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A Study on Chirp-Based Detection and Synchronization Techniques for Wireless Communications

Ana Belén Martínez

der Fakultät Elektrotechnik und Informationstechnik der
Technischen Universität Dresden

zur Erlangung des akademischen Grades

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Abstract

The unstoppable development of wireless communication systems has a profound impact on many aspects of society and this trend is growing at an incredible speed. The recent advancements have made possible not only the definition, but also the implementation of entirely new applications with diverse requirements regarding data rate, coverage, latency and power consumption. Thus, the infrastructure behind these new and upcoming applications has to provide the flexibility necessary to configure each part of a communication system appropriately and fulfill the specific requirements.

This thesis focuses on the investigation of two crucial tasks that have to be performed at the receiver of a communication system, namely frame detection and synchronization. Matched filtering with the assistance of linear frequency modulated (LFM) signals constitutes a low latency and high performance technique for frame detection. Furthermore, in combination with their complex conjugate versions, LFM signals facilitate the estimation of the synchronization parameters by decoupling the time and frequency offsets. However, even though LFM signals are significantly robust against frequency offsets when subjected to matched filtering, the digitalization conducted at the receiver can lead to a strong degradation for certain conditions of time and frequency offsets. Currently, most of existing solutions to this problem resort to oversampling as well as interpolation techniques that are associated with an inevitable increase in complexity.

One of the major goals of this work is to identify and solve the main challenges that degrade the detection performance and the estimation of the synchronization parameters when using matched filtering together with discrete versions of LFM signals. The analysis conducted in this dissertation indicates that the sources of degradation can be efficiently tackled with a suitable extension of the transmitted reference signal and a detector consisting of only two matched filters. It is shown that, without employing computationally expensive procedures, the proposed solution offers a detection performance similar to the ideal one achievable in the absence of offsets. Moreover, profound insights have been gained into the frame detection technique accomplished in frequency domain with the help of periodic signals. Exploiting the periodicity of the reference signal with an accumulative metric has proven to be beneficial in enhancing the detection probability associated to the approach commonly found in the literature.

An important objective of this thesis is the investigation of low complexity detection

approaches based on autocorrelation metrics and the study of the relationship between detection based on matched filtering and autocorrelation. It is demonstrated that, since autocorrelation metrics cannot fully benefit from the knowledge of the signal, longer reference signals are needed to achieve a certain target detection probability than with matched filtering, which has important implications in terms of latency and energy demands.

The structure and properties of the reference signals have been properly taken into consideration for the development of new synchronization algorithms. It is found that reversing the traditional order of estimation and compensation of the components of the carrier frequency offset can lead to a low complexity and ambiguity-free estimation approach. Moreover, the effectiveness of methods based on reversed autocorrelation metrics in resolving estimation ambiguities has been successfully demonstrated.

In conclusion, the results gained during this dissertation prove the validity of the proposed approaches in dealing with the degradation of detection and synchronization performance associated to the use of matched filtering with LFM signals in digital communication receivers. Furthermore, the findings of the comparative study of detection based on different metrics can be used as a guideline for the selection of algorithms and the design of reference signals that can meet specific requirements.

Kurzfassung

Die kontinuierliche Entwicklung von drahtlosen Kommunikationssystemen hat tiefgreifende Auswirkungen auf viele Aspekte der Gesellschaft, und dieser Trend nimmt mit unglaublicher Geschwindigkeit zu. Die neuesten Fortschritte haben nicht nur die Definition, sondern auch die Implementierung von vollkommen neuen Anwendungen mit unterschiedlichen Anforderungen in Bezug auf Datenrate, Abdeckung, Latenzzeit und Stromverbrauch ermöglicht. Daher muss die Infrastruktur, die hinter diesen neuen und zukünftigen Anwendungen steht, die nötige Flexibilität bieten, um jeden Teil eines Kommunikationssystems entsprechend zu konfigurieren und die spezifischen Anforderungen zu erfüllen.

