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Jacqueline Damas

Cost Optimized Radio-over-Fiber System

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Cost Optimized Radio-over-Fiber System

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Abstract

The demand of smaller and portable electronic devices has contributed to the realisation of compact embedded systems using PCB miniaturization techniques. The commercial market is faced with competition of handheld users' devices in medical, communication and automotive industries which are smaller and lighter electronic devices. The possibilities of higher degree of integration in planar technology using cost effective electronic components has lead to different art of design and fabrication of compact units.

I this work, a central station and a base station front-end with small form factor have been realized using commercial components on PCBs. These electronic compacts units were integrated in the IF-over-Fiber system architecture. The IF-over-Fiber architecture comprised of miniaturized electronic components for quadrature modulation and upconversion. The central station supports multi-Gbps data rate modulation formats in order to increase the spectral efficiency of the transmitted information. Multilevel modulation formats are considered spectrally efficient and can double the transmission capacity by transmitting more information in the amplitude, phase, polarization or a combination of all. The BS front-end comprises of the 60 GHz upconverter and a 60 GHz planar 2×2 microstrip antenna. The 10 GHz IF carrier allows an optical transmission with higher spectral efficiency in optical domain, as well as it is less susceptible to dispersion induced power fading inherent in optical fiber. Characterization of the designed central station and base station front-end through measurements are presented and discussed. The IF-over-Fiber system analysis is made for the 2 Gbps QPSK transmission with respect to error vector magnitude (EVM), eye and constellation diagrams.

Zusammenfassung

Die Nachfrage nach kleinen und portablen elektronischen Geräten hat dazu beigetragen, dass unter Nutzung von miniaturisierten Leiterplatten kompakte eingebettete Systeme realisiert werden. Im kommerziellen Markt gibt es einen großen Wettbewerb um kleinere und leichtere Elektronik bei Anwendergeräten im Medizin-, Kommunikations- und Automobilbereich. Die Möglichkeiten, kostengünstige elektronische Komponenten in planarer Technologie zu integrieren, hat zu unterschiedlichen Ansätzen im Entwurf und der Fertigung kompakter Einheiten geführt.

In dieser Arbeit wurden ein Zentralstations- und ein Basisstationsfrontend mit kleinem Formfaktor durch die Nutzung kommerzieller Komponenten auf Leiterplatten realisiert. Diese kompakten elektronischen Einheiten wurden in die IF-over-Fiber-Architektur integriert. Diese IF-over-Fiber-Architektur ist aufgebaut aus miniaturisierten elektronischen Komponenten für Quadratur-Modulation und Aufwärtsmischung. Die Zentralstation unterstützt Modulationen mit Multi-Gbps Datenrate, um die spektrale Effizienz der übertragenen Information zu erhöhen. Multi-Level-Modulationsformate werden in Betracht gezogen und können die Übertragungskapazität verdoppeln, indem mehr Information in der Amplitude, Phase, Polarisation oder einer Kombination von allem übertragen wird. Das Basisstations-Frontend besteht aus dem 60 GHz Aufwärtsmischer und einer planaren 2x2 60 GHz Mikrostreifenantenne. Der 10 GHz Zwischenfrequenzträger erlaubt eine optische Übertragung mit hoher spektraler Effizienz im Optischen und ist auch weniger anfällig gegenüber dispersionsbedingten Leistungsschwankungen, die durch die optische Faser verursacht werden. Die Charakterisierung der entworfenen Zentralstation und des Basisstationsfrontends wird mittels Messungen vorgestellt und diskutiert. Die Systemanalyse des IF-over-Fiber-Systems wird anhand einer 2 Gbps QPSK-Übertragung bezüglich Error Vector Magnitude (EVM), Augen- und Konstellationsdiagrammen vorgenommen.

