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Initial short report on the planned collaborative research activities to be conducted within WPR1

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Abstract:

This deliverable describes the relevant research topics within the scope of WPR1 “Modeling, calibration, and validation of multi-dispersive, multi-link channels” in which NEWCOM++ partners involved in this WP intend to conduct collaborative research activities. This document is meant to provide a roadmap for these cooperative activities during the three-year existence of the NoE. Of course this road map is subject to be amended depending on the progress of work and on how the scientific outcomes of this work will move the frontiers of knowledge in radio channel characterization.

The description of the research topics are arranged task-wise according to the nomenclature defined in WPR1, each section corresponding to one task. The description of each topic consists of two parts, a first part reporting the state of the art in the field, followed by a second part presenting the intended collaborative work including the involved partners.

Keyword list: Body area networks, cooperative and relaying networks, cognitive radio, multi-dispersive channel modeling, multi-link channel modeling, adaptive channel modeling, multi-sensor propagation modeling, reverberation model, model calibration, model validation, channel characterization, channel measurement, channel sounding, switching sounding, channel prediction, positioning and tracking, polarization, spectrum sensing, beamforming, channel parameter estimation, and maximum entropy principle.

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1 INTRODUCTION

1.1 Objective of the Collaborative Research planned in WPR1

The main objective of work-package WPR1 “Modeling, calibration, and validation of multi-dispersive, multi-link channels” is to refine and extend existing standard models of the radio channel, like the 3GPP (WINNER) Spatial Channel Model. The sought models account for all features in the radio channel that affect the behaviour and performance of advanced wireless communication systems or wireless networks operating in it. Under the term “model” we understand here a generic name encompassing any type of models, e.g. purely stochastic, deterministic, or hybrid deterministic-stochastic.

Different sub-goals have been identified, which address specific aspects of the sought models. Collaborative activities have been identified to reach these sub-goals. These activities are organized in tasks, corresponding each to one of the identified sub-goals.

- Task TR1.1 Design and implementation of multi-dispersive models - Multi-dispersive models for radio links will be developed, which reproduce dispersion in all dispersion dimensions, i.e. delay, direction of departure, direction of arrival, Doppler frequency, and polarization. Models describing the long-term temporal fluctuations will be also designed. The frequency-dependent response of scatterers will be included in UWB models too.
- Task TR1.2 Design of multi-link channel models for cooperative and relaying networks - Multi-channel or multi-link models will be designed, which account in a realistic manner for the statistical dependence between the responses of the channel links in a cooperative or relaying network.
- Task TR1.3 Adaptive channel modelling for flexible radio - Based on the information sensed by the receiver (band, environment), an adaptive modelling procedure will be developed taking into account "at best" the information at hand in order for the flexible radio to adapt its power and transmission rate to the statistical model.
- Task TR1.4 Experimental and theoretical model calibration and validation - Channel measurement data will be either made available or collected for calibration and validation of the derived models. Due to the costs of collecting a sufficiently large amount of measurement data to achieve significant statistical results, ray tracing simulations will also be performed for the same purpose. Robust, efficient estimators of the channel parameters and metrics characterizing the proposed models will be derived and their performance will be assessed.

1.2 Contents and Objective of this Deliverable

This deliverable describes the relevant research topics within the scope of WPR1 in which NEWCOM++ partners involved in this WP intend to conduct collaborative research activities.

The process of identifying these topics has taken place within the first few months after NEWCOM++ was launched via e-mail exchange and in two meetings that took place on January 29 2008 in Bologna and on March 28-29 2008 in Vienna.

This document is intended to provide a roadmap for the cooperative activities to be carried out within WPR1 during the three-year existence of the NoE. Of course this road map is subject to be amended depending on the progress of work and how the scientific outcomes will move the frontiers of knowledge in radio channel characterization.

As to the organization of the deliverable, the descriptions of the research topics are arranged task-wise according to the nomenclature in Section 1.1, each subsection corresponding to one task. The description of each topic consists of two parts, a first part reporting the state of the art in the field, followed by a second part presenting the intended collaborative work including the involved partners.

2 DESIGN AND IMPLEMENTATION OF MULTI-DISPERSIVE CHANNEL MODELS

2.1 Modeling Multi-Dispersive Wireless Channels

In this first part, we address the design of new models as well as model extensions in a number of scenarios: wireless cellular networks (with a focus on polarization diffuse scattering aspects), UWB systems, vehicular networks, and body area networks. It must be mentioned that an exhaustive review of existing MIMO channel models was recently published by NEWCOM researchers in [1].

2.1.1 Polarization Properties of Dispersive Components

Due to the heterogeneity of the propagation environment, the received signal at the receiver (Rx) of a radio communication system is the superposition of a number of components. Each component may be dispersive in delay, direction of departure (DoD), direction of arrival (DoA), polarizations, as well as in Doppler frequency. Dispersion of individual components in these dimensions significantly influences the performance of communication systems using MIMO (multiple-input multiple-output) techniques [2].

Recently, a rationale based on the maximum-entropy (ME) principle [3] has been proposed for the selection/derivation of probability distribution functions (pdfs) that can be used to characterize the normalized power spectral density (psd) of individual components [4, 5, 6]. This rationale assumes that each component has a fixed center of gravity and spread, and that no additional information about the psd exists. The center of gravity and spread of the component psd can be described by the first and second moments of a pdf. Therefore, a pdf is derived which satisfies the constraint of fixed first and second moments, while maximizes the entropy of any other constraint. Based on this rationale, pdfs have been derived and applied for modeling the component psd in elevation and azimuth [5, 6], in AoA and AoD [4], as well as in AoA, AoD and delay [7]. Indeed, these entropy-maximizing pdfs coincide with respectively, the Fisher-Bingham-5 pdf [8], the bivariate von-Mises-Fisher pdf [9], and the extended von-Mises-Fisher pdf [10]. Experimental investigations using measurement data demonstrate that these characterizations are applicable in real environments.

The ME characterization methods proposed in [4, 5, 6, 7] can be used to describe dispersion of individual components when a single polarization is considered in the Tx and the Rx. These methods are not applicable for describing the component dispersion in two (orthogonal) polarizations at one site of the Tx and Rx, or at both sites. Most literature dealing with the dispersion of channel in polarization focus on two cases, i.e. *i)* the narrow-band case where the polarization matrix of channel coefficient is investigated [11, 12, 13, 14], and *ii)* a multipath scenario where the polarization matrix of individual specular paths is studied [15, 16]. Characteristics of the polarization of dispersive component has not been investigated.

Planned work: The topics of interest that will be investigated by AAU, UCL, CNIT, Bilkent and CNRS with respect to the analysis of the polarization properties of wireless channels include but are not limited to

- the derivation of a parametric model for describing dispersion of individual components in orthogonal polarizations are considered at one side of the Tx and the Rx.
- the evaluation of the applicability of the characterization method and the parameter estimator.
- the extension of the above studies to the case where orthogonal polarizations are considered at both sides of the Tx and the Rx.

2.1.2 Extension of Ray-Tracing Tools

Ray Tracing (RT) tools based on a 3-D implementation of Geometrical Optics and the Uniform Theory of Diffraction [17] 3D GO/UTD play a key role in modern studies on channel modeling. They have been extensively used for radio planning and optimization of cellular networks in urban environments [18, 19, 20, 21]. Those tools can have great accuracy in channel prediction, provided a sufficiently accurate information about the site-specific environment of interest is available. In fact, the geographical information becomes gradually more easily available [22] and consequently channel modeling through RT may become a building block for future radio systems with enhanced functionalities. If a stochastic propagation models does not allow the system performance to be evaluated over the whole range of realistic propagation environment, RT tools can be used instead. RT predictions are then often used as a complement or a substitute to measurements. RT tools play also today an important role in the evaluation of performances of systems which aims at providing an indoor localization based on exploitation of estimated channel parameters.

RT tools can provide various multi dimensional [23] channel characteristics as the Power Delay Profile (PDP), Delay Spread (DS), Angular spead (AS), Doppler spectrum,etc. that can be exploited further at the system level to evaluate diversity system performances. RT tools are thus used today on a regular base for MIMO channel modeling : [24, 25, 26, 27]. A review of existing MIMO and UWB channel models (including RT tools) with their strengths and limitations can be found in [28]. In [29] a RT model is used to investigate the spectral efficiency of MIMO systems in a rectangular space representing a typical short-range indoor geometry.