Diese Arbeit beschäftigt sich mit der Untersuchung von zwei entscheidenden Aufgaben, die am Empfänger eines Kommunikationssystems durchgeführt werden müssen, nämlich der Framedetektion und der Synchronisierung. Matched-Filterung mit Hilfe von linear frequenzmodulierten (LFM) Signalen stellt eine Technik mit geringer Latenz und hoher Leistung für die Framedetektion dar. Darüber hinaus erleichtern LFM-Signale in Kombination mit ihren komplex konjugierten Versionen die Schätzung der Synchronisationsparameter durch Entkopplung der Zeit- und Frequenzversätze. Obwohl LFM-Signale bei Matched-Filterung sehr robust gegenüber Frequenzversätzen sind, kann die im Empfänger durchgeführte Digitalisierung bei bestimmten Bedingungen von Zeit- und Frequenzversätzen zu einer starken Degradierung führen. Zurzeit greifen die meisten existierenden Lösungen für dieses Problem auf Überabtastungs- und Interpolationstechniken zurück, die zwangsläufig mit einem Anstieg der Komplexität verbunden sind.

Ein Hauptziel dieser Arbeit ist es, die wichtigsten Probleme zu identifizieren und zu lösen, die die Leistung der Detektion und die Schätzung der Synchronisationsparameter bei der Verwendung von Matched Filtern zusammen mit diskreten Versionen von LFM-Signalen beeinträchtigen. Die in dieser Dissertation durchgeführte Analyse zeigt, dass die Ursachen der Degradierung mit einer geeigneten Erweiterung des übertragenen Referenzsignals und einem Detektor, der nur aus zwei angepassten Filtern besteht, wirksam bekämpft werden können. Es wird gezeigt, dass die vorgeschlagene Lösung ohne den Einsatz rechenintensiver Verfahren eine Detektionsleistung bietet, die der idealen Leistung entspricht, wenn kein Versatz vorhanden ist. Darüber hinaus wurden tiefe Einblicke in die Detektionstechnik gewonnen, die im Frequenzbereich

mit Hilfe periodischer Signale durchgeführt wird. Die Ausnutzung der Periodizität des Referenzsignals mit einer akkumulativen Metrik hat sich als vorteilhaft erwiesen, um die Detektionswahrscheinlichkeit zu erhöhen, die mit dem in der Literatur üblichen Ansatz verbunden ist.

Ein wichtiges Ziel dieser Arbeit ist die Erforschung von Detektionsverfahren mit geringer Komplexität auf der Grundlage von Autokorrelation-Metriken und die Untersuchung des Verhältnisses zwischen der Detektion auf der Grundlage von Matched-Filterung und Autokorrelation. Es wird gezeigt, dass Autokorrelation-Metriken nicht in vollem Umfang von der Kenntnis des Signals profitieren können und daher längere Referenzsignale erforderlich sind, um eine angestrebte Detektionswahrscheinlichkeit zu erreichen, als dies bei der Matched-Filterung der Fall ist, was erhebliche Auswirkungen auf die Latenzzeit und den Energiebedarf hat.

Die Struktur und die Eigenschaften der Referenzsignale wurden bei der Entwicklung neuer Synchronisierungsalgorithmen angemessen berücksichtigt. Es hat sich gezeigt, dass die Umkehrung der traditionellen Reihenfolge von Schätzung und Kompensation der Komponenten des Trägerfrequenzversatzes zu einem Schätzungsansatz mit geringer Komplexität und ohne Mehrdeutigkeit führen kann. Darüber hinaus wurde die Wirksamkeit von Methoden, die auf umgekehrten Autokorrelation-Metriken basieren, bei der Lösung von Schätzungsmehrdeutigkeiten erfolgreich demonstriert.

Zusammenfassend lässt sich sagen, dass die in dieser Dissertation gewonnenen Ergebnisse die Gültigkeit der vorgeschlagenen Ansätze im Umgang mit der Verschlechterung der Detektions- und Synchronisierungsleistung im Zusammenhang mit der Verwendung von Matched-Filtern mit LFM-Signalen in digitalen Kommunikationsempfängern belegen. Weiterhin können die Ergebnisse der vergleichenden Studie zur Erkennung auf der Grundlage verschiedener Metriken als Richtlinie für die Auswahl von Algorithmen und die Gestaltung von Referenzsignalen verwendet werden, die spezifische Anforderungen erfüllen können.

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Approaching the end of this journey, and reflecting back, I would like to express my deepest gratitude to those people who have contributed to the success of this project in different ways.

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I would like to express my warmest gratitude to my family, especially to Arantxa, my sister and best friend, for her unconditional encouragement, and to Sven, my partner in life, for his understanding and support throughout this time.

