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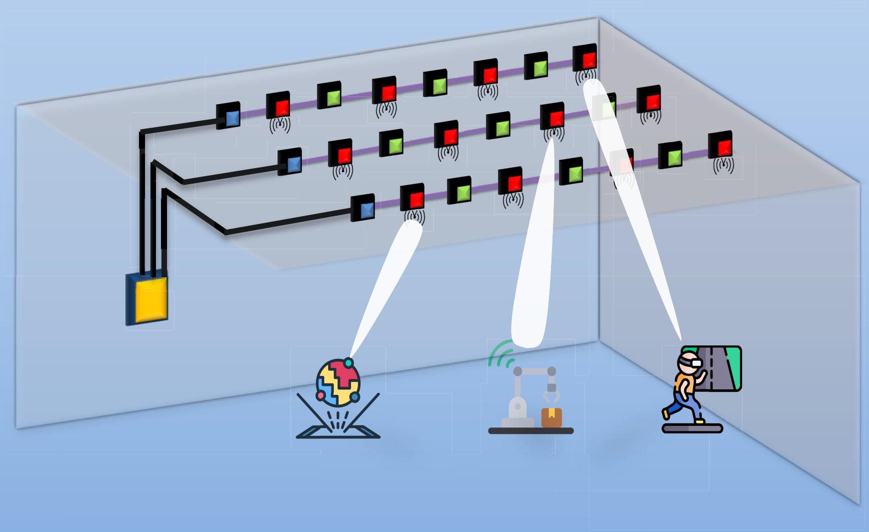
Aspects of Terahertz Radio-over-Fiber Stripes

Dexin Kong



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Abstract

Sub-terahertz (Sub-THz) communication is considered as a key enabler for sixth-generation (6G) and beyond communication systems, owing to its abundant spectrum resources that support extreme data rates, high spatial resolution, and low latency. However, the unfavorable propagation characteristics and significant hardware impairments pose substantial challenges to practical deployment, often resulting in high implementation costs.

Current commercial communication systems predominantly rely on co-located multiple-input multiple-output (MIMO) architectures to provide high spectral efficiency and reliable service. At sub-THz frequencies, although the severe free-space path loss can be largely compensated by large antenna arrays and highly directional beamforming, the susceptibility to blockage remains a fundamental limitation of co-located MIMO systems. Due to the strong dependence on a dominant line-of-sight path and the co-located nature of the antenna elements, obstruction by human bodies, objects, or environmental dynamics can simultaneously degrade all antenna links, resulting in abrupt signal attenuation and intermittent connectivity. Moreover, the pronounced hardware impairments at sub-THz frequencies, such as power amplifier (PA) inefficiency, phase noise, and limited data-converter resolution, increase system complexity and implementation cost, thereby challenging the practical deployment of co-located MIMO architectures in mobile sub-THz communications.

Recent advancements in polymer microwave fiber (PMF) technology have created significant opportunities for robust, low-cost, and high-speed sub-THz radio-over-fiber (RoF) communications. As an alternative, novel RoF architectures can facilitate cost-effective realization of sub-THz systems. Recognizing these potential benefits, this thesis explores a novel RoF structure that interconnects multiple radio units (RUs), booster units (BUs), and a central unit (CU) in cascade via PMF, envisioning its application in indoor scenarios. This structure creates several research opportunities when considering cascaded distortion effects introduced by non-linear PAs and the

propagation channel over the fiber.

Within this context, the contributions of this thesis are twofold.

i) Uplink positioning: We propose uplink positioning algorithms that exploit the cumulative effects of cascaded non-linear PAs and dispersive PMFs. Specifically, we develop maximum-likelihood and non-linear least-squares estimators to determine the entry RU and the time-of-arrival between the RoF system and the user equipment, where identifying the entry RU corresponds to estimating the signal propagation distance along the RoF stripe. For the special case of linear PAs, we derive the Cramér–Rao lower bound (CRLB) to benchmark estimator performance. Our simulation results demonstrate that the proposed estimators remain effective even under cascaded non-linear distortions, and that the architecture enables cost-efficient, high-resolution indoor positioning. In the numerical evaluations, experimentally measured PMF characteristics for high-density polyethylene fibers are also incorporated.

ii) Waveform selection: We introduce a set of candidate waveforms and compare them using multiple performance metrics to assess their robustness against hardware impairments. The considered waveforms are categorized into three operational regimes, each associated with a distinct system configuration. Several waveforms are then generated and evaluated within the considered cascade-structured RoF Sub-THz system. Importantly, we provide new insights and an in-depth comparative analysis of the dominant characteristics of each waveform, highlighting the most suitable option for the envisioned architecture and offering a detailed complexity assessment.

Populärvetenskaplig Sammanfattning

Sub-terahertz (Sub-THz)-kommunikation är en lovande teknik för sjätte generationens (6G) och framtida kommunikationssystem, tack vare dess stora spektrumresurser som möjliggör extremt höga datatakter, hög spatial upplösning och låg latens. Men, dess ogynnsamma utbredningsgenskaper och hårdvarubegränsningar innebär stora utmaningar för praktisk implementering, vilket ofta leder till höga systemkostnader.