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Acronyms

ADC	Analogue-to-Digital Converter
AM	Amplitude Modulation
ASE	Amplified Spontaneous Emission
AUT	Antenna Under Test
BBoF	Baseband-over-Fiber
BER	Bit-Error Rate
BPF	Band Pass Filter
BRS	Broadband Radio Service
BS	Base Station
CERRE	Centre on Regulation in Europe
CNR	Carrier-to-Noise Ratio
COTS	Commercial Off-the-Shelf
CS	Central Station
CW	Continuous-Wave
DAS	Distributed Antenna System
DCF	Dispersion Compensating Fiber
DFB Laser	Distributed Feedback Laser
DML	Direct Modulated Laser
DSL	Digital Subscriber Line
DSO	Digital Storage Oscilloscope
EAM	Electro-Absorption Modulator
ECL	External Cavity Laser
EDFA	Erbium Doped Fiber Amplifier
EIRP	Equivalent Isotropically Radiated Power
ER	Extinction Ratio
ESA	Electrical Spectrum Analyser
EVM	Error Vector Magnitude
RF	Radio Frequency
RoF	Radio-over-Fiber
FSO	Free Space Optical
FTTH	Fiber-to-the-Home
FTTA	Fiber-to-the-Antenna
FWM	Four-Wave Mixing
GVD	Group Velocity Dispersion
IC	Integrated Circuit
IF	Intermediate Frequency
IFoF	IF-over-Fiber
IIR	Infinite Impulse Response

IM	Intensity Modulation
IM-DD	Intensity Modulation Direct Detection
IQ	In-phase and Quadrature
ISI	Inter Symbol Interference
ISM	Industrial, Scientific and Medical
LED	Light-Emitting Diode
LMDS	Local Multipoint Distribution Service
LO	Local Oscillator
LOS	Line-of-Site
LSB	Lower Sideband
MATP	Maximum Point
MITP	Minimum Point
ML	Maximum Likelihood
MMF	Multi-Mode Fiber
M-PSK	M-ary Phase Shifting Keying
M-QAM	M-ary Quadrature Amplitude Modulation
MS	Mobile Station
MZM	Mach-Zehnder Modulator
NCO	Numerical Controlled Oscillator
NF	Noise Figure
NGA	Next Generation Access
NRZ	Non-Return to Zero
NRZ-OOK	Non-Return-to-Zero-on-off-Keying
OCSR	Optical Carrier-to-Side Ratio
ODSB	Optical Double Sideband
ODSB-SC	Optical Double Sideband Suppressed-Carrier
OSSB	Optical Single Sideband
PA	Power Amplifier
PC	Polarization Controller
PCB	Printed Circuit Board
PD	Photodetector
PLL	Phase Locked Loop
PON	Passive Optical Network
PRBS	Pseudo-Random Sequence
PTMP	Point-to-Multipoint
QAM	Quadrature Amplitude Modulation
QP	Quadrature Point
QPSK	Quadrature Phase Shift Keying
RFoF	RF-over-Fiber
RIN	Relative Intensity Noise
ROP	Received Optical Power

RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SCM	Sub-Carrier Multiplexing
SFDR	Spurious Free Dynamic Range
SMA	SubMiniature version A
SMF	Single-Mode Fiber
SNR	Signal-to-Noise Ratio
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
TDM	Time-Division Multiplexing
TRL	Thru Reflect Line
USB	Upper Sideband
UTC-PD	Uni-Travelling-Carrier Photodiode
VCO	Voltage Controlled Oscillator
VCSEL	Vertical-Cavity Surface-Emitting Laser
VNA	Vector Network Analayzer
WDM	Wavelength-Division Multiplexing
WPAN	Wireless Personal Area Network
XPM	Cross-Phase Modulation

List of Symbols

I	Current
E	Electric field
P	Power
P_{MAX}	Maximum RF input power
P_{TX}	Transmitted RF power
P_{RX}	Received RF Power
ω	Angular frequency
ω_C	Cut-off frequency
φ	Angular phase
$\delta P(t)$	Laser intensity fluctuation
V_π	Modulation extinction voltage
P_{bias}	Modulator normalized bias
δ	Modulator normalized bias
β	Modulator normalized index
R	Responsivity of photodiode
$\hbar$	Planck's constant
$\hbar v$	Photon energy
k	Boltzmann's constant
λ_c	Carrier wavelength
c	Speed of light in vacuum
q	Electron charge
f_c	Carrier frequency
E_b	Energy per symbol
E_g	Bandgap of the semiconductor material
N_0	Noise power spectral density
C	Channel capacity
M	Number of bits per symbol
T	Symbol period
$\zeta(t)$	Dirac delta function
T_s	Sample period
n_s	Number of registers
α	Attenuation constant
L	Fiber length
D	Fiber dispersion constant
χ_σ	Shadowing and multi-path fading effects parameter
$\tilde{n}$	Path loss exponent
B	Bandwidth
B_{Sign}	RF signal bandwidth