Several deterministic time domain ray model based on GO-UTD technique have been developed for UWB multipath indoor propagation channel :[30, 31, 32, 33, 34, 35, 36]. UWB RT tools have to take into account the frequency selectivity of the different basic processes. This means that each of the interactions with objects in the environment as well as the antenna [37, 38], has to use the full frequency dependent description. In [39], the RT techniques and data of measured UWB antenna hardware are combined and simulations are performed in typical indoor scenarios, in order to show the impact of antenna paterns on transmitted signal. [40] aims at investigating the frequency influence on the correlation on an antenna arrays in a MIMO UWB indoor propagation scenario. RT can also be advantageously complemented by or associated with FDTD when typical building structures are to be analysed over very large bandwidth as in [41, 42] or [43]. In [43] the performance of the combined RT/FDTD approach for UWB in a realistic three-dimensional indoor scenario are analysed. It shows that the combined RT/FDTD model provides a higher precision for propagation paths with small delay time, with respect to the classical RT method. Although the difference between the two models is observable mostly for paths with large excess delay the improvement due to FDTD-modeling of small objects is in this case marginal in comparison to the error done by neglecting the diffuse scattering in the simulation. Therefore, the complementarity of RT tools which consist in introducing small details of the environment by using electromagnetic codes as FDTD is insufficient when the modeling difficulty is coming from inherent uncertainty on the environment knowledge. In [44], a true 3-D RT approach is employed to predict the UWB impulse response characteristics in a typical office building.

RT tools are of great help when one wishes to evaluate performances of positioning and location systems. In those cases there is typically a need to produce channel impulse responses which are related to a site specific environment. As an example among many, in [45] a RT tool has been used for RSS evaluation and in [46] to provide UWB channel impulse response dedicated to extended Kalman filter and particle filter for tracking applications.

RT tools calculate classically the specular reflections and the diffractions on wedges. However the actual propagation environment contains small scatterers that affect the propagated wave. Compared to the specular components (reflection transmission and diffraction) the diffuse scattering usually conveys a smaller amount of power. However this diffuse contribution is important when it comes to evaluate angular spread or the shape of the Power Delay Profile. The angular spread being a parameter which plays a key role for evaluation of MIMO system performances. In the last few years one of the main challenge has been to study [47] and to include properly the diffuse scattering into RT tools [48, 49]. In [25] a RT tool is used in an urban environment for MIMO capacity evaluation. This work illustrates very convincingly the fact that diffuse scattering as to be incorporated into the RT tool in order to obtain good estimation of the available space diversity. The prediction accuracy of wideband channel characteristics is greatly enhanced from diffuse scattering modeling as it has been recently demonstrated in [23]. [50] describes a diffuse scattering model and evaluates the impact of its insertion it in a 3D ray-launching urban simulator on two cases: LOS and NLOS. The diffuse scattering from rough surfaces has recently been introduced in a RT tool for site-specific channel modeling in indoor environment [51] for channel modeling at 60GHz. The goal in [52] is to simulate a complete RT based model which includes rough surface scattering in indoor electromagnetic wave propagation. The rough surfaces scattering is obtained by using Kirchoff approximation as described in [53]. Moreover, the shape of the PDP can also be exploited in fingerprinting techniques for positioning. This shape is hardly obtained in indoor environment for NLOS situation where a large amount of the received power is not predictable in a deterministic manner. In [54] a first attempt to introduce diffusion into a deterministic 3D indoor UWB propagation model, has shown an improvement is shown in the simulation when introducing the diffuse scattering but that it still remains a gap with measurements.

Planned work: Whether for the evaluation of available diversity in a site-specific context, or whether for being used for fingerprinting in location applications, RT tools have to be complemented in order to access realistically to second order parameters of the channel impulse response, especially in NLOS indoor situations. References highlighted above show that this complementarity has already been successfully implemented for outdoor situation or indoor situation for millimeter wave wireless systems. CNIT, CNRS and UCL propose to study in the framework of NEWCOM++, new strategies to complement RT tools for positioning applications increasing CIR realism while keeping as much spatial coherence as possible. For positioning applications an hybridation between RT and pseudo stochastic or semi deterministic methods as such which has been recently described in [55] could be investigated (see below).

2.1.3 Vehicular Channel Modeling

There are three fundamental approaches to channel modeling: deterministic, stochastic, and geometry-based stochastic.

In a deterministic approach, the boundary value problem for the wave equation (or Helmholtz's equation) is solved subject to boundary conditions imposed by a specific environment. Deterministic vehicle-to-vehicle (V2V) modeling has been explored extensively by [56]. Deterministic modeling requires intensive computations and makes it difficult to vary parameters.

Stochastic channel models provide the statistics of the received power at specified delays, Doppler shifts, and angles, etc. The classic tapped-delay-line model (which is based on the WSSUS assumption) is widely used for cellular system simulations.

For V2V channels, a tapped delay-Doppler profile model was developed in [57, 58, 59]. This model assigns a fixed Doppler spectrum to each single delay tap. The temporal evolution of short-time Doppler spectra in drive-by scenarios is not included in such model. Note that this was adopted early by the IEEE 802.11p standardization group [60].

Geometry-based stochastic channel models (GSCMs) have previously been found to be well suited for dynamic environments. GSCMs are based on discrete and diffuse inter-acting objects which are positioned randomly in space-time, according to a specified joint probability distribution. The signal components scattered by these inter-acting objects are approximated by a greatly idealized ray tracer. Finally the received signal results from the superposition of all components weighted by the receiving antenna characteristics. This modeling approach has a number of important benefits.

Planned work: FTW, TU Wien, Lund University and UCL are currently working towards a V2V channel model. To be more specific, we will approximate the V2V channel impulse response by four super-imposed terms: (i) the LOS component, which may contain more than just the true LOS signal, e.g., ground reflections, (ii) discrete components stemming from reflections off mobile scatterers, (iii) discrete components stemming from reflections off stationary scatterers, and (iv) diffuse components.

2.1.4 Channel Models for Body Area Networks (BANs-Part I)

Body-Centric Wireless Communication Systems are a natural evolution of the increasing demand for anywhere, anytime communications, and will play a key role in future mobile communication systems (fourth generation, and so forth). Their main objective is to connect personalization and convergence of various systems into a single one, through a network of sensors located on the human body, or in its close proximity. In this context, an extension of the concept of Wireless Local Area Networks (WLANs) to the personal sphere arises, the Body Area Networks (BANs) concept, involving communications ranging from the human body to a distance of 3 m, incorporating devices worn on, or implanted in, the body. BANs have a wide range of potential applications, major interests being health care and patient monitoring, personal identification, navigation, personal multimedia entertainment, and task-specific/fully compatible wearable computers.

There are various challenges for the design and study of BANs, most regarding the propagation channel and the influence of the body on system performance. Existing technologies, like Bluetooth, WLAN, or UWB (Ultra Wide Band), may be applied to BANs. As an example, the IEEE 802.15.4a group has developed a low complexity, low cost, low range and low power consumption physical layer based on the promising ultra-wideband (UWB) technology [61, 62]. On the other hand, the ISM band at 2.4 GHz is conventionally suitable for this application [63], but, as this band is being used for WLANs, interferences may occur.

The main criteria for the wireless modules used in BANs, and especially for on-body communications, are the support of high data rates, the small size and the light weight, and the consumption of minimum power. The first two criteria suggest the use of high frequencies, but the third one implies highly efficient links, which is not a characteristic of high frequencies, related to severe propagation losses. The very particular propagation characteristics of BANs, and in special the proximity of the human body, demand for a careful characterization of the radio wave propagation channel in order to ensure efficient performance. Thus, the use of existing WLAN models are not appropriate in most of the cases. Optimum antenna design is also of extreme importance and a challenge in the development of BAN systems. In the literature, one can find some research concerning the development of propagation models for BANs, e.g., [64, 65], which consider propagation losses caused by the surrounding environment, the human body and its movement. In [66], a propagation model for a BAN operating indoors, at 400 MHz, 900 MHz and 2.4 GHz, is derived, being concluded that the order of magnitude of the path loss is close to the power of the multipath components for a medium sized room.

Motivated by the work developed in [67], where the benefits of the use of MIMO in WLANs are exploited, [68], [69] and [70] study the possible application of this technology to BANs. In both works, results from measurement campaigns are presented, considering different configurations of MIMO and the cooperation between devices located in the body or at an office. It is concluded that MIMO enhances systems capacity, even in line of sight situations. This can be further extended by considering multi-sensor cooperation techniques (see Subsection 3.2, BANs-Part II).

