absorption peak in the 60 GHz band due to a resonance of atmospheric oxygen molecules [1]. Therefore, 60 GHz transmission is planned to cover small indoor areas, as also called Pico cell for a low given power.

The short range coverage property of 60 GHz band has several advantages such as avoiding interference and cross talk, frequency reuse, and reduction in the probability of stealing the protected contents by eavesdropping on nearby wireless link. The advances in the fabrication technology for components and as antennas enable improve the operation conditions of 60 GHz transmission systems. For instance, the path loss can be reduced by increasing the antenna gain or using the beam steering to avoid obstacles which prevent line of sight (LOS) transmission.

Different standards are issued in order to classify the 60 GHz band. The band between $(57, 66)$ GHz has been divided into four channels with about 2.61 GHz bandwidth. Japan was the first country to establish standards for 60 GHz in the year 2000 [112]. Different consortia were founded to recommend a standard for the band. IEEE 802.15.3c was finalized in 2009 and was devoted to WPAN communication [31]. The WirelessHD was designed for a short-range (10 m) wireless interchange of high-definition multimedia data between audio-visual devices over an ad-hoc network in the 60 GHz unlicensed band [1]. Recently, the IEEE 802.11ad group has been created by WiGig consortium to support short-range $(1, 10)$ m wireless interchange of data between devices over an ad-hoc network at data rates up to 6.75 Gbps in the 60 GHz unlicensed band [31].

1.4 Advantages of using DSP techniques to recover received signals

At the end of the last century, involvement of signal processing technology in different areas like communication, information processing, radar, medical diagnostic, and scientific instrumentations became inevitable. The main functions, which are handled by signal processing can be summarized as: filtering, detection, estimation, analyzing, and recognition. The invention of transistors as a solid-state device, and development of integrated circuit technology, in addition to proliferation of computers paved the way to replace the analog methods by digital ones. At the mid of fifties in the 20^{th} century, it began to design and implement the first commercial Digital Signal Process (DSP) services for instance, to process seismic data by Texas Instruments.

It is worth to say that the realization of fast Fourier transform and the capability to process the signals in the time domain have a significant impact on the march of DSP development. The 60s was the time to adopt numerical simulation in numerous scientific fields as well as availability of DSP application supported softwares. From the 90s, it is vital for computers to help by analytical and numerical problems through symbolic and object oriented programing.

On the other hand, communications witnessed a big jump forward due to the development of the fiber optic technology. According to the aforementioned benefits of using DSP techniques, adoption of DSP with fiber optic communication system specially in the received side had a big interest from the researcher efforts.

Various experiments dealt with fiber optic impairments are reported. Linear electronic equalizer and Maximum-Likelihood Sequence Estimation (MLSE) have been designed and applied to a fiber optic baseband system for different advanced modulation format by [81]. Alternatively, applying a DSP techniques in order to improve the optical signal quality are suggested. A Look Up Table (LUT) based digital electronic predistortion for optical transmission has been designed and implemented in [109]. Based on DSP algorithms, a Digital Feedback Equalizer (DFE) and Finite Impulse Response (FIR) equalizer are implemented to mitigate the Inter Channel Interference (ICI) for optical fiber system in [114]. Adaptive Blind equalizer based on DSP algorithm to compensate the propagation impairments through fiber optic are investigated and presented in [57].

The all aforementioned reports were dedicated to compensate the fiber optic channel impairments based on DSP techniques for high data rates and long lengths of coverage. An optical coherent receiver is used to retrieve the phase information for advanced modulation formats that means increasing the complexity of the receiver by adding at least two photodiodes and Digital to Analog Converters (DACs).

The aim of work in this dissertation dedicated on investigations of the significant effect of DSP for such a hybrid system like RoF. Contributions in terms of adaption, and processing capability on the received signals of a simplex optical receiver associated with advanced modulation format after electrical downconversion where signal processing taking a place anyway are the main objectives.

