WHERE2 Location Aided Communications

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Abstract—**This paper presents an overview of preliminary results of investigations within the WHERE2 Project [1] on identifying promising avenues for location aided enhancements to wireless communication systems. The wide ranging contributions are organized according to the following targeted systems: cellular networks, mobile ad hoc networks (MANETs) and cognitive radio. Location based approaches are found to alleviate significant signaling overhead in various forms of modern communication paradigms that are very information hungry in terms of channel state information at the transmitter(s). And this at a reasonable cost given the ubiquitous availability of location information in recent wireless standards or smart phones. Location tracking furthermore opens the new perspective of slow fading prediction.**

I. INTRODUCTION

The availability of location information offers opportunities to enhance the wireless communications. The position based information that can be exploited comprises slow fading channel characteristics of various links:

- LOS/NLOS ((Non) Line of Sight)
- attenuation
- delay spread, frequency selectivity
- angular spreads, MIMO channel characteristics (rank)
- speed, direction of movement, acceleration (predictibility of movement), trajectory

Some of these aspects may require the use of databases (containing these characteristics as a function of position), compatible with a cognitive radio setting. Compared to feedback (FB) based approaches: some of these characteristics can not easily be determined from isolated channel estimates, or not predicted at all (e.g. slow fading prediction). Further details on the topics addressed below can be found in the deliverables of Work Package 3 (WP3) of the WHERE2 project [1] and in the references mentioned below.

II. LOCATION AIDED CELLULAR COMMUNICATIONS

A. Location aided Multi-User Resource Allocation

Some possibilities are:

- *Multi-user MIMO/SDMA*: Use environment information to preselect users, to limit channel feedback to a reduced set of preselected users. The user preselection can e.g. involve: users with similar attenuation, users with rank 1 MIMO channels (close to Line-of-Sight (LOS)), ...
- *Multicell aspects* (interference coordination) or for *Cognitive Radio* (interference from secondary to primary systems): the interference level can be predicted from position information.

A transversal aspect is also that location tracking can lead to location prediction. This leads in turn to slow fading predictibility (and not just fast fading prediction, which can in principle be done also from past channel response estimates). Another aspect is that user selection (multi-user diversity) potentially leads to an explosion of Channel State Information at the Transmitter (CSIT) requirements and associated overhead. Location based covariance CSIT might offer a (partial) solution. Below, Tx may stand for transmit/transmitter/transmission and Rx for receive/receiver/reception.

B. Single-Cell Multi-User Communications

Consider the Spatial Division Multiple Access (SDMA) problem, which in Information Theory is called the Broadcast Channel (BC). The SDMA terminology dates from the early nineties. These days it is referred to as the multi-user (MU) MISO (or MIMO) communications problem, and we shall particularly focus on the more difficult downlink. Whereas single-user (SU) MIMO allows to multiply Tx rate by the spatial multiplexing factor when mobile terminals have multiple antennas, MU MIMO allows to reach this same gain with single antenna terminals. However, to achieve this, MU-MIMO requires very good CSIT! Some possible solutions are:

- Increase CSI FB enormously (possibly using analog transmission); LTE-A went recently a bit in this direction.
- Exploit channel reciprocity in TDD (there may be an electronics calibration issue though [2]).
- Limit MU-MIMO (SDMA) to Narrow AoD (Angle of Departure) Aperture (NADA) users and extract essential CSIT from position information (or from Direction of Arrival (DoA) estimates - in both cases the knowledge

of the antenna array manifold is (eventually) required, and location information (plus reduced rate FB) may be used to perform its calibration).

The idea of NADA is to focus on the category of mobiles for which the angular spread seen from the Base Station (BS) is limited [3]. This is a small generalization of the LOS case. In the NADA case, the MIMO channel matrix is of rank 2 (regardless of the DoA spread or of the number of paths in the narrow AoD spread), involving on the Tx side the BS antenna array response and its angular derivative. The LOS case is a limiting case in which the AoD spread becomes negligible and the channel rank becomes 1. The Tx side channel matrix factor depends straightforwardly on position (which translates into LOS AoD), only the Rx side factor remains random [4]. We propose that location based MU MIMO transmission involves position based user selection (attenuation, nominal AoD, AoD spread) and associated beamforming (BF) and power control (PC).

C. Multi-Cell Communications

Whereas single cell designs are applicable even in a multi-cell context for users in the interior of the cell, intercell interference needs to be considered for the cell edge users. In the *single antenna* case: the multi-cell aspect requires Tx power coordination, which can fairly easily be done location-aided (locations translate into distances and attenuations; databases could be used for further location dependent statistical characteristics (e.g. slow fading)).