Dagens kommersiella kommunikationssystem förlitar sig huvudsakligen på samlokaliserade multiple-input multiple-output-arkitekturer (MIMO) för att uppnå kommunikation med hög tillförlitlighet och spektraleffektivitet. Vid sub-THz-frekvenser kan den ogynnsamma utbredningsdämpningen till stor del kompenseras genom stora antennarrayer med starkt riktad transmission, men känsligheten för blockering utgör fortfarande en grundläggande begränsning. Sub-THz signaler kan nämligen blockeras av personer, föremål och ändras signifikant av en miljös dynamik, vilket kan leda till plötslig förlust av signalstyrka och anslutning på ett oförutsägbart sätt. Vidare uppstår hårdvarubegränsningar som ineffektivitet av effektförstärkare (PA), fasbrus och begränsad upplösning i dataomvandlare vilket försvårar användning av sub-THz radio i praktiken.

Nya framsteg inom så kallad "polymer microwave fiber" (PMF) teknik har skapat möjligheter att använda Sub-THz genom fiber-radio "radio-over-fiber" (RoF)-kommunikation. De nya RoF-strukturerna möjligör en kostnadseffektiv realisering av Sub-THz-system. Därför utforskar denna avhandling en ny RoF-struktur som kopplar samman flera radioenheter (RUs), förstärkningsenheter (BUs) och en centralenhet (CU) i kaskad via PMF, för tillämpning i inomhusmiljöer. Strukturen skapar ett antal forskningsmöjligheter med avseende på de kaskadstrukturerade distorsionseffekter som introduceras av icke-linjära PAs och fiberns utbredningskanal.

Avhandlingens bidrag kan i detta sammanhang beskrivas enligt följande:

(i) en uplink-positioneringsalgoritm som utnyttjar de kumulativa effekterna från kaskadstrukturerade icke-linjära effektförstärkare och dispersiva PMF:er;

(ii) val och analys av vågformer för det studerade kaskadstrukturerade RoF-systemet.

Med det första bidraget föreslår vi sannolikhetsmaximering- och icke-linjära minsta-kvadrat-algortimer för att estimera vilken RU som har första signalankomst samt ankomsttiden mellan RoF-systemet och användaren, där estimeringen av RU med först ankomst motsvarar estimeringen av utbredningssträckan längs RoF-strukturen. För fallet med linjära PAs härleder vi Cramér-Rao gränsen (CRLB) som ett prestandamått. Slutligen undersöker vi systemets tillämpbarhet för upplänkspositionering. Våra simuleringsresultat visar att de föreslagna estimatorerna ger god prestanda trots kaskaderade effekter från icke-linjära PAs. Resultaten visar även att den föreslagna RoF-strukturen kan möjliggöra nya kostnadseffektiva lösningar för högupplöst positionering i inomhusmiljöer. I den numeriska utvärderingen används även uppmätta PMF-egenskaper för högdensitetspolyetenfibrer.

Genom det andra bidraget introducerar vi olika vågformer och jämför dem utifrån flera prestandamått för att belysa deras robusthet mot imperfektioner i hårdvara. De studerade vågformerna kategoriseras i tre driftsregimer, vilka motsvarar olika systemkonfigurationer. Vidare genereras och utvärderas utvalda vågformer i ett nyligen föreslaget kaskadstrukturerat Sub-THz RoF-system. Slutligen presenterar vi nya insikter och en omfattande diskussion kring de dominerande egenskaperna av varje vågform, identifierar det mest lämpliga alternativet för den betraktade arkitekturen samt tillhandahåller en komplexitetsanalys.

Contents

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Dexin Kong
Linköping, January 2026

List of Abbreviations

3GPP	3rd Generation Partnership Project
4G	forth-generation
5G	fifth-generation
5G NR	5G New Radio
6G	sixth-generation
ACLR	adjacent channel leakage ratio
ADC	analog-to-digital converter
AI	artificial intelligence
AM/AM	amplitude-to-amplitude
AP	access point
AR	augmented reality
ARQ	automatic repeat request
AWGN	additive white Gaussian noise
BER	bit error rate
BU	booster unit
CE-OFDM	constant envelope-OFDM
CP-OFDM	cyclic prefix-OFDM
CPFSK	continuous phase frequency shift keying
CPM	continuous phase modulation
CPU	central processing unit
CRC	cyclic redundancy check
CRLB	Cramér–Rao lower bound
CU	central unit
DAC	digital-to-analog converter

DFT	discrete Fourier transform
DFT-s-OFDM	DFT spread OFDM
DSP	digital signal processing
eMBB	enhanced Mobile Broadband
EVM	error vector magnitude
FEC	forward error correction
FIM	Fisher information matrix
FSK	frequency shift keying
FSPL	free-space path loss
GDOP	geometric dilution of precision
GMSK	Gaussian minimum-shift keying
GSM	Group Special Mobile
IBO	input power back-off
IDFT	inverse discrete Fourier transform
ISAC	integrated sensing and communication
ISM	industrial, scientific, and medical
ISI	inter-symbol interference
ITU	International Telecommunication Union
LO	local oscillator
LoS	line-of-sight
LTE	Long Term Evolution
LTI	linear time-invariant
mMTC	massive machine-type communication
MIMO	multiple-input multiple-output
ML	maximum likelihood
mmWave	millimeter wave
MSK	minimum shift keying
NLS	nonlinear least squares
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
OTFS	orthogonal time frequency space
PA	power amplifier