I dedicate this thesis to my daughter, Sophie, my best source of happiness.

Dresden, September 2022 Ana Belén Martínez

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List of Abbreviations

ADC	analog-to-digital converter
AC	autocorrelation
AI	artificial intelligence
AWGN	additive white Gaussian noise
BER	bit error rate
BLUE	best linear unbiased estimator
CFAR	constant false alarm rate
CFO	carrier frequency offset
$\mathbf{CFO_{frac}}$	fractional CFO
$\mathbf{CFO_{frac,res}}$	residual $\mathrm{CFO_{frac}}$
$\mathbf{CFO_{int}}$	integer CFO
CLT	central limit theorem
CP	cyclic prefix
CRLB	Cramér-Rao lower bound
CS	cyclic suffix
DA	data-aided
DAC	digital-to-analog converter
DC	direct current
DFT	discrete Fourier transform
eMBB	enhanced mobile broadband
FFT	fast Fourier transform
FIR	finite impulse response
FSC	frequency selective channel
FT	Fourier transform
GSM	global system for mobile communications
HD	high definition
LF	likelihood function
LFM	linear frequency modulated
LLF	log-likelihood function

LO	local oscillator
LoRa	long range
LOS	line-of-sight
LPWAN	low-power wide-area network
LS	least-squares
LTV	linear time-varying
MF	matched filter
ML	maximum likelihood
MMS	multimedia message service
MMSE	minimum mean squared error
mMTC	massive machine type communication
MSE	mean squared error
MVU	minimum variance unbiased
NDA	non-data-aided
NLFM	non linear frequency modulated
NLOS	non-line-of-sight
NMSE	normalized mean squared error
NP	Neyman-Pearson
OFDM	orthogonal frequency division multiplexing
PAPR	peak-to-average power ratio
pdf	probability density function
PDP	power delay profile
PSD	power spectral density
RC	reversed autocorrelation
RF	radio frequency
rms	root mean square
SCO	sampling clock offset
SMS	short message service
SNR	signal-to-noise ratio
SoA	state-of-the-art
STO	symbol time offset
$\mathbf{STO_{int}}$	integer STO
$\mathbf{STO_{frac}}$	fractional STO
US	uncorrelated scattering
URLLC	ultra reliable low latency communication
WSS	wide-sense stationary
WSSUS	wide-sense stationary uncorrelated scattering

XC cross-correlation

Notation

Roman Letters and Arabic Numbers

B	Signal bandwidth
c	Speed of light
f_c	Carrier frequency
f_s	Sampling frequency
n	Discrete time domain index
N	Length of the reference field in samples
t	Continuous time domain variable
T_s	Sampling interval

Greek Letters

ϵ	Carrier frequency offset, normalized by the sampling frequency f_s
ϵ_I	Integer carrier frequency offset, normalized by the frequency bin spacing f_s/N
ϵ_F	Fractional carrier frequency offset, normalized by the frequency bin spacing f_s/N
θ	Symbol time offset, normalized by the sampling interval T_s
θ_I	Integer symbol time offset, normalized by the sampling interval T_s
θ_F	Fractional symbol time offset, normalized by the sampling interval T_s

Blackboard Bold Letters

$\mathbb{N}$	Set of natural numbers
$\mathbb{R}$	Set of real numbers

Calligraphic Letters

$\mathcal{H}_0$	Null hypothesis
$\mathcal{H}_1$	Alternative hypothesis

Operations and Functions

$\hat{\cdot}$	Estimated value
$[\cdot]$	Round operator
$\lfloor . \rfloor$	Floor operator
$E[\cdot]$	Expectation operator
$\lvert \cdot \rvert$	Absolute value
$\mathrm{Re}\{\cdot\}$	Real part of a complex number
$\mathrm{Im}\{\cdot\}$	Imaginary part of a complex number
$*$	Linear convolution

Chapter 1

Introduction

The continuous innovation and development of wireless communication systems is driving tremendous changes with profound economical, cultural and technological impact on society. Cellular communications have been relentlessly evolving through various generations over the past few decades. The early 1980s witnessed the birth of the initial commercial deployments of the first generation (1G) of cellular communication networks. Using analog technology, the main goal of wireless phones operating in 1G was voice telephony. The second generation (2G) adopted the migration to digital technology and introduced applications beyond voice communications, such as the short message service (SMS) and multimedia message service (MMS). The digitization started during the 2G era led to a rapid growth of mobile telephony. The third generation (3G) offered access to Internet applications and basic multimedia streaming. In order to enhance the performance of these services, a network architecture as well as new modulations and digital signal processing techniques were developed during the fourth generation (4G). As a result, 4G experienced a broad acceptance of smartphones, enabling higher voice quality, high-speed Internet access and high definition (HD) video streaming.

