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Channel Parameter Estimation for Current- and Future-Generation Wireless Communication Systems: Advanced Algorithms and Bounds

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To my parents

To my wife Dhoha

To my future little baby Lina

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List of Acronyms

ACM	Adaptive Coding and Modulation
ACRLB	Asymptotic CRLBs
AF	Annihilating Filter
AoA	Angle of Arrival
BPSK	Binary Phase Shift Keying
CA	Code-Aided
CDMA	Code-Division Multiple Access
CFO	Carrier Frequency Offset
CLF	Compressed Likelihood Function
CML	Conditional Maximum Likelihood
CRLB	Cramér-Rao Lower Bound
DA	Data-Aided
DOA	Direction of Arrival
DFO	Data-Free Observation
DML	Deterministic ML
DMO	Data-Modulated Observation
DS-CDMA	Direct-Spread CDMA
EM	Expectation-Maximization

ESPRIT	Estimation of Signal Parameters by Rotational Invariance Techniques
FIM	Fisher Information Matrix
HD	Hard Detection
IML	Iterative ML
IS	Importance Sampling
JADE	Joint Angles and Delays Estimation
QAM	Quadrature-Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
LLF	Log-Likelihood Function
LS	Least-Squares
LTE	Long Term Evolution
MCRLB	Modified CRLB
ML	Maximum Likelihood
MODE	Method of DOA Estimation
MSE	Mean Square Error
MSK	Minimum Shift Keying
MUSIC	MULTiple SIgnal Classification
NDA	Non-Data-Aided
NMSE	Normalized MSE
NRMSE	Normalized Root MSE
PDF	Probability Density Function
RSS	Received Signal Strength

SD	Soft Detection
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
SSF	Signal Subspace Fitting
TD	Time Delay
TDOA	Time Difference of Arrival
ULA	Uniform Linear Array
UCA	Uniform Circular Array

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Short Summary

This thesis deals with the problem of channel parameters estimation which is a crucial task for current- and next-generation wireless communication systems intended to operate in complete awareness of the propagation environment. The estimation of the key channel parameters is investigated such as the signal-to-noise ratio (SNR), Ricean K-factor, Doppler spread, direction-of-arrival (DOA), time delays and angles-of-arrival in multipath channels as well as the three synchronization parameters (i.e., time, phase, and frequency offsets) from both the algorithmic and performance analysis point of views. We develop a number of new powerful and low-cost algorithms that are able to work under various harsh conditions of low SNR levels, short data records, highly time-varying channels, and multipath fading, etc. Most of the newly-proposed algorithms are maximum likelihood (ML) ones which enjoy global optimality and, therefore, exhibit highly accurate estimation performance while being robust to different channel impairments. Indeed, it will be seen that the newly-derived algorithms outperform by far the main state-of-art techniques both in terms of estimation performance and computational complexity. We also derive, for the very first time, the *stochastic* Cramér-Rao lower bounds (CRLBs) for the estimation of the key channel parameters from higher-order square-quadrature-amplitude-modulated signals, a key feature of high-speed communication systems. Both *coded* and *uncoded* transmissions are addressed. The proposed bounds can be readily used as an absolute benchmarks for all the unbiased estimators of the considered parameters.

Résumé Court

Dans cette thèse, nous considérons le problème d'estimation des paramètres du canal, une tâche essentielle pour tout système de communication sans fil. Les paramètre clés du canal sans fil sont considérés à savoir le rapport signal sur bruit (RSB), le facteur de Rice, l'étalement Doppler, la direction d'arrivée du signal, les décalages en temps et/ou les angles d'arrivée dans les environnements multi-trajets ainsi que les paramètres de synchronisation en temps, en phase et en fréquence. Nous proposons plusieurs algorithmes novateurs avec des performances inégalées et qui fonctionnent proprement sous les conditions difficiles de faible RSB, de nombre réduit d'observations, variations rapides du canal, et sélectivité en fréquence, etc. La plupart des algorithmes proposés sont des estimateurs ML qui jouissent d'une optimalité globale et sont donc d'une précision très élevée. Nous développons aussi, pour la toute première fois, les bornes de Cramér-Rao (BCR) pour l'estimation des paramètres considérés à partir des signaux QAM qui sont à la base des systèmes de communications haut débit de demain. Ces nouvelles bornes peuvent être utilisées comme jauge de performance pour tous les estimateurs non-biaisés des paramètres du canal. Nous montrons, à travers des simulations Monte-Carlo, que les nouveaux estimateurs battent les principales techniques existantes en termes de précision et de complexité.

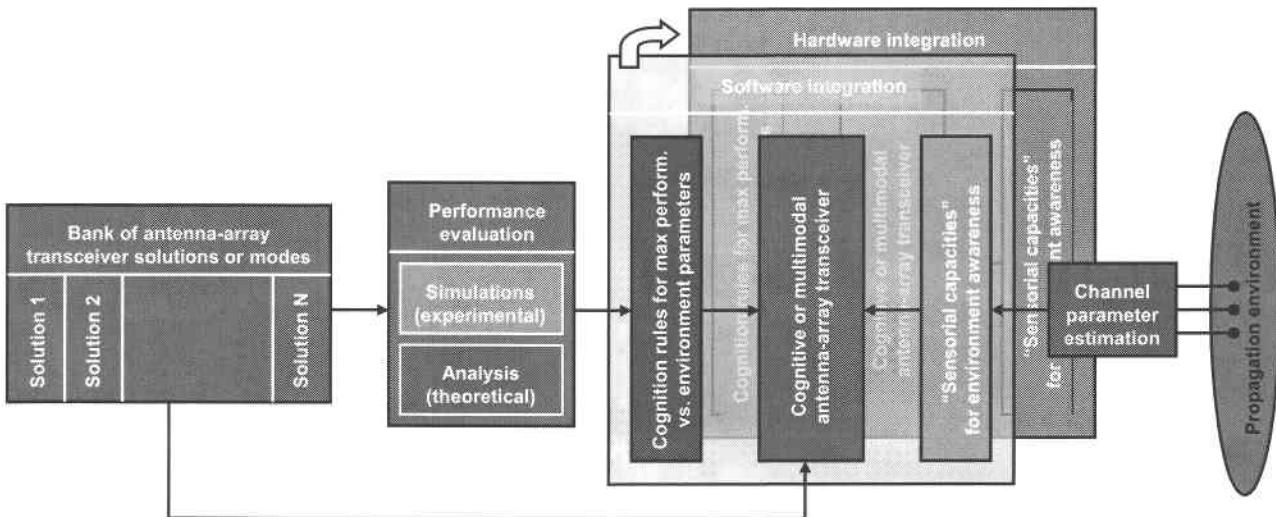
Thesis Overview

Thesis motivation

Wireless broadband is growing at an unprecedented rate and broadband access is considered to be the great infrastructure challenge of the early 21st century. Key drivers for this growth include the maturation of third-generation (3G) wireless network services, development of smart phones and other mobile computing devices, the emergence of broad new classes of connected devices and the rollout of 4G wireless technologies such as Long Term Evolution (LTE) and WiMAX. Major wireless operators in the US (e.g., AT&T and Verizon) have recently reported substantial growth in data traffic in their networks, which is driven in part by smart-phones (e.g., iPhone) usage. According to Cisco, wireless networks in North America carried approximately 17 petabytes per month in 2009, and it is expected that by the end of 2014 they will carry around 740 petabytes, a 40-fold increase. This traffic growth puts much pressure on the service providers because current and future wireless systems are expected to be fast, reliable and bandwidth efficient, which is challenging especially with the conflicting requirements between scarcity of spectrum and increased data rates.

Obviously, achieving reliable communications requires obtaining accurate estimates of the wireless channel parameters at the transceiver (i.e., link level) or the network (i.e., system level). Typically, the *a priori* knowledge/estimation of the various channel parameters endows next-

generation cognitive wireless transceivers and self-organizing networks (SONs) with stronger sensorial capabilities that allow them to tame their surrounding environment and instantly adapt to it and to its variations for maximum achievable performance, thereby making the relatively old research topic of channel parameter estimation more timely than ever. The Wireless Lab at INRS was one of the first research teams to recast the field of parameter estimation into this broader and original perspective. Fig. 1 illustrates the scope of its complimentary R&D activities towards achieving this new vision. Indeed, a growing number of advanced schemes such as diversity, adaptive coding and modulation (ACM), turbo decoding and turbo equalization, relaying, spatial multiplexing, interference mitigation (avoidance, cancellation, or alignment), etc. could potentially match online (i.e., in real time) their operation to the observed channel parameters, so as to push the wireless transceiver's performance to the achievable limits [1].



Source: 2008-2013 NSERC Discovery Grant Program of Prof. Affes on "Enabling Signal Processing Techniques for Cognitive Wireless Transceivers".

Figure 1: New crucial role — from the Wireless Lab <www.wirelesslab.ca> perspective — of parameter estimation as the “eyes and ears” of next-generation cognitive wireless transceivers (i.e., link level) and self-organizing networks (i.e., system level).

As one example, Fig. 2 illustrates the relatively recent design in [2] of a new CDMA cognitive wireless transceiver with a multi-modal modem that constantly selects the best modulation and pilot-use schemes to maximize throughput, increase coverage, and/or reduce power consumption. Optimal selection relies on decision rules illustrated in Fig. 3 (cf. next page) that instantly translate a given subset of wireless channel parameters estimates (namely the SNR, the speed or Doppler, and the received pilot power in the considered case) into the corresponding best mode of operation (in terms of modulation and pilot-use choices).

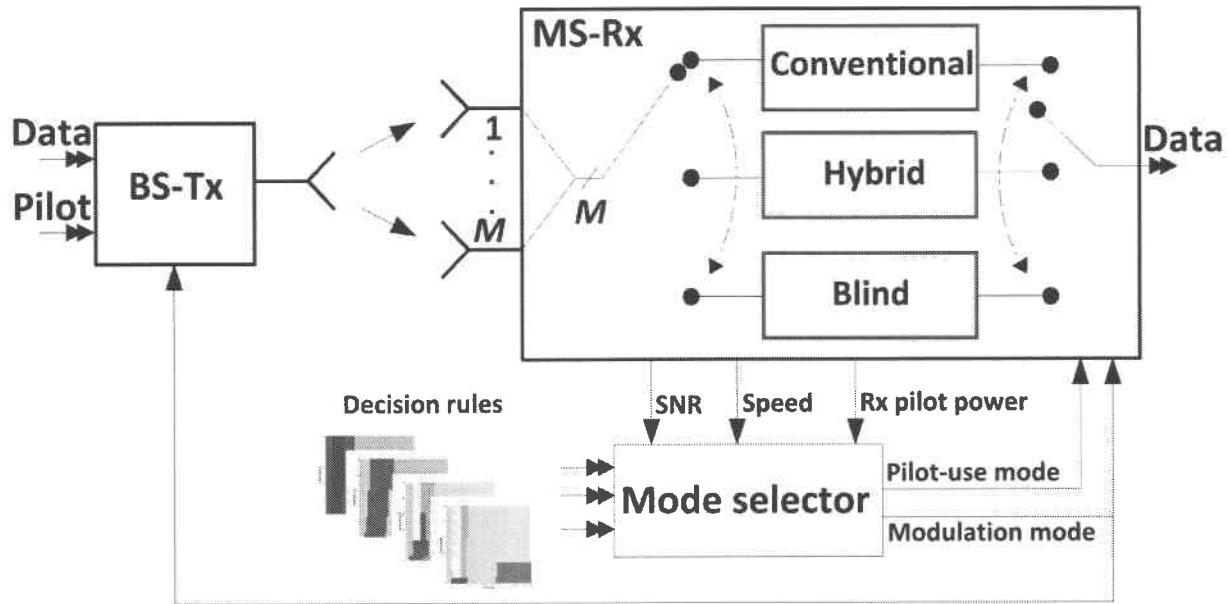


Figure 2: Block diagram of a cognitive wireless array-transceiver with a multimodal pilot-use modem [2].

This thesis falls exactly within the framework of the renewed motivation above for wireless channel parameter estimation and embodies a number of novel contributions in this very exciting topic for current- and future-generation wireless communications systems.

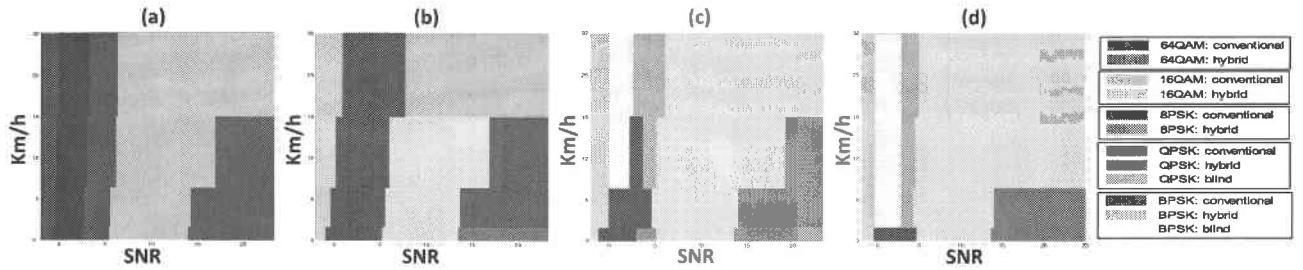


Figure 3: Decision rules for best mode selection (i.e., modulation and pilot use) w.r.t. SNR, speed and a Rx pilot power of (a) 0 dB, (b) -10 dB, (c) -20 dB, and (d) -30 dB relative to the Rx power of the desired user [2].

Thesis Objectives

Our goal within the framework of this thesis is to introduce new advanced estimators for key channel parameters such as the signal-to-noise ratio (SNR), the Ricean K-factor, the main three synchronization parameters, namely the time delay, the phase offset, and the frequency offset, the multipath channel parameters, the direction of arrival (DOA), the Doppler spread, etc. We shall account for the different types of diversity, higher-order quadrature amplitude modulations (QAMs), as well as advanced coding schemes (such as turbo coding) which stand all as key features of current- and future-generation wireless communications systems. From the algorithmic point of view, we will favor as much as possible the development for the first time of totally new maximum likelihood (ML) channel parameter estimators which are expected to exhibit, inherently, remarkable performance advantages against state-of-the-art techniques whenever their challenging derivation with a low computational implementation cost is feasible and successful. We will also aim to derive for the very first time closed-form expressions for the *stochastic* Cramér-Rao lower bounds (CRLBs) of different key channel parameter estimators from square-QAM-modulated transmissions.

Thesis Organization

In Section 1.1, we consider the estimation of the channel-quality parameters (i.e., the SNR and the Ricean K-factor) for SIMO systems, a research topic that has never been addressed before. We develop the ML estimators for the per-antenna SNRs of linearly-modulated channels both under *constant* and *time-varying* channels and, in each case, both data-aided (DA) and non-data-aided (NDA) estimations are investigated. In the DA mode, the new ML estimators are developed in closed-form. In the NDA case, however, we resort to the well-known expectation-maximization (EM) concept in order to develop iterative solutions that converge within very few iterations. In particular, under the time-varying channels, we capture the time variations of the channels through their polynomial-in-time expansion and it is found that the log-likelihood function (LLF) is *multimodal*. Therefore, we propose an adequate initialization procedure that makes the EM-based ML estimator converge to the global maximum of the LLF. The proposed ML estimators exhibit very accurate performance as they achieve the CRLB over a wide range of practical SNRs. In another work, we also derive the closed-form CLRBs for the code-aided (CA) estimation of the SNR parameter from *coded* binary phase shift keying (BPSK)-, minimum shift keying (MSK)-, and square-QAM-modulated signals in turbo- and LDPC-coded systems. In CA estimation, the SNR estimation task is assisted by the decoder by relying on some soft information that is delivered during the decoding process. The newly derived bounds range between the CRLBs for NDA SNR estimates and those for data-aided DA ones, thereby highlighting the expected potential in SNR estimation improvement from the coding gain. We also introduce a new moment-based estimator for the Ricean K-factor parameter that is tailored specifically to modulated data under SIMO channels. It is based on the fourth-order cross-antennae moments and beats the main state-of-the-art techniques in

terms of performance and robustness.

In Section 1.2, we tackle the problem of digital transceivers synchronization through the estimation of the time, phase, and frequency offsets. We first develop a new non-iterative ML timing recovery algorithm for linearly-modulated signals using the *importance sampling* (IS) concept. We show that a grid search and lack of convergence from which most iterative estimators suffer can be avoided. The new estimator enjoys guaranteed global optimality and enables very accurate time synchronization at far lower computational cost than with classical iterative methods. We also derive for the very first time the closed-form expressions for the *stochastic* CRLBs of the NDA estimation of the three synchronization parameters over square-QAM transmissions. The newly-derived *analytical* bounds corroborate their *empirical* counterparts computed previously — using exhaustive Monte-Carlo simulations — from very complex expressions. The new CRLBs can be used as absolute benchmarks for all the unbiased estimators of the synchronization parameters and, being derived analytically, they show explicitly the impact of the signal parameters on the theoretical achievable performance regarding the estimations of the time, phase and frequency offsets. We also consider the synchronization of turbo-coded systems which have recently gained an increased attention due to the introduction of the *turbo synchronization* concept which embeds the synchronization task in the decoding process. In this context, we derive the closed-form expressions for the CRLBs of phase and frequency offsets CA estimation. In particular, we introduce a new recursive process that enables the construction of arbitrary Gray-coded square-QAM constellations. Some hidden properties of such constellations will be revealed, owing to this recursive process, and carefully handled in order to decompose the system’s likelihood function (LF) into the sum of two analogous terms. This decomposition makes it possible to carry out *analytically* all the statistical expectations

involved in the Fisher information matrix (FIM) and, therefore, the considered CA CRLBs.

In Section 1.3, we consider the estimation of the multipath-resolution parameters (i.e., the parameters that enable resolving the paths in space and/or time) using the powerful IS and EM concepts. When a single antenna is used at the receiver side, each path is characterized by a time delay (TD) and a path gain. In presence of multiple receiving antennae branches, however, each path is additionally characterized by an angle of arrival (AoA) on the top of the associated TD and path gain. In the first case, we develop a new IS-based ML estimator for multiple TDs estimation after recasting the problem, in the frequency domain, as a manifold-based model which is widely used in array signal processing. In the second case, however, we develop a new IS-based super-resolution ML technique for the joint angles and delays estimation (JADE) that outperforms, by far, the main state-of-the-art techniques both in terms of performance and computational complexity. It also reaches the corresponding CRLB starting from SNR levels as low as -10 dB and is able to resolve multipath components with angular separation as low as 1° . We also consider direct-spread code-division multiple access (DS-CDMA) and multi-carrier DS-CDMA systems where the estimation process can be performed using the channel estimates or pilot-modulated signals [i.e., from a data-free observation (DFO)] or blindly from the received data-modulated signal [i.e., data-modulated observation (DMO)] thereby covering all possible DFO and DMO cases. We develop two new IS-based and IS-based ML TDs estimators which achieve the CRLB over a wide range of practical SNRs. Moreover, we prove analytically and through simulations, in the data-modulated observation (DMO) case where the TDs are estimated directly from the observed data and not from channel coefficient estimates, that spatial, temporal and frequency samples indistinguishably play equal roles in time delays estimation. In all the considered scenarios, we succeed in recasting the original *multi-*

dimensional optimization problem, with prohibitive complexity, into a set of *one-dimensional* ones that can be solved in parallel, resulting thereby in huge computational savings.

In Section 1.4, finally, we consider the problem of *location* and *mobility* parameters estimation, namely the direction of arrival (DOA) and Doppler spread parameters. Within the specific context of DOA estimation, we first consider uncorrelated sources and we develop a new low-cost DOA estimator using the annihilating filter (AF) approach. The new AF-based approach exhibits very low computational complexity — as compared to main state-of-the-art methods — and is able to accurately estimate the DOAs from short data records and even from a single snapshot. Secondly, we consider the problem of DOA estimation under more realistic scenarios where the sources' signals and the noise components are correlated in time and/or space and we propose a new method which is the first of its kind that is able to properly handle *noncircular* signals under the aforementioned types of correlations. It exhibits remarkable performance advantages against the existing techniques and highlights the potential gain that both noncircularity and temporal correlation provide when considered together. Then, we consider the problem of DOA estimation in modulated transmissions and we develop, for the first time, the closed-form expressions for the CRLBs for NDA DOA estimates from square-QAM-modulated signals. We unify, in an elegant manner, both uniform linear arrays (ULAs) and uniform circular arrays (UCAs) through a common geometrical factor which reflects the only difference between the two configurations.

Regarding the problem of mobility estimation, we propose a new low-cost and robust maximum likelihood (ML) Doppler spread estimator for Rayleigh flat fading channels. In fact, relying on a an elegant approximation of the channel covariance matrix by a two-ray model, we are able to invert the overall approximate covariance matrix *analytically* thereby obtaining a low-cost

closed-form approximation of the likelihood function. It will be seen that the new estimator is accurate over a wide Doppler spread range and that it outperforms many state-of-the-art techniques. In contrast to the latter, it exhibits an unprecedented robustness to the Doppler spectrum shape of the channel since it does not require its knowledge *a priori*.

Thesis Work Publications

The content of this thesis will be embodied, respectively, by 8 *published* and 3 *submitted* IEEE Transaction papers (without accounting for 5 other journal versions and one tutorial paper currently under preparation) as well as 14 published/accepted IEEE conference papers which are listed hereafter:

- **Accepted/published/submitted journal papers**

- [J11] F. Bellili, S. Ben Amor, S. Affes, and A. Stéphenne, “A new super-resolution and low-cost exact ML estimator for time delays and angles-of-arrival acquisition in multipath environments,” submitted to *IEEE Trans. on Signal Process.*, July 2014, under 1st round review.
- [J10] F. Bellili, R. Meftehi, S. Affes, and A. Stéphenne, “Maximum likelihood SNR estimation of linearly-modulated signals over time-varying flat-fading SIMO channels,” submitted to *IEEE Trans. on Signal Process.*, Mar. 2014, Decision: major revisions, June 2014, under revision.