PAM	pulse amplitude modulation
PAPR	peak-to-average power ratio
PDF	probability density function
PLL	phase-locked loop
PMF	polymer microwave fiber
PSK	phase shift keying
PSD	power spectral density
PSO	particle swarm optimization
PTRS	phase tracking reference signal
QAM	quadrature amplitude modulation
RF	radio frequency
RoF	radio-over-fiber
RRC	root raised cosine
RMSE	root mean squared error
RU	radio unit
SC-FDMA	single-carrier frequency domain multiple access
SC-FDE	single-carrier with frequency-domain equalization
SE	spectral efficiency
SNR	signal-to-noise ratio
Sub-THz	sub-terahertz
ToA	time-of-arrival
UE	user equipment
UL	uplink
URLLC	ultra-reliable low-latency communication
VR	virtual reality

Chapter 1

Introduction

Mobile communication systems have been evolving since the 1970s and are envisioned to transition into the sixth generation (6G) in 2030 [1]. It has expanded the boundaries of the digital world, and its applications span several fields, including not only traditional telecommunication, but also healthcare, transport, and industry [2]. The reason behind this evolution is the rising demand for wireless connectivity. The 6G mobile network is envisioned to offer ubiquitous connectivity, extreme data rate, and new services. Despite extensive investigation in the use cases, trends, and capabilities of 6G, we are still to define technical performance requirements, system architecture, and operational feasibility in the following years.

Despite the ambitious vision and promising capabilities of 6G, fundamental limitations remain. In particular, the congested spectrum has become a bottleneck for communication systems. Existing communication systems occupy sub-10 GHz frequencies, where the contiguous bandwidth per carrier is typically limited to at most a few hundred megahertz. Giving that the envisioned transmission rate of 6G is unprecedented (even up to Terabits per second), implementing future communication systems in a frequency band that offers an ultra-large bandwidth is crucial for some applications. The sub-terahertz (sub-THz) frequency band has been attractive due to its abundant spectrum resources [3]. However, there are several drawbacks for operating communication systems in sub-THz frequencies, which include i) low penetration ability [4], ii) increased path loss [3], iii) degraded hardware energy efficiency, iv) significant hardware impairments, and v) increased hardware cost.

This thesis investigates a novel, low-cost, and densely deployable radio-over-fiber (RoF) system that connects several radio units (RUs) or booster units (BUs), and polymer microwave fiber (PMF) segments in a cascade. Both the RUs and BUs can amplify the incoming signals and forward them to the subsequent component of the stripe. However, only the RUs are equipped with antennas and can therefore function as access points (APs). Unlike conventional APs, the cost of RUs are significantly reduced due to the absence of a digital signal processing (DSP) unit. The dense deployment of APs ensures the coverage and compensates for the high path loss. Operating at high frequencies imposes strict power efficiency constraints, and PAs present limited gain; they are forced to work in saturation where non-linearities occur. Therefore, this thesis addresses key challenges associated with the application of RoF systems, with particular emphasis on accounting for various impairments. Despite the significant challenges that cumulative hardware impairments pose to received-signal processing, they also embed distance-dependent signatures that can be exploited to estimate the propagation distance of incoming signals in a RoF stripe. On the other hand, selecting and designing a suitable waveform that is sufficiently robust to severe hardware impairments is crucial to achieving high-quality information transmission in the RoF system considered. Consequently, the contributions of this work are two-fold.

1.1 Thesis Outline

In Chapter 2, we introduce the characteristics of PMF and working principles of RoF technologies to lay the background of this thesis. We also highlight the novelty of the studied cascade-structured RoF system and its difference to the conventional RoF system. In Chapter 3, we discuss the principles of waveform design, waveform selection criteria, and the key challenges in selecting or designing waveforms for cascade-structured RoF systems. Chapter 4 lists the included and excluded papers. Chapter 5 provides the conclusions and potential future directions. Subsequently, we present the contributions of this thesis through the included papers, i.e., Paper A and Paper B.

Chapter 2

Radio-over-Fiber Technologies

This chapter begins by outlining the working principles of RoF communication. Then, the current status of PMF is presented, followed by an analysis of the characteristics of its propagation channel. The differences between the considered RoF system and conventional RoF systems are highlighted. Lastly, we provide the main challenges in the studied RoF system.

2.1 RoF Communication

The primary motivation for developing RoF systems is to mitigate the excessive path loss associated with high-frequency wireless propagation channels. The idea of a traditional RoF communication is to merge radio frequency (RF) and optical fiber in one system, where the transmission of high-frequency RF signals between the central unit and the APs is via low-loss optical fiber (shown in Fig. 1). A traditional RoF system employs optical components, and the RF signals are converted to optical signals and transmitted through the optical fiber. On the receiver side, the optical signals are converted to RF signals for further processing. During this process, the signals are confined in the optical fiber all the time. Therefore, the received signals have more energy. The wireless propagation channel only constitutes a small fraction of the whole communication link.