Multi-antenna techniques: require downlink channel knowledge, in principle of all channels at all transmitters (cells). Several approaches are possible, of increasing complexity:

- *single-cell Tx, multi-cell Rx*: the BSs perform single-cell Tx; inter-cell interference gets handled by the terminal Rx antennas. The CSIT requirements remain local, per cell. In the LOS case, the Mobile Terminal (MT) needs to have a number of antennas at least equal to the number of cells (BS signals) to be handled (ZF). In the NADA case, the required number of antennas gets doubled.

- *multi-cell coordinated beamforming*: also called the MISO or MIMO Interference Channel (IC) in the case of one MT per cell. In the MISO case, the BSs need to zero-force (ZF) towards the users in other cells. In the MIMO case, this ZF can be shared between Txs and Rxs (interference alignment (IA)). The case of multiple MTs per cell, with interfering cells, is called the Interfering Broadcast Channel (IBC), or sometimes also simply the multi-cell problem. The IC/IBC models are applicable also when the interfering cells correspond to heterogeneous systems (e.g. macro-femto coexistence).

- *network MIMO*: also called Coordinated Multi-Point Tx (CoMP): requires not only global CSIT at all Txs (BSs) but furthermore distribution of all Tx signals over the BSs.

Whenever we mention ZF BF above, this refers to the high SNR case, and could be replaced by optimized BF at finite SNR. Also BF could be replaced by Dirty Paper Coding (DPC) or other more optimal Tx techniques.
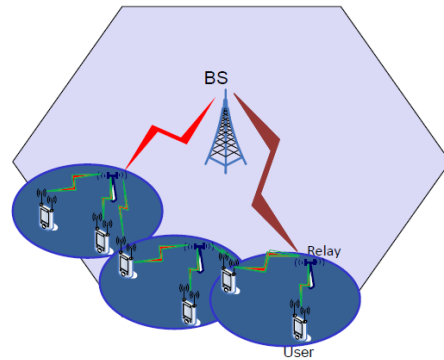

Fig. 1. User in a network with relays and base stations

The MIMO IC approach is perhaps the most interesting. However, its joint Tx/Rx design is plagued by numerous local optima. At high SNR, the optimum weighted sum rate (WSR) design becomes ZF (IA), with typically many possible solutions due to the nonlinearity of the ZF conditions. Nevertheless, the ZF problem simplifies enormously in the LOS case [4]. Indeed, the usually coupled roles of the Tx and Rx in overall ZF get now distributed over Txs and Rxs: the design of the Tx and Rx filters becomes decoupled, and their design only requires knowledge of the channels connected to them (in general the design of a Tx or Rx filter in the MIMO IC problem requires the knowledge of all channels appearing in the IC). Furthermore, the Tx filters can be designed knowing only the antenna array responses of the BSs and the location of the terminals.

III. CELLULAR: GEOLOCATION AIDED RELAY SELECTION

Optimal node selection algorithms for a network with cooperative relays has received a lot of attention in recent years. As such, there has been a lot of research work in relay selection mechanisms that can be divided in single relay selection and multiple relay selection. Single relay selection mechanisms have been investigated in [5] where the neighbor node with the maximum signal to interference and noise ratio (SINR) is selected as the most appropriate node, while in [6] the node that is closest to the base station is used as the best relay. The research is extended to multiple relay selection in [7] by exploiting the concepts of relay ordering and recursion. The above algorithms select the node according to one criterion which may not be an optimal solution for maximizing the performance of communication links. This report utilizes the geolocation of the user which is implicitly related to two criteria of quality of service (QoS) which are the received signal strength indicator ($RSSI_i$) of the ith cell that a relay node has and the link data rate R_i between the user's terminal and the selected relay node. The RSSI has a higher value when the user's terminal is closer to the node and decreases when the user gets away from it. The senario used in this section is represented in Fig. 1. From this figure it can be seen that as the distance of the user from the relay node and the base station varies, the rate and the RSSI change. The incorporation of relays in a network provides an attractive solution for
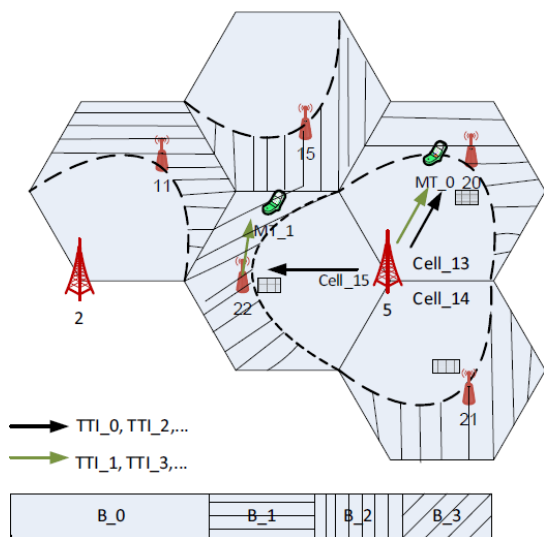
Fig. 2. The layout of a Type-II relay-aided LTE-A cellar network using Fractional Frequency Reuse (FFR).