$B_{Optical}$	Optical signal bandwidth
J_n	Bessel function of the n^{th} order
d	Distance
d_0	Reference distance
η_{TX}	Laser slope efficiency
η_{RX}	Photodiode responsivity
Z_{in}	Input impedance
Z_{out}	Output impedance
Z_w	Microstrip impedance
F	Noise factor
NF	Noise figure
G	Gain
G_{RoF}	Radio over fiber link gain
G_{RX}	Receiving antenna gain
G_{conv}	Conversion gain
G_{AUT}	Antenna gain under test
G_{horn}	Horn antenna gain
PL	Path loss
$PL_{FS}(d_0)$	Path loss of the reference distance
$\alpha_{dielectric}$	Material dielectric loss
$\alpha_{conduction}$	Material dielectric loss
$\tan\delta$	Material dispersion factor
ε_{r}	Material dielectric constant
ε_0	Dielectric constant of free space
H	Substrate material height
θ	Carrier phase offset
w	Microstrip trace width
ϵ	Symbol timing error
P_b	Bit error probability
μ	Fractional time delay

1 Introduction

The enormous capacity offered by the optical fiber, combined with the mobility and the seamless flexibility of wireless access, developed to what is known today as radio-over-fiber (RoF) technology. RoF based optical–wireless networks are emerging as cost-effective solutions in environments where seamless connections are needed, such as in conference centers, railways, airports, hotels, homes and small offices [81, 95, 130, 166]. Advances in RF and microwave circuitry go hand in hand with everyday evolution in technology. A large portion of these innovations consist of bandwidth-intensive applications on hand-held wireless devices for medical, industrial, and communicational applications. These applications in a variety of fields are migrating from desktop models to portable communication units [112, 121]. This induced undeniable demand for data-rates boosted beyond 10 Gbps with no end in sight, calls for system architectures that support multi-Gbps data modulation schemes to increase spectral efficiency of transmitted signal. Not only is RF becoming more ubiquitous, but also microwave circuitry. Both capturing very high frequencies in millimeter wavelength within the frequency spectrum from 30 GHz to 300 GHz. For indoor deployments and applications, the research interest is now on the 60 GHz bands [71, 132].

The fundamental principle of RoF transmission is that it requires a transportation of analogue radio signals through an optical fiber link. This is because the optical source is always operated in "on" state and the optical modulation depth is so small that small signal analysis of the various link devices is possible. In contrast to digital optical links, the optical modulation depth approaches almost 100% [66], whereby, the laser is operated in the "on" and "off" states depending on the modulating data sequence. Compared to copper cables, the loss in the optical fiber is a function of the optical wavelength shown in Figure 1.1 and does not depend on the frequency of the RF signal being transported. The C-Band and L-Band windows have minimum losses in the wavelength ranging from 1.53 µm to 1.625 µm.

For standard single mode fibers, the loss of this transmission distance due to the fiber attenuation is 0.2 dB/km at the wavelength of 1550 nm, see Figure 1.1. The chromatic dispersion effect introduces distortions of the signal. It

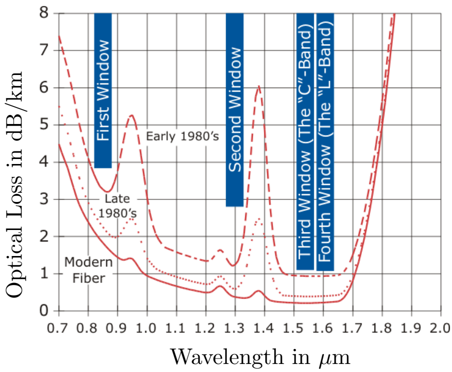

Figure 1.1: Attenuation characteristics of a typical optical fiber [98].

has been shown in [74] that for a standard single mode fiber with a chromatic dispersion of 17 ps/km·nm and a length of 1 km, the SNR-penalty induced by the fiber dispersion for a signal frequency of 30 GHz is less than 1 dB. The effect is even less prominent for lower signal frequencies, which is the interest of investigation in this dissertation. Consequently, due to the abundant bandwidth and frequency-independent low-loss properties, multiple RF carriers can be multiplexed and transmitted via a single mode optical fiber. These are the techniques used for long haul undersea optical transmission systems [66].