1.5 Objective and scope

The scope of the work in this dissertation, as introduced in Figure 1.4, is consisted of two main parts: RoF system realization, and applying of carrier recovery (frequency, and phase) algorithms by utilizing DSP techniques. First, RF upconversion, IQ data modulation, detection and down conversion have to be implemented. Then, received data through RoF system implemented in the first part will be stored and exported to offline process. The process includes the carrier recovery algorithms which applied to remedy the synchronization issue between 60 GHz carrier and the local oscillator in the down converter.

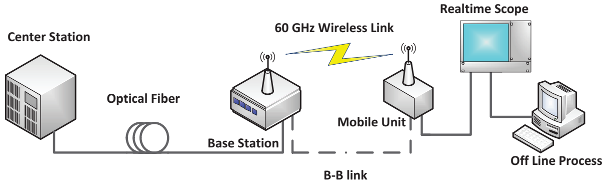

FIGURE 1.4: Scope of work.

1.6 Thesis outline

The dissertation is organized as follows: In chapter 2, a comprehensive description of the RoF system in terms of classification, RF upconversion techniques, system structure, and system impairments is presented supported by a literature survey and closed up by a conclusion.
Chapter 3 deals mainly with the theoretical background of estimation theory. An adequate description for phase estimation algorithm is also given. Three different techniques, i.e, maximum likelihood, least square algorithm, autocorrelation based estimation, are intensively discussed and characterized.
In chapter 4, a full documentation for the implemented RoF system is accomplished, including system setup description, 60 GHz carrier generation and upconversion optimization. Carrier characterization is also performed. Implementation of IQ data modulation by using Dual Parallel Mach Zehnder (DPMZ) modulator is demonstrated and the impairments are researched. An Optical Single SideBand (OSSB) and Optical Double SideBand (ODSB) modulation format are compared. Bit Error Rate (BER) measurements for the baseband for both modulation format are evaluated. Furthermore, RoF system characterization in terms of frequency and system response is carried out.
An elaborated set of numerical simulations and system simulations are performed. This allowed to investigate the ability of adopting the frequency and phase recovery techniques to be utilized for such a new emerged technology like RoF system are presented in chapter 5.
Finally, the work of thesis is summarized, concluded, and outlook for alternative further steps are pointed in chapter 6.

Chapter 2

Radio over Fiber Systems

2.1 Radio over Fiber system structure

The modern generations of wireless communication should realize several important factors such as a quest for high data rates, fairness in access, cost and size to attain the broadband service, which is considered as the keystone for achieving what's known today as e-society. High data rates can be acquired by appealing for high carrier frequency in range of mm-waves to provide the required broad bandwidth. Nevertheless, the high attenuation and absorption ratios, which the mm- wave signal conducts, leads to make the transmission range short to maintain the line of sight condition. Therefore, the covered transmission area should be split into a small unit of size called Macro, Micro, and Pico-cells. To increase the capacity and the diversity, MIMO antennas could be used. High carrier frequencies and numerous distributed antennas confront a difficulty of mm-wave carrier frequency generation by conventional electrical means, size limitations and cost of the base stations.

Using the optical facilities, as will be described in the following sections, to generate a carrier in the mm-wave region is a promising solution. Taking into consideration the favorable specifications of optical fiber as compared with copper as a transmission media in terms of low signal loss (0.3 dB/km for 1550 nm, and 0.5 dB/km for 1310 nm wavelengths) leads to a significant increase in the length of transmission before amplification is needed, weight, and the immunity to interference with electromagnetic signal. The transparency property of the fiber, which means that any format of transmitted data can be sent without any change in the RF transceiver as well as in the antennas, used in the system. This offers the potential to significantly reduce the cost of such telecommunication systems, and enables using a simple remote access unites. Therefore, radio over fiber systems architecture, as depicted in Figure 2.1, has three main parts, a Center Unit (CU), which is designed to assemble most of the signal processing operations like, RF up/down conversion, frequency allocation, modulation, and coding for economic and ease of maintenance reasons. The CU is connected through a fiber optic cable to numerous simple RAUs, which consist of Optical-to-Electrical (O/E) and Electrical-to-Optical (E/O) conversion devices in addition to power amplifiers and antennas to communicate with the Mobile Units (MU) through wireless transmission of millimeter wave signals. As a consequence, the structure of the RoF systems offers advantages because of the centralization of signal processing operations in the center unit, which enables equipment sharing, dynamic allocation of resources, and simplified system operations and maintenance, which in turns leads into reductions in the capital and operational investments. Moreover, the simplified remote access unit improves the system reliability as well as the cost , size, and ease of installation.