Fig. 3. Experimental Cumulative Density Function of the total throughput of central MTs, in the scenario of 1) conventional Round-Robin Scheduling; and 2) proposed location-aided scheduling algorithm.

improving and enhancing the coverage of a network. This leads to an effort for finding the best route between the relays and base stations for minimizing the latency and maximizing the network throughput. It uses metrics for the path selection which are the ($RSSI_i$) and the link data rate R_i as mentioned above. A management database in MySQL is configured that stores the values of the user's geolocation, the RSSI and the data rate. It communicates with the user's terminal and when it calculates the optimal function based on the measured metrics, it gives instruction to the terminal to switch to the best node. This way the network can be improved in terms of minimizing the latency of the transmitted data and maximizing the data rate.

IV. CELLULAR: LOCATION AIDED SCHEDULING FOR LTE-A RELAYS WITH FRACTIONAL FREQUENCY REUSE

In order to achieve higher cell-edge throughput in an urban area, 3GPP has defined Type-II Relay Nodes (RN) [8], which share the same cell id and locate within the coverage of its donor eNodeB. Cell-edge Mobile Terminals (MTs) in such a network receive better connection from the RNs, but also suffer more interference not only from the surrounding BSs, but also from the closer RNs in other cells. One solution is to employ Fractional Frequency Reuse (FFR) [9], in which the entire bandwidth is divided into four portions as shown in Fig 2. The frequency band B_0 is reused in the central area of every cell, while the other frequency bands are applied at the RN covered cell-edge area with a reuse factor of 3.

One problem of employing FFR is that the available bandwidth at the central areas becomes only a fraction of the entire bandwidth, which may not satisfy the heavy traffic demand which may occur during busy hours. One solution is to select some central-MTs and some edge-MTs to temporarily share the same frequency band with minimum intra-cell interference. The selection could be implemented according to instantaneous channel knowledge, which requires all users to feedback channel state information of $B_0, ..., B_3$. Alternatively, the
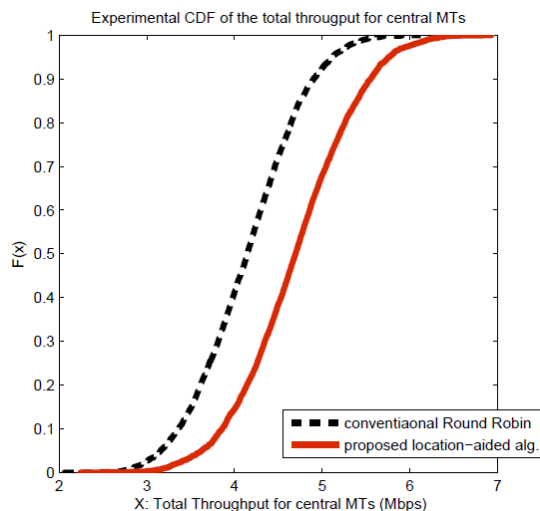
selection could exploit the location knowledge of each user and the long-term channel knowledge (e.g. pathloss) associated with locations. The latter scheme requires less amount and less frequent (if users are in low speed movement) feedback information compared to the former one. Hence, we propose a location-aided round robin scheduling algorithm [10] to allow central MTs to temporarily share part of the RN frequency band with cell-edge MTs with minimum intra-cell interference, so as to satisfy the traffic demand in the central area in busy hours. As demonstrated in Fig. 3, the proposed algorithm achieves higher total throughput than the conventional method.