Planned work: Considering the need of research in the area, the main objective of our work is to exploit several issues related to the radio channel and the modeling of propagation characteristics of BANs. In particular, strategies for an efficient use of the radio channel, exploiting various frequencies, will be studied by UCL and IST-TUL. The use of MIMO in BANs will be deeply analyzed, and a theoretical model will be developed, incorporating the main features of BANs, and allowing the extension for several scenarios, being supported by simulations and measurements. This task is closely related to multi-sensor aspects for BANs, discussed in BANs-Part II.

2.1.5 Implementing the COST 273 Model

The new COST 273 MIMO channel model [71] aims to model a large number of different scenarios. Its generic structure uses clusters, i.e. groups of multipath components, to model the wideband, time-variant, double-directional, fully-polarimetric radio channel. Its ultimate goal is to provide time series of the multiple-input multiple-output (MIMO) channel for link- and system-level simulations, yielding values of essential characteristics of the MIMO channel (space-time correlations, mutual information, etc.), as a function of environmental and antenna array parameters.

In contrast to analytical models, such as the Kronecker or the eigenbeam representations, it must be understood that the COST 273 MIMO channel model does not allow for the explicit design of space-time coding techniques. While analytical models provide a tractable mathematical framework for algorithm design, they neglect important properties of the radio channel. Thus it is necessary to test MIMO algorithms against a realistic channel model, such as the COST 273 MIMO channel model, to quantify its applicability in real-world environments. The COST 273 MIMO channel model is not yet completely parameterized for all of the envisioned scenarios. Particularly, the cluster parameters are still an open issue. Furthermore, clutter and terrain effects are not directly considered.

To find consistent model parameters, automatic methods identifying the model parameters from measurements, are required. To do so, multipath clusters need to be identified in measurement data. Identifying clusters from measurements was automated in the last years [72]. However, the main difficulty in parameterizing the COST 273 MIMO channel model is the fact that it uses different kinds of clusters to accurately model the radio channel.

Planned work: An extension of COST 273 channel model, introducing terrain and clutter information into radio channel generation, and an extended parameterization will be carried out by IST-TUL, UCL and FTW.

2.2 Channel Prediction, Antenna Aspects and Model Classification

This section does not deal directly with the design of models for new applications, but investigates various aspects of channel modeling, ranging from prediction and reciprocity to antenna design and classification.

2.2.1 Channel Prediction for Positioning and Tracking

With the emerging needs for high data rate mobile applications, operating over MIMO channels, prediction methods are more than ever needed to achieve the maximum spectral efficiency. Advanced wireless systems, such as the 3GPP Long-Term-Evolution (LTE), the Worldwide Interoperability for Microwave Access (WiMAX), aim at providing reliable services in time-varying environments. The techniques, such as adaptive modulation, beamforming and Orthogonal Frequency Division Multiple Access (OFDMA), used for achieving this goal, need reasonably accurate channel estimates based on knowledge of the channel evolution. When estimates are only available after a delay (usually due to a feedback link with limited capacity), the process of estimating the current channel is known as prediction. To maintain a good performance, accurate estimates of the temporal correlation behavior of the channel coefficients should be available. This is, however, not the case when the environment changes rapidly.

A variety of prediction methods have been studied with mixed success so far. A number of methods are based on the decomposition of the measured channel over a basis in time, and on the extrapolation of the elements of the bases (see e.g. the use of a sinusoid basis in [73] and [74], of discrete prolate spheroidal sequences in [75], spectrum poles identification in [76], or spectrum estimation through maximum entropy methods in [77]). Other classical signal-processing approaches based on auto-regressive or state-space models have been considered [78]. Use of the time and spatial correlation is advocated in [79]. Linear interpolation methods and parametric model-based (nonlinear) methods have also been proposed. The former methods interpolate the channel coefficients based on the minimum-mean-square-error (MMSE) principle [80, 81].

However, none of the above methods has been demonstrated to achieve satisfactory prediction performance when the predicted horizon is greater than the channel coherence time (commonly defined as the time required for the mobile side of the link to move by half a wavelength). It can be argued that this failure is due to the fact that the proposed prediction methods operate component-wise, due to the fact that the application of vector Wiener filter theory [82] is not practical for the typical number of dimensions (including delay spread in the case of wideband transmission, space at the transmitter and receiver in MIMO cases) encountered in wireless channels.

While the methods described previously try to model statistically the behaviour of the observed channel, parametric model-based methods focus on the identification of the underlying physical components of the channel. Usually of higher complexity, they involve subspace-based estimation algorithms, such as ESPRIT and root-MUSIC, to calculate the parameters, e.g. the orientations and velocities, of moving scatterers in an environment. Then, the future contributions of these scatterers are reconstructed based on the parameter estimates assuming they remain constant in the future observations. Recently, two novel positioning and tracking algorithms based on particle filtering have been proposed [83, 84]. The first algorithm can be used to estimate the time-variant parameters of individual propagation paths, while the second method is applicable to track the trajectories of moving scatterers in the environment. These two algorithms estimate the parameters in state-space models directly from the complex base-band data observed in the receiver. Simulations showed that these algorithms outperform conventional approaches in terms of higher positioning and tracking accuracy and lower computational complexity. The outputs, i.e. the tracks of the path parameters given by the first algorithm and the scatterer trajectories returned by the second algorithm, can be used to predict the variations of the propagation channel in the future. Since parametric methods involve the estimation of physical quantities (angles, distances...), channel tracking and positioning can benefit from each other.

This also indicates that a solution to the complexity problem could lie in the sparsification of the geometric model used for prediction. Past efforts by the authors focused on developing sparse models for channel temporal variations [85, 86, 87]. They aim at complexity reduction, while preserving the performance of the parametric physical-model based methods, by exploiting the highly structured characteristics of time-varying MIMO channels resulting from the analysis of the geometric model. For instance, one scatterer with a given speed (relative to the transmitter and receiver) will exhibit the same Doppler spectrum irrelevant of the Tx-Rx antenna pair. Furthermore, its characteristics (Doppler spectrum and space-time signature on the antenna arrays) changes at the scale of the movement, which is expected to be larger than the scale defined by the wavelength. Therefore, decomposition of the channel time variations along the specular components (each specular component being associated to a Doppler and spatial signature) is expected to extend the achievable time horizon of prediction methods.

Apparently, these parametric model-based methods are applicable in the case where the constant-parameter assumption holds. The validity of this assumption is closely related to the environment, as well as the movement of the scatterers, the Tx and Rx. Recently published analysis of time-varying channel measurements [88, 89] confirmed that local stationarity of the channel model is a valid hypothesis. Analysis of the results presented in [88] and [89] demonstrate the predictability of its non-stationary, longer-term characteristics.

In [86], a method based on blind identification (based on spectrum diagonalization [90]) of the specular components under the stationarity assumption was proposed. Identifiability of the specular components (under mild assumptions on linear independence of their respective spectra and spatial signatures, which are verified a.s.) was demonstrated, and a proof-of-concept experimental validation of this approach was proposed in [87].

Planned work: The topics of interest with respect to channel prediction using positioning and tracking algorithms that will be investigated by AAU, CNRS-SATIE and FTW include the construction of a channel prediction technique based on the two novel tracking algorithms [83, 84], the analysis of the performance of the proposed technique by simulation studies and using experimental data, and the extension of prediction methods to the non-stationary case. Adaptive methods for the blind identification and tracking of the specular components and of the spectrum, based on the dual Kalman filter [91, 92], will be investigated, together with the issues associated to non-stationarity, and the performance of the proposed methods will be assessed.

2.2.2 Integration of Antenna Array Response in Multi-Antenna Channel Models

Inclusion of the electromagnetic effects of antenna arrays into the MIMO channel has been generally studied from the mutual interactions point of view. Mutual coupling effects on the spatial correlation and bit error rate (BER) were firstly investigated by [93] for a compact space time diversity receiver in a Nakagami fading channel, considering the received signal as the multiplication of the signal without mutual coupling by the array admittance matrix. An expression for the normalized power correlation with coupling was given, and it was concluded in [93] that, the mutual coupling effect reduces the spatial correlation and improves BER performance. The reason behind this result was explained by the diversity provided by the pattern distortion due to coupling.