- [J9] F. Bellili, A. Methenni, and S. Affes, "Closed-form CRLBs for CFO and Phase Estimation from Turbo coded square-QAM-modulated transmissions," submitted to *IEEE Trans. on Wireless Commun.*, Jan. 2014, *Major Revision*, May 2014, revised, May 2014, under 2nd round review.
- [J8] F. Bellili, A. Methenni, and S. Affes, "Closed-Form CRLBs for SNR estimation from turbo-coded BPSK-, MSK-, and square-QAM-modulated signals," accepted for publication in *IEEE Trans. on Signal Process.*, Apr. 2014, to appear.
- [J7] A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, "A maximum likelihood time delay estimator in a multipath environment using importance sampling," *IEEE Trans. Sig. Process.*, vol. 61, no. 1, pp. 182-193, Jan. 2013.
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- [J1] F. Bellili, S. Ben Hassen, S. Affes, and A. Stéphenne, “Cramér-Rao lower bounds of DOA estimates from square QAM-modulated signals,” *IEEE Trans. on Commun.*, vol. 59, no. 6, pp. 1675-1685, June 2011.

- **Published/accepted conference papers:**

- [C14] F. Bellili, A. Methenni, and S. Affes, “Closed-form CRLBs for SNR estimation from turbo-coded square-QAM-modulated signals,” accepted for publication in *IEEE GLOBECOM’14*, to appear.
- [C13] F. Bellili, A. Methenni, and S. Affes, “Closed-form Cramér-Rao lower bounds for CFO and phase estimation from turbo-coded square-QAM-modulated signals,” accepted for publication in *IEEE GLOBECOM’14*, to appear.
- [C12] F. Bellili, S. Ben Amor, S. Affes, and A. Samet, “A new importance-sampling ML estimator of time delays and angles of arrival in multipath environments,” in *Proc. of IEEE ICASSP’14*, Florence, Italy, May 5-9, 2014.

- [C11] F. Bellili, R. Meftehi, S. Affes, and A. Stéphenne “Maximum likelihood SNR estimation over time-varying flat-fading SIMO channels,” in *Proc. of IEEE ICASSP’14*, Florence, Italy, May 5-9, 2014.
- [C10] F. Bellili and S. Affes, “A Low-cost and robust maximum likelihood Doppler spread estimator,” in *Proc. of IEEE GLOBECOM’13*, Atlanta, GA, USA, Dec. 9-13, 2013.
- [C9] A. Masmoudi, F. Bellili, and S. Affes, “Time delays estimation from DS-CDMA multipath transmissions using expectation maximization,” in *Proc. of IEEE VTC’2012-Fall*, Québec City, Canada, Sept. 3-6, 2012.
- [C8] A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, “A new importance-sampling-based non-data-aided maximum likelihood time delay estimator”, in *Proc. of IEEE WCNC’2011*, Cancun, Mexico, Mar. 28-31, 2011.
- [C7] A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, “Closed-form expressions for the exact Cramér-Rao bounds of timing recovery estimators from BPSK and square-QAM transmissions”, Proc. of *IEEE ICC’2011*, Kyoto, June 5-9, 2011.
- [C6] A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, “A maximum likelihood time delay estimator using importance sampling,” in *Proc. of IEEE GLOBECOM’2011*, Houston, USA, Dec. 5-9, 2011.
- [C5] F. Bellili, S. Affes, and A. Stéphenne, “DOA estimation for ULA systems from short data snapshots: An annihilating filter approach,” in *Proc. of IEEE GLOBECOM’2011*, Houston, USA, Dec. 5-9, 2011.

- [C4] A. Masmoudi, F. Bellili, and S. Affes, "Maximum likelihood time delay estimation for direct-spread CDMA multipath transmissions using importance sampling," in *Proc. of 45th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, USA, Nov. 6-9, 2011.
- [C3] S. Ben Hassen, F. Bellili, A. Samet, and S. Affes, "DOA estimation from temporally and spatially correlated narrowband signals with noncircular sources," in *Proc. of IEEE WCNC'2011*, Cancun, Mexico, Mar. 28-31, 2011.
- [C2] F. Bellili, S. Affes, and A. Stéphenne, "Second-order moment-based direction finding of a single source for ULA systems," in *Proc. of IEEE PIMRC'2011*, Toronto, Canada, Sept. 11-14, 2011.
- [C1] I. Bousnina, F. Bellili, A. Samet, and S. Affes "Joint estimation of the Ricean K-factor and the SNR for SIMO systems using higher order statistics," in *Proc. of IEEE GLOBECOM'11*, Houston, TX, USA, Dec. 2011.

Contributions to Students' Coaching and Training within this Thesis Work

During my Ph.D. studies, I have been given the unique opportunity by my supervisor, Prof. Sofiène Affes, to coach six undergraduate and graduate students (on the top of three others already coached during my M.Sc. studies, cf. above) and to contribute significantly to their training. It happens that all of them are listed as co-authors at least once in the above work publications.

Table 1: PH.D CONTRIBUTIONS TO STUDENTS MENTORING

	ID	Students	Program			Conference Publications		Journal Publications			Total
			Undergrad.	M.Sc.	Ph.D.	Published	Accepted	Published	Accepted	Submitted	
When I was in the M.Sc. program	1	Atitallah	✓			1		1			2
	2	Ben Hassen	✓			1		1			2
	3	Boujelbenne	✓			1		1			2
	4	Descure	✓			2					2
Sub-total			4	0	0	5	0	3	0	0	8
When I was in the Ph.D. program	5	Ben Amor		✓		1				1	2
	6	Bousnina			✓	1		0			1
	7	Masmoudi	✓			3		2			5
	8	Masmoudi		✓		2		1			3
	9	Meftehi		✓		1	0			1	2
	10	Methenni		✓		1					1
	11	Methenni			✓		2		1	1	4
	12	Ben Hassen			✓	2		1			3
Sub-total			1	4	3	11	2	4	1	3	21
Total			5	4	3	16	2	7	1	3	29

Contributions to Thesis Work Publications

In all the papers where I am listed as the first co-author, I was the one who derived the solution and carried out large parts of the disclosed simulations. I was also the one who wrote the paper and took care of its successive revised versions. Therefore, in the following, I shall rather emphasize on my own contributions/role regarding each of the papers where I am listed as a second co-author. I shall also focus on the journal papers only since they naturally contain more elaborate versions of their conference counterparts:

- In [J2], a ML SNR estimator for SIMO systems was derived. The first co-author, Mr. Mohamed Ali Boujelbene, was an *undergraduate* student at the time who joined our research group at INRS-EMT for a four-month stay to carry out his graduation project. Being among the first trainees that Prof. Sofiène Affes put under my direct guidance, I

have set another challenge to myself of making his internship a “success story”. Mr Boujelbene being totally new to scientific research and given only a fourth-month internship duration, I felt compelled to providing him with the complete theoretical derivations of a new SNR estimator that I have previously established as an extension of the following old work out of my own M.Sc. thesis:

- [Ref. 1] A. Stéphenne, F. Bellili, and S. Affes, “Moment-based SNR estimation over linearly-modulated wireless SIMO channels”, *IEEE Trans. on Wireless Commun.*, vol. 9, no. 2, pp. 714-722, Feb. 2010.

Mr Boujelbene was then in charge of carrying out thorough computer-based simulations in order to assess the empirical performance of the new SNR estimator. Later on, I provided him with the necessary guidelines for the derivation of the theoretical bias and variance of the new estimator in order to corroborate the obtained empirical performance. Overall, being offered the theoretical solutions, Mr Boujelbene was of extreme efficacy as he succeeded in accomplishing the missing “performance analysis” aspect; a necessary task for a mature research work in estimation practices. In fact, by the end of the very first month of his stay, we were ready to write a *full* IEEE Transactions paper [J2]. After such successful beginning of his first research experience, Mr Boujelbene manifested his intention to pursue his graduate studies within our research group. In order to encourage him, I offered him the opportunity of being the leading author on that paper although I had later on contributed, even more, by writing the vast majority of the manuscript’s content given the fact that Mr Boujelbene had no experience in writing scientific papers. All in all, under my somewhat devoted guidance during his four-month stay, Mr Boujel-

bene was able to submit the *full* IEEE Transactions paper [J2] even before going back to his homeland country to defend his graduation project. Then I was in total charge of the paper during its review process.

- Motivated by the successful experience with Mr Boujelbene, Prof. Sofiène Affes has once again put his confidence in me to supervise another *undergraduate* student, namely, Mr. Ahmed Masmoudi during a four-moth internship as well the following year. As a personal response to such endless confidence, I had to set the bar very high this time and make an *undergraduate* student submit two *full* IEEE Transactions papers, during a four-month stay, instead of only one as I already did with Mr. Boujelbene the previous year. Therefore, as a first step, I provided Mr Masmoudi with the essential theoretical derivations of the Cramér-Rao lower bounds of timing recovery in square-QAM transmissions that I have established as an extension of the following work I published during my M.Sc. studies:

[Ref. 2] F. Bellili, A. Stéphenne, and S. Affes, “Cramér-Rao lower bounds for non-data-aided SNR estimates of square QAM modulated transmissions”, *IEEE Trans. on Commun.*, vol. 58, no. 11, pp. 3211-3218, Nov. 2010.

The task mandated to Mr Masmoudi was to perform the necessary computer simulations for the newly derived bounds. Mr Masmoudi was able to accomplish this task in a couple of weeks and even before joining our research group in Canada. Consequently, days after joining the Wireless Lab at INRS-EMT, we started directly the preparation of a *full* IEEE Transactions paper, namely [J4] above. Then, I provided him with the main guidelines

along with the key derivation steps of a completely new technique of NDA ML timing recovery approach, namely *importance sampling* (IS). Mr Masmoudi was simply asked to finalize the derivations and assess the performance of the new estimator through exhaustive computer simulations. Under my close supervision, he was able to successfully carry out this task in the following weeks and we started the preparation of the second *full* IEEE Transactions paper (i.e. [J5] above). Once again, it was another personal achievement for me to help an *undergraduate* student — with no previous experience in scientific research — in understanding and contributing to a timely and complicated research topic, as well as, in preparing **two** *full* IEEE Transactions papers. A goal that is rarely achieved even by a graduate student within such a short time period of four months only. In order to expedite their submissions, I have also contributed to writing most of the two papers. But having at hand an already well-established publications record by the end of my first year of PhD studies (6 *full* IEEE Transactions papers), I felt very comfortable and also pleased to give deliberately Mr Masmoudi the unique opportunity to lead the two papers (as a first author) in order to encourage him to join our research group in the framework of his graduate studies. After returning to INRS-EMT — as an M.Sc. student — I provided him with another sketched solution and the main guidelines for the derivation of another time delay estimator, in multipath environments, using the IS concept which he had accomplished with success during his first session. This estimator was later published in [J7] above.

- Finally, [J6] in which Mme Ben Hassen is a first author is an extension of my own work on DOA estimation disclosed in [J1]. In fact, my collaboration with Mrs. Ben Hassen started while she was working on a four-month internship graduation project in our research

group. At the time, I provided her with all the theoretical derivations of the closed-form expressions for the CRLB of NDA DOA estimates from square-QAM signals. She was then in charge of numerically evaluating and plotting the newly derived CRLBs published in [J1]. Since then, she enrolled in a Ph.D. program in Tunisia Polytechnic School and continued to collaborate with us from her homeland country where I provided her with a sketched solution and the key derivation steps for a new DOA estimator using noncircular signals. Mrs. Ben Hassen was able to finish all the derivations of the new estimator and to assess its performance through computer-based simulations which finally led to [J6]. I was once again the most involved in the manuscript preparation and successive milestone revisions of the underlying paper.

Positioning of Thesis's Technical Contributions

The hierarchical diagram of Fig. 4 below is designed to help the reader properly position — within the broad area of wireless channel parameter estimation — our research contributions most-thoroughly disclosed in this thesis through a set of 16 representative PhD-work publications among a total of 25 (published, accepted or submitted, cf. above), referred to hereafter as Appendices A1 to A16.

From the algorithmic point of view, our contributions span over the three most-known classes of estimators, namely the moment-based, subspace-based and ML-based techniques. More details about these classes are provided in the extended summary of this thesis. Under the specific class of ML-based estimation, we adopt three common approaches to the implementation of the ML criterion which are:

1. Iterative implementation using the well-known *expectation-maximization* (EM) concept;

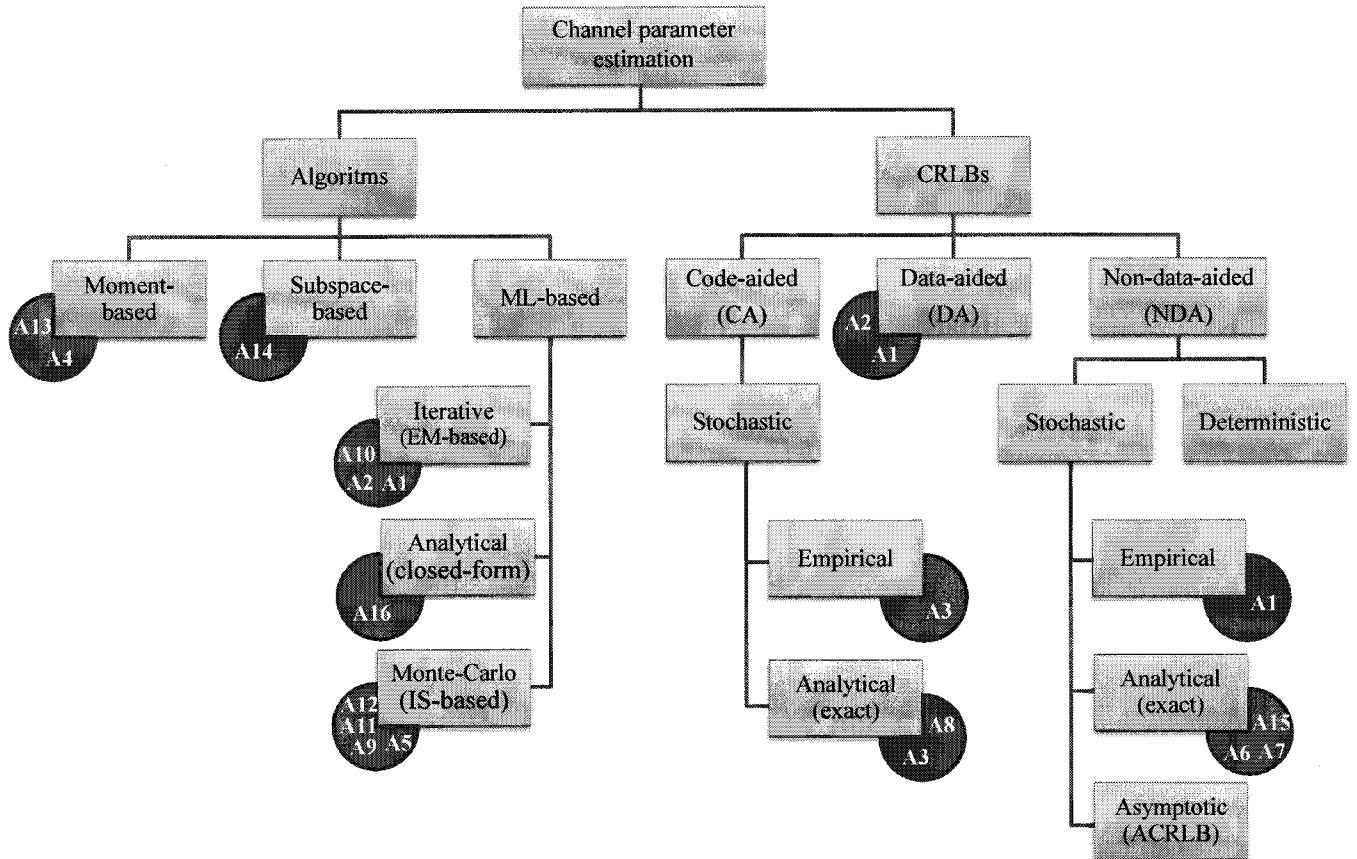


Figure 4: Positioning of our contributions within the broad landscape of parameter estimation techniques and bounds.

2. Empirical implementation using the well-known but relatively very new concept to signal processing for communications, namely the powerful Monte-Carlo *importance sampling* (IS);
3. Analytical or closed-form solutions.

More details about these different implementations are provided in the extended summary of this thesis. From the “performance bounds” point of view, we also considered the most

known types of CRLBs under data-aided (DA), non-data-aided (NDA), and code-aided (CA) estimations. As shown in [3], the CRLB for vector parameter estimation is given by:

$$\text{CRLB}(\boldsymbol{\theta}) = \mathbf{I}^{-1}(\boldsymbol{\theta}), \quad (1)$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, \dots, \theta_M]^T$ is a vector that gathers the M unknown parameters to be estimated, jointly, from a received data vector $\mathbf{y} = [y_1, y_2, \dots, y(N)]^T$, and $\mathbf{I}(\boldsymbol{\theta})$ is the Fisher information matrix (FIM) whose entries are defined for $i, j = 1, 2, \dots, M$ as follows:

$$[\mathbf{I}(\boldsymbol{\theta})]_{i;j} = -\mathbb{E}_{\mathbf{y}} \left\{ \frac{\partial^2 \ln(p[\mathbf{y}; \boldsymbol{\theta}])}{\partial \theta_i \partial \theta_j} \right\}, \quad (2)$$

in which $p[\mathbf{y}; \boldsymbol{\theta}]$ is the probability density function (pdf) of the received vector, \mathbf{y} , parameterized by the unknown parameter vector $\boldsymbol{\theta}$. In DA estimation, the transmitted symbols are perfectly known to the receiver and, therefore, the pdf of the received vector is Gaussian. Consequently, the DA CRLB can be easily derived in closed form. In completely NDA estimation, however, the CRLB is usually untractable in the general case of linearly-modulated signals and, therefore, the *modified* CRLB (MCRLB)—an easier bound to derive in practice—is usually considered.

It is defined as follows:

$$\text{MCRLB}(\boldsymbol{\theta}) = \mathbf{I}_M^{-1}(\boldsymbol{\theta}), \quad (3)$$

where $\mathbf{I}_M(\boldsymbol{\theta})$ is the *modified* FIM whose entries are defined for $i, j = 1, 2, \dots, M$ as follows:

$$[\mathbf{I}(\boldsymbol{\theta})]_{i;j} = -\mathbb{E}_{\mathbf{y}, \mathbf{x}} \left\{ \frac{\partial^2 \ln(p[\mathbf{y}|\mathbf{x}; \boldsymbol{\theta}])}{\partial \theta_i \partial \theta_j} \right\}, \quad (4)$$

in which $p[\mathbf{y}|\mathbf{x}; \boldsymbol{\theta}]$ is the pdf of the received vector, \mathbf{y} , *conditioned* on the transmitted vector of unknown symbols, \mathbf{x} , and parameterized by the unknown parameter vector $\boldsymbol{\theta}$. Since $p[\mathbf{y}|\mathbf{x}; \boldsymbol{\theta}]$ is also Gaussian, the MCRLB is much easier to derive than the CRLB but it is unfortunately a loose bound in the low-SNR region. For these reasons, it is not considered in this thesis and we mainly focus on the CRLB where we distinguish the following two types in the NDA case:

1. Deterministic CRLBs where the unknown transmitted symbols are assumed to be *deterministic*. The corresponding *deterministic* CRLBs are easier to derive in closed form, but they are unfortunately very loose bounds especially at low or medium SNR levels, i.e., they cannot be achieved by any practical estimator over these two practical SNR ranges and therefore lack true practical insight and are invoked only by necessity when deemed as the sole tractable bound. In this thesis, we will be able to break many long-standing deadlocks and as such will never need to recur to this loose bounds.
2. Stochastic CRLBs where the unknown transmitted symbols are assumed to be *random*. In this case, averaging over the possible set of the random symbols (i.e., the signal constellation) makes the corresponding LLF extremely non-linear especially for higher-order constellations. For these reasons, the *stochastic* CRLBs are usually computed *empirically* using exhaustive computer Monte-Carlo methods. Alternatively, they can be derived analytically but solely for very specific SNR ranges (i.e., extremely-low or extremely-high SNR levels) and they are referred to as *asymptotic* CRLBs (ACRLBs). As such, the ACRLBs are also very loose bounds for a wide range of practical (i.e., medium) SNR values. In practice, the exact *stochastic* CRLBs are known to be achievable asymptotically (in the number of data records) by *stochastic* ML estimators over the entire SNR range. This is the reason why we will mostly focus on exact *stochastic* CRLBs in this thesis. For the very first time, we will be able to derive them all in closed-form expressions for higher-order square-QAM transmissions, providing thereby invaluable exact solutions to long-lasting impasses within this challenging research topic.

In code-aided (CA) estimation, however, the unknown transmitted symbols need to be decoded and the LLF is found by averaging over the constellation points weighted by the actual a

priori probabilities of the transmitted symbols. In doing so, the latter are always considered as *random* and, therefore, one can only derive the *stochastic* CRLBs. Likewise, *stochastic* CA CRLBs can be evaluated either *empirically* or *analytically*. Within the framework of this thesis, we will be able once again, for the very first time, to derive the closed-form expressions for such *stochastic* CA bounds and as well as their empirical counterparts (whenever necessary) for the sole purpose of cross-validation.

Extended Summary

Brief literature review and contributions in wireless channel parameter estimation

This extended summary will give a brief literature review about the wireless channel parameter estimation problem and summarize our contributions under four sub-topics. It will be structured in four sections each treating a set of key parameters of the wireless channel. In every section, we will provide a short motivation (i.e., applications) for the estimation of the considered set of parameters followed by a brief overview of key state-of-the-art estimators before discussing our findings and contributions.

1.1 Channel-quality parameters

1.1.1 SNR estimation: motivation and preliminary notions

The SNR is considered to be a key parameter whose *a priori* knowledge can be exploited at both the receiver and the transmitter (through feedback), in order to reach the desired enhanced/optimal performance using various adaptive schemes. As examples, just to name a few, the SNR is required in all power control strategies, adaptive modulation and coding, turbo decoding, and handoff schemes [4,5]. SNR estimators can be broadly divided into two major categories: i) data-aided (DA) techniques in which the estimation process relies on a perfectly known (pilot) transmitted sequence, and ii) non-data-aided (NDA) techniques where the estimation process is applied with no *a priori* knowledge about the transmitted symbols (but possibly the transmit constellation). They can also be categorized differently, depending on how the received samples are exploited: i) moment-based techniques which rely only on the envelope of the received signal and ii) maximum likelihood (ML) approaches which use its inphase (I) and quadrature (Q) components.