For system simplicity, cost-efficient and low-maintenance high-performance links, analogue intermediate frequency (IF) or radio frequency (RF) signal over fiber systems is preferred [57]. Conversely, nonlinear distortions, limited dynamic range, and additional noise are introduced to the transmitted signal. One approach to mitigate these induced signal impairments is to use digitized IF or RF signal over fiber from the central station (CS) to the base station (BS). Digitalized transmission (I and Q baseband) consumes more capacity than analogue transmission, and increases system complexity and cost; as it requires signal conversion prior and after transmission over fiber. Moreover, for analogue optical links, the propagation delay is simply given by the speed of light in the fiber and the fiber length; contrarily, in digital links, additional delays are typically acquired in the digitization process. Optical techniques at the CS have traditionally been used to generate stable signals over a wide range of frequencies, employing a variety of methods such as direct modulation, external modulation, mode-locking and optical heterodyning [66]. Usually, in typical analogue optical fiber links, signal distortion is caused mainly by the modulating device, rather than the photodetector or the fiber. Once the CS has to be connected to the multiple distributed antenna system (DAS), multiplexing techniques are implemented to reduce the number of optical fiber counts. The progress in the development of optical components enables the design of a RoF system capable of transporting RF signals with advanced multilevel modulation formats over significant distances, thereby enabling its use in any next generation DAS network. A combination of wavelength and subcarrier multiplexing is the most convenient method in analogue RoF links. In digitized RoF links, time-division multiplexing (TDM) with combination of wavelength division-multiplexing (WDM) is often applied for long haul transmission [66].

In the RoF system design, the rule of thumb is selecting appropriate technologies for each subsystem with a goal of reducing capital and operational expenses of the network [38]. At the CS, high frequency electro-optical modulators and electronics have to be avoided due to their high cost [122] and power consumption [159]. Concurrently, complex implementation of downlink transmission techniques are also not preferred because they result in higher manufacturing and maintenance costs. The cost of the optical link is mainly determined by the fiber installation rather than by the optical components. Thus, integrating optical segments into hybrid solutions (fiber sharing) for the next generation of access networks is a key measure for reducing cost. However, it is important to minimize fiber length because topologies with minimum fiber lengths often offer poor availability performance [47]. Regarding the BS, it is critical to keep it as simple as possible because an elevated number of them are required in the RoF system, meaning a BS with the lowest possible number of components. The simplicity of the BSs, drives the reduction of costs associated with site acquisition, site leasing and energy consumption. It is desirable for the BS to work without any expensive climate control facilities at the remote site [38]. On the other hand, as a classical downsizing technique, miniaturization attempts have been performed using different types of the substrate material. The existing RoF systems are huge and bulky with large transmitting antenna at the BS, which render their mass production inconceivable. On the contrary, using printed circuit board (PCB) technology to converge the electrical components of the system into a compact unit is realistic. The challenge is taken to design and assemble electrical components and microwave circuitry of the analogue RoF on PCB.

1.1 Evolution of Access Technology

The chronicle of access technology commences with copper cables. The use of copper cables traces way back to the beginning of the 19th century, where text and voice were the main content for transmission. Discovery of mobile phones by Motorola in 1973 promoted growth in the access network. Subsequently, ten years later, handheld mobile phones named "DynaTAC 8000x" became commercial. Mobile voice and text messages were amazing, although consumers wanted more. Consumers were later introduced to broadband internet access in the homes and offices. From 1983 to 2010s, mobile networks evolved through four generations with insatiable demand for broadband bandwidth and data services. Thanks to the second generation (2G) of mobile networks which enabled more users to acquire mobile subscriptions. Innovations in device technology resulted in the era of the smartphone. The proliferation of smartphones paved the way for networks of wireless connectivity on top of secure wired backbones linking base stations to the overall global communications network. The wireless infrastructure is essentially always a hybrid of wired and wireless, which offers a completely different level of flexibility and access compared to wired-only network infrastructure.

Fiber optics inherently have huge bandwidth and offer higher data rates than copper cables. They are immune to electromagnetic interference and have a low bit error rate. Although copper cables are already installed for telephone signals and cable television services, fiber optics cables can reach longer distances and facilitate data rates beyond 1 Gbps. The fiber cable installation for copper cable replacement has been conceived in many countries, albeit proved to be far more expensive. In the beginning, this concept was implemented to cover small distances in the communication network, abbreviated to FTTx meaning fiber-to-the-x, where x defines end users configurations for fiber deployment. In many instances, FTTH (fiber-to-the-home) has become a standard choice for fiber utilization in greenfield areas [51]. In addition, many countries have embarked on new big fiber installation projects interconnecting cities and remote centers. Most of the telecommunication companies are currently using fiber optics for long-distance communication. Repeaters are required at distance intervals to amplify and preserve transmitted signal contents. Beyond imagination, fiber is now explored for space and cloud radio access widely referred to as free space optical (FSO) communication.