Later, the coupling matrices of [94] showed up. These matrices are obtained via the mutual interactions matrix and termination impedances due to one of the most common circuit models for an antenna array. Results lead to the conclusion that coupling can have a decorrelating effect on the channel matrix and increase the capacity [94]. The ease of the use of the technique in [94], which allows to obtain the coupling included channel matrix by simply multiplicating the uncoupled one with the coupling matrices of transmitter and receiver, has created lots of different applications of the coupling matrices [95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113].

A rigorous network theory framework including the effects of both mutual coupling and antenna matching has been developed in [114, 115]. Realistic models for channel noise and receiver noise were introduced in [114, 115] as well. The scattering parameter matrices were obtained using finite difference time domain (FDTD) method for antenna simulations in different matching network cases, in conjunction with a path-based channel model. In [114, 115], the mutual information was maximized by giving a modified water filling capacity solution for transmitters with full channel state information (CSI), under a radiated power constraint; thereby the resulting capacity expression provided an upper bound on system performance. It was also shown that, mutual coupling can provide a capacity benefit even for antenna spacings between $0.1 - 0.3$ wavelengths (λ), using appropriate transmitting schemes. Another network theory approach was presented by [116]; and different array configurations exploiting spatial, polarization and pattern diversity were compared in terms of channel capacity. In [117] a rigorous network theory framework is applied to mitigate the mutual coupling in compact antenna arrays and formulate optimal (Hermitian) match condition for coupled networks. In addition, they demonstrated the potential of diversity benefit offered by different possible termination conditions. Later, the work was expanded in [114, 115, 117] for noisy amplifiers; and showed that matching for minimum noise figure results in more capacity than matching for maximum power transfer does [118]. They further improved the framework to include the noise effects of the receiver front end in [119]. Pattern diversity via coupled two-element circular patch antenna array was analyzed in [120] by the use of the network models in [115, 116]. [121] generalized the two-port optimal noise matching condition to the multiport case. The transmission strategy with mutual coupling was discussed and optimal input covariance matrix was given in [122] using the network framework.

A number of different studies of Bilkent on mutual coupling in MIMO channels can be found in [101, 102, 123, 124, 125, 126]. In the very recent years, novel array configurations for wireless applications have been frequently encountered in the literature. Examples can be listed as follows: printed planar antennas [127] and wrapped microstrips [128] integrated with laptops for wireless local area network applications, reconfigurable antennas [129, 130, 131, 132, 133, 134], PIFA [135, 136] and multiband PIFA arrays for MIMO [137, 138, 131]. Vector antennas [139, 140], discrete lens arrays [141], circular polarized microstrips [142] were presented for polarization diversity. Adaptive MIMO arrays employing loaded parasitic elements were studied to improve the channel capacity [143]. Compact microstrip antennas exploiting multiple orthogonal modes [144]; printed monopole antennas [145], microstrip Yagi antennas [146], PIFA antennas electromagnetic compatible with nearby condducting elements [147] were presented for WiMAX and WLAN applications. The use of polarization-agile antennas were advised to improve MIMO capacity [148] against rotation out of optimal polarization. A wideband adaptive MIMO array is analyzed experimentally in [149].

Planned work: This task involves collaboration between IST-TUL and Bilkent. Very compact multi-antenna topologies will be characterized. Different antenna elements with different radiation characteristics and with different inter-element spacing will be considered. Furthermore, special consideration will be given to compact orthogonally polarized antennas with very good isolation between adjacent elements over a broad range of frequencies [150, 151], enabling to closely pack the antenna elements while maintaining minimum mutual coupling. A prototype of 2 ×2 antenna elements for a WiMAX access point will be fabricated and experimentally characterized. Simulation and experimental S-Matrix and 3D vector radiation pattern data for the analyzed antennas will be provided to other interested partners, for inclusion into their propagation channel models and simulators. Furthermore, printed planar arrays of dipole and patch elements will be analyzed in terms of MIMO performance. The numerical simulations will be obtained using a MoM/Green's function technique. The technique can be used in conjunction with any geometrical channel model. Thus, accurate inclusion of the antenna electromagnetic effects into a developed geometrical channel model is possible. The numerical efficient nature of the technique allows to analyze arrays with large number of elements in short times. It should be noted that, the technique at the moment is limited with certain antenna types such as microstrip (or freestanding) patch and dipole elements on planar (or conformal) substrates, since it is capable of analyzing dielectric slab and free space Green's functions. Impact of electrical and geometrical properties of printed arrays, such as dielectric thickness and permittivity, on the MIMO performance will be obtained. Appropriate arrays designs will be fabricated and MIMO measurements will be conducted with a setup as in [143]. Comparisons of results by the technique with measurements will be given. A ready-to-use particle swarm optimization (PSO) tool will be used in order to increase the capacity of a MIMO array by including parasitic elements onto optimal locations in a limited physical size. The parasitic elements can be considered as near field scatterers; and by the inclusion of NFS, the capacity in poor multipath/LOS environments can be increased [152]. The PSO tool has generic properties so that it was used for different applications such as increasing MIMO performance of nonuniform dipole arrays [125] and accelerating the maximization step of SAGE algorithm [153].

2.2.3 Unitary Analysis and Classification of Channel Models

This last task is more prospective, and involves numerous partners at various levels. Although the activity commonly referred to as modeling represents a fundamental one, only a few papers have been written so far on the general subject of modeling as referred to wireless communication research. A very high number of scientific papers have been written in recent years to propose new radio-propagation or -channel models, highlighting their qualities and adherence to experimental investigation. However, what seams lacking is a unitary theoretical framework where the different propagation or channel models can be placed, defining scope, characteristics and common criteria for validation and performance assessment.

Some relevant work in the field has been done within the COST 273 framework, defining a set of environments for wireless system simulation (MORANS) [71]. There is however still work to be done.

Planned work: CNIT, Aalborg University, FTW, TU Wien and IST-TUL will carry out a general study on propagation/channel modeling, with the scope of defining a common background and a common vocabulary for the research activity of WPR1. In particular, the proposed study will have to investigate on the following topics.

- The definition of the concept of model, with reference to propagation and channel models. How can/should a model be derived?
- Propagation/channel model classification. For example, propagation and channel models can be classified in a unitary way by placing them into a 2-dimensional space whose axis refer to the following couples of adjectives: empirical vs. physical; stochastic vs. deterministic.
- The purpose of a model in relation to the classification of it (see above). Channel models and simulators for system design are usually empirical or stochastic models, while propagation models for planning are usually physical or deterministic. Can these two different points of view be put in relation to each other? Can we fill-in the gap? Of course, too deterministic can mean too particular, but on the other hand, too stochastic can be too general, with total uselessness in both cases.
- The concept of spatial-scale-level for space-related model [154]. The spatial scale-level refers to the size of the spatial region over which parameters are computed or measured. For example, local

field strength averaged over fast-fading refers to an area with a radius of a few wavelengths, while mean outage probability within a cell refers to the whole cell area. Of course, the scale-level is related to the degree of determinism/accuracy of the results and thus of the model: the lower the scale level the higher the degree of determinism. The scale level adopted in a model should be related to the degree of accuracy of both model and environment description: it is nonsense to run an accurate deterministic model on a rough database and vice-versa.

- The problem of model validation: model performance assessment in relation to the spatial scale-level and to the scope of the model. Definition of a common validation procedure based on the concept of experiment, similarly to what is usually done in other research disciplines such as Physics or Medial Science.

3 DESIGN OF MULTI-LINK CHANNEL MODELS FOR COOPERATIVE AND RELAYING NETWORKS

3.1 Channel Correlation in Multi-User and Multi-Node Systems

In a cellular network, cooperation between users can be used to greatly increase power efficiency, reliability and throughput. Cooperation can be achieved by using the antennas of multiple users to form a virtual antenna array and by using MIMO transmittion/reception techniques. The development and realistic performance assessment of such distributed MIMO systems requires measurement and characterization of the different channel links in these systems. To this end, only a limited amount of channel measurements of such distributed MIMO systems is available.

Static indoor channel measurements of multi-user MIMO (MU-MIMO) systems have been used in [155] for the evaluation of the proposed MU-MIMO scheme. [156] also use static indoor measurements to analyze the capacity performances of two interfering flat-fading MIMO channels. Dynamic outdoor channel measurements have been used in [157] to study limited feedback in MU-MIMO systems. However, all the cited channel measurements use several single-link MIMO measurements and combine them to form a multi-link scenario.