1.1.2 SNR estimation under *constant* SIMO channels

State of the art

Under the *constant* (i.e., block-fading) channels assumption, many SNR estimators have been proposed, so far, for the traditional single-input single-output (SISO) systems (see [1- 7] and references therein). Yet, current and future generation wireless communication systems such as long-term evolution (LTE), LTE-Advanced (LTE-A) and beyond (LTE-B) are characterized by the use of multiple receiving antenna branches in order to satisfy the ever increasing demand

for data traffic. Developing new SNR estimators that are specifically tailored to such diversity-combining systems is of high importance in order to optimally realize all the aforementioned SNR-dependent applications. In this context, we have recently been the first to tackle this timely problem in [8] where we developed a moment-based SNR estimator that relies on the cross-antennae fourth-order moments in a SIMO system (hence referred to as the M4 estimator). This work showed that exploiting the antennae diversity in SIMO systems can improve SNR estimation appreciably over traditional SISO systems. However, as it relies on the envelope of the received samples only, this moment-based approach does not glean all the information carried by the received signal.

Contribution

Motivated by this fact, we tackle in this thesis (cf. Appendix 1), for the first time as well, the problem of ML SNR estimation under flat-fading SIMO channels where the I/Q components of the recorded data are used during the estimation process. We first derive the DA maximum-likelihood (ML) SNR estimator in closed-form expression. The performance of the DA ML estimator is analytically carried out by deriving the closed-form expression of its bias and variance. Besides, in order to compare its performance with the fundamental limit, we derive the DA CRLB in closed-form expression as well. In the NDA case, the expectation-maximization (EM) algorithm [15] is derived to iteratively maximize the log-likelihood function (LLF). Moreover, we introduce an efficient algorithm, which applies to whatever one/two-dimensional M -ary constellation, to numerically compute the corresponding NDA CRLBs. In both cases, we show that our new SIMO SNR estimators offer substantial performance improvements over ML SNR estimation in SISO systems due to the optimal usage of the antennae *diversity* and *gain*, and

that it reaches the corresponding CRLB over a wide range of practical SNRs. As depicted in Fig. 1.1, we also show that the use of the I/Q-based ML estimators in a SIMO system can lead to remarkable performance improvements over the only existing moment-based estimator that we developed earlier in [8] (referred to therein as the M4 estimator). In addition, we show that SIMO configurations can contribute to decreasing the required number of iterations of the EM algorithm as seen in Fig. 1.2. This work was published in *IEEE Transactions on Signal Processing* [9].

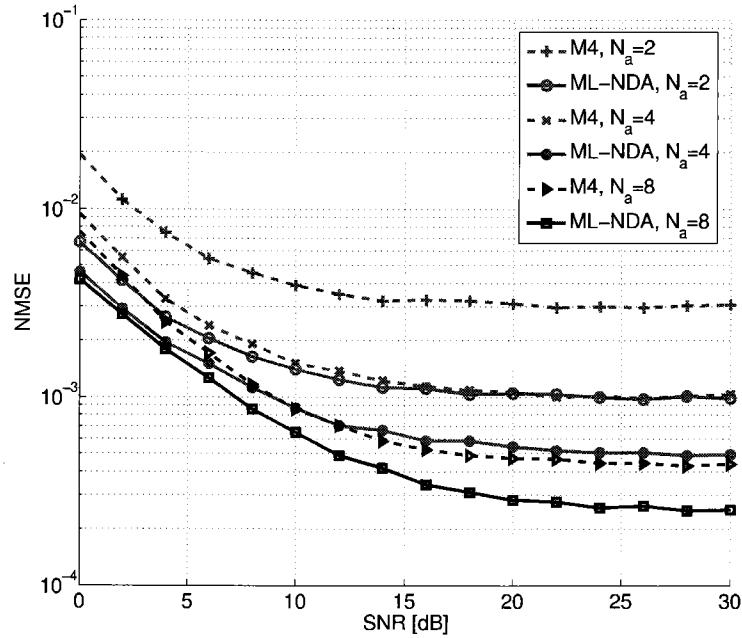


Figure 1.1: NMSE of the new NDA ML (ML-NDA) and the M4 SNR estimates for different numbers of antennas, N_a , with $N = 512$ received samples of QPSK-modulated signals (please see Section V of Appendix 1 for more details).

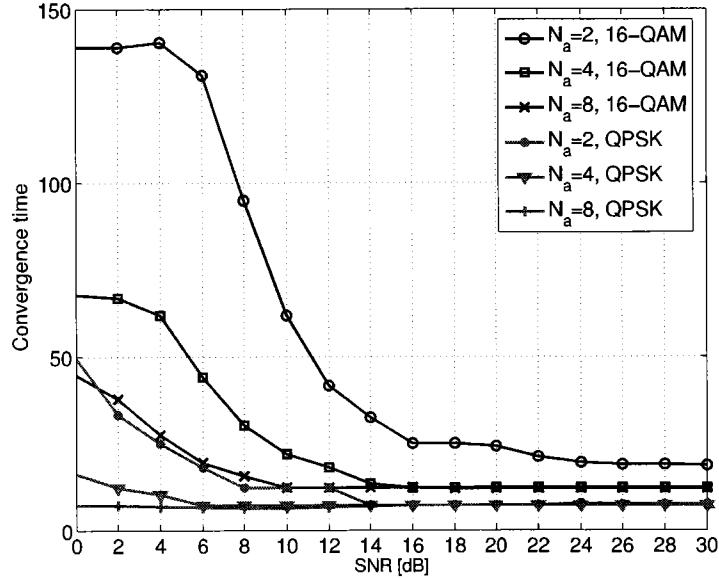


Figure 1.2: Convergence time (in average iterations number) of the new NDA ML SNR estimator for different numbers of antennas using $N = 512$ received samples (please see Section V of Appendix 1 for more details).

1.1.3 SNR estimation under *time-varying* SIMO channels

State of the art

The ML SNR estimators that we developed in [9] are specifically tailored to slowly-time varying channels which can be reasonably assumed as constant over the observation interval. This covers already a vast variety of applications in practice especially for outdoor cellular communications where the mobile velocity is essentially limited by law. In indoor communications, as well, the mobile is compelled to move slowly due to space limitations. Yet, current and future generation multi-antennae systems such as LTE, LTE-A and LTE-B are expected to support reliable communications at very high velocities reaching 500 Km/h [10]. For such systems, classical assumptions of *constant* channels no longer hold and consequently all the existing

SNR estimators that build upon such assumptions shall suffer from severe performance loss. Therefore, one needs to explicitly incorporate the channel time-variations in the estimation process and, so far, very few works have been reported on this subject. In fact, ML SNR estimation under SISO *time-varying* channels was investigated in [11, 12] and [13] for the DA and NDA modes, respectively. Under SIMO *time-varying* channels, however, the only work that is available from the open literature is based on a least-squares (LS) approach which we proposed earlier in [14].

Contribution

Motivated by all these facts, we tackle in this thesis (cf. Appendix 2) the problem of *instantaneous* SNR estimation over fast *time-varying* SIMO channels. We derive the per-antenna ML SNR estimators for both the DA and NDA schemes. Our newly proposed estimators are based on a piece-wise polynomial-in-time approximation for the channel process with very few unknown coefficients. In the DA scenario where the receiver has access to a pilot sequence from which the SNR is to be obtained, the ML estimator is once again derived in closed form. In the NDA case, however, where the transmitted sequence is partially unknown and random, the LLF becomes very complicated and its maximization is analytically intractable. Therefore, we resort to a more elaborate solution using the EM concept [15] and we develop thereby an iterative technique that is able to converge within very few iterations (i.e., in the range of 10). We also solve the challenging problem of local convergence that is inherent to all iterative techniques. In fact, we propose an appropriate initialization procedure that guarantees the convergence of the new EM-based SNR estimator to the global maximum of the LLF which is indeed *multimodal* under complex time-varying channels (in contrast to real channels).

Most interestingly, the new EM-based SNR estimator is applicable for linearly-modulated signals in general (i.e., PSK, PAM, or QAM) and provides sufficiently accurate estimates [i.e., *soft detection* (SD)] for the unknown transmitted symbols. Therefore, *hard detection* (HD) can be easily embedded in the iterative loop to further improve its performance over the low-SNR region. Moreover, we develop a bias-correction procedure that is applicable in both the DA and NDA cases and which allows, over a wide practical SNR range, the new estimators to coincide with the DA CRLB. Simulation results show the distinct performance advantage offered by fully exploiting the antennae *diversity* and *gain* in terms of instantaneous SNR estimation. In particular, the new NDA estimator (either with SD or HD) shows overly superior performance against the most recent NDA ML technique (referred to as WGM) both in its original SISO version [13] and even in its SIMO-extended version developed in Appendix 2 to further exploit the antennae *gain*. This is more clearly depicted by Figs. 1.3 and 1.4 below. Part of this work was already accepted for publication in *IEEE ICASSP'14* conference [16] and a complete version has been recently submitted to *IEEE Transactions on Signal Processing* [17].

1.1.4 CRLBs for SNR estimation in coded transmissions

State of the art

In estimation theory, the Cramér-Rao lower bound (CRLB) is a well-known fundamental bound which serves as an absolute benchmark for all the unbiased estimator of a given parameter. It sets the lowest possible achievable error variance given a sequence of recorded samples with all the *a priori* information that one can use during the estimation process. Unlike other loose bounds, the *stochastic* CRLB is known to be achieved, asymptotically, by the stochastic

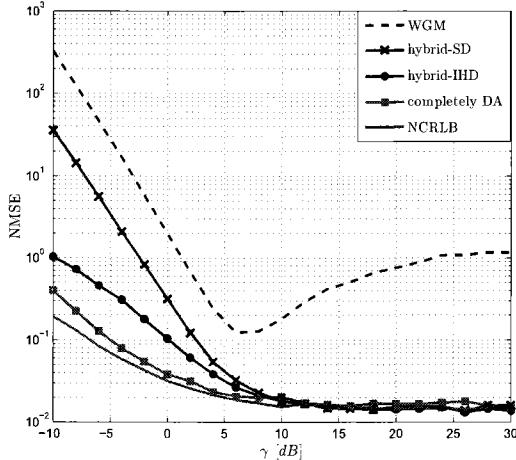


Figure 1.3: Comparison of our new SNR estimators [i.e., hybrid EM with SD and *iterative* HD (IHD)] with WGM over SISO systems (i.e., $N_r = 1$ receiving antenna element) with normalized Doppler frequency, $F_D T_s = 7 \times 10^{-3}$, QPSK (please see Section V of Appendix 2 for more details).

maximum likelihood estimator. Yet, even in the case of uncoded transmissions, the complex structure of the likelihood function makes it extremely hard, if not impossible, to derive analytical expressions for such bounds, especially for higher-order modulations. Therefore, they are usually evaluated empirically, for both non-coded and coded systems.

More than a decade ago, the first SNR CRLBs in closed-form expressions were derived in the DA scenario [18] for different modulations types and orders. In the same work, they were likewise obtained in the NDA case only for BPSK and QPSK modulations. This was followed by our own investigations in [19, 20] by finding a way out of the long-lasting impasse standing between the very first set of analytical results in [18] and their generalization to arbitrary higher-order square-QAM modulations due to the increasingly inextricable form of the likelihood function. Obviously, the latter is expected to become even more complicated in code-aware or code-aide

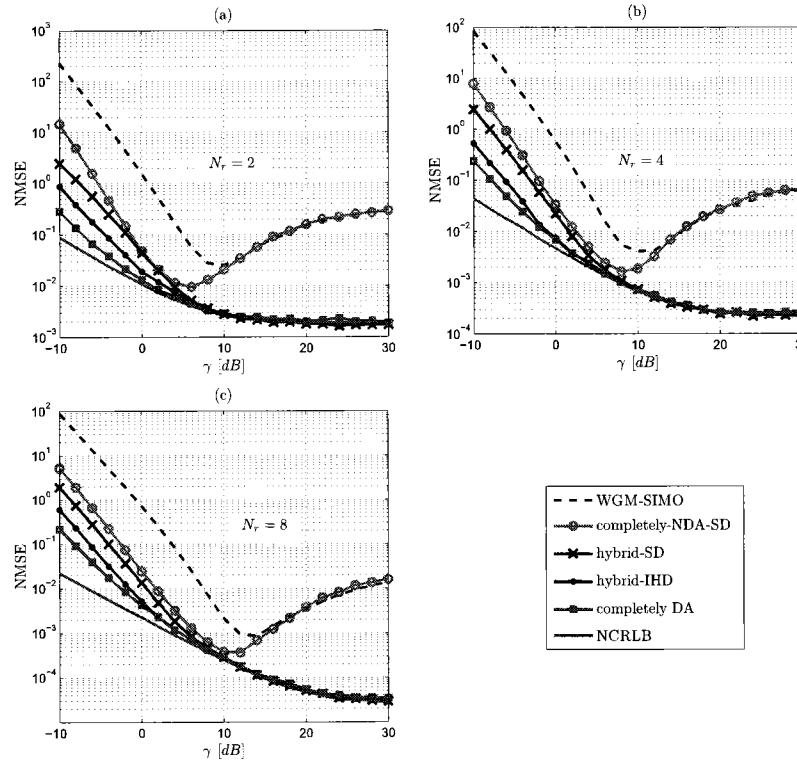


Figure 1.4: Comparison of our estimators against WGM-SIMO (the SIMO-enhanced version of WGM introduced in [13]) for different numbers, N_r , of receiving antenna elements: (a) $N_r = 2$, (b) $N_r = 4$, and (c) $N_r = 8$, with normalized Doppler frequency $F_D T_s = 7 \times 10^{-3}$, $N = 112$ received samples, local DA and NDA approximation window sizes $\bar{N}_{\text{DA}} = 112$, $\bar{N}_{\text{NDA}} = 56$, and approximation polynomial order $L = 4$, QPSK (please see Section V of Appendix 2 for more details).

(CA) estimation, thereby revealing unambiguously the extreme challenge and value of deriving the CA SNR CRLBs when properly positioned in the current state of the art. A compelling illustration of the literature limitation persisting so far is that CA SNR estimators have been very often compared in performance (as recently done in [21] and [22]) to the DA CRLBs. The latter might offer an accurate benchmark for BPSK signals, but become excessively optimistic in the presence of higher-order-modulated signals, especially at low SNR values. Indeed, the DA CRLBs are the same for all linearly-modulated signals [18], i.e., they would misleadingly

suggest the same bound regardless of the modulation type or order if taken as a benchmark when it is in fact different in CA transmissions. So far, the CRLBs for CA SNR estimation have been derived analytically only in the very basic case of BPSK-modulated signals [23].

Contribution

In Appendix 3 of this thesis, we derive for the first time the analytical expressions for the CA CRLBs of SNR estimates from coded BPSK-, MSK- and arbitrary square-QAM-modulated signals. For the purpose of their validation, we also derive their empirical counterparts and show through numerical simulations (as seen in Figs. 1.5 and 1.6 below) that the new analytical CRLBs, indeed, coincide with their empirical values. They also reveal that the CA scheme lies between the NDA and DA schemes in terms of CRLB performance limit, acting therefore as its upper and lower ends, respectively. The CA's performance bound moves up or down to either ends with the coding rate relatively increasing or decreasing, respectively, thereby highlighting the expected potential in SNR estimation improvement from the coding gain. Part of these work was recently accepted in *IEEE GLOBECOM'14* conference [24] and a complete version has been also recently accepted for publication in *IEEE Transactions on Signal Processing* [25].

1.1.5 Joint Ricean K-factor and average SNR estimation in SIMO systems

Motivation and preliminary notions

In wireless communications, the Ricean channel model is often used to simulate and study real-life scenarios. The involved Ricean distribution is mainly characterized by the K-factor which

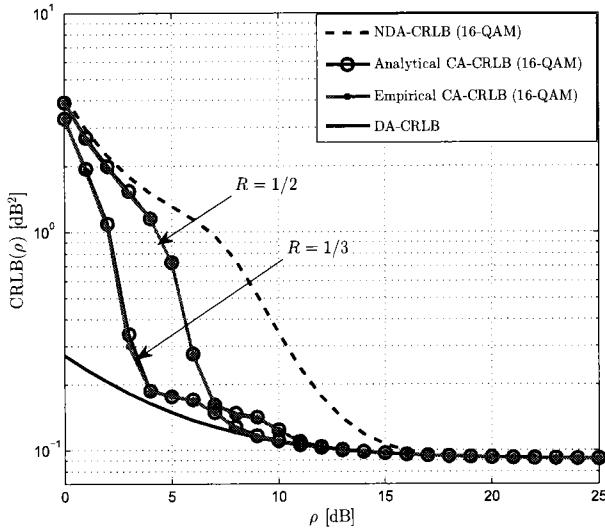


Figure 1.5: CA vs. DA and NDA CRLBs [dB^2] for SNR estimation as function of the true SNR ρ [dB] with two different coding rates ($R = 1/3, 1/2$): 16-QAM (please see Section V of Appendix for more details).

is defined as the ratio of the signal power in the direct component over the scattered power. In general, the value of the Ricean K-factor is a measure of the fading severity. Therefore, its estimation is a good indicator of the channel quality and is important for link budget calculations and handoff applications [28]. Moreover, as already mentioned in Section 1.1.1 (and references therein), reliable SNR estimates are required by many applications and as such jointly estimating the two key channel quality parameters (i.e., the SNR and the Ricean K-factor) is of trivial importance to any wireless communication system.

The K-factor estimators can also be categorized into three broad categories: ML techniques, moment-based and correlation-based techniques. Most of the existing Ricean factor estimators obtain the K-factor from the estimates of the channel coefficients since the observed samples at pilot positions form a sequence of such channel estimates. In NDA modes, however, a preliminary stage is required wherein the channel at non-pilot positions are estimated before

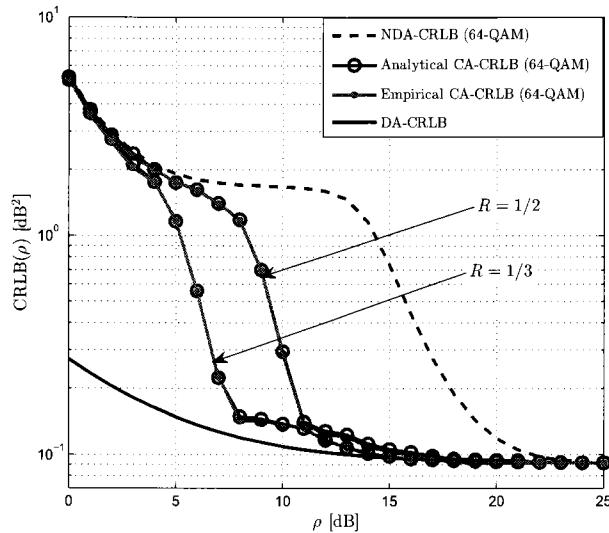


Figure 1.6: CA vs. DA and NDA CRLBs [dB^2] for SNR estimation as function of the true SNR ρ [dB] with two different coding rates ($R = 1/3, 1/2$): 64-QAM (please see Section V of Appendix 3 for more details).

proceeding to K-factor estimation.

State of the art

Many K -factor estimators have been developed in the last two decades. In [26], the Kolmogorov-Smirnov statistic was used to measure the maximum deviation between the theoretical Ricean distribution and its empirical counterpart. In [27], the ratio between the first moment and the zero crossing rate of the received signal instantaneous frequency was used to estimate the K -factor. In [28] and [29], a general class of moment-based and an in-phase (I) and quadrature (Q) I/Q-based estimators were proposed. The first moment and the root mean square fluctuation of the power gain of the received signal were used to estimate the K -factor in [30]. The Ricean

channel kurtosis and the ratio of the first-order and the squared second-order moments were also used to estimate the K -factor in [31]. All the aforementioned methods consider non-modulated signals or perform its estimation from the estimates of the channel coefficients and not directly from the received data. Only in [32], a joint K -factor and local average SNR estimator based on the autocorrelation function of a modulated signal is presented. Both DA and NDA estimations are discussed. In the DA case, the transmitted data symbols are assumed to be perfectly known *a priori*. In the NDA case, the transmitted symbols are completely unknown but, the proposed approach in [32] is only valid when the autocorrelation function of the transmitted data is non-zero. Moreover, this autocorrelation-based approach assumes perfect knowledge of the Doppler spread. Finally, it should be stressed that all existing methods were tailored to traditional SISO systems.

Contribution

In Appendix 4 of this thesis, we propose a joint estimator of the Ricean K -factor and the average SNR for SIMO fading channels. The second- and fourth-order cross-antennae moments of the received signal are used to estimate the desired parameters. The K -factor is estimated using the kurtosis of the Ricean channel gain while the SNR is obtained by separately estimating the powers of the useful signal and the additive noise components. Two versions are developed depending on the value of the transmitted data kurtosis. Unlike the autocorrelation-based K -factor and SNR estimator developed in [32], it does not require the knowledge of the maximum Doppler spread. Besides, the proposed method is NDA and therefore does not impinge on the whole throughput of the system. Simulations results show — as depicted in Figs 1.7 and 1.8 below — the clear superiority of the newly proposed approach and its resilience to Doppler

spread mismatch against [32] the only benchmark of the same class (i.e., joint K-factor and average SNR estimation from modulated signals) suitable for proper comparisons. Recall here that the DA estimator of [32] assumes perfect knowledge of the Doppler spread and in order to practically test its robustness toward the estimation error of this nuisance parameter, we use the following model:

$$\hat{\omega}_D = \omega_D + w, \quad (1.1)$$

where $\hat{\omega}_D$ is an estimate of the *actual* Doppler spread, ω_D , with a zero-mean estimation error, w , of variance σ_w^2 . This work was also published in *IEEE GLOBECOM'11* conference [33].