RoF was proposed in the 1990s [5,6] and has been attracting attention since the development of millimeter wave (mmWave) communication because it has a promising potential to offer a reliable and efficient service for high-frequency broadband communication [7]. However, the optical components, especially

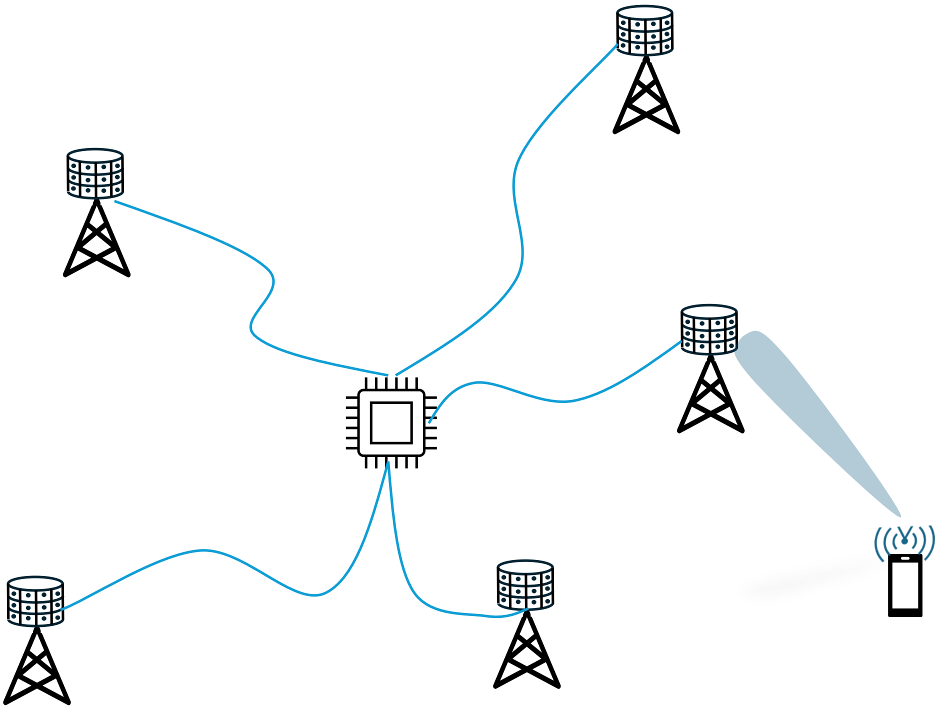


Figure 1: RoF communication system.

lasers and materials, usually introduce significant non-linear distortion.

2.2 RoF with PMF

On the other hand, PMF enables the transmission of RF signals without requiring any optical components, thereby avoiding undesired non-linear distortion. Moreover, PMF usually has a larger size than optical fibers, which offers simpler alignment. Inspired by recent advances in PMF, the implementation of a system RoF with PMF has been envisioned to be a robust, low-cost, and flexible solution for the future communication system [8].

When a PMF segment serves as the propagation medium, it acts as a dielectric waveguide where signals are well confined in and around the fiber [8]. Comparing the path loss of the same propagation distance over the PMF with the wireless channel, the state-of-the-art PMF only attenuates the signals less than 5 dB per meter [9] in the D-band (110 GHz to 170 GHz), while the Friis' equation tells us the free space path loss (FSPL) is around 70

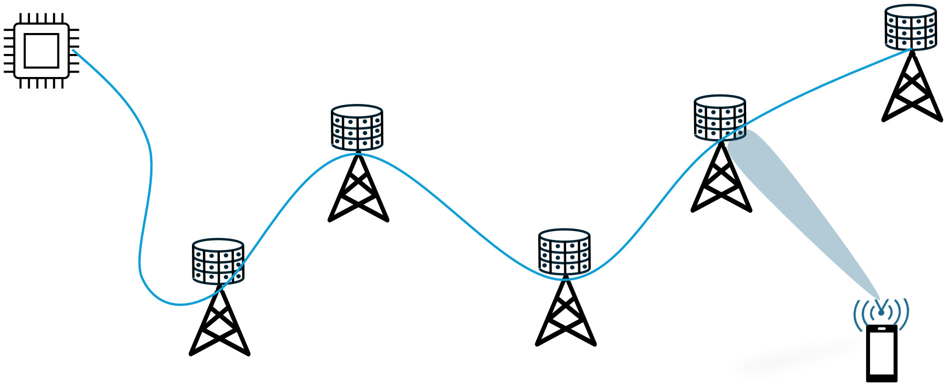


Figure 2: Cascade-structured RoF System.

dB [10].

In addition to the benefit of low loss, another stringent advantage of PMF is low cost. PMFs are made of cheap plastics, where many excellent materials are available, for example, the fiber considered in this thesis is made of polythylene [9]. In addition, PMF is flexible for deployment. The distance of a PMF segment can be flexible, and its channel response can be calculated based on the given channel knowledge over a fixed length. For a fixed-length PMF segment, it can be modeled as an linear time-invariant (LTI) system, and its impulse response is assumed to be $h(t)$. Taking the length of this PMF segment as the unit length, an r-unit length PMF segment is equivalent to connecting r identically the same LTI systems in a cascade, and its impulse response can be written as

$$\tilde{h}(t) = \underbrace{h(t) * h(t) * \cdots * h(t)}_{r\text{ convolutions}}. \tag{1}$$

In addition, with the increase in the carrier frequency, the signal is better confined in the fiber. Consequently, employing PMFs in high frequencies, such as the D-band, is robust to the bending of PMFs.