Recently, two different groups conducted MU-MIMO measurements synchronously over multiple users. In [158] the authors use a MEDAV-LUND channel sounder along with its corresponding receiver as well as the receiver of an Elektrobit channel sounder. The two receivers are perfectly synchronized. The authors present capacity with interference results, based on the dynamic multilink measurements, as well as path-loss and delay spreads for the measured scenarios.

In [159, 160] realistic MU-MIMO channel measurements have been obtained using Eurecom's MIMO Openair Sounder (EMOS) [161]. The EMOS can perform real-time channel measurements synchronously over multiple users moving at vehicular speed. The measured channels are used to calculate the capacity of the MU-MIMO broadcast channel.

Planned Work: Ftw. and CNRS/EURECOM plan to use the spectral divergence measure [162, 163, 164] to characterize the similarity of the second order statistics of the individual MU-MIMO links. First, we will evaluate the power delay profile extending the work of [160]. And extension to the Doppler domain requires software changes in the Eurecom MIMO OpenAir Sounder (EMOS) and will be carried out in a second step. Furthermore, Ftw. and UCL plan to characterize the cooperative indoor channel. Measurement campaigns will use a state-of-the-art wideband multi-antenna channel sounder, focusing on characterizing virtual multi-antenna (distributed) rather than classical multi-antenna (co-located) systems. This will allow characterizing e.g. the shadowing correlation between the various channels, as well as the correlation between wideband channel responses. The targeted environments are rooms in typical indoor offices or apartments, with non-line-of-sight between the (indoor) collaborative nodes and the (outdoor) base station.

3.2 Multi-Sensor Propagation Modeling in Body Area Networks (BANs-Part II)

As already mentioned in BANs-Part I (Subsection 2.1.4), Body-Centric Wireless Communication Systems will be investigated within this action. Whereas the focus in BANs-Part I is on sensor-to-sensor propagation modeling, possibly including classical MIMO schemes, the focus in BANs-Part II lies in the multi-sensor aspects. Indeed, path loss for on-body communications is very high, so that the communication between a sensor and the central recording device might not be achievable, because of prohibitive loss and the reduced transmit power. Hence, an elegant solution consists in using cooperative or relay techniques to ease the communication. Yet, such techniques mostly rely on Rayleigh uncorrelated fading between the nodes. This is not necessarily the case for on-body communications, as radio propagation takes place via two mechanisms: a surface wave on the body, and multipaths arising from obstacles (arms, close objects, ground and walls, etc.). The combination of these two mechanisms makes therefore unlikely the channel to be Rayleigh distributed and uncorrelated.

Planned Work: IST-TUL and UCL will extend the work carried out in BANs-Part I in view of multi-sensor relaying schemes, characterizing the channel correlations between the various multi-sensor links.

3.3 Performance Evaluation of Beamforming Algorithms for Multiuser/Multicell Scenarios

Broadcast/Multicast: In the context of the development of beamforming algorithms for multicell multiuser scenarios, the scenario of multicasting is a special case. Herein we understand the joint transmission of a number of sources to a number of users, with every source transmitting the same signal and every user interested in the same data. Examples for such a scenario are the nation-wide transmission of video or audio content, using standards like DAB or DVB-T. Upcoming communication standards like WiMAX and LTE boast similar services, with the novelty of providing an uplink for channel state feedback and antenna arrays at the base stations. These two factors enable the use of beamforming algorithms for the transmission of multicast data.

The evaluation of algorithms for beamforming in multicell/multiuser scenarios [165][166] requires channel models that mimic not only the characteristics that are important in a single-link communication but on top of that also other characteristics, such as shadowing, which may be correlated between different sites, and user distribution across space, which might deviate substantially from the ubiquitously assumed uniform distribution.

The nature of a joint transmission from multiple base stations to multiple users implies a high number of links in such a scenario. Therefore, finding an optimal trade-off between modeling accuracy and complexity is of paramount importance.

Unicast: In cellular communication, the worst reception conditions occurr at the cell edge due to intercell interference. We want to study multi-antenna techniques to minimize the interference received from other cells. Here, the main problems are the same as mentioned above, namely a high number of links which exist in the system. In the case of no cooperation between base stations, not all links in the system need to be modeled exactly. For example communication outside the cell of interest may be modeled as an additive noise term, whose variance depends on the location of the user within his cell. In the case of cooperation between base stations, simply modeling intercell interference as a location dependant constant noise power would prohibit the evaluation of advanced interference coordination schemes such as precoding. Modeling the communication of neighboring cells exactly however entails the same high complexity as in the aforementioned case of broadcasting/multicasting, which necessitates exact yet low-complex multilink channel models.

Channel Modelling via Ray Launching: Ray Launching has been proposed as a low-complexity alternative to ray tracing [167], which makes this technique well suited for channel modelling in a multicell/multiuser scenario. In ray launching, the standard and somewhat artificial assumption of uncorrelated channels for different base stations and/or different users is not required. Furthermore, there is no requirement for a shadowing model which features the correct correlation properties between different base stations/users. However, in ray launching, as opposed to ray tracing, only a very low number of rays is being traced from any source voxel (volume element) to any sink voxel. This low number prohibits accurate representation of the power angular density and the power delay profile, which must be taken care of.

Planned Work: We want to study techniques to effectively merge statistical channel modeling and ray launching channel modeling to combine the positive characteristics of both techniques. One such way would be a combination of ray launching results for pathloss and shadowing coefficients and statistical channel modeling results for fast fading, power angular density and frequency selectivity. Furthermore, we want to study the trade-off between the number of simulated rays per voxel and modeling accuracy.

3.4 Reverberation Models for Indoor Communication and Positioning

Traditional stochastic radio channel models reflect the statistical properties of the (time-variant or time-invariant) impulse response of the channel between the input of any antenna element at the transmitter site and the output of any antenna element at the receiver site. The probability distributions of the parameters of the channel impulse response are generally difficult to obtain from environment parameters such as the scatterer size and density. Instead, the model parameters are often inferred from measurements. Motivated by experimental results, conventional models implement an exponentially decaying delay-power spectrum and impulse response magnitude by including various ad-hoc constraints on the random model parameters. The two contributions [168] and [169] follow this approach. In these models a key parameter for modeling the arrival times of individual signal components is the "cluster arrival rate". However this parameter is difficult to derive from a propagation environment. In the model given in [170] the scattering coefficients are corrected to account for the effects observed experimentally like the exponential decay of the delay-power spectrum. These approaches, however, do not reflect the underlying physical mechanisms that lead to this decaying behavior.

A different approach is followed by Franceschetti in [171] where the radio propagation mechanism is modelled as a "stream of photons" performing a continuous random walk in a cluttered environment with constant clutter density. The transmitted signal is a pulse of finite duration. When a photon interacts with an obstacle, it is either absorbed (with a certain probability) or scattered and changes direction.

A group of models exploit an analogy between the acoustical wave-fields and electromagnetic wave-fields In the field of room acoustics there is a long tradition for reverberation modeling with the earliest model dating back to the work by W. C. Sabine from the late 1890's [172, 173]. Several attempts to exploit this knowledge to model the power-delay profile for indoor electromagnetic wireless channels has been made. As examples the contributions [174, 172, 175, 176] model the exponentially decaying power of the diffuse tail has been modeled using Sabine's acoustical reverberation theory. Besides being relevant to indoor communications models of this type of models are well-suited for indoor positioning applications as they relate the power delay profile to the room geometry.

A well-studied effect within room acoustics is that the impulse response of a room exhibits a transition from early "specular" components to a later "diffuse" reverberation tail [177]. A similar transition effect has previously been observed and modeled in [178, 179] for ultra wide band measurements. In the work presented in [180, 181] the propagation environment was modeled using random graphs where vertices of a graph represent scatterers and edges model the wave propagation between scatterers. When a graph is generated, a closed form expression for the channel impulse response is available [181]. As a result of the structure of the graph, the realizations channel impulse response obtained with this model exhibit the specular-to-diffuse transition effect.

Planned Work: The topics of interest with respect to reverberation models include but are not limited to

- Investigations of the statistical properties of reverberant channel impulse responses in indoor wide band communications and localization.
- Indoor multi-link communications in reverberant channels.
- Model parameter estimation from measurement data including.
- Models for indoor localization including models relevant for finger printing applications.