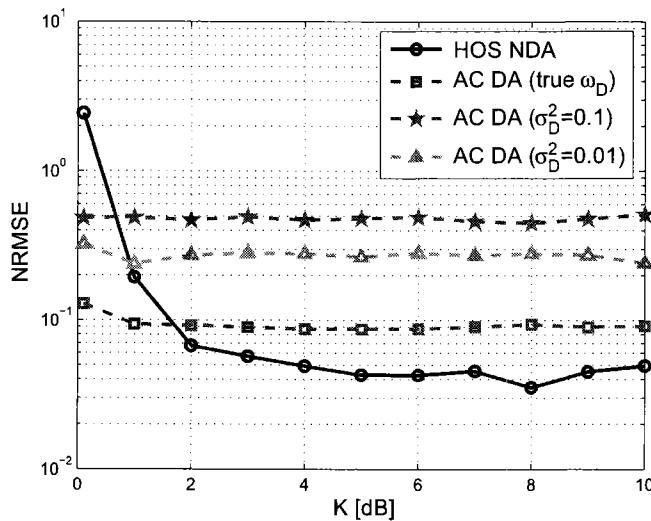


Figure 1.7: NRMSE of our new HOS NDA technique against the DA method of [32] in terms of Ricean K-factor estimation, 16-QAM modulation (please see Section IV of Appendix 4 for more details).

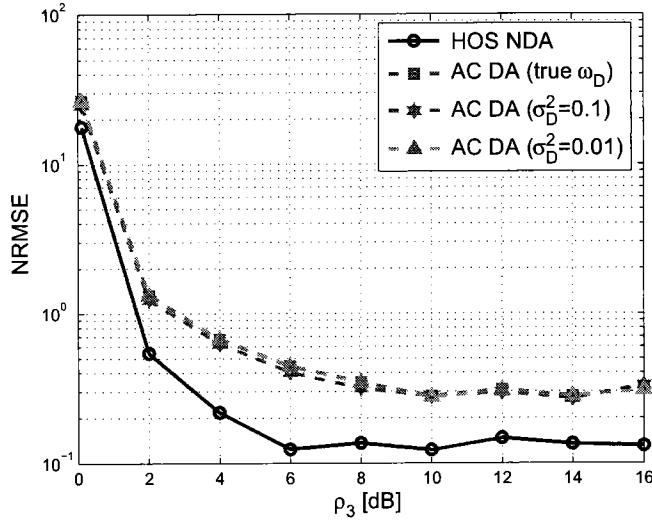


Figure 1.8: NRMSE of our new HOS NDA technique against the DA method of [32] in terms of SNR estimation on the third antenna element: $K = 10$ dB, 16-QAM modulation (please see Section IV of Appendix 4 for more details).

1.2 Synchronization parameters

1.2.1 Motivation and preliminary notions

In synchronous digital transmissions, the information is conveyed by uniformly-spaced pulses each transporting the information about a transmitted symbol. The received signal is completely known except for the data symbols and a group of variables referred to as *synchronization parameters* which are the time delay, the phase shift and the carrier frequency offset(CFO). Although the ultimate task of the receiver is to produce an accurate replica of each transmitted symbol, it is only by exploiting knowledge of the synchronization parameters that the detection process can be properly performed.

For instance, the knowledge/estimation of the time delay is required in order to sample the analog received signal at the right time positions. Indeed, the received waveform is first passed through a matched filter and then sampled at the symbol rate. The optimum sampling times correspond to the maximum eye opening and are located at the peaks of the signal pulses. Clearly, the locations of the delayed pulse peaks must be accurately determined—via accurate time delay estimation—for reliable detection [34].

Moreover, coherent demodulation is used with passband digital communications when optimum error performance is of paramount importance. This means that the baseband data signal is derived making use of a local reference with the same frequency and phase as the incoming carrier. This requires accurate CFO and phase distortion estimation as they introduce crosstalk between the in-phase and quadrature components of the received signal and degrade the detection process [34]. It should be mentioned here that the CFO arises due to the Doppler shift and/or any mismatch between the transmitter and receiver local oscillators.

1.2.2 Time synchronization

State of the art from an algorithmic point of view

Most of the proposed timing estimators are based on the cyclostationarity induced by the oversampling of the received signal. In particular, Oerder and Myer proposed the squared nonlinearity technique [35] whose performance was later assessed analytically in [36]. Various extensions of this early technique were also introduced in [37-39]. An approximation of the likelihood function at low SNRs was also exploited to develop a logarithmic nonlinearity approach in [37]. ML timing recovery was also considered in [41-42] and all the proposed techniques were iterative in nature. Therefore, they require a good initial guess about the unknown time delay

in order to converge to the global maximum of the underlying LLF. Other non-iterative ML time delay estimators were also proposed in [43, 44] which are built upon the approximation of the LLF by its Fourier series expansion. Thus, the performance/complexity of these two technique depends on the order of the underlying expansion. In fact, it was found that good performance can be achieved by taking a large number of Fourier coefficients which entails, in turn, excessively high computational load.

Contribution

In Appendix 5 of this thesis, we develop a new *non-iterative* approach to find the *conditional* maximum likelihood (CML) estimates of the time delay. We implement the CML estimator in a non-iterative way and avoid the grid search, essential in traditional iterative approaches, by using the importance sampling (IS) concept. The latter is a powerful tool in performing NDA ML estimation and was successfully applied to estimate other crucial parameters such as the direction of arrival (DOA), the carrier frequency or the joint DOA-Doppler frequency (see [97] and references therein). In this thesis, it is used for the very first time in the context of time delay estimation. Moreover, we adopt the discrete-time model widely used in the field of array signal processing and more recently formulated in the context of time-delay estimation [41]. As seen from Fig. 1.9 below, the resulting IS-based CML estimator enjoys guaranteed global optimality as it attains the modified CRLB (MCRLB) over both the medium and high SNR regions, whereas the traditional CML estimator, being iterative and thus dependent on the initial guess, may converge to a local minimum and thus departs from the MCRLB. Part of this work was published in the *IEEE WCNC'11* conference [45] and its complete version was published in *IEEE Transactions on Signal Processing* [46].

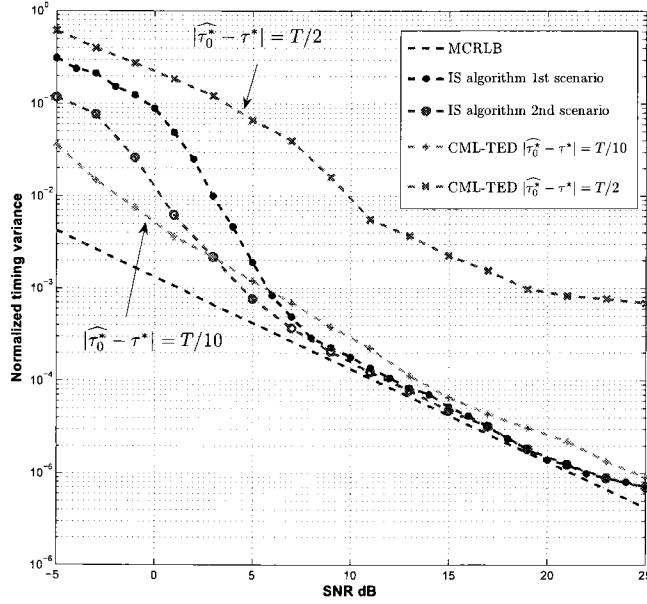


Figure 1.9: Comparison between the estimation performance of the new IS-based ML estimator using the two scenarios (1st scenario: the true time delay $\tau^* \in [0, T]$ and 2nd scenario $\tau^* > T$ where T is the symbol period) and the tracking performance of the *iterative* CML-TED (using two intial guesses, $\hat{\tau}_0^*$, about τ^*) using QPSK signals (please see Section VII of Appendix 5 for more details).

State of the art from the CRLB point of view

The performance of the aforementioned time delay estimators is usually compared to the CRLB as an absolute benchmark (i.e., lower bound) on their error variances. The computation of this bound has been previously tackled by many authors, under different simplifying assumptions. For instance, assuming the transmitted data to be perfectly known, one can derive the DA CRLB. The MCRLB, which is also easy to derive, has been introduced in [34], but unfortunately it is an extremely loose bound especially at low SNR levels.

Therefore, the exact (stochastic) time delay CRLBs for higher-order modulations were tackled

in previous works but their analytical expressions were explicitly derived for specific SNR regions only (i.e., very low or very high-SNR values) and the derived bounds are referred to as ACRLBs (asymptotic CRLBs). In fact, in [47] the stochastic time delay CRLBs were tackled under the low-SNR assumption and an analytical expression of the considered bound (ACRLB) was derived for arbitrary PSK, QAM and PAM constellations. In this SNR region, the authors of [47] approximated the likelihood function by a truncated Taylor series expansion to obtain a relatively simple ACRLB expression. An analytical expression was also introduced in [48] under the high-SNR assumption. This high-SNR ACRLB coincides with the stochastic CRLB in the high-SNR region but unfortunately it cannot be used even for moderate (practical) SNR values. Another approach was later proposed in [41] and [49] to compute the NDA deterministic (or conditional) CRLBs. Yet, it is widely known that the conditional CRLB does not provide the actual performance limit which is reflected by the unconditional or stochastic CRLB. In [50], the stochastic CRLB was empirically computed assuming perfect phase and frequency synchronization and a time-limited shaping pulse. Later in [51], its computation was tackled in the presence of unknown carrier phase/frequency and pulses that are unlimited in time. Both [50] and [51] simplified the expression of the bounds but ultimately resorted to empirical methods to evaluate the exact CRLB, without providing any closed-form expression.

Contribution

In Appendix 6, we derive for the very first time the closed-form expressions for the stochastic CRLBs of symbol timing recovery from BPSK-, MSK- and square-QAM-modulated signals. We consider the general scenario as in [51] in which the carrier phase and frequency offsets are completely unknown at the receiver, and show that this assumption does not actually affect

the performance of time delay estimation from perfectly frequency- and phase-synchronized received samples. The derivations assume an AWGN-corrupted received signal and a shaping pulse that verifies the first Nyquist criterion which is satisfied by most of practical shaping pulses. As clearly seen from Fig. 1.10 below, the new closed-form expressions allow us to interpret and see clearly the impact of key design parameters (such as the roll-off factor or the modulation type and order) on the achievable performance within the specific context of time delay estimation. Part of this work was published in the *IEEE ICC'11* conference [52] and its complete version was published in *IEEE Transactions on Signal Processing* [53].

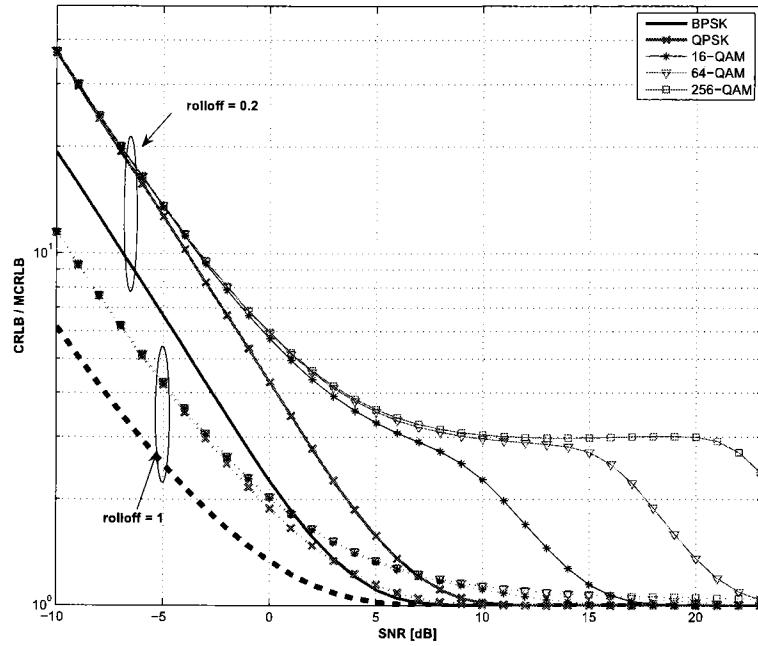


Figure 1.10: CRLB/MCRLB ratio vs. SNR for different modulation orders using $K = 100$ symbol-rate received samples and a raised-cosine pulse with rolloff factor of 0.2 and 1 (please see Section V of Appendix 6 for more details).

1.2.3 Phase and frequency synchronization

State of the art: CRLBs under *uncoded* transmissions

Under uncoded transmissions, where no *a priori* knowledge is available about the transmitted symbols, the ACRLBs of the phase and frequency estimates were earlier investigated in [48, 54]. The MCRLB for the separate estimation of the carrier frequency and the carrier phase was also derived in [55]. It was later extended in [56] to the joint estimation of the carrier frequency, the carrier phase and the symbol epoch of a linearly-modulated signal, but assuming the signal amplitude and the noise power to be perfectly known. In practice, however, the latter parameters are unknown to the receiver and need to be estimated as well. Furthermore, it is well known that the MCRLB is a good approximation of the exact CRLB only at high SNR levels and that it becomes significantly loose at low and moderate SNRs. Therefore, without the knowledge of the exact CRLB in the latter SNR regions, it is impossible to evaluate and compare the accuracy of a given unbiased NDA estimator with the fundamental performance limit.

Consequently, several reported works (see for e.g. [57, 2] and the references therein) dealt with either the empirical/numerical computation or the analytical derivation of the exact CRLBs of the carrier phase and frequency offsets, depending on the SNR region. In fact, for QAM signals, the CRLBs for the joint phase and frequency estimation were numerically computed, from very complex expressions, at low SNR values and empirically evaluated at moderate and high SNRs using Monte-Carlo computations [57]. For PSK signals, however, using a Taylor series expansion of the LLF, approximate analytical expressions for the carrier phase and frequency exact CRLBs were derived in [58], but only in the low-SNR regime (i.e., ACRLB). Besides, in these two works [57, 58], the noise power and the signal amplitude were considered as perfectly known. The

closed-form expressions of the exact CRLBs pertaining to the joint estimation of the carrier phase, the carrier frequency, the signal amplitude and the noise power were recently derived by Delmas in [59], but only in the very particular cases of BPSK/MSK and QPSK transmissions. However, considering higher-order QAM constellations, which are widely adopted in current and future high-speed communication technologies, there are no closed-form expressions for the exact CRLBs of the carrier phase and frequency offset NDA estimates.

Contribution

In Appendix 7, we derive closed-form expressions for the NDA CRLBs of the considered synchronization parameters, in uncoded transmissions, from any square QAM waveform over AWGN channels by further assuming the signal amplitude and the noise power to be completely unknown. Our new expressions generalize the elegant expressions recently derived in [59] from the BPSK/MSK and QPSK cases to higher-order square QAM signals. Besides, we prove that we are actually dealing with two disjoint problems regarding the estimation of the carrier frequency and phase offsets, on one hand, and the estimation of the signal amplitude and the noise power on the other hand. The newly derived expressions are of a great value in that they allow to quantify and analyze the achievable performance on the carrier frequency and the carrier phase NDA estimation from square QAM waveforms. These bounds are plotted in Figs. 1.11 and 1.12 below, for different modulation orders. Moreover, they corroborate the previous attempts to evaluate these practical bounds empirically [57] and allow their immediate evaluation under arbitrary square QAM constellations without the need for exhaustive and unpractical Monte-Carlo simulations. This work was published in *IEEE Transactions on Signal Processing* [60].

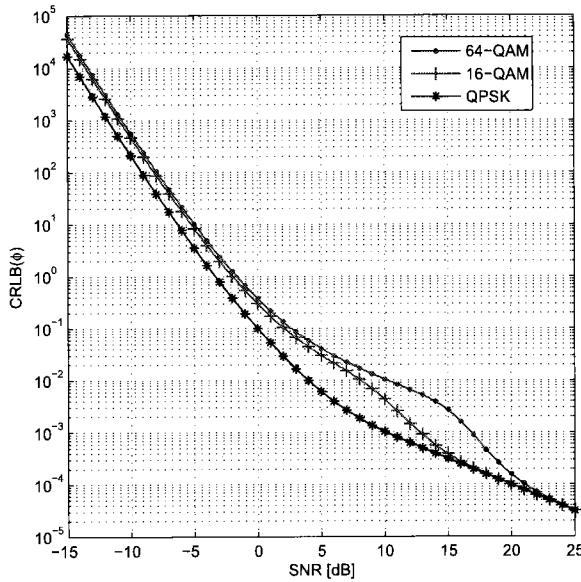


Figure 1.11: $\text{CRLB}(\phi)$ vs. SNR whith $N=100$ received samples (please see Section IV of Appendix 7 for more details).

State of the art: CRLBs under *coded* transmissions

As current and next-generation wireless communication systems are called upon to provide high quality of service, while satisfying the ever-increasing demand in high data rates, the use of powerful error-correcting codes in conjunction with high spectral efficiency modulations such as high-order QAMs is advocated. Yet, turbo codes are known to be very sensitive to synchronization errors. That is, even small mismatches between the transmitter's and receiver's local oscillators (CFO) and/or small phase shifts (introduced by the wireless channel) can lead to severe performance degradations. One of the obvious solutions to this problem consists in using turbo codes in conjunction with a coherent detection scheme where the carrier phase shift and the CFO are estimated and compensated for before proceeding to data decoding. As such, the synchronization parameters are estimated directly from the received samples at the

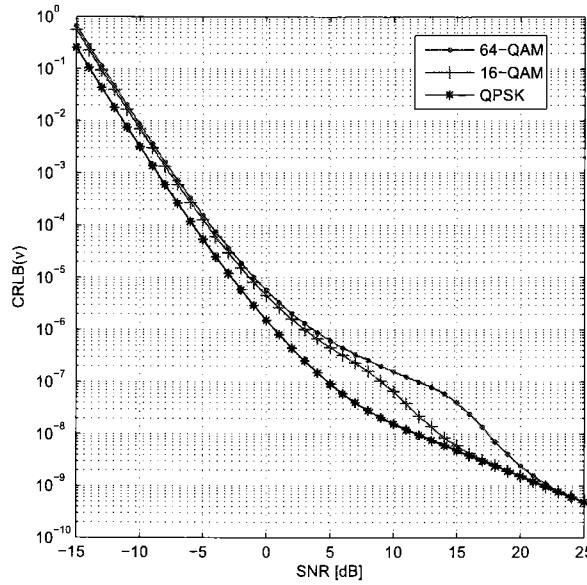


Figure 1.12: $\text{CRLB}(\nu)$ vs. SNR when $N=100$ received samples (please see Section IV of Appendix 7 for more details).

output of the matched filter with no *a priori* knowledge about the transmitted symbols (i.e. NDA estimation). However, NDA accurate synchronization is quite challenging for turbo-coded systems since it is primarily intended to operate at low signal-to-noise ratios (SNRs). Indeed, in such adverse SNR conditions, practical NDA techniques may result in high estimation errors, affecting thereby the overall system performance.

To circumvent this problem and properly synchronize turbo-coded systems at low SNRs, a more elaborate approach—usually referred to as *turbo synchronization*—was adopted in the open literature. In *turbo synchronization*, the estimation task is assisted by the decoder and, therefore, it is referred to as *code-aware* or *code-assisted* (CA) estimation, as opposed to non-code-aided (NCA) estimation (i.e., NDA scenario) discussed in the previous subsection. In this context,

several CA estimators for the carrier phase and frequency offsets have been so far introduced in the open literature (see [61-65] and references therein). Once again, in order to assess their performance, these CA estimators need to be gauged against the corresponding CRLBs (as absolute benchmarks). Within the same context, exhaustive Monte-Carlo simulations have been recently used by Noels *et al.* in [66, 67] to evaluate *empirically* the CRLBs for CA estimates of the carrier phase and CFO parameters from turbo-coded linearly-modulated signals. However, although much needed, their closed-form expressions have not been yet reported in the open literature.

Contribution

Motivated by these facts, we tackle in this thesis (cf. Appendix 8) the problem of joint phase and carrier frequency offset (CFO) estimation for turbo-coded systems. We derive for the first time the closed-form expressions for the exact CRLBs of turbo-coded square-QAM modulated signals. In particular, we introduce a new recursive process that enables the construction of arbitrary Gray-coded square-QAM constellations. Some hidden properties of such constellations will be revealed, owing to this recursive process, and carefully handled in order to decompose the system's likelihood function (LF) into the sum of two analogous terms. This decomposition makes it possible to carry out *analytically* all the statistical expectations involved in the Fisher information matrix (FIM). The new analytical CRLB expressions corroborate the previous attempts to evaluate the underlying bounds *empirically*. In the low-to-medium SNR region, the CRLB for CA estimation lies between the bounds for completely blind (i.e., NDA) and completely DA estimation schemes, thereby highlighting the effect of the coding gain. Most interestingly, in contrast to the NDA case, the CA CRLBs start to decay rapidly and reach the

DA bounds at relatively small SNR thresholds. The derived bounds are also valid for LDPC-coded systems and they can be evaluated when the latter are decoded using the turbo principal. The new CA CRLBs are illustrated in Figs. 1.13 and 1.14 below. Part of this work has been recently accepted for publication in *IEEE GLOBECOM'14* conference [68]. A complete version work was also submitted to *IEEE Transactions on Wireless communications* [69] and got very positive feedback from the anonymous reviewers. It was revised according to the reviewer's suggestions/comments and is now under 2nd round review.

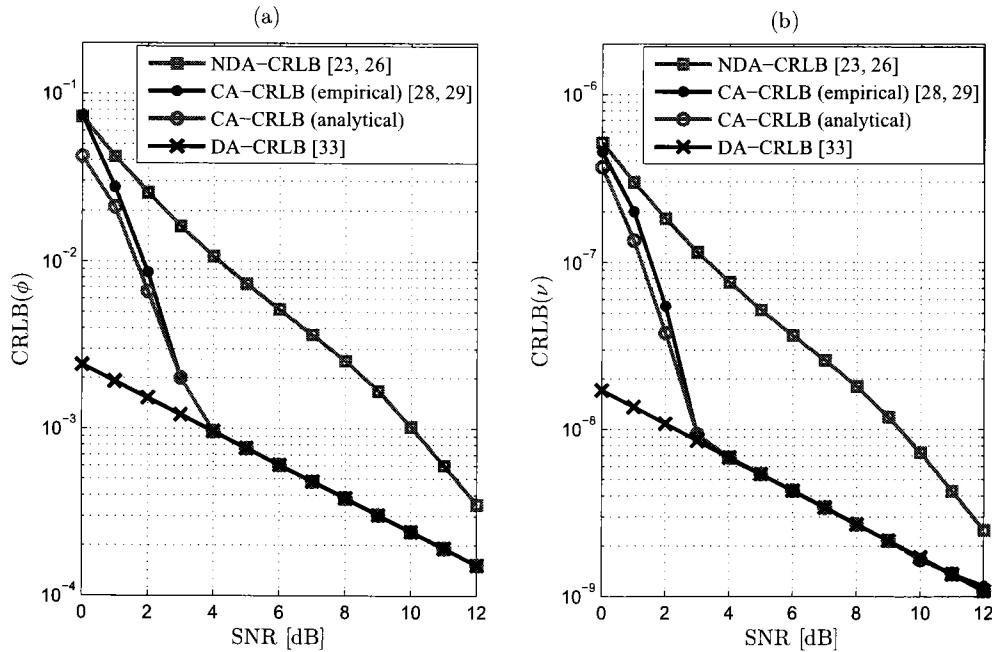


Figure 1.13: NDA, DA, and CA (analytical and empirical) estimation CRLBs for (a) the phase shift, and (b) the CFO: 16-QAM; $K = 207$ received samples (please see Section VI of Appendix 8 for more details).