The fifth generation (5G) differs significantly from the previous generations. The proposed usage categories for 5G include ultra reliable low latency communication (URLLC) for mission critical applications, enhanced mobile broadband (eMBB) for applications demanding high data rates and high coverage, and massive machine type communication (mMTC) for applications aiming to connect a large number of low-power and low-cost devices. In 5G, the entire infrastructure is intended to act as a flexible platform for innovative applications in a variety of industry verticals. Currently, with 5G in the deployment phase, the sixth generation (6G) is gradually taking momentum. Numerous studies share their vision of 6G and analyze its requirements as a follow up and enhancement of 5G [FB21] [Net19].

In a wireless communication system, all components have to be carefully designed to properly perform their tasks while meeting specific application requirements. This thesis focus on two of the most critical tasks to be executed at the receiver of a communication system, namely frame detection and synchronization.

Only after having detected the presence of an incoming signal, the receiver can activate the subsequent blocks to recover the original message. Due to the significance of this step, considerable effort has been placed on the development of algorithms that can provide satisfactory detection probability. In order to achieve fast and accurate results, most existing solutions rely on reference signals that are sent prior to the information data, such as in the family of IEEE 802.11 standards [IEE99]. In principle, frame detection can be accomplished in time domain as well as in frequency domain. The most frequently used approaches that attempt to detect the frame in time domain can be divided into two categories. Algorithms belonging to the first category exploit the periodicity of the incoming signal with metrics based on autocorrelation. The second category includes those algorithms that filter the received signal with a filter that is matched to a known transmit signal. In frequency domain, the concept of matched filtering can be accomplished using dechirping and spectral analysis. In combination with periodic signals, this method has recently gained considerable attention, especially in the context of long range (LoRa) [Sem21] technology for low-power wide-area networks (LPWANs).

The received signal can be significantly affected by various factors related to the channel and hardware impairments. The signal arrives at a certain time instant, which, in principle, is completely unknown to the receiver. Furthermore, Doppler effects and inaccuracies between the oscillators at the transmitter and receiver can lead to relevant differences between the carrier of the received signal and the reference used at the receiver to perform the down-conversion. These synchronization parameters, known as symbol time offset (STO) and carrier frequency offset (CFO), have been shown to play a crucial role in achieving a reliable communication performance. Therefore, after frame detection, proper estimation and compensation of these parameters have to be accomplished. An initial estimation of the synchronization parameters is usually obtained by leveraging the information gained during the detection process previously conducted, fact that reveals the strong relationship between the detection and synchronization procedures. It becomes thus evident that not only the implementation of algorithms, but also the design of reference signals that can assist in both tasks, has to be carefully taken into consideration.

1.1 Background and Motivation

When aiming at low latency and high detection performance, the classical approaches par excellence are based on matched filtering. Since the signal knowledge is incorporated in the detection metric, this technique allows for fast results. Furthermore, for known deterministic signals in additive white Gaussian noise (AWGN), matched filtering is considered optimal according to the Neyman-Pearson (NP) criterion and in terms of signal-to-noise ratio (SNR) maximization [Kay98]. However, in the presence of unknown frequency offsets, the detection performance attainable with matched filtering can be severely degraded. Since the level of degradation highly depends on the properties of the reference signal utilized during the detection process, significant effort has been devoted to investigating the robustness of reference signals against this offset.

Signal design has been undoubtedly pioneered by radar scientists, who, with the application of pulse compression waveforms, developed numerous waveform modulations and processing techniques, thus establishing a radical change in radar communications. By adding frequency or phase modulation to a single pulse, pulse compression waveforms can be strategically designed to fulfill specific requirements. Various non linear frequency modulated (NLFM) signals [Coo64] have been proposed to obtain an output of the matched filter (MF) with low sidelobes, beneficial for the detection of closely separated targets. Linear frequency modulated (LFM) signals, with higher sidelobes than the non-linear versions, possess valuable features, such as the ease of implementation and the high level of tolerance to frequency offsets when being subjected to matched filtering. These properties have contributed to their widespread application not only in radar systems, but also in wireless communications systems.