4 ADAPTIVE CHANNEL MODELLING FOR FLEXIBLE RADIO

Dynamic reconfiguration of radio devices, or flexible radio, is a currently the object of very active research. Reconfiguration typically implies the capability for devices to change the properties of the air interface in general (carrier frequency, data rate, protocol, ...) according to their radio-frequency environment (channel quality, interference situation, ...). Optimization (e.g. through intelligent allocation) of radio resources is a key factor in many environments. However, the channel and interference models used so far in the analysis of communication systems based on cognitive radio were mostly ad-hoc. In the field of collaborative communications, the effect of the channel statistics is not yet well understood. The goal of this task is therefore to identify the needs in terms of channel models and channel representations associated with cognitive and collaborative communication systems, and to develop suitable adaptive models.

Adaptive channel modelling is concerned with the problem of designing channel representations that can be updated in real time by a device, according to measured quantities. Since the knowledge of the environment is hard to acquire and patchy, it is particularly important to design proper representations and methods to incorporate the sampled data, and use it to make optimal decisions about the adaptive parameters of communication algorithms.

4.1 Application Scenarios and Critical Parameters for Channel Models in Cognitive Radio

Relatively little work has been done so far in characterizing the behaviour of opportunistic or cooperative communication schemes, under imperfect channel knowledge. From an information theoretic point of view, cooperative cognitive transmitters have been shown to approach the capacity of the corresponding MIMO system [182]. However, little is known about the relevant parameters in this context.

In the presence of delay and outage limited communications, cooperative protocols provide substantial gains in error performance by describing the exact manner with which the different participating nodes can communicate between themselves so that they essentially form virtual antenna arrays, or equivalently so that information reaches the destination via several different paths.

If the channel is randomly changing, the network's error performance is heavily affected by the event of channel outage as well as by the channel statistics. In such networks, the role of proper channel modelling for the different channels between the different nodes of the network is of great importance because channel statistics define the optimal operational parameters governing cooperation.

We are interested is addressing some similar issues that arise in the presence of imperfect channel modelling in cooperative networks.

We will focus first on already well understood protocols (amplify-and-forward, and decode-and-forward), in particular on dynamic protocols where certain parameters (e.g. the duration of the phases) is a function of the ergodic capacity of the channel as well as of the 'distance' of the rate of transmission to the ergodic capacity of the channel. A well known example of a dynamic protocol is the dynamic decode-and-forward protocol, [183, 184] which has been shown [185] to achieve near MISO performance for certain channel statistics. The effect of imperfect channel knowledge on the performance of these protocols will be studied, and channel parameters relevant for performance optimization will be identified, with the ultimate goal of designing corresponding estimators.

The performance of these protocols has been studied then the channel knowledge about the channel (in particular, diversity) when this knowledge is not complete. We seek to understand how the performance (in terms of the diversity-multiplexing tradeoff) of the different protocols deteriorates in the presence of reduced knowledge of the channel statistics (i.e., in the presence of uncertainty on the ergodic capacity for the different source-to-relay and relay-to-destination paths, or on the multiplexing gain).

Planned work: CNRS-Eurecom, FTW-TUV and CNRS-Supelec will collaborate to identify application scenarios and their critical parameters. Diversity under channel uncertainty will be studied in the light of previous results on the Orthogonal Amplify and Forward (OAF) and the Selection Decode and Forward (SDF) protocols [186, 187] for the case of a single relay, and of [188] for an arbitrary number of relays. Non Orthogonal Amplify and Forward (NAF) [189] will be considered too, and the unitary transformation on the received signal vector [190], and Slotted Amplify And Forward (SAF) [191] will be considered as well. The equivalent channel model induced by the relaying protocol will be considered as a first approach.

In the long term, quantifying the above relation between imperfection on channel knowledge and error performance can lay the groundwork for introducing similar questions in the setting of cross-layer optimization.

4.2 Design of Adaptive Channel Models for Cognitive Radio

Up to this date, cognitive radio has mostly considered under the angle of spectrum sensing, i.e. estimating the presence or the strength of interference in a given part of the available spectrum. A variety of approaches to obtain the spectrum opportunity information has been proposed [192]. Cooperative sensing, where multiple users collaborate in this estimation process, has been considered [193, 194]. However, the indicator of primary signal absence or presence does not always provide enough information for opportunistic spectrum access decision, since cognitive users should also be aware of "how good" the spectrum opportunities are and make access decision collaboratively to maximize overall network throughput. Efforts in characterizing more accurately the interference sources, through their power or their location in beamspace, have been made [195, 196].

Richer information related to the primary cognitive link can be obtained through sensing and estimation (e.g. noise variance, channel gain, transmit covariance of the primary signal). Adaptive channel modelling can be derived based on the sensing results for cognitive radio to adapt its transmission parameters, for instance, to exploit power allocation and adaptive modulation and coding.

It is desirable to cast this problem in a probabilistic context: even if the interest only lies in the current channel realization, methods considered as optimal in the context of estimation theory (such as the maximum-likelihood estimator) fail at answering probabilistic optimization problems, for instance the one of achieving a prescribed outage (packet-loss) probability. On the contrary, probabilistic models can incorporate (at least in theory) all sorts of information based on various estimated properties of the channel, and their accuracy (based e.g. on the knowledge of the estimation error variance, or on data ageing models for cases where only outdated measurements are available) can be dealt with.

Bayesian inference promises to be a cornerstone for the development of such models. The principle of entropy maximization introduced by Jaynes [197] provides powerful tools to deal with uncertainty in inference problems. This principle, based on the fact that Shannon entropy is a good measure of uncertainty, enables to model gracefully the channel properties, using both prior information about the channel statistics (such as power or power delay profile, correlation in time, space or frequency, as well as interference power spectral density), as well as information from measured quantities (current and past channel estimates, collision or outage statistics, . . .). One of the major specificities of flexible radio systems is the fact that the statistics of the channel are in general hard to estimate, due to the large dimension of the hypothesis space and the relative small amount of measurements available to the devices. Furthermore, these can not be assumed stationary over long periods of time. The adaptive model has therefore to be able to handle smoothly missing data, which the maximum entropy principle helps to fill in the gaps of missing information by maximizing the uncertainty of the probability density function (pdf).

A number of previous works on the topic focused on establishing priors. Priors based only on the hypothesis space were proposed first in [198]. The fact that the uninformative prior is not invariant to reparameterization is used in [199, 200, 201, 202, 203] to derive priors based on a stochastic spatial correlation. These results, based on random matrix theory, are built upon the fact (justified by entropy considerations) that unknown correlation matrices are best modeled using the well studied class of Wishart matrices.

Methods for obtaining posterior pdfs based on channel measurements have been proposed as well. Selection and derivation of pdf based on the maximum entropy principle have been used to characterize the normalized power spectral density (psd) of individual components in [4, 5, 6]. Each component is assumed to have a fixed center of gravity and spread in the multiple dispersion dimensions, and that no additional information about the psd exists. A posterior pdf is derived which satisfies the constraint of fixed first and second moments, while maximizes the entropy of any other constraint.

Adaptive models based on geometric models have also been developed. Using again this ME-based rationale, some pdfs have been derived and applied for modeling the component psd in elevation and azimuth [5, 6], in AoA and AoD [4], as well as in AoA, AoD and delay [7]. Indeed, these entropy-maximizing pdfs coincide with respectively, the Fisher-Bingham-5 pdf [8], the bivariate von-Mises-Fisher pdf [9], and the extended von-Mises-Fisher pdf [10]. A similar methods has been applied in [204] to ultra-wideband channels. Experimental investigations using measurement data demonstrate that these characterizations are applicable in real environments. ME models have also been used for mobility tracking and resources management [205].

Planned work: RWTH, CNRS-Supelec and AAU will collaborate on the design of spectrum sensing methods at the cognitive receiver. Methods based on distributed detection and estimation theory will be developed. The intended work will include modelling the primary transmission profile combining spectrum occupancy statistics [206] with sensing parameters, i.e., identify the primary transmit power and channel gain between each link in the spatial-temporal dimension according to localization results. The effects of imperfect sensing errors in channel modelling and adaptive transmission (e.g., joint beamforming and power allocation) will be further investigated.