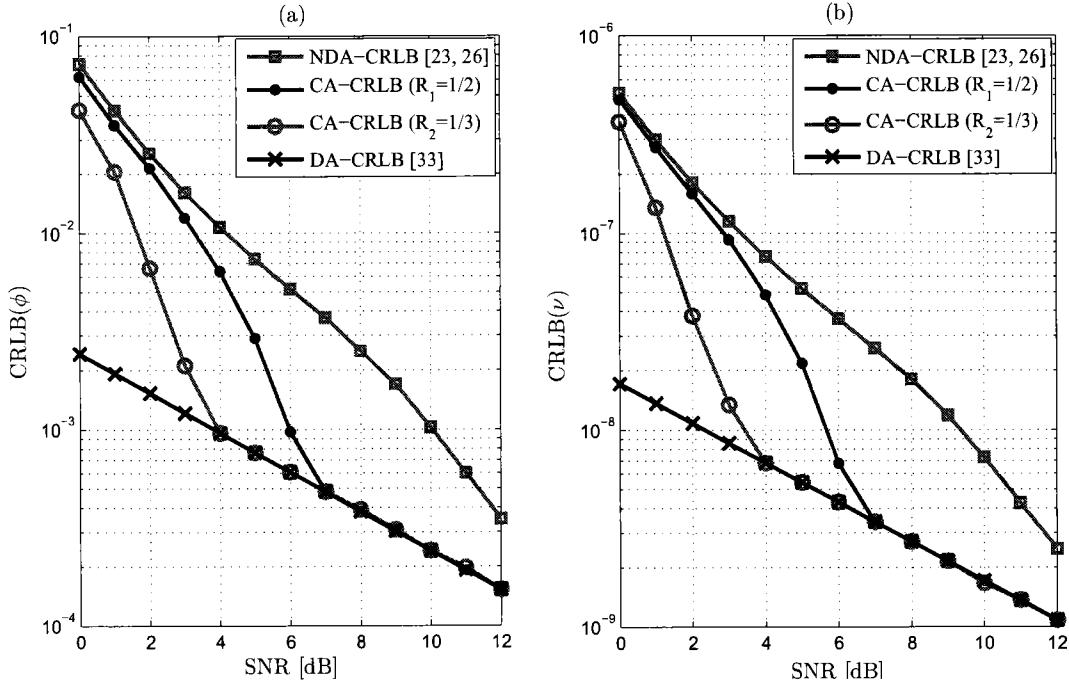


Figure 1.14: CA estimation CRLBs (analytical) for (a) the phase shift, and (b) the CFO with two different coding rates ($R_1 = 1/2$, $R_2 = 1/3$) and $K = 207$ received samples; 16-QAM (please see Section VI of Appendix 8 for more details).

1.3 Multipath-resolution parameters

1.3.1 Motivation and preliminary notions

In parametric multipath propagation models, a source signal impinges on the receiver through a number of rays usually called multipath components in communication engineering terminology. If the receiver is equipped with a single antenna element, then each path is fully described by a time delay (TD) and a complex path gain. The estimation of the path delays is a well-studied problem with applications in many areas such as radar [70], sonar [71], and wireless communication systems [72]. We distinguish two modes depending on the *a priori* knowledge

of the transmitted signal. In the *active* mode, an *a priori* known waveform is transmitted through a multipath environment, which consists of several propagation paths, among which the dominant ones, relatively few, are considered. In this case, the actual TDs of the different multipath components can be estimated even if the receiver is equipped with a single antenna branch. In the *passive* mode, however, the transmitted waveform is completely unknown to the receiver and, in this case, only the time difference of arrivals (TDOAs) can be estimated [73]. Both modes will be treated in this thesis under the TDs-only estimation problem.

When the receiver is endowed with multiple antenna elements, each path can be additionally characterized by its angle-of-arrival (AoA) on the top of the corresponding TD and complex path gain. In this case, the joint angles and delays estimation (JADE) problem can be envisaged endowing thereby the system with stronger sensorial capabilities leading, for instance, to more robust beamforming techniques [74] and enhanced equalization performance [75]. Moreover, as location-aware services for handhelds are likely to be in high demand for future wireless communication systems, the information about the AoAs and the TDs can be used to design highly-accurate localization techniques [76]. In this context, in order to cope with dense multipath environments, the so-called *fingerprinting* paradigm which recasts the localization problem as a pattern recognition problem was envisaged [77-81]. In particular, it was recently shown that *fingerprinting* techniques with location signatures that are characterized by AoAs and TDs of each candidate location lead to substantial improvements against those with location signatures that are characterized by the received signal strength (RSS) [82]. In fact, contrarily to the RSS which varies substantially over a distance of wavelength (due to constructive and destructive multipath interference), the AoAs together with the associated TDs form a unique fingerprint for each location [83]. Hence, accurate and low-cost estimation of

such multipath parameters can be used along with the *fingerprinting* paradigm to develop very efficient localization algorithms.

1.3.2 TDs-only estimation

State of the art

Both *active* and *passive* TD-only estimation problems have been extensively studied in previous years [84-89]. Although, the ML estimator is well known to be an optimal technique, the LLF depends on both the TDs and the complex channel coefficients making its analytical maximization mathematically intractable. Moreover, a direct numerical solution to the ML criterion requires a multidimensional grid search whose complexity increases with the number of unknown delays. Therefore, many iterative methods, such as the *expectation maximization* (EM) algorithm [88-89], were developed in order to achieve the corresponding CRLB at a lower cost. Yet, their performances are closely tied to the initialization values and their convergence may take many complex iterative steps and hence a good complexity/accuracy trade-off must be found by developing a non-grid-search-based non-iterative ML estimator. In this context, sub-optimal methods based on the eigen-decomposition of the sample covariance matrix, which initially gained much interest in the direction of arrival estimation, were later exploited in the context of TDs-only estimation [84-87]. While these suboptimal techniques offer an attractive reduced complexity compared to the grid search implementation of the ML criterion, they still suffer from heavy computation steps due to the eigenvalue decomposition. Moreover, their performances are relatively poor compared to the ML estimator, especially for closely-spaced delays and/or few numbers of samples.

Contribution

Motivated by the aforementioned facts, we derive in Appendix 9 a new non-iterative implementation of the ML TDs estimator under both *active* and *passive* modes. The new ML solution avoids the multidimensional grid search by applying:

- i) the global maximization theorem of Pincus proposed in [90] and;
- ii) a powerful Monte-Carlo technique called importance sampling (IS) offering thereby an efficient tool to find the global maximum of the likelihood function.

Note here that many other traditional Monte-Carlo techniques (besides the IS method) can also be successfully applied. However, unlike the IS method, they often require a larger number of realizations that are, in addition, usually generated according to a complex probability density function (pdf). Hence they appear to be less attractive for practical considerations. In this sense, the importance sampling technique lends itself as a powerful alternative in which the required realizations are easily generated according to a simpler pdf. Additionally, it offers a way to process the obtained realizations in a more judicious manner [91]. As seen from Figs. 1.15 and 1.16 below and those in Appendix 9, the new TDs-only ML estimator offers substantial performance gains against state-of-the-art techniques with a clear advantage in terms of computational complexity as well. This work was published in part in the *IEEE GLOBECOM'11* conference [92] and the complete version was published in *IEEE Transactions on Signal Processing* [93].

In Appendices 10 and 11, we also address the problem of time delay estimation from Direct-Sequence CDMA (DS-CDMA) multipath transmissions in the presence of receive antenna diversity. We derive for the first time a closed-form expression for the CRLB of multiple time delay estimation in single-carrier (SC) DS-CDMA systems (cf. Appendix 10). We develop two

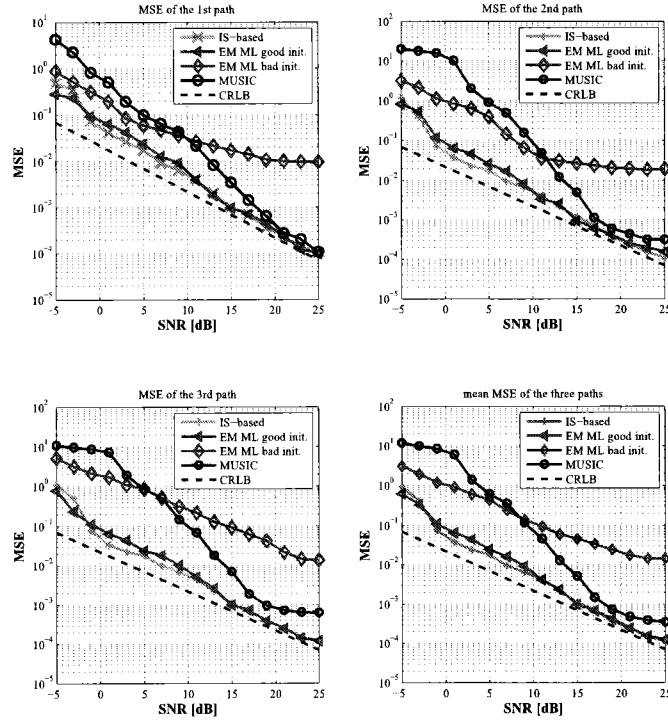


Figure 1.15: Estimation performance of the IS-based, EM ML and the MUSIC-type algorithms in an active system vs. SNR (please see Section V of Appendix 9 for more details).

time delay estimators based on the ML criterion. The first one — developed in Appendix 10 — is based on the iterative EM algorithm and provides accurate estimates whenever a good initial guess of the parameters is available at the receiver. The second approach (Appendix 11) implements the ML criterion in a non-iterative way and finds the global maximum of the *compressed* likelihood function using the IS technique. Unlike the EM-based algorithm, this non-iterative IS-based method does not require any initial guess of the parameters to be estimated. We also extend both the SC CRLB and the newly proposed SC algorithms to multicarrier (MC)-DS-CDMA systems.

In this work, the estimation process can be performed using the channel estimates or pilot-modulated signals [i.e., from a data-free observation (DFO)] or blindly from the received data-modulated signal [i.e., data-modulated observation (DMO)] thereby covering all possible DFO

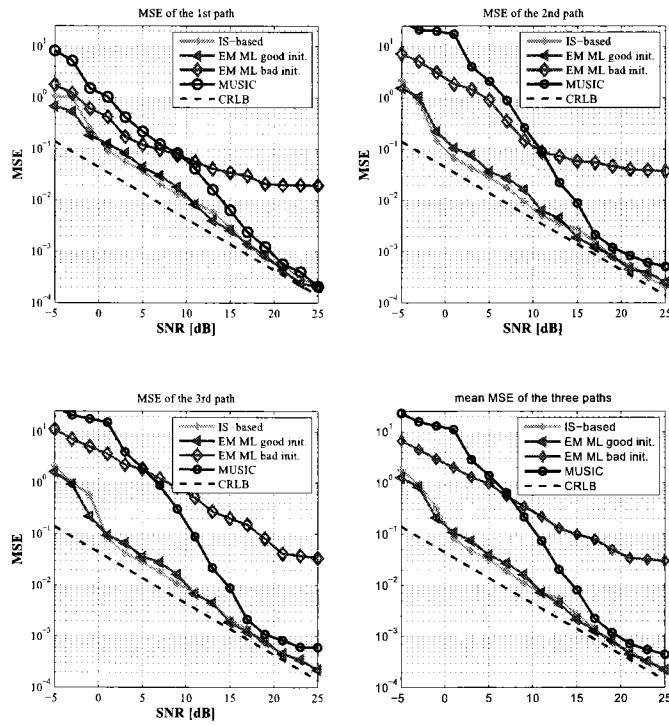


Figure 1.16: Estimation performance of the IS-based, EM ML and the MUSIC-type algorithms in an passive system vs. SNR (please see Section V of Appendix 9 for more details).

and DMO cases. By an adequate formulation of the problem in the former case (i.e., DFO), we are also able to cope with the time and frequency correlations of the channel. We show by simulations that the EM-based algorithm is suitable for CDMA systems with large receive antenna-array sizes whereas the IS-based version offers better performance for small array sizes. Moreover, we prove analytically and through simulations, in the DMO case, that spatial, temporal and frequency samples indistinguishably play equal roles in time delays estimation. The IS-based ML estimator was published in *IEEE ASILOMAR'11* conference [94] and the EM-based one along with the CRLB and extensions to MC-CDMA systems was published in *IEEE VTC'12-Fall* conference [95]. Due to other prioritized investigations, preparation of a journal version that discloses much more comprehensive and detailed expressions and results was delayed, but is currently under preparation.

1.3.3 Joint angles and delays estimation (JADE)

State of the art

Unlike JADE, the separate (or disjoint) estimation of the time delays or the directions of arrival (DOA) has been heavily investigated for decades now. For prior works on DOA-only estimation, see the conditional and unconditional ML methods [96,97], MUSIC [98], ESPRIT [99], and MODE [100] algorithms as well as the subspace fitting methods [101, 102], etc. For TD-only estimation, see[88-89] and references therein.

In comparison with disjoint estimation techniques which can first estimate the delays and then the corresponding angles, the joint estimation of these space-time parameters (i.e., JADE) is more accurate in cases where multiple rays have nearly equal delays or angles [74]. Moreover, contrarily to JADE, the number of estimated angles in DOA-only estimation must be smaller than the number of antennae. Thus DOA-only estimators would require large-size antenna arrays in highly dense multipath environments.

So far, a number of JADE techniques have been reported in the literature and, roughly speaking, they can be broadly categorized into two major categories: subspace-based and ML-based estimators. Most of the subspace-based techniques are built upon the well-known MUSIC and ESPRIT algorithms or their variants [103-105]. In practice, subspace-based approaches are more attractive due to their reduced computational load. However, since they rely on the sample estimate of the covariance matrix, they are usually suboptimal and suffer from severe performance degradation (both in terms of resolution and estimation accuracy) for low SNR levels and/or closely-spaced paths. ML approaches, however, apply the estimation process directly on the received samples and as such always enjoy higher accuracy and enhanced resolution. Despite their promising advantages, their computational complexity has been often

considered as the major culprit for a widespread reluctance of designers to their implementation in practice.

In the specific JADE context, to the best of our knowledge only two ML estimators have been so far introduced in the open literature. The very first ML solution was proposed by Wax *et al.* in [106] which is *iterative* in nature and thus will be referred to, hereafter, as the iterative ML (IML) estimator. The other ML solution is also *iterative* and it has been derived in [107] based on the space-alternating generalized expectation maximization (SAGE) algorithm. However, like any *iterative* approach, the performance of these two ML estimators is closely tied to the initial knowledge about the unknown parameters. If the initial guess is not reliable, such ML *iterative* techniques will not converge to the global maximum of the log-likelihood function (LLF). On the other hand, for both ML estimators, a fixed sampling grid is selected to serve as the set of all candidate estimates for the unknown TDs and AoAs. Then, by assuming that all true (unknown) parameters are exactly on the selected grid, IML and SAGE attempt to maximize the LLF iteratively. Consequently, they suffer from the inevitable off-grid problem which arises in practical situations where some of the true TDs and/or AoAs are not considered on the sampling grid. For accurate estimation, it is compulsory to use a densely-sampled grid since it reduces the gap between the true parameters and their nearest points on the grid. Since “there is no free lunch”, however, the cost of a dense grid sampling is the excessive increase in computational complexity.

Contribution

The aforementioned problems, among many others, have spurred a widespread belief among the signal processing research community that resorting to suboptimal solutions is inevitable by

trading estimation accuracy for lower complexity. One of the contributions embodied by this thesis (cf. Appendix 12) challenges that basic percept by deriving a novel ML JADE technique that beats state-of-the-art subspace-based methods both in terms of accuracy and complexity. Most remarkably, as seen from Fig. 1.17 below the new ML estimator reaches the CRLB for SNR levels as low as -10 dB while resolving multipath components with angular separation as small as 1° .

The proposed estimator builds upon the global maximization theorem of Pincus [90] along with

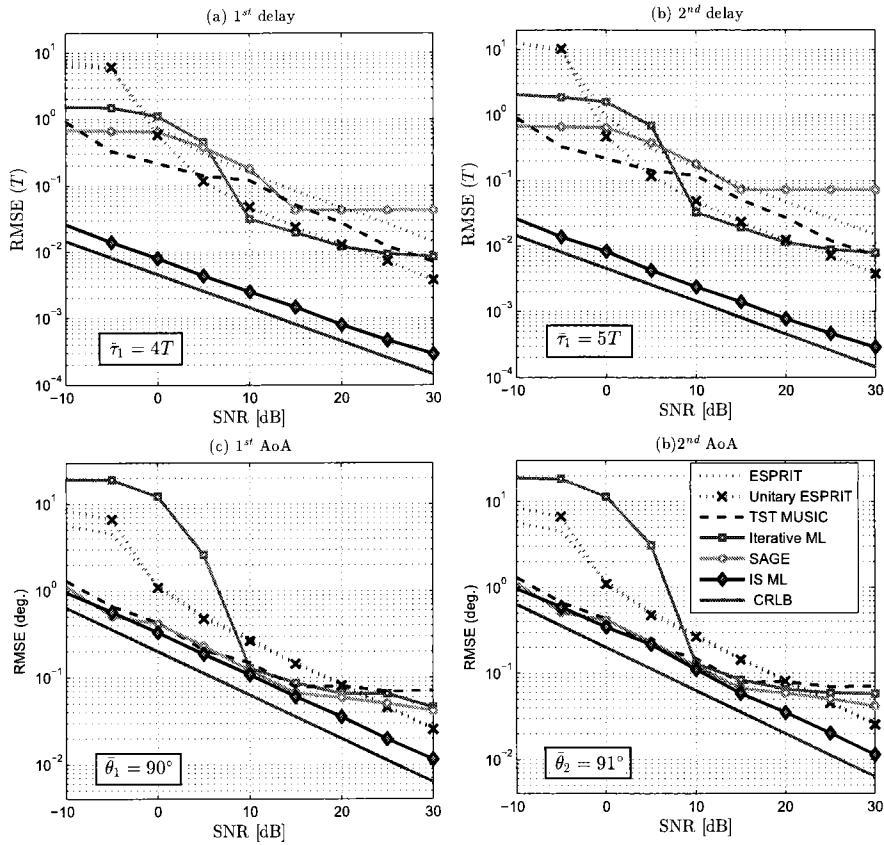


Figure 1.17: RMSE for the TDs and AoAs with $M = 128$ samples for *small* angular separation (please see Section VIII of Appendix 12 for more details).

the *importance sampling* (IS) concept. In particular, owing to a very accurate approximation of the true compressed likelihood function (CLF), we transform the original *multidimensional*

optimization problem into multiple *two-dimensional* optimization ones resulting thereby in tremendous computational savings. Even more, the underlying two-dimensional optimization problems are totally disjoint and can be performed separately in practice. From this perspective, the new IS-based ML estimator lends itself as a very attractive solution to parallel computing that can be efficiently performed on nowadays multiprocessor platforms. Roughly speaking, the major difficulty with IS consists in generating multiple realizations according to a given pdf. In the JADE context, we propose a separable (factorizable) joint angle-delay pseudo-pdf which allows a very easy generation of the required realizations. Moreover, by exploiting the sparsity of the proposed pseudo-pdf, we derive — as a by-product of this contribution — a simple and yet very accurate approach to estimate the number of paths which is also *a priori* unknown in practice. Part of this work was recently accepted for publication *IEEE ICASSP'14 conference* [108] and a full version has been recently submitted to *IEEE Transactions on Signal Processing* [109].

1.4 Location and mobility parameters

1.4.1 DOA estimation: motivation and preliminary notions

In recent years, there has been a surge of interest in array signal processing applications fueled by the deployment of communication systems that are endowed with multiple receiving antenna elements. Typically, direction of arrival (DOA) estimation of multiple plane waves impinging on an arbitrary array of antennas has been the subject of intensive research [131, 132]. In fact, from military to civil communications, the task of direction finding has been at the heart of many applications. Indeed, the concept of estimating the DOAs of unknown sources naturally comes

to mind when invoking radar or sonar systems. In addition, in modern mobile communication systems, for example, based only on the data received at the antenna array, estimating the DOAs of the desired users and those of the interference signals allows their extraction and cancellation, respectively, by beamforming technologies [133, 134] in order to improve the wireless systems' performance.

1.4.2 DOA estimation of *uncorrelated* sources

State of the art

Many DOA estimators have been extensively studied assuming different data models. Indeed, a number of high-resolution DOA estimation algorithms have been developed assuming the signals to be independent and identically distributed (iid) and generated from circular sources. The well-known estimators derived in this case are the deterministic (or conditional) and the unconditional ML estimators [96]. However, the ML estimator is computationally quite expensive due to the required multivariate nonlinear maximization. Therefore, researchers have derived the so-called eigenstructure or signal subspace methods such as the MULTiple SIgnal Classification (MUSIC) estimator [135, 136] and the Estimation of Signal parameters via Rotational Invariance Technique (ESPRIT) estimator [137] which offer more computationally attractive methods for DOA estimation. Despite their relatively reduced computational cost, these two techniques were proved to be statistically less accurate than the ML estimator. The Method Of DOA Estimation (MODE) technique which advocates a compromise between the good performance of the ML method and the computational simplicity of MUSIC was later proposed in [138]. However, this method was shown to be statistically inefficient in the case of coherent sources. Furthermore, authors have proposed in [101] some signal subspace fitting (SSF)

methods. In fact, the MD-MUSIC which is an alternative multidimensional array processing that is technique based on subspace fitting was derived as an extension of the one-dimensional MUSIC algorithm. This estimator was proved to be performed by an optimal multidimensional subspace fitting based technique referred as the weighted subspace fitting (WSF) method. This technique was shown to be asymptotically identical to the MODE estimator when the sources are non-coherent. However, for coherent sources only WSF is efficient.