Since the time and frequency offsets contained in an LFM signal are strongly intertwined, LFM signals in combination with their associated complex conjugates have been extensively employed in the literature for synchronization purposes. In theory, the information obtained after applying the corresponding MFs to these signals facilitates the decoupling of the mentioned offsets, and consequently, their estimation.

In wireless communication systems based on digital signal processing, the above-mentioned LFM signals have to be substituted by their discrete versions. Sampling LFM signals at the Nyquist rate leads to polyphase codes P3 or P4 [LK82], depending on whether the minimum phase slope occurs at the beginning or in the middle of the signal [Ric14]. Polyphase codes P3 and P4 inherit from the corresponding LFM signals the robustness against frequency offsets. Indeed, the output of the MF applied to theses codes only exhibits a slight attenuation in its envelope with increasing values of CFO. However, due to the discrete nature of the codes, the output of the MF cannot always be evaluated at the theoretical peak value, thus degrading the detection and synchronization performance. In order to overcome this degradation, numerous approaches assume a working frequency at the receiver significantly higher than the Nyquist rate [VPSE07] [LS09] [ZWX19] [ZY17]. In addition to oversampling, several interpolation techniques, such as least-squares (LS) [LH13], parabolic [ZWX19] or quadratic [VPSE07] interpolation, are usually applied. In frequency domain, approaches commonly rely on discrete Fourier transform (DFT) operations with selected upsampling factors [Lin14] [VPSE07]. Hence, the performance is largely determined by the computational burden.

In LoRa networks, in order to minimize the power consumption and keep the computational complexity to a minimum, it is a common practice to assume Nyquist-rate receivers [BDD20], a fact that poses a challenge in the detection and synchronization performance. Whereas frame detection is generally performed following the recommendations provided in [SS19] with slight modifications [GACB19] [EME+19] [XABL21], most of recent studies concentrate on the development of algorithms for accurate time and frequency synchronization. Assuming a normalization of the STO and the CFO by the sampling interval and the frequency bin spacing, respectively, dedicate approaches for the estimation of the integer and fractional parts of both offsets are described in [BDD20]. However, merely integer STO values are considered during the simulations. In [TAM+20], whose algorithms for the estimation of integer offsets are extracted from [BDD20], the simulations and measurements lack of a detailed description of the time and frequency offsets generation. Only the work presented in [XABL21] seems to efficiently handle the estimation of the synchronization parameters, showing superior evaluation performance than [BDD20] for arbitrary values of STO and CFO. Nevertheless, novel algorithms aiming to enhance the detection of a new frame remain unexplored.

Despite the well-proven detection performance of matched filtering, due to its sensitivity to the CFO and high computational burden, other approaches based on autocorrelation are commonly found in the literature. Indeed, among the main advantages of autocorrelation metrics are the robustness against the CFO and the low-complexity implementation [TMK+08] [CAFV12]. Frequently, the length of the sequence fields is either chosen according to the number of subcarriers of the multicarrier system employed to convey the information [SC97] [RAV+09] or specifically designed to facilitate the estimation of the CFO [MM99]. Thus, the structure of the reference sequence is usually determined based on the system parameters, with focus on synchronization, and might not be optimally designed in terms of detection performance.

In the past, numerous studies have compared the performance associated to various detection techniques. Especially in the field of spectrum sensing for cognitive radio, detection based on matched filtering is frequently compared to energy detection [PN20] and to other methods that exploit the cyclostationary properties of the signal [SGKF15] [BM10]. With particular emphasis on low complexity, the work in [WRKH17] evaluates the detection performance of the energy detector and several approaches derived from matched filtering. A comparison of the performance achievable with autocorrelation metrics using periodic sequences and with matched filtering has not been addressed in the literature.

Since basic information about the synchronization parameters can be obtained during the detection process, the reliability of the initial offsets estimation is closely related to the detection metric. Hence, the accuracy of the STO and CFO estimates gained through matched filtering highly depends on the presence of fractional offsets in the received signal. With detection approaches based on autocorrelation, the fractional part of the CFO can be estimated with high accuracy. However, low accuracy in the STO estimates can be expected. Therefore, the properties of the reference sequence play an important role in the development of further algorithms for fine estimation of the synchronization parameters.