2.3 RoF with a Cascaded Structure

As exhibited in Fig. 1, the conventional RoF systems have a star structure, where several APs are directly connected to the center via a fiber. By contrast, the RoF system considered in this thesis has a daisy-chain structure, where several APs are connected in a cascade by a shared medium-fiber, and a central unit is connected at the end of each stripe. This concept should not be confused with radio stripe, which was proposed by Ericsson in 2019 [11]. The main difference between the radio stripe architecture and the studied system is that the latter does not operate as a distributed multiple-input-multiple-output (MIMO) system. Due to the operation in the sub-THz frequency band, only a small fraction of APs can capture the incoming signals, whereas the radio stripe assumes that all APs can receive the transmitted signals. Another significant difference is the absence of a digital signal processing unit at the APs in the studied system, which is intended to further reduce cost and energy consumption.

The studied cascade-structured RoF system is considered to be densely deployed in indoor scenarios to provide extreme data rates and reliable wireless connectivity for user equipments (UEs). As for the uplink, the UE transmits sub-THz signals over the air and the antennas at the nearby one or multiple APs capture the incoming signals. At each component in a stripe, one power amplifier (PA) is equipped to amplify the signals. From the perspective of energy efficiency, PAs are allowed to work in the non-linear regime. A third-order memoryless polynomial model can well capture the characteristics of a PA [12], which can be written as

$$y_n = G(x_n + \lambda x_n |x_n|^2), \tag{2}$$

where x_n and y_n denote the input sample and the output sample, G is the amplitude amplification factor, and λ is the non-linear factor. Between any two components in a stripe, the interconnection is provided by a PMF segment, whose channel can be modeled as an LTI system. Therefore, the studied system connects non-linear systems and LTI systems in cascade.

2.4 Main Challenges in RoF with a Cascaded Structure

To the best of the author's knowledge, the signal processing of a system that sequentially connects LTI systems and non-linear systems has never been investigated before. In this section, we provide an analysis of the main challenges in this novel system.

2.4.1 Hardware Impairments

Hardware impairments such as non-linear distortions, phase noise, and dispersion are severe in this system due to two factors: i) the high center frequency, ii) the cascaded structure.

With an increase in the center frequency, the phase noise becomes more significant, thus degrading the performance of the demodulator. Additionally, the energy efficiency of the PA decreases with a higher center frequency. Therefore, the PAs must adopt a smaller input power back-off, resulting in more non-linear distortion. More problematically, the longer the propagation distance in a stripe is, the more PAs and PMF segments are included in the link. During propagation in a stripe, the signals undergo non-linear amplification and dispersion sequentially until they reach the central unit. Consequently, the undesired hardware impairments accumulate along the transmission of signals in a stripe.

2.4.2 Noise

In each amplification stage of this system, the noise from many different independent sources aggregates. According to the Central Limit Theory, the aggregate noise can be approximated as an additive white Gaussian noise (AWGN). Each PA introduces an independent AWGN term. Apparently, the signal-to-noise ratio (SNR) decreases along the signal propagation in a stripe because the noise accumulates. More importantly, the AWGN noise also experiences non-linear amplification and dispersion. If we assume the PAs work in the linear regime, the aggregated noise at the central unit is still a Gaussian variable because the LTI system preserves the Gaussianity. However, if the PAs work in the non-linear regime and the number of amplification stages is not large enough, the distribution of the aggregated noise at the central unit is unknown. As a result, mathematical tools that are optimal under a Gaussian model are no longer optimal, for example, the maximum-likelihood estimator.

2.4.3 Initial Access

There are many ways to configure the APs in a stripe. An option is that the APs can be in sleep mode and be awakened when they detect the antenna port receives more energy than a predefined threshold. However, it is not feasible considering the absence of a digital signal processing unit in APs. A more practical solution is that the central unit activates APs one by one in a sequential order. Without the prior knowledge of the UE position, the central unit is unable to find the most suitable AP to be active. However, this configuration may increase the latency and reduce the reliability of the communication when the UE moves. Despite the many possible configurations of the stripe, we assume all APs in a stripe are active, and the signals can enter the stripe via any of them.

Adopting the aforementioned configuration brings a critical problem for localizing the UE because the central unit lacks the knowledge of the location of the AP that captures the incoming signals. At least three anchors are required to localize a point in a two-dimensional space [13]. In this system, the anchors are APs that capture the signals in different RoF stripes. To enable the positioning service of the studied system, the central units must estimate the location of the anchors as well as the distance between the UE and the anchor. Paper A proposes an uplink positioning algorithm for this task.