Despite their reduced complexity, all the aforementioned subspace-based DOA estimators suffer from dramatic performance degradations in presence of short data records. In the latter situation, ML estimators would provide satisfactory performance but as mentioned earlier their complexity increases rapidly with the number of DOAs. Therefore, complexity/performance tradeoffs need to be considered for many practical purposes and there is a need to develop a DOA estimation technique that is able to properly handle the low-number-of-snapshots scenario with reduced complexity.

Contribution

In this context, we propose in Appendix 13 a new low-cost moment-based technique for multiple DOA estimation from very short data snapshots using uniform linear array (ULA) antenna configurations. The noise components are assumed temporally and spatially white across the receiving antenna elements. The transmitted signals are also assumed to be temporally and spatially white across the transmitting sources. The new DOA estimator is based on the *annihilating filter* (AF) technique: finding the roots of an annihilating filter (AF) which are directly related to the unknown DOAs. It should be noted that the AF technique has been well known for a very long time in the mature field of spectral estimation. About a decade ago,

it was also used to successfully develop the so-called finite-rate-of-innovation (FRI) sampling method [140] where it led to signal sampling and reconstruction paradigms at the minimal possible rate (far below the traditional Nyquist rate). In this contribution, we apply for the first time the AF approach to DOA estimation for ULA configurations. The coefficients of the corresponding AF are calculated by the singular value decomposition (SVD) of a matrix whose elements are built from second-order cross moments across the receiving antenna elements of the received samples. Interestingly, this matrix is of reduced dimensions yielding thereby a very low computational load of the SVD decomposition.

In the multiple snapshot case, the new technique is compared in accuracy performance to the corresponding CRLB [96] and to the root-MUSIC algorithm — a popular powerful technique of DOA estimation for ULA systems — which is also based on finding the roots of a polynomial objective function. In the single-snapshot scenario, it is compared to the corresponding CRLB as well as to the deterministic ML (DML) estimator and to another Bayesian method that were designed specifically for this challenging scenario (single snapshot) [141]. We mention here that a more recent *iterative* technique that handles the single-snapshot case has also been proposed in [142]. Unfortunately, in its NDA version, it relies on the prior availability of an initial guess about all the unknown DOAs whose accuracy affects the overall performance of the method. Therefore, for the sake of fairness, this technique is not considered since none of the considered techniques (including our AF-based estimator itself) requires an initial guess about the DOAs. Even more, it has been recently recognized in a comparative study of various DOA estimators [143] that the DML method is indeed the most attractive one if the DOAs are to be estimated from a single snapshot. It will be shown by Monte-Carlo simulations (cf. for instance Fig. 1.18 below) that the new AF-based method is able to accurately estimate the DOAs from short data

snapshots and even from a single-shot measurement.

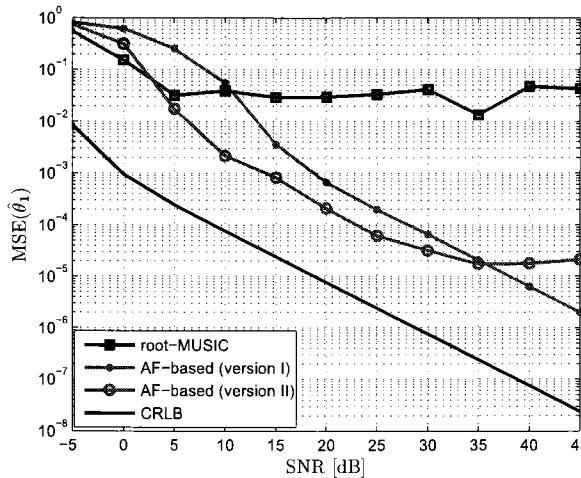


Figure 1.18: MSE for the first DOA (of two independent sources) versus the SNR, $N = 3$ snapshots, $\theta_1 = 0.1\pi$, $\theta_2 = 0.2\pi$, $N_a = 16$ antenna elements (please see Section IV of Appendix 13 for more details).

It outperforms the classical Bayesian and deterministic ML estimators over a wide SNR range. Moreover, it enjoys a substantially reduced computational complexity as compared to all the existing DOA estimators. This work was published in *IEEE GLOBECOM'11 conference* [144]. Due to other prioritized investigations, preparation of a journal version that discloses much more comprehensive and detailed expressions and results of this work was delayed, but is currently under preparation.

1.4.3 DOA estimation of *correlated* sources

State of the art

Despite their efficiency, all the aforementioned estimators have some practical limitations. In fact, they are mainly developed assuming the snapshots to be iid or uncorrelated in time.

This iid assumption presents a challenging limitation on the applicability of the results in the real world and results in some practical difficulties. Therefore, efforts have been directed to considering more realistic models assuming the signals to be temporally correlated. In this context, a novel instrumental variable (IV) approach to the sensor array problem was proposed in [145]. This IV technique that assumes the signals to be temporally correlated and circular Gaussian distributed does not require any knowledge of the noise covariance matrix but its uncorrelatedness in time. Although the IV method was proved to be computationally much less expensive than the eigendecomposition or ML-based techniques, it was shown to give inaccurate estimates in difficult scenarios involving highly-correlated and/or closely-spaced signals. Therefore, authors have proposed in [146] a new IV method that combines the ideas of signal subspace fitting (SSF) and IV. This combination resulted in a more computationally complex method than the one presented in [145]. However, the new method was proved statistically to be greatly accurate as compared to the previous technique especially in the case of highly and fully correlated signals. More recently, Haddadi, Nayebi and Aref proposed in [147] a new algorithm for correlated-in-time signals which presents performance improvements over the method developed in [146]. All the aforementioned DOA estimation techniques are tailored toward *circular* signals.

Yet, *noncircular* complex signals such as BPSK- and offset QPSK (OQPSK)-modulated signals are also frequently encountered in digital communications. Therefore, in the past few years years, there has been a surge of interest in deriving new DOA estimation algorithms that exploit the *unconjugated* spatial covariance matrix for *noncircular* signals (see [148, 149] and references therein). However, the latter techniques are designed to uncorrelated sources and—to the best of our knowledge—no contributions have dealt yet with the problem of DOA estimation from

temporally and spatially correlated signals that are generated from *noncircular* sources.

Contribution

The aim of Appendix 14, in this thesis, is to tackle the problem of DOA estimation in the case of both temporal/spatial correlation and noncircularity of the signals. We derive the first method ever of estimating the DOA parameters under temporal/spatial correlation and in presence of noncircular signals. The new approach, based on a significant enhancement of the two-sided instrumental variable signal subspace fitting (IV-SSF) method, outperforms its classical version in terms of lower bias and error variance. Moreover, our new method is statistically more efficient than MODE especially in the case of partly and fully coherent signals where only the extended and the classical two-sided IV-SSF methods are applicable. We also derive an explicit expression for the stochastic CRLB of the DOA estimates from temporally and spatially correlated signals generated from noncircular sources. The new CRLB is compared to those of *circular* temporally-correlated and *noncircular* independent and identically-distributed signals to show that the CRLB obtained assuming both *noncircular* sources and temporally-correlated signals is lower than the CRLBs derived considering only one of these two assumptions. This illustrates the potential gain that both noncircularity and temporal correlation provide when considered together. We show that the difference between the three CRLBs increases with the number of snapshots. However, as the SNR increases, the CRLBs merge together and decrease linearly. Moreover, at low SNR values, we show that temporal correlation is more informative about the unknown DOA parameters than noncircularity. Finally, the CRLB derived assuming *noncircular* and temporally-correlated signals depends on the noncircularity rate, the circularity phase separation and the DOA separation. Part of this work was published in the *IEEE*

WCNC'11 conference [150] and its full version was published in *IEEE Transactions on Signal Processing* [151].

1.4.4 CRLB for DOA estimation of *modulated* sources

State of the art

Several works which deal with the computation of the stochastic CRLB for DOA estimates have been reported in the literature. In fact, an explicit expression of the DOA CRLBs for real Gaussian distributions was earlier derived in [152, 153] by Slepian and Bangs. This work was later extended to circular complex Gaussian distributions in [154]. The stochastic and deterministic DOA CRLBs were also derived in [96], where both the signal and noise are jointly circular Gaussian for the stochastic model and deterministic and circular Gaussian for the deterministic model, respectively. More recently, an explicit expression for the stochastic DOA CRLB of noncircular Gaussian sources in the general case of an arbitrary unknown Gaussian noise field was derived in [155].

However, despite the very rich literature on the problem of direction finding, there is not so much information about DOA estimation from modulated sources, especially regarding the bounds on estimation accuracy. In this context, we cite the recent work [156] carried out by Delmas and Abeida who, for the first time, successfully addressed this challenging problem, but only for BPSK and QPSK signals. In another work related to [156], the same authors derived the CRLBs of the DOA parameters from BPSK-, QPSK- and MSK-modulated signals corrupted by a nonuniform Gaussian noise [157]. But to the best of our knowledge, no contribution has dealt so far with the stochastic CRLB for higher-order modulated signals in DOA estimation.

Contribution

In Appendix 15, we address the problem of DOA estimation from square-QAM-modulated signals with any antenna configuration. We derive for the very first time analytical expressions for the NDA Fisher information matrix (FIM) and then for the stochastic CRLB of the NDA DOA estimates in the case of square QAM-modulated signals. We show that in the presence of any unknown phase offset (i.e., non-coherent estimation), the ultimate achievable performance on the NDA DOA estimates holds almost the same irrespectively of the modulation order. However, the NDA CRLBs obtained in the absence of the phase offset (i.e., coherent estimation) vary, in the high SNR region, from one modulation order to another. This work was published in *IEEE Transactions on Signal Processing* [158].

1.4.5 Doppler spread estimation

Motivation and preliminary notions

The environment of mobile communication systems is characterized by a multipath time-varying fading channel where the received signal and its phase are time varying randomly. As known, the fading rate of the channel depends on the Doppler spread (or equivalently the maximum Doppler frequency) which is related to the velocity of the mobile terminal. The Doppler spread is therefore a key parameter for transceiver optimization in mobile communication systems. The characterization of the time variations of such a propagation channel is directly related to the Doppler information. The knowledge of the Doppler parameter or time variations rate (such as the coherence time for example) can be used to optimize the interleaving length in order to reduce the reception delay in addition to optimizing the feedback rate of CSI-based schemes [110]. From the signal processing point of view, the Doppler spread is involved in opti-

mizing the adaptation steps of adaptive channel estimation algorithms [111]. It has also been a key parameter for many other wireless communication applications such as power control and handoff schemes [112-113]. Moreover, due to the very nature of the newly deployed heterogeneous networks (HetNets), the well-known interference mitigation and handoff hysteresis issues are exacerbated when a moving user temporarily enters or even approaches a small cell (i.e., picos or femtos), thereby interfering with its users and possibly resulting in brief macro/small and small/macro cell-reassignments[114]. Reducing interference and avoiding useless handoffs can be achieved by predicting the evolution of the interferer's trajectory through its Doppler spread information (i.e., velocity).

State of the art

In practice, the Doppler spread estimates are usually obtained from the estimates of the channel coefficients. Then, depending on how the channel estimates are processed, four classes of Doppler estimators are encountered in the open literature: the level-crossing rate (LCR)-based [115-116], the covariance-based [117-119], the spectrum-based [120], and the ML techniques. The covariance-based estimators are usually preferred as compared to the LCR-based ones. Indeed, the latter need a very large observation window size. Otherwise, the number of crossings may be very small (or there may even be no crossings at all for small Doppler values). The performance of the covariance-based estimators themselves degrades drastically for a relatively small number of received samples, due to a weaker averaging effect (i.e., unreliable estimates of the channel autocorrelation coefficients). The same holds for the spectrum-based ones, since the estimated spectrum is the Fourier transform of these autocorrelation coefficients. In adverse conditions such as in data shortage cases, the ML estimators are known to be the most accurate

by relying, among other things, on the direct use of the channel coefficients themselves.

ML estimators are known to be the most accurate and four ML-based Doppler estimators were previously introduced in the open literature. In fact, one of the first implementations of the ML criterion was proposed in [121] based on the maximization of the power spectral density (PSD) of the estimated channel and a hypothetical one (namely the Jakes' model). Another early ML approach was developed in [122], in the specific context of TDMA transmissions, where periodic pilot symbols are transmitted over each time slot. It involves, however, the numerical inversion of the covariance matrix, a quite demanding operation in complexity. Later, another ML estimator was proposed in [123] using the Whittle approximation. However, it works only for very large normalized Doppler frequencies ($f_n > 0.1$ where $f_n = F_d T_s$ and T_s is the sampling period). Estimation of very low normalized Doppler frequencies is, however, more challenging and more useful. Indeed, current 3G and 4G wireless communication systems and beyond are characterized by high-data-rate transmissions and, hence, require very high sampling rates (e.g., typically $T_s = 70 \mu\text{s}$ in LTE systems [124]). Hence, the target normalized Doppler frequency region for these systems is typically in the range of $0.0001 \leq f_n \leq 0.03$ for a maximum Doppler frequency F_d ranging from 1 to 450 Hz. A more recent ML estimator was specifically designed to cope with relatively small normalized Doppler frequencies [125] and, hence, shown to outperform the two previous ML versions. It will be therefore selected as a first benchmark against which we will compare our new ML estimator. In [125], the actual channel autocorrelation function is approximated by a Taylor series of (high) order K_0 . Hence, its complexity remains high as it involves the numerical inversion of $(K_0 \times K_0)$ matrices at each point of the search grid on the top of several matrix multiplications. Another limitation of the four ML estimators [121, 125] discussed above is that they assume the *a priori* knowledge of the channel spectrum form (its

analytical expression) and most of them were specifically designed for the very special case of the *uniform* Jakes model.

Contribution

In our quest for a low-cost and more accurate Doppler spread estimation technique, we develop in Appendix 16 a new ML estimator which i) avoids the numerical inversion of the autocorrelation matrix and, therefore, exhibits a very reduced computational complexity; ii) does not require the *a priori* knowledge of the analytical expression of the channel PSD and is robust to its shape; and iii) is able to accurately estimate extremely small normalized Doppler spreads. Indeed, it is based on a frequency-domain second-order Taylor approximation that is valid for most known Doppler PSD models, including the very basic and widely studied *uniform* Jakes as well as the *restricted* Jakes (rJakes) and the Gaussian, biGaussian, rounded, bell, and 3-D flat models, etc. The new estimator is also compared in performance to a more recent technique proposed in [126], selected here as a second benchmark, since it outperforms many other traditional approaches, namely, the HAC technique [119] (which is a combination of [112] and [127]), the ML-based technique in [121], and the Holtzman and Sampath's method [128]. Yet, it will be shown by computer simulations that our new ML estimator outperforms the two selected (most accurate) benchmark techniques, i.e. [125] and [126], over a very wide practical Doppler range, especially in the presence of short data records (cf. for instance Fig. 1.19 below). This work was already published in *IEEE GLOBECOM'13 conference* [129] and an extension which deals with the joint estimation of the Doppler spread and the CFO is under preparation for future submission to *IEEE Transaction on Signal Processing* [130].

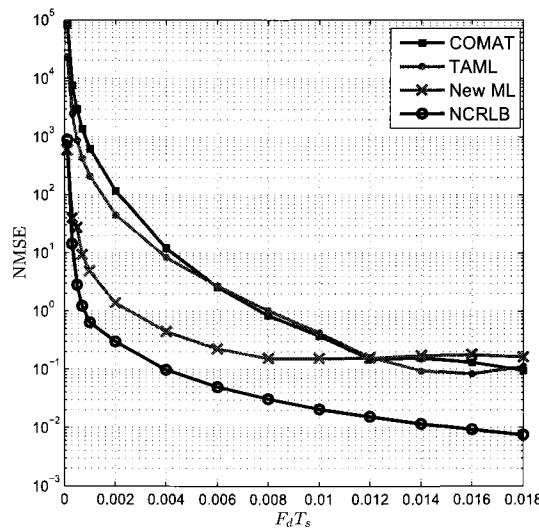


Figure 1.19: NMSE of the three estimators vs. the normalized Doppler frequency, $F_d T_s$, at sampling period $T_s = 10 \mu\text{s}$, SNR = 0 dB, and $N = 100$ received samples (please see Section IV of Appendix 16 for more details).

Collaboration with industry

By the end of the second year of my Ph.D. studies, I had the unique opportunity to lead a fruitful eight-months collaborative project with one of the leading companies in the field of wireless communications. Indeed, our research group was mandated by Huawei Technologies Canada to develop a robust Doppler spread/velocity estimator/classifier that must comply with the stringent specifications of the FDD UL LTE-ADV standard. My Ph.D. advisor, Pr. Sofiène Affes, provided me with the unique opportunity to manage a group of three graduate students with the watchword “successful execution of this exciting industrial project using the highest professional standards”.

As agreed upon with Huawei, the ultimate goal of this project was to provide them with Doppler estimation solutions (and velocity classifiers for a two-category mobility: low or high) that i) fulfil its minimum performance requirements, and that ii) comply with its LTE-ADV specifications on the uplink with one transmit and two receive antennas over a spatially-correlated Ricean channel. During the execution of the project, we were faced with many challenges which are mainly due to practical considerations:

- The extremely small values for the normalized Doppler spread to be estimated over a relatively very short period of time.
- The very high level of noise plus interference imposed by Huawei as dictated by practical constraints.
- The frequency hopping of the allocated carriers (or resource blocks), between subframes, which does not guarantee any continuity in time of the channel over a long-enough dura-

tion to have a sufficiently large number of pilot symbols.

In spite of these extremely severe requirements, we have ultimately succeeded after a long period of perseverance in developing a novel solution — disclosed in a 192-page final report to Huawei — that:

- complies with the stringent specifications of the FDD UL LTE-ADV and satisfies Huawei's minimum performance requirements over the entire targeted Doppler range at very low SINR level and using only a very limited number of symbols;
- is able to resolve the extremely challenging problem of temporal discontinuities of the channel over the relatively short observation time allowed;
- is robust to the presence of a strong line-of-sight (LOS) component and a high correlation coefficient between the two receiving antenna elements;
- provides very accurate velocity classification results.

Although the proposed technical solution remains confidential as it is governed by a non-disclosure agreement with Huawei, I have much more to say about my personal experience within the framework of that challenging project.

First and above all, if there is a lesson that I have learned ever since, it would be the awareness of practical and real-world integration constraints of wireless manufacturers as well as the specifications of the underlying wireless technology to which the research work is oriented. This experience has indeed marked my subsequent research activities by making them from then much more aware and mindful of wireless standards specifications, real-world application constraints, and industrial practical concerns.

In fact, as one positive aftermath of this unique experience that came to strengthen even further

the team's long and rich record in Doppler spread or velocity estimation, an extremely challenging problem to this day, we have been later on able to engage in a new industrial collaboration project on the same theme with Nutaq, a leading manufacturer and provider of model-based rapid prototyping platforms. Having been later able to develop a new Doppler spread ML estimator presented in Section 1.4.5 (please cf. Appendix 16 for details), this new estimator was then at the heart of a new fruitful industrial mandate by Nutaq to have it implemented and showcased in real-time and over-the-air over their picoSDR new-generation model-based rapid prototyping platform (please check the webpage <http://nutaq.com/en/search/node/bellili> for more details). This project was successfully executed and the estimator was indeed successfully tested in real-time and over-the-air in-lab using Anite's Propsim wireless channel emulator of the Wireless lab (www.wirelesslab.ca). The obtained experimental results (performance) confirmed that the new estimator's hardware implementation is a low-cost and very attractive solution for LTE systems. They have also validated the computer-based simulation results that were originally disclosed in the paper.

Conclusions and Future Perspectives

In this thesis, we tackled the problem of channel parameters estimation for wireless communication systems. We proposed a number of advanced estimators and performance bounds under different diversity schemes. The main key channel parameters where considered such as the SNR, the Ricean K-factor, the direction of arrival, the Doppler spread, the multipath channel parameters such as the time delays and the angles of arrival as well as the synchronization parameters such as the time, phase, and frequency offsets. Most of the proposed algorithms are ML ones which enjoy both global optimality and low computational burden. They are mainly based on the two powerful *expectation maximization* and *importance sampling* concepts. The EM-based ML estimators are iterative in nature and, therefore, we proposed appropriate initialization procedures that make them converge to the global maximum of the LLF, within very few iteration. The IS-based ML estimators, however, are not iterative and are guaranteed to find the global maximum by appropriate selection of some design parameters. Some other algorithms are moment-based ones and also perform very well under different practical scenarios with low complexity as well. We have shown that the newly-proposed algorithms have clear advantages against the main state-of-the-art techniques both in terms of performance and complexity.

Additionally, we derived for the very first time the closed-form expressions for the CRLBs of

different parameter estimators from in square-QAM transmissions, a key feature of current- and future-generation high-speed communication systems. Both *uncoded* and *coded* systems were considered where in the latter case the estimation process is assisted by the decoder output [i.e., code-aided (CA) estimation]. The newly derived bounds can be readily used as absolute performance benchmarks for any of the unbiased estimators of the considered parameters. Most interestingly, the new CA CRLBs suggest that exploiting the decoder output enhances the estimation performance as compared to NDA or *completely blind* estimation. Motivated by these facts, our ongoing and future research works aim in the short term at

1. Further investigating the CA estimation research topic by developing new ML estimators that can take advantage of the decoder structure and output in order to reach the CA CRLBs derived in this thesis.
2. Exploiting the time-varying channel and SNR estimators proposed in Appendix 2 in order to develop a new cognitive transceiver modem (cf. original approach in [2]) for HetNets that self-switches between different detection modes to exploit pilots differently.
3. Extending the time-varying SNR estimators disclosed in Appendix 2 in order to account for time-frequency interpolations instead of time-only interpolation as currently done in Appendix 2. Our goal is also to elaborate more on the channel estimation aspect that is inherently tackled in Appendix 2 but not fully investigated due to the focused scope of the submitted paper on SNR estimation.
4. Developing a new low-cost and robust ML estimator for the angular spread, another key channel parameter that has not been investigated within the framework of this thesis. The new solution is already hand-written but has not been yet fully investigated due to

lack of time.