Based on the communication technology standards being applied, the terminologies of the RoF systems could be defined in different ways. For instance, with GSM systems, CU could be called a Mobile Switching Center (MSC) and the remote station known as base station. While with wireless local and/or personal area network, the CU would be defined as a head end whereas the RS would be called a Radio Access Point (RAP).

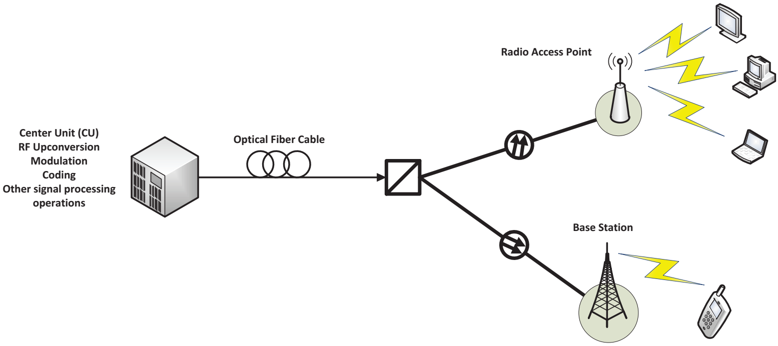

Figure 2.1: Radio over Fiber structure.

2.2 Classification of RoF

RoF systems can be classified in different ways based on the merit of classification. In this section, RoF systems categorization will be reviewed in terms of transportation of the signal, modulation approach, types of optical fiber, and multiplexing techniques.

2.2.1 Transportation category

Three alternative approaches are presented for feeding the signal from the CU through optical fiber cable to the RAU and vice versa. Each tactic has its own advantages and disadvantages as well as its field of application which will be presented and discussed in the sequel of this section.

The classification of the RoF system is based on the frequency used. The most simple and widespread used one is RF-over fiber system [30]. In this configuration, the complexity of the system is aggregated in the CU, keeping the RAU as simple as possible with only O/E and E/O conversion and amplification. The broadband signal is transferred through the optical medium in the RF form, which enables the RAU to transmit directly without the need for any kind of conversion, as depicted in Figure 2.2. RF over fiber is considered as an attractive solution for the communication systems use mm-wave band range in the Micro and Pico cells [41]. With such systems, numerous base stations are required and keeping them simple is cost effective and more reliable [100]. However, for high RF frequencies, very high speed optical modulators and photo diodes are required [41]. Furthermore, the transmitted signal suffers severely from the power fading produced by the chromatic dispersion [89] (refer to chapter 4).

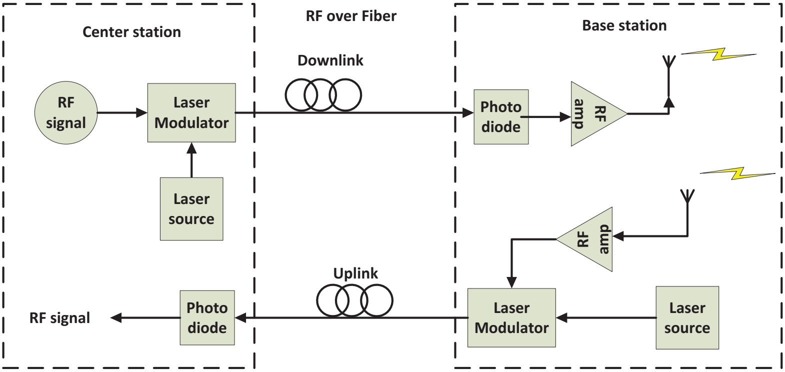

FIGURE 2.2: RF over Fiber down/uplink system diagram.