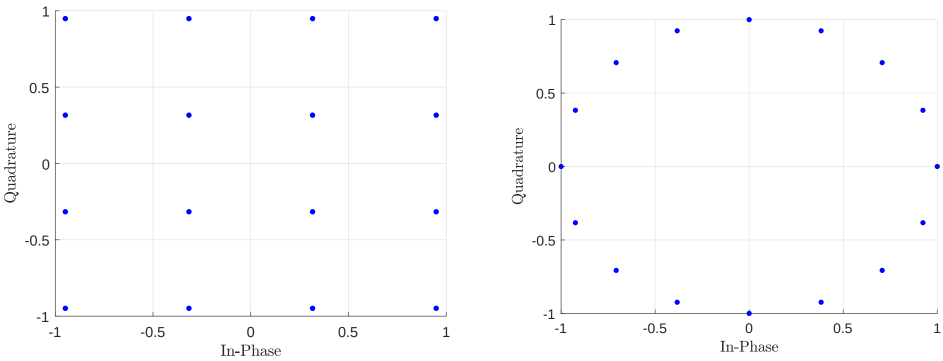
Chapter 3

Waveform Design: Selection Criteria and Challenges

This chapter provides the preliminaries of the waveforms and the main challenges of waveform design in the cascaded-structured RoF system considered in this thesis.

3.1 Principles of Waveform Design

Given the information bits, they are mapped to symbols and modulated to generate the transmitted signal. In general, information can be conveyed by modulating one or more of the following signal parameters: amplitude, phase, and frequency. One of the basic methods for embedding bits into a signal is amplitude modulation, where the amplitude of the carrier signal is varied according to the information bits; for example, the amplitudes 1 and 3 are mapped to '00' and '01,' respectively, while -1 and -3 are mapped to '10' and '11.' This is a pulse amplitude modulation (PAM) scheme with four possible bit combinations, corresponding to a constellation order of $M = 4$. Besides the amplitude of the signal, its phase can also be used in non-linear modulations. One of the basic forms is phase shift keying (PSK), the phase $1/4\pi$ and $3/4\pi$ are mapped to '00' and '01' while $-1/4\pi$ and $-3/4\pi$ are mapped to '10' and '11.' As both the amplitude and phase of the signals can carry information, it is reasonable to expect that we shall design a constellation that utilizes both dimensions of the transmitted signals, i.e., conveying information bits in phasors. A phasor, e.g., $Ae^{j\theta}$, represents the amplitude and phase of a sinusoidal signal. Considering the celebrated Euler's equation $Ae^{j\theta} = A\cos\theta + jA\sin\theta$. Each phasor admits



(a) 16-QAM

(b) 16-PSK

Figure 3: Constellation plots of different modulation schemes.

an equivalent complex-valued representation, in which the real part $A\cos\theta$ is referred to as the in-phase component, and the imaginary part $A\sin\theta$ is referred to as the quadrature component. This modulation scheme can be seen as a combination of amplitude and phase modulation and is known as quadrature amplitude modulation (QAM), which is widely employed in existing communication systems [14]. Typically, we use a constellation plot to illustrate the modulation order and the transmitted symbols. For example, Fig. 3 illustrates the constellation plots of 16-QAM and 16-PSK, respectively.

Waveform characterizes the shape of the transmitted signal as a function of time. To generate a waveform, discrete symbols must be mapped onto the continuous-time signal. Generally, there are two mapping strategies: i) linear mapping, in which the symbols are firstly modulated by using a set of basis functions and subsequently shaped by a pulse-shaping filter, and ii) non-linear mapping, in which the transmitted signal depends non-linearly on the symbol sequence.

Regarding the linear mapping strategy, an orthonormal basis can be used to modulate different symbols in the time domain [15]. Any orthonormal basis can be interpreted as a unitary matrix $\boldsymbol{U} = [u_0, u_1, \cdots, u_{N-1}]$. Therefore, the transmitted baseband signals in discrete time are

$$\boldsymbol{s} = \boldsymbol{U}\boldsymbol{x}. \tag{3}$$

The simplest basis is the identity matrix $\boldsymbol{I}_N$, indicating that symbols are transmitted sequentially in the time domain, which corresponds to single carrier (SC) transmission [16]. The most commonly employed waveform in existing communication systems is orthogonal frequency division multiplexing

(OFDM), which utilizes a normalized discrete Fourier transform (DFT) matrix $\boldsymbol{F}_N^{\mathrm{H}}$ as its basis. The transmitted symbols are mapped onto N subcarriers, after which a DFT is applied to spread the symbols across the full time-domain signal [16]. Given discrete-time baseband symbols, a pulse-shaping filter is applied to generate a continuous-time waveform. Therefore, the transmitted baseband signals in continuous time are

$$s(t) = \sum_n s_n p(t - nT), \tag{4}$$

where $p(t)$ denotes the pulse shaping impulse response and T is the symbol duration. The choice of pulse shaping filter depends on the waveform. For example, raised root cosine (RRC) filters are widely used in SC transmission, whereas OFDM is typically modeled using rectangular pulse shaping in the time domain. Finally, the continuous-time baseband signal is upconverted to the carrier frequency for transmission.

Regarding the non-linear mapping strategy, a representative waveform of this category is continuous phase modulation (CPM), where information symbols is embedded in the continuous phase trajectory of the transmitted signal [17].