As for the mid- to long-term follow-up research topics that are related to this PhD thesis, they can be summarized as follows:

1. Altough this thesis already achieved a huge step forward by extending many SISO estimators to SIMO ones for the very first time, the next challenge to be tackled is extension of the new advanced estimators to MIMO and MISO.
2. We will also target other extensions that go beyond point-to-point and single-user scenarios addressed so far in the thesis. In this context, we shall also focus on application of the new advanced estimators to the emerging relaying systems in a multi-user context.
3. We will aim to tackle the newly derived parameter estimation techniques over relayed or cooperative and collaborative wireless transmissions by properly exploiting distributed processing or computing.
4. We will seek hardware implementation by the Wireless Lab of new advanced estimators and their integration into LTE-compliant wireless transceiver prototypes operating in real-time and over the air. Our objective will be the assessment in real-world conditions of i) their accuracy and robustness; ii) their contribution to increasing/improving context awareness of cognitive radios (cf. figure 2 on page 4), and iii) their impact on other estimators' performance operating jointly and on both link- and system-level performances. In particular, the ML Doppler spread estimator introduced in Appendix 16 of this thesis has already been succefully implemented and tested over-the-air by the Wireless Lab hardware implementation team. It was confirmed that the proposed Doppler spread estimator is indeed a very low cost solution to LTE, LTE-A, and LTE-B systems. Another

estimator, namely the ML estimator over time-varying SIMO channels that is introduced in Appendix 2, is also now being implemented on a real-world platform by the Wireless Lab. This line of work adheres actually to the Wireless Lab vision (cf. Figure 1 on page 3) under the leadership of Prof. Sofiéne Affes who, among very few academic researchers in the world, has been advocating early on a challenging “system-integration-oriented approach” in algorithmic research on signal processing for wireless communications that jointly tackles most of physical-layer issues, takes into account interaction between subsystem components, any source of imperfection such as estimation and modeling errors, implementation feasibility and costs, etc..., and that integrates prototyping and real-world evaluation in the assessment methodology, thereby providing tremendous added values in terms of scientific impact and potential technological transfers.

In the very short term, we are currently working on submitting very soon five other journal papers on the CA CRLBs and estimators of two key parameters, on Doppler spread estimation, on AF-based DOA estimation, and on CDMA multipath-resolution parameter estimation; and one tutorial paper on Doppler spread estimation.

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Résumé Long

Aperçu de l'état de l'art et contributions en estimation de paramètres de canaux sans fil

Ce chapitre est structuré en plusieurs sous-sections selon le type de paramètre du canal sans fil à estimer. Pour chaque type de paramètre, nous énumérons quelques applications en communications sans fil qui sont basées essentiellement sur sa connaissance/estimation. Ensuite, nous présentons une brève revue de littérature sur l'estimation de chacun de ces paramètres avant d'y rapporter nos propres contributions récentes dans le cadre de cette thèse.

2.1 Estimation du RSB dans les systèmes SIMO

2.1.1 Applications et catégories de techniques existantes

Applications:

Avec la croissance rapide du nombre d'utilisateurs dans les réseaux de communications sans fil, le contrôle de la puissance de transmission est devenu une procédure nécessaire pour minimiser l'interférence entre les utilisateurs. En effet, les émetteurs doivent ajuster leur puissance de transmission selon les conditions de propagation afin de garder l'interférence qui résulte de l'accès multiple au canal en dessous d'un seuil qui garantit la qualité de service minimale souhaitée. Ces conditions de propagation sont souvent jugées en termes du rapport signal sur bruit (RSB) des liaisons. En outre, si le RSB est suffisamment élevé (au dessus d'un seuil prédéfini), l'émetteur peut diminuer sa puissance de transmission. Ceci permettra, entre autres, d'assurer une autonomie énergétique plus élevée au niveau des terminaux mobiles (qui ne sont pas la plupart du temps reliés au secteur). La connaissance du RSB est aussi très utile pour les opérateurs en vue de dimensionner les réseaux sans fil à déployer. Elle permet, par exemple, en communications radio mobiles de déterminer à quel point la taille des cellules peut être réduite afin de d'augmenter le facteur de réutilisation des fréquences. Ceci permet en l'occurrence d'augmenter la capacité totale du système. La connaissance du RSB est aussi utile pour optimiser les procédures de handoff et d'allocation adaptative des ressources. Le handoff réfère à l'opération de faire passer un utilisateur de façon transparente d'une cellule à une autre. Ceci est dû essentiellement à la mobilité des utilisateurs dans le réseau. L'allocation dynamique de ressources consiste à optimiser l'exploitation des ressources du système selon les changements du trafic et du niveau d'interférence. Plusieurs de ces opérations reposent sur la

qualité de la liaison qui est généralement caractérisée en fonction du RSB. Le RSB est aussi un paramètre clé pour la technique de modulation adaptative qui consiste à changer au niveau de l'émetteur le type et/ou l'ordre de la modulation afin d'augmenter le débit effectif. En effet, si le niveau du RSB est élevé, l'ordre de la modulation utilisé peut être augmenté tout en gardant le même taux d'erreur binaire (TEB) de départ. Ceci permet, en outre, d'augmenter le débit de la liaison étant donné que les modulations d'ordre supérieur permettent de transmettre plus de "d'information binaire" par symbole. Cette stratégie est surtout utilisée en communications OFDM (orthogonal frequency division multipluxing) où la connaissance *a priori* du RSB joue un rôle primordial.

L'estimation du rapport signal sur bruit est aussi nécessaire dans plusieurs autres applications telles que le codage turbo, l'égalisation, les antennes adaptatives, etc., mais nous ne pouvons pas les détailler toutes dans cette thèse par souci de brièveté.

Catégories d'estimateurs du RSB

Les techniques d'estimation du RSB peuvent être catégorisées selon différent critères. En effet, selon l'information présente *a priori* au niveau du récepteur, concernant les symboles envoyés, les estimateurs du RSB peuvent être classés en deux grandes catégories: méthodes autodidactes et méthodes assistées. En estimation autodidacte, les symboles transmis sont supposés complètement inconnus par le récepteur. L'estimation du RSB repose alors uniquement sur les échantillons reçus. Les estimateurs qui appartiennent à cette catégorie sont appelés estimateurs NDA (non-data aided). Ils requièrent souvent un grand nombre d'échantillons reçus pour obtenir des estimées suffisamment précises du RSB. Les techniques NDA sont, par contre, plus appréciées en pratique parce qu'elles n'affectent pas le débit effectif du système. Elles

permettent, en effet, une estimation en temps réel du paramètre en question et elles sont de ce fait aussi qualifiées d'estimateurs “in service”.

Les méthodes assistées, par contre, nécessitent la connaissance *a priori* de la séquence transmise par l'émetteur. Elles sont connues en littérature sous le nom d'estimateurs DA (data-aided). Il y a, en fait, deux types de techniques DA:

- Techniques TxD A: ces techniques nécessitent l'introduction d'une séquence de symboles qui est parfaitement connue par le récepteur. La fidélité de la séquence du message utilisée pour l'estimation est garantie par le fait même qu'une copie conforme de cette séquence est disponible à la réception. En pratique, de petites séquences de données connues (séquences pilotes) peuvent être insérées périodiquement dans un flux de données à transmettre. Les procédures d'égalisation et de synchronisation utilisent aussi ce genre de séquences, dites aussi séquences d'apprentissage. L'utilisation de telles séquences pour l'estimation du RSB diminue cependant le débit utile du système. Néanmoins, pour des systèmes utilisant déjà des séquences pilotes pour la synchronisation ou l'égalisation, on peut utiliser ces mêmes séquences pour l'estimation du RSB sans aucune pénalité supplémentaire. Notez ici que l'emploi de cette méthode n'est pas adéquate dans les cas où une estimation continue du RSB est exigée. puisqu'une estimation TxD A ne peut être faite qu'en présence de la séquence pilote.
- Techniques RxDA: Ces méthodes reposent sur l'utilisation des symboles détectés. Ces derniers remplacent alors la séquence des symboles pilotes pendant le processus d'estimation. Ces algorithmes sont aussi appelés DD (decision-directed). La détection des symboles peut se faire directement à la sortie du filtre adapté ou après le décodage des bits dans un système codé. Dans le dernier cas, la procédure d'estimation est dite assistée par le

code [i.e., code-assisted (CA) estimation].

Peu importe le type d'estimation NDA ou DA, les estimateurs peuvent être aussi classés, selon la façon dont ils profitent du signal reçu, en deux grandes catégories:

- Estimateurs du type IQ (inphase and quadrature): Ces estimateurs reposent sur l'utilisation des composantes en phase et en quadrature du signal reçu. Les composantes en phase et en quadrature d'un signal donné réfèrent à ses parties réelle et imaginaire, respectivement. Ces techniques sont conçues pour exploiter l'information complète véhiculée par le signal puisqu'elles n'écartent pas l'information contenue dans la phase des échantillons. Cependant, elles sont plus compliquées que les méthodes du type moments expliquées ci-dessous.
- Estimateurs du type enveloppe: Ces algorithmes sont dérivés en utilisant uniquement l'enveloppe du signal reçu. Ils rejettent alors l'information contenue dans la phase reçue. Une sous-catégorie de ces algorithmes est connue sous le nom d'estimateurs du type moments. Ces derniers reposent uniquement sur les moments du signal reçu. Leurs performances sont donc inférieures à celles des estimateurs du type IQ, mais ils sont beaucoup plus faciles à implémenter. Ils sont donc plus adéquats pour des applications temps réel où la complexité de calcul est d'une grande importance.

2.1.2 Revue de littérature et contributions

Les premiers estimateurs du RSB remontent aux années 60 [7, 8] où un estimateur à maximum de vraisemblance et un estimateur basé sur les moments d'ordre deux et quatre ont été proposés. Depuis la publication de [7] et [8], d'autres contributions enrichissant cette littérature ont vu le

jour [9-13]. On pourrait citer toutes les contributions faites sur ce sujet. Néanmoins, l'article de Pauluzzi et Beaulieu en 2000 [4] a eu le grand mérite de comparer plusieurs estimateurs de RSB et de fournir une vue exhaustive sur les techniques qui l'avaient précédé. Après cet article pionnier, d'autres contributions ont été introduites sur ce sujet. On cite surtout le travail de Gao et *al.* en 2005 [5] où une classe d'estimateurs du type moments a été introduite avec une étude complète de leurs performances. Ces estimateurs sont conçus surtout pour les constellations à enveloppe non constante, à savoir les signaux QAM. Dans cet article, il a été démontré que l'estimateur du RSB du type moments le plus connu, M_2M_4 [4], se réduit à un cas particulier d'une classe plus générale d'estimateurs du même type. Dans cet article, les bornes de Cramér-Roa pour les signaux QAM ont été calculées numériquement, mais seulement pour les estimateurs qui exploitent l'enveloppe du signal reçu.

Plus récemment, d'autres travaux sur l'estimation autodidacte du RSB ont aussi été publiés. En effet, les estimateurs à maximum de vraisemblance du type IQ et du type enveloppe, pour les signaux numériques, ont été développés dans [14] et [15], respectivement. Un autre estimateur du type moments pour les constellations à enveloppe non constante a été introduit par Valcarce et *al.* en 2007 [6]. Tous ces estimateurs sont développés pour les systèmes SISO (single-input single-output).

Tout récemment, nous avons été les premiers à considérer l'estimation du RSB dans les systèmes à diversité spatiale. En effet, nous avons développé un estimateur du RSB [22] qui est basé sur les moments croisés (entre les antennes) d'ordre quatre dans les systèmes SIMO (signle-input multiple-output). Cet estimateur — nommé M4 — est développé pour des canaux quasi-constants et peut être utilisé avec toutes les modulations linéaires. Nous avons aussi développé un autre estimateur pour les canaux SIMO variables dans le temps [27] qui repose sur la

technique des moindres carrés.

Dans Annexe 1 de cette thèse, nous développons l'estimateur ML (maximum likelihood) du RSB dans pour les canaux SIMO quasi-constants. Le nouveau estimateur est basé sur l'algorithme EM (expectation maximization) et il peut être appliqué à tous les signaux linéairement modulés. En particulier, nous montrons que l'exploitation de la diversité spatiale réduit énormément le nombre d'itérations requis pour la convergence de l'algorithme EM. En plus, à travers l'exploitation optimale de l'information reçue via les composantes en phase et en quadrature du signal, le nouveau estimateur présente des gains énormes en performance par rapport à l'estimateur M4, de type moment, que nous avions développé auparavant dans [22]. Ce travail a été publié dans la prestigieuse revue *IEEE Transactions on Signal Processing* [28].

L'estimateur que nous développons dans [28] fonctionne très bien pour des canaux qui varient lentement dans le temps et il atteint la borne de Cramér-Rao sur une large plage du RSB. Cependant, sa performance subit une dégradation relativement sévère sous des canaux qui varient rapidement. De ce fait, nous développons aussi dans Annexe 2 l'estimateur ML du RSB instantané (idem, local) pour les systèmes SIMO avec des canaux variables dans le temps toujours en utilisant l'algorithme itératif EM. Les variations du canal sont modélisées localement par des polynômes dans le temps. Contrairement aux canaux constants traités jusque-là, il se trouve que la fonction de vraisemblance présente plusieurs maxima locaux. Pour éviter le problème de convergence locale, nous proposons alors une procédure d'initialisation adéquate qui permet à l'algorithme itératif de converger vers le maximum global de la LLF (log-likelihood function). Le nouvel estimateur est capable à la fois d'estimer le canal, la variance du bruit (et donc le RSB) et de détecter les symboles émis, et ce pour n'importe quelle modulation linéaire. Une partie de ce travail a été acceptée à la conférence *IEEE ICASSP'14*[29] et une version

complète a été soumise à la prestigieuse revue *IEEE Transactions on Signal Processing* [30]. Une étude approfondie de la littérature a aussi révélé que les expressions analytiques des bornes de Cramér-Rao (BCRs) du RSB pour des transmissions codées n'avaient jamais été établies. Les travaux existants ne considèrent que les BCRs de l'estimation totalement autodidacte. En effet, ces dernières ont été considérées pour la première fois par Alagha en 2001 dans [16] et leurs expressions ont été dérivées uniquement pour les signaux BPSK (binary phase shift keying) et QPSK (quaternary phase shift keying). Ces bornes ont été plus récemment calculées pour les modulations d'ordre supérieur dans [17], mais numériquement et à partir d'expressions très complexes. Ce n'est que tout récemment que nous avons enfin réussi à dériver leurs expressions analytiques exactes pour les transmissions QAM carrées non codées [20].

Dans Annexe 3 de cette thèse, nous dérivons aussi pour la première fois les expressions exactes de ces BCRs pour l'estimation du RSB à partir des signaux QAM carrés *turbo-codés*. Pour ce faire, nous proposons un nouveau processus récursif qui permet la construction de n'importe quelle constellation QAM carrée avec codage de Gray. Des propriétés cachées de ces constellations sont alors révélées et ensuite exploitées pour factoriser la densité de probabilité des échantillons reçus. En effet, nous montrons que cette densité fait intervenir deux termes statistiquement équivalents, ce qui simplifie énormément les expressions des dérivées secondes de la LLF ainsi que le calcul analytique de leurs espérances. Par conséquence, nous obtenons les expressions exactes des éléments de la matrice de Fisher de l'estimation du RSB à partir des signaux QAM carrés *turbo-codés* et donc les expressions des BCRs considérées en fonction des LLR des éléments binaires. Dans un système turbo-codé, ces LLRs sont approximés par les *informations extrinsèques* délivrées par le décodeur et sont ensuite utilisées pour évaluer les BCR du SNR dans un système codé. Les nouvelles expressions analytiques des BCR englobent

les expressions proposées auparavant dans les deux cas d'estimations aveugle et assistée comme deux cas extrêmes. Elles montrent le gain potentiel en performances d'estimation du RSB attribuables à l'exploitation de l'information *a priori* concernant les données transmises et qui est délivrée au cours du décodage des éléments binaires.

2.2 Estimation conjointe du facteur de Rice et du RSB dans les systèmes SIMO

2.2.1 Applications et informations préliminaires

En propagation radio-mobile, l'enveloppe des composantes multi-trajets du signal reçu suit, en général, une distribution de Rice. [80, p. 47]. La valeur du facteur de Rice, K , est une mesure de la sévérité de l'évanouissement du canal. En effet, le cas d'évanouissement le plus sévère correspond à $K = 0$ (idem, canal de Rayleigh) et $K = +\infty$ correspond à l'absence totale de l'évanouissement. Le facteur de Rice est donc un bon indicateur de la qualité du canal et sa connaissance/estimation est importante dans les calculs de budgets de liaisons [92]. En plus, la puissance locale et la vitesse du mobile sont analytiquement liées au facteur de Rice et donc leur estimées peuvent être directement obtenues une fois que ce paramètre clé est estimé [93]. Les estimateurs du facteur de Rice se classifient sous trois grandes catégories: estimateurs ML, estimateurs basés sur la corrélation et estimateurs basés sur les moments du signal reçu.

2.2.2 Revue de littérature et contributions

La majorité des techniques proposées dans la littérature considèrent des échantillons non modulés [94-98]. Ceci correspond aux deux cas suivants: i) le facteur de Rice est obtenu à partir

des estimées des coefficients du canal ou ii) une connaissance parfaite des symboles envoyés. Dans le premier cas, une autre étape préliminaire est requise (avant l'estimation du facteur de Rice) au cours de laquelle le canal doit être estimé. Ceci rajoute inutilement de la complexité au processus d'estimation du facteur K puisque dans plusieurs applications, telles que le calcul du budget de liaison, on a besoin juste d'estimer le facteur de Rice sans nécessairement passer par l'estimation du canal. Dans le second cas, le facteur de Rice est obtenu à partir d'une séquence de symboles connus (appelée séquence pilote) insérée dans les données, ce qui réduit le débit effectif du système. Le seul travail qui a traité l'estimation du facteur de Rice à partir des signaux modulés est celui de Y. Chen et C. Beaulieu [99].

Dans Annexe 4, nous proposons une nouvelle technique d'estimation du facteur K à partir des signaux modulés pour les systèmes SIMO. Les symboles transmis sont supposés complètement inconnus et tirés de n'importe quelle constellation. La nouvelle technique est basée sur les moments croisés entre les antennes réceptrices. L'estimateur est développé sous forme de formule exacte et sa complexité est très réduite. En plus, contrairement à toutes les techniques existantes, le nouvel estimateur ne nécessite pas l'estimation de l'étalement Doppler. Il présente aussi des gains de performances remarquables par rapport à la seule technique du genre, i.e., pour signaux modulés [99]. Ce travail a été publié à la conférence *IEEE GLOBECOM'11* [100].

2.3 Synchronisation en temps, en phase et en fréquence

2.3.1 Applications

En communications numériques, la connaissance du décalage en temps est primordiale pour pouvoir échantillonner le signal reçu aux bons instants. En effet, le signal reçu est, en premier

lieu, passé à travers un filtre adapté puis échantillonné au taux symbole. Les instants optimaux d'échantillonnage correspondent à l'ouverture maximale du diagramme de l'œil et ils sont situés aux sommets des impulsions [31]. Il est donc clair que les positions de ces sommets doivent être déterminées, de façon précise, pour une détection fiable des symboles transmis. Ceci est exactement le rôle de l'opération “synchronisation dans le temps”, une étape primordial pour tout système de communication sans fil. Cette opération est réalisée à travers l'estimation du décalage en temps introduit par le trajet de propagation du signal de la source au récepteur. L'estimation du décalage en temps est aussi utile dans les systèmes radars et sonars et pour d'autres types d'applications de localisations.

L'estimation des décalages en phase et en fréquence est aussi une étape nécessaire pour la démodulation cohérente des symboles afin d'avoir des performances optimales. En effet, le signal en bande de base doit être extrait en utilisant une référence locale avec une fréquence et une phase quasi-identiques à celle de la porteuse incidente [31].

Tout comme l'estimation du RSB, l'estimation des paramètres de synchronisation peut aussi être catégorisée en deux grandes catégories: méthodes *aveugles* et méthodes *assistées*. Il est à rappeler ici que, dans la seconde catégorie, le processus d'estimation peut être assisté soit par l'insertion d'une séquence pilote soit par le décodeur.

2.3.2 Revue de littérature et contributions

Décalage en temps

La plupart des estimateurs du décalage en temps sont basés sur la la cyclo-stationnarité induite par le suréchantillonnage du signal reçu. En particulier, Oerder et Myer ont proposé un estimateur basé sur la non-linéarité carrée [32] et sa performance a été analysée dans [33]. Plusieurs

extensions de cette technique ont été aussi proposées dans [34-36]. Dans [37], une approximation de la fonction LLF à faible RSB a été aussi utilisée pour développer un estimateur qui est basé sur la non-linéarité logarithmique. Plus tard, une solution itérative de l'estimateur ML a été proposée dans [38-39]. Étant donnée sa nature itérative, cet estimateur nécessite une bonne initialisation pour ne pas converger vers un maximum local de la LLF. Récemment, deux solutions améliorées de l'estimateur ML proposées dans [40, 41] sont basées sur l'approximation de la fonction de vraisemblance par ses séries de Fourier. La performance de chacune de ces deux techniques est néanmoins limitée par la précision de cette approximation et le nombre de coefficients de Fourier qui sont pris en compte.

Dans Annexe 5 de cette thèse, nous proposons un nouvel estimateur ML autodidacte du décalage en temps qui exploite le concept “*importance sampling*” (IS). Le nouvel estimateur jouit d'une convergence globale et ne nécessite aucune initialisation. C'est un estimateur autodidacte qui s'applique à toutes les modulations linéaires. Il présente des avantages remarquables en termes de performances et de complexité par rapport aux meilleures techniques existantes. Une partie de ce travail a été publiée à la conférence *IEEE WCNC'11* [42]. Une version plus complète a été aussi publiée dans la prestigieuse revue *IEEE Transactions on Signal Processing* [43].