FTW-TUW, CNRS-Supelec and CNRS-Eurecom will carry out research on the data fusion problem. The integration of priors and field measurements into a pdf best describing the knowledge about the current channel state, and the numerical methods to achieve it, will be considered in this task. Improved modeling of time correlation will also be targeted. Specifically, the extension of the stochastic spatial correlation models to the spatio-temporal correlation model is planned, using in particular the recent results of [207] on correlated Wishart matrices.

AAU and CNRS-Eurecom will work on the characterization of geometric models using experimental data. The adaptive geometric models will be extended to characterize more dispersion dimensions of individual components, namely the directions (angles+elevations) of arrival and departures, and delay. Without any further constraints, the derived pdf can have 20 parameters, which may lead to high computational complexity in the parameter estimation. It is necessary to identify some “reasonable” constraints such that the number of parameters in the pdf can be reduced. Experimental analysis of the applicability of the derived models will be performed using measurement data.

5 EXPERIMENTAL AND THEORETICAL MODEL CALIBRATION AND VALIDATION

5.1 Methods for Measuring Multi-link Channels

To measure multi-link channels, all nodes in the channel have to be perfectly synchronized. Several methods will be tested and compared, using a MIMO channel sounder and a multi-port vector network analyser (VNA). The related phase noise issues and their effect on multi-link measurements are studied also within the subtask on improving channel sounding.

The Eurecom MIMO OpenAir Sounder (EMOS) can perform real-time channel measurements synchronously over multiple users moving at vehicular speed. The EMOS base station consists of a workstation with four data acquisition cards, which are connected to four RF chains. As an antenna, an off-the-shelf Powerwave 3G broadband antenna (part no. 7760.00) composed of four elements which are arranged in two cross-polarized pairs is used. The user equipments consist of a laptop computer with dual-RF CardBus/PCMCIA data acquisition cards and two clip-on 3G Panorama Antennas (part no. TCLIP-DE3G). The most important parameters of the platform are summarized in Table 1 [159].

The EMOS establishes synchronization by using an OFDM modulated sounding sequence. It consists of a synchronization symbol (SCH) used for the slot synchronization of the UEs to the BS. A broadcast data channel (BCH) comprising 7 OFDM symbols carries the frame number of the transmitted frame and is used for frame synchronization among the UEs. The rest of the frame comprises 48 pilot symbols, which are used for the channel estimation. The pilot symbols are taken from a pseudo-random QPSK sequence defined in the frequency domain. The subcarriers of the pilot symbols are multiplexed over the four transmit antennas to ensure orthogonality in the spatial domain.

The symmetry of the electromagnetic propagation channel w.r.t. exchange of the roles of the transmitter and receiver, or reciprocity, is often cited in the literature as a convenient way to obtain channel knowledge at the transmitter without feedback. Indeed, in systems where the channel is used in both directions using a time-division duplexing scheme, the channel estimates obtained from the received signals can theoretically be used to infer the state of the channel during a subsequent transmission, provided that the channel does not change too fast.

However, this symmetry is in practice disturbed by the characteristics of the radio-frequency circuitry of the transmitter and receiver. Indeed, the channel representation which is used typically by digital signal processors in communication applications is a combination of the characteristics of the digital-to-analog converters and power amplifiers at the transmit side, the antennas on both transmit and receive sides, the electromagnetic channel itself, and the characteristics of the low-noise amplifier and analog-to-digital converters at the receive side. Although the electromagnetic channel between the antennas is demonstrably reciprocal (see for instance [208] and references therein), the RF circuits on both sides are usually not identical. This indicates that exchanging the roles of the transmitter and the receiver would actually change the channel behaviour as measured by the digital signal processing algorithms. In fact, the phase errors between antennas introduced by this phenomenon can be particularly harmful to algorithms relying on reciprocity to provide channel estimates, in particular in systems using antenna arrays where the relative phase of the signals transmitted by various antennas in the array is a critical parameter.

Parameter	Value
Center Frequency	1917.6 MHz
Bandwidth	4.8 MHz
BS Transmit Power	30 dBm
Number of Antennas at BS	4 (2 cross polarized)
Number of UE	4
Number of Antennas at UE	2
Number of Subcarriers	160

Table 1: Parameters of the EMOS measurement platform

Various solutions to this issue have been proposed. One of them is the calibration of each RF circuit involved [209], requiring additional hardware. Another alternative, limited to low-power transmission, is to use a specially crafted transceiver where the same op-amp is used for both transmitting and receiving [210]. A third alternative [211, 212], termed relative calibration, achieves the same effect as normal calibration without the requirement for extra hardware. However, it requires the collaboration of both sides of the communication link, through the exchange of channel estimates, and is only valid for one pair of transmitter and receiver. The method relies on modelling the measured channel as the cascade of the impulse responses of the transmit circuitry, electromagnetic propagation path, and receive circuitry.

The focus of our work is the extension of the relative calibration method to multi-user scenarios (the channel being alternatively a broadcast and multiple-access channel). Estimators for the calibration parameters will be derived, and their performance and robustness (e.g. with beamforming techniques) will be evaluated. The estimator should be able to handle optimally heterogeneous measurements (mobiles might report their calibration information with different periods, with different estimation error variances). Experimental validation of the proposed solution will be pursued (in relation with Topic 1) with the collaboration of CNRS-Eurecom, who will provide their multi-user channel sounder [213].

Planned Work:

- UCL will measure muti-link channels. Several methods will be tested and compared, using a MIMO channel sounder or a multi-port vector network analyser (VNA) in combination with long cables. Suitable calibration procedures will be developed and investigated for both cases. The targeted environments are indoor rooms in offices and apartment.
- FTW/TUW and EureCom design of the protocols and of the scheduling necessary for multi-user reciprocity measurements [211].
- At CNRS/EureCom, a successor to the hardware currently used in EMOS under development and will be available for use it the beginning of 2009. It comprises two parts: Express MIMO, which is the baseband processing unit, and Agile RF, which is the RF unit. Agile RF will offer significantly more RF functionality in terms tuning range and channel bandwidth. The tuning range per RF chain is 180MHz-8GHz with 20MHz channels. The Express MIMO card will house 4 high-speed A/D and D/A converters, and thus allowing for measurements with up to four antennas.

5.2 Gathering of Database of Experimental Data

A centralised documentation database of channel measurements was set-up within the activities of the FP6 network of excellence NEWCOM, workpackages WP2.3.2 and WP6. The first release of the database of measurements coincided with the first productive release of the NEWCOM DataBase for Knowledge Networking (DBKN), in November 2005 [214]. Since December 2005, all NEWCOM partners could input and search the DBKN for available channel measurements.

Since then, it constitutes a durable, credible, renewable and publicly available depository of the collective wisdom of NEWCOM in the various areas of its expertise, namely wireless communications systems. In essence, the DBKN represents a collection of research-enhancing and referencing tools which can be accessed from the outside (and, obviously, from the inside) via secure methods and can serve a variety of purposes such as: enriching the global research community; promoting the research dialogue at a large-scale Institutional level; encouraging individual contributions; promoting individual research guidance; providing reference models for contributions to standards and regulatory bodies; and so on. For further details on the architecture and implementation of the DBKN, we refer to [215] although there were some changes in the meantime.

The existing database covers the documentation and distribution of existing radio channel measurement data within NewCom. A centralised data base was implemented which contains the documentation of measurements only Ð not actual measurement data sets. It was considered sufficient to define a database of measurement documentation with pointers to contact persons at the specific NEWCOM partner where the data are made available. Due to the typical file sizes of measurement data, it was not practical to set up a centralized data base of measurement data together with the documentation. The database includes pointers to the specific files of measurement data stored in the individual servers of NEWCOM participants.

A wide range of measurements have been conducted at Eurecom and can be made avaliable to the members of Newcom++ on request. The outdoor measurements were conducted in the vicinity of the Eurecom institute. The scenario is characterized by a semi-urban hilly terrain, composed by short buildings and vegetation with a predominantly present LOS. The BS is located at the roof of Eurecom's southmost building. The antenna is directed towards Garbejaire, a small nearby village. The UEs were placed inside standard passenger cars which were beeing driven along the measurement routes. The outdoor-to-indoor measurement was conducted in the neighboring building. The indoor scenario is characterized by strong reflections (the buildings is actually located behind the main lobe of the antenna) and thus there is no LOS. The users were all in the same room, moving around slowly.