3.2 Selection Criteria

Although there is a wide range of candidate waveforms, selecting or designing a waveform that is well matched to both the channel characteristics and the system objectives is crucial. For instance, an OFDM waveform is well suited for multipath propagation channels due to its simple frequency domain equalization, whereas constant-envelope waveforms are attractive for transmission when non-linear components are employed in the communication system. Moreover, different applications impose different waveform requirements. Radar systems typically favor waveforms with low normalized sidelobe magnitudes in the ambiguity function to enable accurate sensing and target detection, while communication systems typically emphasize waveforms that achieve high data throughput. Waveform design continues to evolve across a wide range of signal transmission systems. For instance, in emerging integrated sensing and communication (ISAC) systems, it is evolving toward the use of a single waveform that simultaneously supports sensing and communication tasks with conflicting requirements. The balance between these sensing- and communication-oriented requirements must be struck, which motivates the development of joint waveform design frameworks.

3.3 Challenges in Selecting Waveforms for Cascade-Structured RoF Systems

In the cascade-structured RoF system, the hardware impairments are expected to be severe; hence, selecting a waveform that is well-tolerant to the hardware impairments is crucial. First, PAs constitute a major source of non-linear distortion. This issue is particularly pronounced at sub-THz frequencies, where the energy efficiency of PAs is inherently low due to limited device gain and increased circuit losses. To avoid excessive efficiency loss caused by output back-off, PAs are often operated close to saturation, making non-linear operation a practical necessity. Second, the phase noise induced by the local oscillator must be carefully addressed, as its effect is strongly amplified at sub-THz frequencies due to the high carrier frequency. Finally, waveform design must also account for baseband processing power consumption, as waveform-dependent requirements on sampling rate and signal processing complexity can make digital processing a significant contributor to the overall energy budget.

The aforementioned challenges are common to systems operating at sub-THz frequencies; however, cascade-structured RoF systems introduce several additional, system-specific challenges. The cascade of non-linear PAs and dispersive PMF segments leads to an accumulation of non-linear distortions. Moreover, noise introduced and amplified by successive PAs stages accumulates along the propagation in the RoF system, leading to a pronounced degradation in system performance.

While waveform selection is well understood for many communication systems, the behavior of different waveforms in cascade-structured RoF systems—where non-linear components and LTI systems are connected in a cascade—has not yet been systematically investigated. To bridge this gap, this thesis evaluates multiple candidate waveforms in the considered RoF architecture to understand their performance better and identify waveforms that are well-suited to the system.

Chapter 4

Contributions of the Thesis

This thesis contributes to the cascade-structured RoF with PMF system and includes two papers. In Paper A, we focus on the initial access of the studied system and propose an uplink positioning algorithm that exploits the cumulative hardware impairments and noise while the incoming signals propagate in a RoF stripe. In Paper B, we investigate several candidate waveforms for sub-THz communication and select the most suitable waveform for the studied system.

4.1 Included Papers

Paper A: Radio over Fiber with Cascaded Structure: Algorithm for Uplink Positioning

Authored by: Dexin Kong, Diana Pamela Moya Osorio, and Erik G. Larsson

Accepted by IEEE Transactions on Wireless Communications, Dec. 2025

Abstract: Recent advancements in polymer microwave fiber (PMF) technology have created significant opportunities for robust, low-cost, and high-speed sub-terahertz (THz) radio-over-fiber communications. Recognizing these potential benefits, this paper explores a novel radio-over-fiber (RoF) structure that interconnects multiple radio units (RUs), booster units (BUs), and a central unit (CU) in cascade via fiber, envisioning its application in indoor scenarios. This structure creates a number of research opportunities when considering cascaded distortion effects introduced by non-linear power amplifiers (PAs) and the propagation channel over the fiber.

We propose maximum-likelihood and non-linear least-squares algorithms

to estimate the entry RU and the time-of-arrival between the RoF and the user equipment, where estimating the entry RU is equivalent to estimating the propagation distance along the RoF stripe. For the case of linear PAs, we derive the Cramér-Rao lower bound to benchmark the performance of the estimators. Finally, we investigate the use of the system for uplink positioning. Our simulation results demonstrate that the proposed estimators perform satisfactorily even with the cascaded effects of non-linear PAs, and that the deployment of this RoF structure can enable new cost-effective opportunities for high-resolution positioning in indoor scenarios. In the numerical evaluation, we also use measured PMF characteristics for high-density polyethylene fibers.

Paper B: Hardware-Aware Waveforms for Sub-THz Cascade-Structured Radio-over-Fiber Systems

Authored by: Dexin Kong, Diana Pamela Moya Osorio, Ove Edfors, and Erik G. Larsson

Draft manuscript in preparation

Abstract: Sub-terahertz (Sub-THz) communication is a promising enabler for ultra-high data-rate transmission, owing to its abundant spectrum resources that support extreme data rates, high spatial resolution, and low latency. However, the unfavorable propagation characteristics and significant hardware impairments pose substantial challenges to practical deployment, often resulting in high implementation costs. As an alternative, novel radio-over-fiber (RoF) architectures can facilitate cost-effective realization of sub-THz systems. Nevertheless, the choice of waveform remains a critical design factor, as it directly influences both the overall system performance and the transceiver architecture.

This paper introduces candidate waveforms and compares them across several performance metrics to elucidate their robustness against hardware impairments. We classify the investigated waveforms into three operational regimes, each corresponding to distinct system configurations. Furthermore, selected waveforms are generated and evaluated within a recently proposed cascade-structured RoF Sub-THz system. Importantly, we provide novel insights and comprehensive discussions on the dominant characteristics of each waveform, highlighting the most suitable option for the considered architecture, along with a detailed complexity analysis.