It can be stated that, in spite of the wide variety of existing methods for frame detection and synchronization, there are still significant limitations that open new directions for future research.

1.2 Objectives and Outline

The main objective of the current thesis is to provide a comprehensive investigation of data-aided (DA) algorithms for frame detection and initial synchronization suitable for wireless communications systems. The reference sequence selected to assist in these processes is sent as a preamble prior to the information data and is completely known by the receiver. Based on the high potential of polyphase codes P3 and P4 as discrete versions of LFM signals for detection and synchronization, and considering the previously mentioned limitations, the preamble is generated using polyphase codes P4, while its structure is designed taking into account specific detection and synchronization schemes. Frame detection is investigated with approaches in time domain, based on metrics derived from matched filtering and autocorrelation, as well as in frequency domain, using dechirping and spectral analysis. The information gained during the detection step is further utilized for an initial estimation of the synchronization parameters. Subsequently, additional techniques are implemented to provide accurate estimations of the time and frequency offsets.

In particular, this work aims to identify and solve the major challenges that compromise the detection performance and the estimation of the synchronization parameters when using reference sequences based on polyphase codes P4. Hence, a thorough examination of the properties of the individual polyphase codes as well as the sequences composed with them is likewise sought. Furthermore, this thesis intends to provide an in-depth study of the detection performance achievable with metrics based on autocorrelation using sequences with different periodic structures and establish a relationship between the performance attainable with autocorrelation metrics and matched filtering. Moreover, profound insights into the frame detection accomplished in frequency domain with periodic sequences are targeted, aiming to derive approaches able to outperform those found in the current literature.

In more detail, the remainder of this thesis is organized as follows:

Chapter 2 reviews the principles needed to comprehend the approaches developed in this thesis. After introducing the wireless communication system with its main compounding blocks, a description of the wireless communication channel is provided. Subsequently, representative approaches for frame detection as well as for the estimation of time and frequency offsets are presented. Finally, sequences commonly employed for detection and synchronization are briefly introduced, highlighting the relationship between LFM signals and polyphase codes P4.

In Chapter 3, the major focus is on joint low latency and high detection performance, seeking a detection approach based on matched filtering that is tolerant to the CFO. For this purpose, and assuming integer values of STO, being the latter normalized by the sampling interval, the effect of arbitrary values of CFO on the detection performance is analyzed, the main sources of degradation are identified and suitable approaches to cope with them are systematically presented. The basic reference sequence employed for detection, which consists of a polyphase code P4 with linearly increasing frequency, is properly extended with the corresponding complex conjugate to facilitate the estimation of the synchronization parameters. The properties of the resulting reference sequence are advantageously harnessed to resolve estimation ambiguities and achieve accurate STO and CFO estimations with low latency and low computational complexity.

Chapter 4 investigates low complexity detection techniques based on autocorrelation and synchronization approaches appropriate for periodic sequences. A primary goal of this chapter is to determine the properties that periodic sequences have to fulfill in order to attain a given detection performance when using a predefined autocorrelation metric in the detection process. Furthermore, this chapter aims to establish a relationship between the detection performance associated to matched filtering and the proposed autocorrelation-based approach. In order to fully exploit the properties of the polyphase codes for synchronization, the sequence used for detection, consisting of a concatenation of identical polyphase codes P4, is complemented with a new set of corresponding complex conjugate versions. The structure of the newly created preamble is beneficially employed to define innovative algorithms for the estimation of the synchronization parameters. The STO is considered an as integer number, whereas the CFO takes arbitrary values within a predefined range.

Chapter 5 is devoted to the investigation of frame detection in frequency domain and subsequent estimation of the synchronization parameters. A thorough description of the detection technique based on dechirping and spectral analysis in combination with periodic sequences is firstly provided. After that, a novel method that aims to enhance the detection performance of the state-of-the-art (SoA) approach is presented and evaluated. The reference sequence selected in this chapter follows the structure of the preamble conventionally used in LoRa systems, with three sets of sequences based on polyphase codes P4. New algorithms for the estimation of the strongly intertwined time and frequency offsets are proposed and their validity is examined. For generality, the STO and CFO are assumed to be real numbers.

The main conclusions of this thesis and perspectives for future work are provided in Chapter 6.