FSO systems have initially attracted attention as an efficient solution to the "last mile" problem to bridge the gap between the end user and the fiber optic infrastructure already in place. Unlike RF carrier where spectrum usage is restricted, optical carrier does not require any spectrum licensing. As a result it is an attractive prospect for high bandwidth and capacity applications.

Contrary to its great potential, the performance of FSO communication is limited by the atmospheric channel effects of absorption, scattering and turbulence. Different communication protocols were developed [99, 97], and FSO communication is considered as a candidate for 5G backhaul [65].

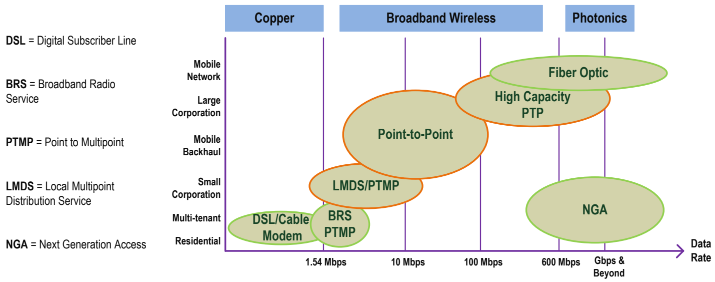

Figure 1.2: Evolution of access technology.

Access technology evolution enables varying Gbps data rate experiences and beyond; as depicted in Figure 1.2. Still, many households in Europe await the next generation access (NGA) networks according to the Centre on Regulation in Europe (CERRE) report on "State aid for broadband infrastructures in Europe" released in 2018 [119]. NGA technologies have low share in fixed broadband lines with an increase in data rates and quality of service. In order to achieve the transmission of such higher data rates, systems with high spectral efficiencies beyond 10 bit/s/Hz have to be developed, which will be very challenging. The simultaneous multi-channel transmission has been employed to attain such higher spectral efficiency of the transmitted signals. Standardized systems with transmission data rates of 2.5 Gbps, 10 Gbps, 40 Gbps, 100 Gbps and 200 Gbps are operational and commercial. Besides, quadrature modulation is desired for its ability to accommodate more transmission bits per channel; utilizing both amplitude and phase variations of the transmitted data signal.
Modern optical communication systems fulfilling optical networking functionalities at data rates of about 40 Gbps and above are now commercially available. They employ wavelength division multiplexing (WDM) technique due to the rapid development of high-speed electronics and optical component technologies over the last few years. NGA networks are envisioned to operate at a data rate as high as 400 Gbps.

1.2 Mobile Broadband Capacity Demand

Mobile broadband services are undergoing a period of dramatic growth causing a tremendous increase in data traffic. This surge of traffic is driven by the growing number of mobile subscribers, especially smartphone users connecting to faster network applications such as video streaming, full HD video and cloud computing. These applications require wireless data rates of several 10s of Gbps and the real feel of being ubiquitous by mobile subscribers. These bandwidth-hungry applications are highly dependent on the capacity provided by the telecommunication infrastructures. In fact, with a capacity-demand growth doubling every year [50], the paradigm in telecommunication networks has rapidly changed from supporting local and low bandwidth traffic to providing worldwide connections with high bandwidth-consuming traffic. This evolution has been verified in all segments of the telecommunication networks, ranging from the access to the metropolitan and backbone networks, which were forced to cope with larger traffic volumes by upgrading their systems and technologies.

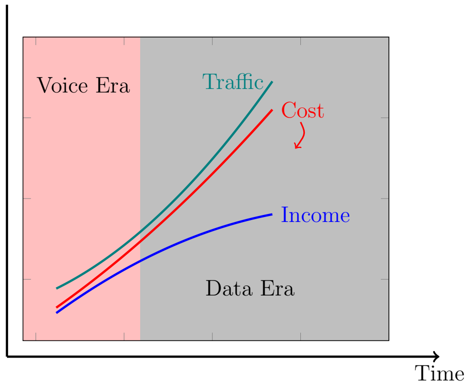

Figure 1.3: An increasing gap between traffic and operator's income (data from [50]).