Notre revue de littérature nous aussi révélé que les BCRs de l'estimation du décalage en temps en présence de signaux modulés n'a vaient pas encore été développées analytiquement. En effet, ces bornes étaient calculées numériquement auparavant dans [44] sans dériver aucune expression analytique. En plus, [44] suppose une absence totale de l'interférence inter-symboles (ISI), est une hypothèse contre-intuitive en présence du décalage en temps. De ce fait, nous développons dans Annexe 6, pour la première fois, les formules exactes de ces bornes pour tous

les estimateurs non-biaisés du décalage en temps à partir des signaux BPSK, MSK et QAM carrés en présence de l'ISI. Les résultats de ce travail ont été publiés dans *IEEE ICC'11* [45] et *IEEE VTC'11* [46] et une version complète a été publiée dans la prestigieuse revue IEEE Transactions on Signal Processing [47].

Décalages en phase et en fréquence

Concernant la synchronisation en phase et en fréquence, notre revue exhaustive de la littérature, a aussi révélé que les BCRs pour les estimateurs non biaisés de ces deux paramètres clés n'ont pas encore été développées analytiquement. En effet, ces bornes ont seulement été évaluées empiriquement dans [49], pour l'estimation totalement *autodidacte*, à partir des expressions très complexes et en utilisant des simulations Monte-Carlo très lourdes. Dans Annexe 7 de cette thèse, nous développons alors les expressions exactes de BCRs pour l'estimation *aveugle* des ces deux paramètres clés de synchronisation, à savoir les décalages en phase et en fréquence à partir des signaux QAM carrés. Ce travail a été publié dans la prestigieuse revue IEEE Transactions on Signal Processing [48]. Les nouvelles bornes servent comme jauge pour tous les estimateurs non biaisés aveugles en absence de toute information *a priori* concernant les symboles transmis. Ces BCRs révèlent, en effet, qu'il y a un manque à gagner important en termes de performances qui est dû à la méconnaissance totale des symboles transmis surtout à de faibles niveaux du RSB. Motivés par cette observation, nous développons aussi dans Annexe 8, les expressions exactes de ces BCRs dans un système codé et nous montrons que ce manque peut être presque totalement comblé en exploitant l'information *a priori* qui est fournie par le décodeur turbo. Ce travail a été soumis à la prestigieuse revue *IEEE Transactions on Wireless*

Communications [50].

2.4 Estimation des paramètres des canaux multi-trajets

2.4.1 Applications et informations préliminaires

Dans un environnement multi-trajets, la caractérisation de chaque trajet avec son propre angle d'arrivée et décalage en temps est très utile pour développer des techniques plus robustes de ("beamforming") [51] et d'égalisation [52]. D'un autre côté, la connaissance de ces paramètres clés permet de localiser les mobiles dans les réseaux de communications sans fil. Par ailleurs, un nouveau paradigme—connu sous le nom de "*fingerprinting*"—qui reformule le problème de localisation en un problème de reconnaissance de forme a été proposé [53, 57]. Dans ce contexte, il a été démontré que les signatures basées sur les angles d'arrivées et les décalages en temps de chaque position présentent des avantages énormes, en termes de performances, par rapport aux signatures qui sont basées sur le niveau du signal reçu [58]. Ceci est dû au fait que ce dernier varie largement sur une distance d'une longueur d'onde suite aux additions constructives et destructives des trajets. Par conséquent, une estimation précise et à faible coût de ces paramètres clés peut être combinée avec la technique *fingerprinting* pour développer des techniques de localisation très efficace [59].

Les techniques d'estimation des décalages en temps et des angles d'arrivée (ou leur estimation conjointe) sont aussi classifiées en deux grandes catégories: les techniques sous-espaces et les techniques ML. Les méthodes sous-espaces sont basées sur la matrice de covariance des échantillons reçus tandis que les méthodes ML utilisent directement les composantes en quadrature et en phase du signal reçu.

2.4.2 Revue de littérature et contributions

Estimation des décalages en temps uniquement

Un nombre de techniques sous-espace pour l'estimation des décalage en temps uniquement ont été proposées dans la littérature [60-63]. Ces techniques reposent sur la matrice de covariance des échantillons reçus et donc leurs performances se dégradent en présence d'un nombre réduit d'échantillons ou à faible niveau du RSB. Dans ces conditions sévères, l'estimation ML est souvent préférée et deux techniques ML ont été introduites en littérature [64-65]. Ces deux méthodes ML sont néanmoins itératives et rien ne garantit leur convergence vers le maximum global de la LLF.

Dans Annexe 9 de cette thèse, nous proposons un nouvel estimateur ML des décalages en temps uniquement, dans un environnement multi-trajets, en se basant sur la technique IS. Nous traitons les deux cas où le signal transmis est connu ou inconnu, idem, modes *actif* et *passif*, respectivement. En mode actif, les décalages en temps peuvent être estimés même en présence d'une seule antenne réceptrice. En mode passif, seulement les différences des temps d'arrivées peuvent être estimés en utilisant un réseau d'antennes. Le nouveau estimateur retourne le maximum globale de la fonction LLF et ne nécessite aucune initialisation des paramètres à estimer. Il présentent des avantages énormes, en terme de performance et complexité, par rapport aux techniques sous-espaces et ML proposées dans la littérature. Une partie de ce travail a été publiée dans la conférence *IEEE GLOBECOM'11* [66]. Une version complète a été aussi publiée dans la prestigieuse revue *IEEE Transactions on Signal Processing* [67].

Dans Annexes 10 et 11 de cette thèse, nous proposons aussi deux nouveaux estimateurs ML des décalages en temps pour les transmissions multi-trajets dans les systèmes DS-CDMA (direct-spread code-division multiple access). Le premier estimateur est itératif et il repose sur le

fameux concept EM et le second est basé sur le concept IS. Nous développons aussi les BCRs correspondantes. Dans ce travail, nous traitons deux cas d'estimation où les décalages en temps sont estimés à partir: i) des estimées du canal ou ii) directement à partir des échantillons reçus qui correspondent à des signaux modulés. Nous généralisons aussi les deux estimateurs proposés ainsi que les BCRs aux systèmes MC-DS-CDMA (multi-carrier-DS-CDMA). Les résultats de simulations montrent que les deux nouveaux estimateurs ML offrent des avantages énormes en termes de performances et de complexité par rapport aux techniques existantes. Nous montrons aussi que l'estimateur de type EM est plus approprié à un nombre d'antennes élevé alors que l'estimateur de type IS est plus approprié à un nombre plus faible. Ce travail a été publié dans deux articles de conférences, à savoir *IEEE ASILOMAR'11* [69] et *IEEE VTC'12-Fall* [69]. Du fait que nous devions prioriser de nouvelles directions de recherche, la transformation de ce travail en un article de revue a été jusque-là reportée. La version journal est pourtant bien avancée et nous comptons la finaliser et la soumettre sous peu.

Estimation conjointe des décalages en temps et des angles d'arrivée

Un nombre d'estimateur JADE (joint angle and delay estimation), sous-espaces et ML, ont aussi été proposés durant les deux dernières décennies. La plupart des méthodes sous-espaces reposent sur les fameuses techniques MUSIC et ESPRIT ou leurs variantes [70-72]. A meilleure de nos connaissances, uniquement deux estimateurs ML ont été proposés, jusqu'à présent, dans le contexte de l'estimation JADE. Il s'agit de l'estimateur itératif introduit par Wax *et al.* [73] et celui basé sur le fameux algorithme SAGE (space-alternating generalized expectation maximisation) [74]. Ces deux estimateurs sont itératifs et nécessitent une bonne initialisation pour ne pas converger vers un maximum local de la fonction LLF. Dans Annexe 12, nous

introduisons une nouvelle technique ML pour l'estimation conjointe des décalages en temps et des angles d'arrivée des composantes multi-trajets du canal en utilisant n'importe quel réseau d'antennes. Le nouvel estimateur atteint la BCR correspondante à de faibles niveaux du RSB (à partir de -10 dB) et il est capable de résoudre des trajets avec une séparation angulaire aussi petite que 1°. Il présente aussi un avantage remarquable en terme de performance et complexité par rapport à toutes les techniques existantes dans la littérature. Une version préliminaire de ce travail a été acceptée à la conférence *IEE ICASSP'14* [75] et une version complète a été soumise à la revue *IEEE Transactions on Signal Processing* [76].

2.5 Estimation des directions d'arrivée du signal (DOA)

2.5.1 Applications et catégories de techniques existantes

Le problème d'estimation des DOAs de plusieurs ondes planes reçues par un réseau d'antennes a aussi suscité l'intérêt d'un grand nombre de chercheurs au fil des années [101, 102]. En effet, l'estimation de DOA est au cœur de plusieurs applications militaires et civiles. Par exemple, l'estimation des directions d'arrivée de plusieurs sources est une tâche essentielle pour les systèmes radars et sonars. En plus, dans les systèmes modernes de communications radio-mobiles, la connaissance des DOAs des utilisateurs désirés et celles des utilisateurs interférants permet, respectivement, l'extraction et l'annulation de leurs signaux en utilisant les techniques de *beamforming* afin d'améliorer les performances du système sans fil. [103, 104]. Les méthodes d'estimation des DOAs sont aussi classées en techniques sous-espaces et techniques ML.

2.5.2 Revue de littérature et contributions

La littérature sur l'estimations des DOA est très vaste. Il y a deux types d'estimateurs ML [105]: i) estimateurs ML *conditionnels* où les signaux inconnus des sources sont supposés déterministes, et ii) estimateurs ML *inconditionnels* où les signaux sont supposés aléatoires avec une distribution connue *a priori*. Parmi les méthodes sous-espace, on cite les fameux algorithmes MUSIC [106], ESPRIT [107], MODE [108] ainsi que les techniques SSF (subspace fitting) [109, 110]. Les techniques ML sont généralement plus précises mais leur complexité est très élevée. Les techniques sous-espaces offrent une meilleure alternative en termes de complexité, mais leur performance est sévèrement affectée en présence d'un nombre réduit d'observations (snapshots). Dans Annexe 13, nous proposons une nouvelle technique pour l'estimation de plusieurs DOAs en utilisant les réseaux d'antennes ULAs (uniform linear arrays). Elle repose sur technique AF (annihilating filter) et elle a une complexité très réduite par rapport à toute les techniques sous-espace. Contrairement à ces dernières, elle est aussi capable d'estimer les DOAs à partir d'un nombre réduit d'observations et même à partir d'un seul snapshot. La technique AF consiste à trouver les coefficients d'un filtre qui annihile une séquence d'observations qui s'écrivent comme la somme de sinusoides. Dans cette thèse, nous montrons que les moments croisés (entre antennes) d'ordre deux ont cette structure intéressante et que la technique AF est appliquée à une séquence consécutive de ces moments. L'idée est de trouver les coefficients d'un filtre AF qui annule une telle séquence (par convolution) et où les DOAs sont exactement les zéros du polynôme dont les coefficients sont ceux du filtre AF. Ce travail a été publié à la conférence *IEEE GLOBECOM'11*. [111]

La majorité des techniques d'estimation de DOA supposent que les signaux sont décorrélés dans le temps et/ou l'espace. Ceci pose une vraie limitation, en pratique, vue que les la corrélation

dans le temps/espace et souvent présente. Motivés par ce fait, nous développons aussi, dans Annexe 14, une nouvelle technique SSF pour les signaux non-circulaires et corrélés dans le temps et l'espace. Nous montrons que l'exploitation des corrélations dans le temps/espace et la non-circularité des signaux améliore nettement l'estimation des DOAs. Ce travail a été publié en partie à la conférence *IEEE WCNC'11* [112] et une version complète a été publiée dans la prestigieuse revue *IEEE Transactions on Signal Processing* [113]. Finalement, nous développons dans Annexe 15, pour la première fois aussi, les expressions analytiques des bornes de Cramér-Rao exactes pour l'estimation du DOA à partir des signaux QAM carrés en utilisant des réseaux d'antennes ULAs et UCAs (uniform circular arrays). Ce travail a été publié dans la revue *IEEE Transactions on Signal Processing* [114].

2.6 Estimation de l'étalement Doppler

2.6.1 Applications et catégories de techniques existantes

L'étalement Doppler est un autre paramètre clé du canal sans fil qui est dû à la mobilité de l'usager. En effet, le taux d'évanouissement du canal est directement lié à la vitesse du mobile et la caractérisation de ses variations en temps sont directement liées au Doppler. À titre d'exemple connaissance de ce paramètre ou le taux de variation du canal (tel que le temps de cohérence) est extrêmement utile pour optimiser la longueur de l'entrelaceur afin de réduire le délai de réception et/ou le taux du renvoi des estimées du canal sur la liaison inverse [77].

Côté traitement de signal, la connaissance de l'étalement Doppler est nécessaire pour optimiser le pas d'adaptation des algorithmes adaptatifs d'identification et de poursuite des canaux variables dans le temps [78]. Elle est aussi utile pour plusieurs autres applications sans fil telle

que le contrôle de puissance et le handoff [79-80]. En plus, de par à la nature des réseaux hétérogènes (HetNets) qui ont été récemment déployés, les problèmes reliés à l'interférence et le handoff sont exacerbés quand un usager mobile entre ou même approche une petite cellule (idem, pico ou femto). En effet, ce dernier va interférer avec les usagers de ces petites cellules, ce qui résulte en de nouvelles réassigations entre grandes/petites et petites/grandes cellules [81]. Réduire ces interférences et éviter les opérations de handoff inutiles peut être réalisé en prévoyant l'évolution de la trajectoire de l'interférant à travers l'information de son étalement Doppler.

En pratique, le Doppler est souvent obtenu à partir des estimées des coefficients du canal et selon la façon avec laquelle ces estimées sont exploitées, on distingue quatre catégories principales d'estimateurs de l'étalement Doppler. Les techniques LCR (level-crossing rate), celles basées sur la matrice de covariance du canal, celles basées sur le spectre du canal et finalement les techniques basées sur le principe ML.

2.6.2 Revue de littérature et contributions

On peut citer [82], [83, 84] et [85], respectivement, comme approches basées sur le LCR, la matrice de covariance, et le spectre du canal. Quatre estimateurs ML ont été aussi proposés durant la dernière décennie [86-89] qui sont tous basés sur une approximation de la vraie matrice de covariance du canal. Parmi tous les estimateurs ML, le plus récent [89] est le seul capable à estimer les Doppler très faibles. Cependant, il est basée sur une approximation de Taylor d'ordre élevé pour les coefficients de corrélation du canal. De ce fait, il nécessite l'inverse d'une matrice de taille relativement grande à chaque point de la grille de recherche , ceci au cout en pratique d'une complexité très élevée. Dans Annexe 16 de cette thèse, nous proposons un

nouvel estimateur ML de l'étalement Doppler à complexité est très réduite qui ne nécessite aucune inversion de matrice et donc sa complexité est très réduite. En plus, contrairement à tous les estimateurs existants, notre nouvelle technique ML ne nécessite pas la connaissance a priori de la forme de la densité spectrale du canal . En plus, est capable d'estimer des étalements Doppler extrêmement faibles, même à partir d'un nombre très réduit d'échantillons. Il est à noter qu'en pratique qu'il est toujours beaucoup plus difficile d'estimer les Doppler faibles que les Doppler élevés. Ce travail a été publié à la conférence *IEEE GLOBECOM'13* [90]. Une version plus complète est cours de préparation pour soumission à la revue *IEEE Transactions on Signal Processing* [91] où nous traitons l'estimation ML conjointe de l'étalement Doppler et du décalage en fréquence.

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Appendix 1:

SNR Estimation over SIMO Channels from Linearly-Modulated Signals

The content of this appendix was published in *IEEE Transactions on Signal Processing* in the following paper:

M. A. Boujelben, F. Bellili, S. Affes, and A. Stéphenne, “SNR estimation over SIMO channels from linearly-modulated signals,” *IEEE Trans. on Signal Process.*, vol. 58, no. 12, pp. 6017-6028, Dec. 2010.

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Appendix 2:

Maximum Likelihood SNR Estimation of Linearly-Modulated Signals over Time- Varying Flat-Fading SIMO Channels

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F. Bellili, R. Meftehi, and S. Affes, “Maximum likelihood SNR estimation of linearly-modulated signals over time-varying flat-fading SIMO channels,” submitted to *IEEE Trans. on Signal Process.*, Mar. 2014, major revision, June 2014, under revision.

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Appendix 3:

Closed-Form CRLBs for SNR Estimation from Turbo-Coded BPSK-, MSK-, and Square-QAM-Modulated Signals

The content of this appendix was accepted for publication to *IEEE Transactions on Signal Processing* in the following paper:

F. Bellili, Achref Methenni, and S. Affes, "Closed-Form CRLBs for SNR estimation from turbo-coded BPSK-, MSK-, and square-QAM-modulated signals," accepted for publication in *IEEE Trans. on Signal Process.*, Apr. 2014, to appear.

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Appendix 4:

Joint Estimation of the Ricean K -factor and the SNR for SIMO Systems Using Higher Order Statistics

The content of this appendix was published in *IEEE GLOBECOM'11* conference in the following paper:

I. Bousnina, F. Bellili, A. Samet, and S. Affes “Joint estimation of the Ricean K -factor and the SNR for SIMO systems using higher order statistics,” in *Proc. of IEEE GLOBECOM'11*, Houston, TX, USA, Dec. 2011.

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Appendix 5:

A Non-Data-Aided Maximum Likelihood Time Delay Estimator Using Importance Sampling

The content of this appendix was published in *IEEE Transactions on Signal Processing* in the following paper:

A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne “A non-data-aided maximum likelihood time delay estimator using importance sampling,” *IEEE Trans. on Signal Process.*, vol. 59, no. 10, pp. 4505-4515, Oct. 2011.

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Appendix 6:

Closed-Form Expressions for the Exact Cramér-Rao Bounds of Timing Recovery Estimators from BPSK, MSK and Square-QAM Transmissions

The content of this appendix was published in *IEEE Transactions on Signal Processing* in the following paper:

A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, “Closed-form expressions for the exact Cramér-Rao bounds of timing recovery estimators from BPSK, MSK and square-QAM signals,” *IEEE Trans. on Signal Process.*, vol. 59, no. 6, pp. 2474-2484, June 2011.

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Appendix 7:

Cramér-Rao Lower Bounds for Frequency and Phase NDA Estimation from Arbitrary Square QAM-Modulated Signals

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F. Bellili, N. Atitallah, S. Affes, and A. Stéphenne, “Cramér-Rao Lower Bounds for Frequency and Phase NDA Estimation from Arbitrary Square QAM-Modulated Signals,” *IEEE Trans. on Signal Process.*, vol. 58, no. 9, pp. 4517-4525, Sept. 2010.

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Appendix 8:

Closed-Form CRLBs for CFO and Phase Estimation from Turbo-Coded Square- QAM-Modulated Transmissions

The content of this appendix was submitted to *IEEE Transactions on Wireless Communications* in the following paper:

F. Bellili, A. Methenni, and S. Affes, “Closed-form CRLBs for CFO and Phase Estimation from Turbo coded square-QAM-modulated transmissions,” submitted to *IEEE Trans. on Wireless Commun.*, Jan. 2014, *Major Revision*, May 2014, revised, May 2014, (*under review*).

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Appendix 9:

A Maximum Likelihood Time Delay Estimator in a Multipath Environment Using Importance Sampling

The content of this appendix was published in *IEEE Transactions on Signal Processing* in the following paper:

A. Masmoudi, F. Bellili, S. Affes, and A. Stéphenne, “A maximum likelihood time delay estimator in a multipath environment using importance sampling,” *IEEE Trans. Sig. Process.*, vol. 61, no. 1, pp. 182-193, Jan. 2013.

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Appendix 10:

Time delays estimation from DS-CDMA multipath transmissions using expectation maximization

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A. Masmoudi, F. Bellili, and S. Affes, "Time delays estimation from DS-CDMA multipath transmissions using expectation maximization," in *Proc. of IEEE VTC'2012-Fall*, Québec City, Canada, Sept. 3-6, 2012.

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Appendix 11:

Maximum likelihood time delay estimation for direct-spread CDMA multipath transmissions using importance sampling

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A. Masmoudi, F. Bellili, and S. Affes, "Maximum likelihood time delay estimation for direct-spread CDMA multipath transmissions using importance sampling," in *Proc. of 45th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, USA, Nov. 6-9, 2011.

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Appendix 12:

A New Super-Resolution and Low-Cost Exact ML Estimator for Time Delays and Angles-of-Arrival Acquisition in Multipath Environments

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Cet article a dû être retiré de la version électronique en raison de restrictions liées au droit d'auteur.
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Appendix 13:

DOA estimation for ULA systems from short data snapshots: An annihilating filter approach

The content of this appendix was published in *IEEE GLOBECOM'11* conference in the following paper:

F. Bellili, S. Affes, and A. Stéphenne, "DOA estimation for ULA systems from short data snapshots: An annihilating filter approach," in *Proc. of IEEE GLOBECOM'2011*, Houston, USA, Dec. 5-9, 2011.

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Appendix 14:

DOA Estimation of Temporally and Spatially Correlated Narrowband Noncircular Sources in Spatially Correlated White Noise

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S. Ben Hassen, F. Bellili, A. Samet, and S. Affes, "DOA estimation of temporally and spatially correlated narrowband noncircular sources in spatially correlated white noise," *IEEE Trans. on Signal Process.*, vol. 59, no. 9, pp. 4108-4121, Sept. 2011.

Cet article a dû être retiré de la version électronique en raison de restrictions liées au droit d'auteur.
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Appendix 15:

Cramér-Rao Lower Bounds of DOA Estimates from Square QAM-Modulated Signals

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F. Bellili, S. Ben Hassen, S. Affes, and A. Stéphenne, “Cramér-Rao lower bounds of DOA estimates from square QAM-modulated signals,” *IEEE Trans. on Commun.*, vol. 59, no. 6, pp. 1675-1685, June 2011.

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Appendix 16:

A Low-Cost and Robust Maximum Likelihood Doppler Spread Estimator

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