4.2 Excluded Papers

Paper C: Propagation Distance Estimation for Radio over Fiber with Cascaded Structure

Authored by: Dexin Kong, Diana Pamela Moya Osorio, and Erik G. Larsson

Published in the proceedings of 25th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Lucca, Italy, 2024, pp. 691-695.

This paper contains preliminary results of Paper A.

Abstract: Recent developments in polymer microwave fiber (PMF) have opened great opportunities for robust, low-cost, and high-speed sub-terahertz (THz) communications. Noticing this great potential, this paper addresses the problem of the estimation of the propagation distance of a sub-Thz signal along a radio-over-fiber structure. Particularly, this paper considers a novel cascaded structure that interconnects multiple radio units (RUs) via fiber for applications in indoor scenarios. Herein, we consider the cascaded effects of distortions introduced by non-linear power amplifiers at the RUs, and the propagation channel over the fiber is based on measurements obtained from transmissions of sub-THz signals on high-density polyethylene fibers. For the estimation of the propagation distance, non-linear least-squares algorithms are proposed, and our simulation results demonstrate that the proposed estimators present a good performance on the propagation distance estimation even in the presence of the cascaded effect of non-linear PAs.

Chapter 5

Conclusions and Future Directions

In this chapter, we conclude the main takeaways of this thesis and provide several future directions that are worth further investigation.

5.1 Conclusions

In this thesis, we study a novel cascade-structured RoF system operating at sub-THz frequencies, which is a promising, low-cost, densely deployable, and energy-efficient solution for indoor communications. To the best of the author's knowledge, this thesis is the first to contribute to the signal processing of cascading LTI components and non-linear elements.

In the study of uplink signal processing, we propose an uplink positioning algorithm that jointly estimates the time-of-arrival (ToA) between the UE and the RoF stripe as well as the distance that the signals propagate in a stripe. We consider two scenarios: i) PAs work in the linear regime, and ii) PAs work in the non-linear regime. The proposed algorithm comprises a maximum likelihood (ML) estimator operating in the linear regime and an non-linear least squares (NLS) estimator designed for the non-linear regime. We show that the proposed ML estimator achieves the Cramér-Rao lower bound (CRLB). Although the CRLB for the NLS estimator is not available in closed form, we demonstrate through simulations that the proposed NLS estimator attains high positioning accuracy for UE localization in an indoor scenario. This contribution can be a building block for a high-resolution indoor positioning solution.

From the perspective of the waveform, we identify the primary sources of hardware impairments in sub-THz communication systems and study several candidate waveforms for the sub-THz communication systems. We evaluate multiple candidate waveforms in the cascade-structured RoF system considered and demonstrate that a constant-envelope waveform, which is commonly regarded as the preferred choice for non-linear systems, performs poorly in the considered system. Moreover, the single-carrier with frequency domain equalization (SC-FDE) achieves the lowest bit error rate (BER) in a 4-stage RoF stripe. In terms of digital baseband complexity and power consumption, cyclic-prefix orthogonal frequency division multiplexing (CP-OFDM) has the lowest complexity/power consumption. These findings pave the way for further investigations into waveform design that is robust to cascaded LTI and non-linear elements.

5.2 Future Directions

To enable the practical deployment of the cascade-structured RoF system, some future directions are:

- The distribution of a Gaussian random variable subjected to non-linear distortion and dispersion in a cascaded system is unknown. Consequently, the optimality of the proposed estimators cannot be theoretically verified. A potential direction for future work is to characterize this distribution through the estimation of its second-order statistics.

- The deployment of RoF stripes plays a crucial role in both positioning accuracy and communication performance. In Paper A, we investigate the impact of the topology formed by three RoF stripes on the positioning performance. To enhance positioning accuracy, RoF stripes should be deployed in a topology that minimizes the geometric dilution of precision (GDOP). However, the topology that yields the minimum GDOP is not necessarily optimal for communication performance; for instance, it may result in a large average communication distance. A potential direction for future work is to develop an optimization framework for the deployment of multiple RoF stripes under different deployment scenarios.

- The configuration of PAs is challenging. The considered system consists of multiple PAs in a cascade. The PA gains and the input power back-off (IBO) of the input signal must be carefully designed to preserve the desired signal power while ensuring that the resulting non-linear distortion remains tolerable. Some proposed optimization solution [18] is to select PA gains and IBO to reduce the out-of-band radiation. However, the PMF dispersion was not considered in the optimization framework. Future work may incorporate the PMF dispersion to render the optimization framework more practical.

- Equalization in cascade-structured systems is challenging. Conventional communication systems typically employ linear equalizers, such as the zero forcing (ZF) equalizer. However, the presence of non-linear PAs significantly degrades the performance of linear equalization. Similarly, pilot-based channel estimation is unable to accurately capture the distortions introduced by non-linear PAs.

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Included Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789181184884

PAPER A

Radio over Fiber with Cascaded Structure: Algorithm for Uplink Positioning

Refereed paper published in IEEE Transactions on Wireless Communications

PAPER B

Hardware-Aware Waveforms for Sub-THz Cascade-Structured Radio-over-Fiber Systems

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