At present, mobile service operators and the telecommunication industry as a whole, face an important challenge of users expecting high bandwidths, low loading times and reduced latency in real-time services. Telecommunication networks, apart from providing a high transmission capacity also need to be reliable, flexible, fault-tolerant and low energy consuming with ever decreasing cost per transported bit. As depicted in Figure 1.3, and referred to by many different organizations, mobile operators currently face a growing gap between their income revenues and the increasing traffic demand. This is verified because the increasing expenditures necessary to upgrade the network capacity are typically not supported by proportionally augmenting mobile operator income revenues. In reality, most mobile operators experience a very slow, income revenue increase. Therefore, the present challenge requires new network technologies and architectures which allow upgrading the capacity while simultaneously reducing the cost per transported bit. In order to reduce the telecommunication system cost and provide solution for the increase in mobile traffic demand, RoF technology has been proposed since it supports simple BSs that are interconnected to a CS via an optical fiber. The RoF as part of optical communication system could be one of the solution for the high demand of high speed communication with broad bandwidth. It has been proven to be one of the best integrated optical fiber communication for an indoor high speed transmission system [66, 121].

1.3 RoF Technology for Seamless Indoor Wireless Communication

To deliver on this significant wireless system demand, particularly for inbuilt coverage, millimeter wave wireless technology, which is capable of multi-Gbps throughput, is very promising. Progress in the wireless personal area networks (WPAN) from RFID, ZigBee, Bluetooth 2.0, W-USB to 60 GHz wirelessHD appears to be rising at a much faster rate than ordinary wireless technologies [61]. Anyhow, the apparent rapid increase in capacity of WPANs is a clear testimony of the significance of high-speed wireless access for the users, and an introduction of new fast communication networks. These emerging personal wireless communication networks (that support new broadband services) provide increased opportunities for photonics technologies to play a prominent role in the realization of the next generation integrated optical and wireless networks.

RoF transmission has extensively been studied as a means of realizing a fiber optic wireless distribution network that enables seamless integration of the optical and wireless network infrastructures [38, 66, 121, 166]. An unprecedented 7 GHz bandwidth of un-channelized spectrum for operation between 57-64 GHz is available in Europe for ISM (Industrial, Scientific, and Medical) band for RoF systems. This license-free spectrum is exploited due to its enhanced characteristics of point-to-point link transmission with a higher

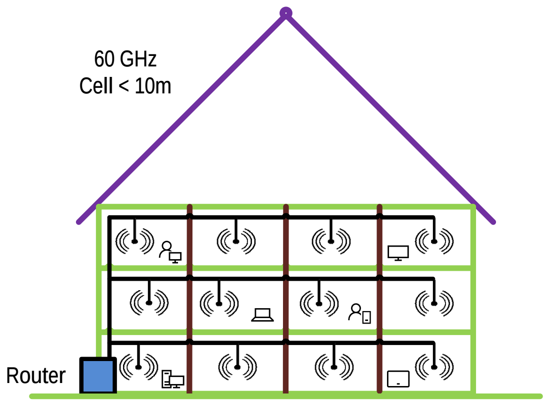

Figure 1.4: Indoor deployment of wireless networking at 60 GHz.

throughput greater than 1 Gbps. A particular strong interest is now on the 60 GHz bands, especially for in-building applications. Nevertheless, these frequencies have an inherent high propagation loss characteristic of wireless signals resulting in network architectures featuring significantly smaller cell sizes. Increasing interest in the use of fiber optic for wireless transmission is stimulated by the ability of the RoF system to support very small antenna transmission sizes of pico and femto dimensions in a confined area (Figure 1.4), which increases transmission throughput and enhance frequency reuse. Yet, deployments of these pico and femto cells require many DAS. Antenna density is required for improved wireless signal coverage and indoors capacity, whereas, poor wireless signal results in wireless system performance degradation. Integrating a 60 GHz wireless system with a fiber optic distribution network enables efficient delivery of high-speed wireless signals to a large number of indoor wireless access points, ensuring optimized radio coverage. Consequently, 60 GHz wireless presents great opportunities for multi-Gbps wireless communication. Even when using only low spectrally efficient basic modulation formats like NRZ-OOK, the capacity of the millimeter wave band already surpasses the capacity of conventional microwave band due to the availability of channel bandwidth.