The second configuration is called IF over fiber, as the name of this configuration highlights to down convert the RF signal to the intermediate frequency band (IF in few GHz range) [77]. The IF signal is modulated on the optical carrier and propagated through the optical cable. At the receiver side after the conversion to electrical domain by a photodiode, another up conversion stage should be located to up convert the IF signal to the RF band in order to prepare the signal for transmission through the antenna, as shown in Figure 2.3. This kind of configuration is perfect for other communication systems that work in the L band frequencies (WLAN) [41], since it does not require up conversion to RF frequency at the receiver side, which keeps the base station simple.

The system affords two pioneer advantages as compared with RF over fiber: using relaxed RF bandwidth for optical modulator and photo diode since the system works in a lower frequency [89], while the second advantage is reducing the Chromatic Dispersion (CD) effects on the transmitted signal [30]. These advantages obtained at the expense of complexity of the whole system [100].

Digitized IF over fiber is considered as a special case from the IF over fiber, where the system converts analog signals to the digital form before sending it to the receiver side and recovers it to the analog form after the photodiode and prior to the RF upconversion stage, as alluded in Figure 2.4. The main reason behind this kind of configuration is the significant reduction in the signal to noise ratio requirements as compared to normal RF and IF over fiber system as well as only lower linearity condition is required [77].

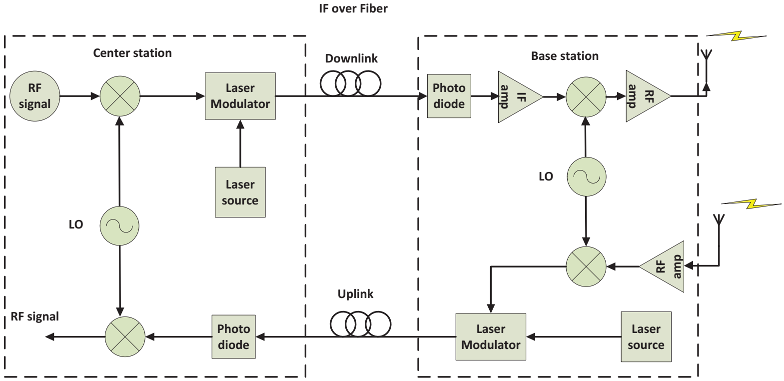

FIGURE 2.3: IF over Fiber down/uplink system diagram.

Nevertheless, the system is more complex in terms of using high speed Analog-to-Digital (A/D) and Digital-to-Analog (D/A) converters, which are quit power consumers and occupy more bandwidth. This configuration is adopted for remote radio heads for Worldwide Interoperability for Microwave Access (WiMAX) and 3GPP/LTE wireless systems[30].

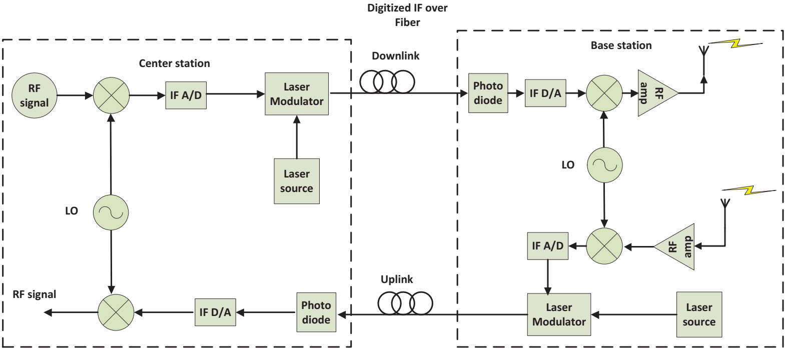

FIGURE 2.4: Digitized IF over Fiber down/uplink system diagram.

Transmitting the baseband over fiber is the third approach. Baseband over fiber on the contrary from the RF over fiber shifts the complexity of the system to the RAU, as illustrated in Figure 2.5. By transmitting the base band signal, the CD effect can be relaxed, which makes this kind of configuration suitable for long spans applications [41]. The optoelectronics component are at the lowest requirements, but on the other hand the RAU becomes a more complex and costly unit [41].