Planned work:

- FTW/TUW and ISMB will migrate the existing database to the plone server employed in NewCom++.
- UCL will per se participate in the gathering of data, but will not contribute to the actual building of the database (UCL may offer its data, but will not spend and collect the data to build the database).
- FTW/TUW and CNRC/EureCom plan to carry out a multi-user reciprocity measurement campaign with the Eurecom sounder.
- CNRS/Rennes will calibrate their Ray Tracing tool for UWB indoor channel simulation based on a 4-channel digital sampling oscilloscope with 20 GS/s per channel and a pulse generator. CNRS/Rennes is developing its own testbed and will be glad to share data with interested partners.

5.3 Improvement of Channel Sounding

The design and optimization of multiple-input multiple-output (MIMO) communication systems require realistic models of the propagation channel, which incorporate dispersion in delay, Doppler frequency, direction of departure, direction of arrival, and polarization. In order to develop realistic parametric models of the channel response it is of great importance to be able to accurately measure the dispersive behavior of the propagation channel, that is, simultaneously measure dispersions in the above dispersion dimensions. Dispersion of the propagation channel in one dimension can be estimated from an observation using an aperture in the corresponding Fourier domain. For example, if Doppler frequency is to be estimated, observations at different time instants are required.

It is shown in [216] that the design of spatio-temporal apertures is critical to the joint estimation of Doppler frequency and bi-direction. Various algorithms for the estimation of directions and Doppler shifts from data obtained from spatio-temporal arrays have been proposed, see e.g. [217, 218, 219, 216] and references therein. Until recently, it was believed that the maximum absolute Doppler frequency that can be estimated with a switched sounding system is inversely proportional to the product of the number of elements of the transmit and receive arrays. This limitation was considered a major draw-back of switched systems [220]. However, as shown in [219] and [216], this limitation is an effect caused by the (inappropriate) choice of the spatio-temporal aperture and is not a fundamental (Nyquist) limit. This inappropriate choice leads to an ambiguity in the estimation of Doppler frequency and direction [216]. An intuitive interpretation of this effect is that the phase changes induced by a plane wave at the outputs of the array elements may result either due to the fact that the wave exhibits a Doppler frequency or due to the wave's impinging direction, when switching sounding is used. The ambiguity effect occurs when it is not possible to distinguish which effect has really caused this phase changes. In particular it was shown in [216] that by appropriately selecting the spatio-temporal aperture it is possible to extend the above maximum Doppler frequency to the largest value that can be estimated with a similar single-input single-output sounding system. As illustrated by these results, the theoretical understanding of the impact of the spatio-temporal aperture on the estimation of model parameters such as bi-direction and Doppler is in demand.

To save hardware cost and alleviate the needed calibration procedures, most advanced multiple-input multiple-output (MIMO) radio channel sounders rely on a time-division multiplexing (TDM) technique. In such a system, a single sounding waveform generator is connected to a number of transmit antennas via a switch. Similarly, the output terminals of the receive array are sensed via another switch. Thereby channel observations of all sub-channel can be obtained.

It has been shown recently that concatenated phase noise of the oscillators in the transmitter and the receiver affects the estimation of MIMO channel capacity when using the standard channel matrix estimator to obtain a capacity estimate [221, 222]. For short we call this concatenated noise the phase noise of the sounding system. The effect of phase noise on MIMO capacity estimation is studied in [222] assuming that phase noise is a random walk process. Theoretical investigations reported in [221, 223] show that, provided phase noise is white and Gaussian, it leads to large measurement errors in terms of estimated channel capacity of a low-rank MIMO channel. In [223] a number of analytical results are given under the assumptions that the TDM, i.e. the spatio-temporal array [224], fulfills a separability condition and that the phase noise process is white. However, experimental studies reported in [225] show that the phase noise cannot be assumed to be white or a random walk on the time-scale of a measurement period [226, 225]. In addition, the spatio-temporal array induced by the used switching schemes [224] determines the ordering of the phase noise samples in the estimation of the standard channel matrix estimate. Both effects significantly affect the performance of capacity estimation based on this matrix estimator [227]. In the contribution [228] phase noise mitigation is considered for estimation of channel parameter estimation.

Planned Work:

- AAU will evaluate the effect of the spatio-temporal aperture to the estimation of channel parameters. In a next step, AAU will optimize spatio-temporal apertures in channel sounding for parameter estimation. Concerning phase noise issues: simplified phase noise models are used to study its impact on standard parameter estimators and for developing mitigation techniques for parameter estimation. The effect of phase noise in multi-link channel measurements is studied.

- CNRS/(SATIE will work on methods to alleviate the calibration procedure. In the case of a limited number of nuisance parameters, it is proposed to recover the wavefront response from reduced calibration measurements. The minimal bounds derivedl enable a theoretical investigation of the optimum antenna design which includes element distance, beam pattern shape, aperture size etc. We are interested by the definition of new adaptive waveform.

- FTW/TUW will extend relative calibration methods. Estimators for the calibration parameters will be derived, and their performance and robustness (e.g. with beamforming techniques) will be evaluated.

5.4 Robust, Computationally Efficient, and Accurate Channel Parameter Estimators and Metrics

Recently, characterization and modeling of time-variant, multi-dimensional dispersive MIMO propagation channel have gained much attention. In [229], a state-space model is used to describe the dynamics of propagation paths in a time-variant environment. A particle filtering-based tracking algorithm is proposed to estimate the temporal behavior of path parameters. In [4, 5, 6], the multi-dimensional dispersion of the components in the channel impulse responses is characterized using parametric models. A SAGE algorithm is used for estimation of the model parameters. Preliminary experimental investigations show that the proposed characterization approaches together with the parameter estimators form efficient tools for characterization of the propagation channel.

Parametric characterization and estimation of time-variant, multi-dimensional propagation channel should be extended to include more dispersion dimensions, such as direction of arrival, direction of departure and polarizations. High-resolution algorithms with low-computational complexity should be used for estimation of the characteristic parameters. Theoretical bounds and suitable metrics are required for evaluation of the performance of the estimators. Measurement data will be used to assess the performance of the estimators.

We will investigate the performances of MUSIC and Maximum likelihood estimators in presence of modelling errors. This modelling error is due to a difference between the theoretical steering vector used in the DOA/DOD algorithms and the true one. This mismatch comes from receiver distortion (gain and phase), sensor positioning, mutual coupling, cable bending, bandwidth, near field sources, distributed sources, multipaths... We hope so to provide the quality of the calibration which is necessary to reach a given target performance.

As a benchmark for algorithms performances, CNRS/(SATIE proposes to use alternative lower bounds (other than the Cramer–Rao lower bound), which also take into account the side lobes (at the origin of a rapid degradation of performances at low SNR and/or small sample size). For that we will investigate the minimal bounds in a theoretical point of view. For this we focus on deterministic bounds as Barankin or Chapman Robbin Bounds and bayesian bounds as Ziv Zakai and Weiss and Weinstein bounds. Our work will concern principally the underlying theoretical hypothesis and the link between these bounds and the beam pattern array, in order to obtain tractable bounds. Indeed, for the moment, these bounds are not widely spread because of their computational coast. Such tight tractable bounds will allow antenna array design in more refined fashion than the Cramer Rao Bound.

Planned work:

- FTW/TUW will work on the design of estimators for the reciprocity parameters that can handle MIMO multi-user cases. The estimator should be able to handle optimally heterogeneous measurements (mobiles might report their calibration information with different periods, with different estimation error variances.

- CNRS/(SATIE will derive robust algorithms taking into account near field sources, modeling mismatch, multipaths, dispersive source. Further, CNRS/(SATIE will also work in the definition of self-calibration algorithms in order to be robust to some calibration errors.

- AAU will design appropriate characterization methods for time-variant multi-dimensional dispersive propagation channel and design computationally efficient estimations for the model parameters. Further, various theoretical bounds for the estimators are derived together with CNRS/(SATIE. Finally, proposals of matched metrics for the evaluation of the estimator performance are evaluted and the performance of the estimators is assessed using measurement data.

6 CONCLUSIONS

With the contents of Sections 2 to 5 the partners involved in WPR1 have defined an ambitious research programme of collaborative activities that address relevant aspects in channel characterization for advanced wireless systems and networks. With this roadmap in hand, the partners are strongly convinced that the planned investigations will lead to novel results that will durably and significantly impact on the scientific community in wireless communications.

Meanwhile, some of these activities have been launched and are under good progress. The first results of these investigations will be presented at the 2nd workshop of WPR1 scheduled on September 11-12 2008 at the premises of Eurecom.

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