The RoF transmission is characterized as analogue transmission; owing to the fact that RF signal is used to modulate the lightwave, not a baseband digital signal as it is the case in most optical communication links. The use of the

RF signal means that the link is analogue in nature and its operation must be characterized as such. Analogue RoF architecture can be implemented using RF or IF. The advantage of using IF-over-fiber is the fact that the impinging fiber chromatic dispersion effects are reduced at the expense of additional components for upconverting IF to RF. Power fading due to chromatic dispersion lowers the transmission distance with increasing frequency. As well, distributed feedback (DFB) laser used for lightwave generation and a photodiode at the receiver for lightwave detection and conversion to electrical domain operate at lower frequencies. Certainly, IF-over-Fiber is a good compromise between electrical bandwidth that will be available and component effort. IF instead of RF over fiber enables metro network distances and multiple carrier transmission. This architecture offers flexibility to support system outgrowth and expansion to accommodate new interfaces and components. On the other hand, RF-over-fiber transmission severely suffers from chromatic dispersion effects with the increase in fiber transmission length. Complex techniques in carrier recovery at the receiver have to be employed in order to detect transmitted signal. Therefore, it is not preferred for multichannel transmission over fiber [94].
Fiber-to-the-antenna (FTTA) is a new innovation for broadband network architecture in which optical fiber is used to connect a remote antenna of the BS [176]. FTTA can be seen as a subset of RoF where the optical fiber is brought closer to the transmitting antenna at the BS. This system setup allows for enhanced energy efficiency, increased bandwidth, improved flexibility and low latency which are the defined properties of the NGA network.

1.4 Objectives and Synopsis of the Dissertation

Undertaking this research on RoF systems is intended to seek ways of simplifying the system architecture. Designing a RoF transmission system consisting of compact CS and BS units while optimizing electrical component's cost, size and performance. The goal is to explore a compromise between high performance at 60 GHz frequency of WiFi routers available in the market and compact size of the receiver (BS) designed. Therefore, the design and realization of a cost-effective RoF system with improved portability (reduced bulkiness) and high data rate using off-the-shelf RF components is proposed. In addition, the study aims at mitigating optical transmission losses using a transmission carrier at intermediate frequencies.
The study comprises of seven chapters. Basic concepts of microwave photon-

ics in relation to fiber optic communication is introduced and discussed in the next chapter. Intensity and phase (including frequency) data modulation formats are reviewed. This comprises the physical quantity used to convey digital information, and the number of symbols used to represent the binary transmit data. Likewise, the distribution of radio signals over optical fiber to take advantage of the low loss, mitigating chromatic dispersion effects and utilizing broadband bandwidth of the state-of-the-art IF-over-Fiber architecture transmission are reviewed. The intensity of an optical signal is the square of its amplitude, where its detection is carried out using direct envelope detection scheme by a photodetector (PD). Chapter three introduces the system design and criteria for consideration; which are simplicity, affordability, and easy deployment while minimizing insertion loss and system noise. Selection of transmission frequency, RF components and fabrication technology are presented. It shows that the transmission with high linearity for a system consisting of numerous power amplifiers has trade-offs between poor system efficiency and high transmission spectral efficiency. The downlink transmission layout comprising the CS and BS, which are interconnected by optical fiber for electro-optical and optical-electro conversions respectively, have been discussed.

Chapter four is dedicated to the design, fabrication and characterization of the CS on PCB using Isola I-Tera MT substrate material. The CS supports multi-Gbps data modulation schemes in order to increase spectral efficiency of the analogue transmitted signal. Special attention has been given to external laser modulated link using Mach-Zehnder Modulator (MZM) biased at quadrature. RF amplifiers are incorporated in order to drive the MZM into full capacity. Chapter five deals with the BS for wireless transmission at 60 GHz. This consists of design and fabrication of integrated microstrip antenna array transmitting at 60 GHz. At 60 GHz frequency, signal transmission experiences more losses as it crosses the PCB. A proposed hybrid solution of using two substrate materials has been realized using a PCB (Isola I-Tera MT substrate) and a wafer (silica substrate). Thereafter, chapter six focuses on the performance of the IF-RoF link transmission; characterization and experimental results. The dissertation is concluded by chapter seven with commentary and summary of the work and its contribution to the ongoing research on RoF systems.