V. CELLULAR: LOCATION AIDED COOPERATIVE RELAYING

Cooperative relaying has attracted much research interest, ranging from capacity theorems to practical relaying protocols [11]. Moreover, it has been deployed in wireless standards, e.g., in 3GPP Long Term Evolution (LTE-Advanced), wireless relays are deployed to enhance coverage of cellular services. Such mobile systems can be modeled as a single source, multi-relay, and single destination network when sources transmit information over an orthogonal medium. However, the orthogonality between source and relays require extra cost either in time or frequency, which reduces the spectral efficiency. To solve this problem, adaptive relaying protocols including incremental relaying (IR) and opportunistic relaying (OR) have been introduced. Meanwhile, it is considered here that every node involved has the location information of all communication nodes through an advanced positioning system. This motivates us to exploit location information to further improving the spectrum efficiency in such multiple relay networks, using IR or OR.

First, location-aided relay selection has been investigated for IR over asymmetric fading channels in [12]. Based on the analytical results derived there, a relay can be selected according to minimum outage probability, under constraints of

total transmit power and average SNR, assisted by location information. Here, the role of location information is to provide the mobile nodes (via a database) with the statistical channel knowledge of the communication links, which is important for the evaluation of the outage probability. Furthermore, a novel adaptive HARQ scheme has been proposed by exploiting the knowledge of channel quality information (CQI), which allows to determine the suitable transmission mode to guarantee a specific Frame Error Rate (FER) during the first transmission. The proposed HARQ scheme is suitable for machine-to-machine (M2M) type communications with low mobility, where location information can easily be translated into channel quality information [13].

In Opportunistic Relaying (OR) on the other hand, the goal is to choose the best relay node amongst all available relays through a certain policy. To improve the spectrum efficiency for OR with the Decode and Forward (DF) relaying protocol, a novel adaptive modulation scheme for opportunistic DF relaying is proposed in [14], which allows the source and relay to transmit information in different modulation formats. Then we investigated the adaptive protocol for OR with location information [15]. The proposed scheme is a two-step procedure. In a first step, a set of candidate relays are selected based on their geolocation; the second step then selects the best relay from the set of candidates. It has been shown that the proposed scheme can reduce signalling overhead by 97% with the spectral efficiency comparable to that of the conventional best-relay selection scheme.

VI. CELLULAR HETNETS: LOCATION AIDED SYNCHRONIZATION

Particularly at cell edge areas of a mobile communications system, signals are received from different base stations (BSs) with similar power levels. This causes interference even for synchronization since sync signals transmitted at different BSs are usually not perfectly orthogonal and received with different propagation delays. Knowledge about the mobile terminal (MT) position allows us to relate sync signals received from different BSs to each other regarding their propagation delays. With this relation, formerly interfering signal energy from adjacent BSs can be exploited for synchronization as well [16].

We consider 3 BSs (BS_p, $p = 1, \ldots, 3$) with an inter site distance of 1 km. These BSs synchronously transmit LTE secondary synchronization signals (SSSs) [17] with different IDs, denoted as $S_p[\ell]$ in frequency domain. At the MT, which is located at the cell edge central to the 3 BSs, we receive

$$R[\ell] = \sum_{p=1}^{3} \alpha_p\, S_p[\ell]\, \mathrm{e}^{-\mathrm{J}2\pi\,\ell\, f_{\mathrm{SC}}\, \tau_p} + N[\ell] \qquad (1)$$

in frequency domain, where $N[\ell]$ is additive white Gaussian noise with zero mean and variance $\mathrm{E}\left\{|N[\ell]|^2\right\} = \sigma^2$. The propagation delays τ_p depend on the distances between the MT and BSs. In LTE the subcarrier spacing is $f_{\mathrm{SC}} = 15\,\mathrm{kHz}$ [17]. The flat fading coefficients α_p contain path loss and shadow
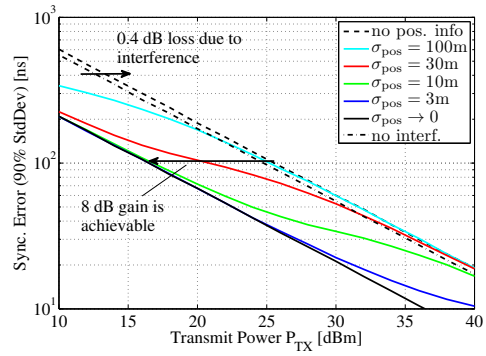

Fig. 4. CRLB for the synchronization error (standard deviation) vs. the base station transmit power P_{TX}. The MT is at the cell edge central to 3 BSs. Distance between BSs is 1 km. LTE SSS-IDs are 142, 411, 472.

fading according to the WINNER C2 typical urban macro cell channel model [18].

Based on the signal model in (1) we calculate the Cramér-Rao lower bound (CRLB) [16] for the variance of unbiased estimates of the signal propagation delays $\tau_1, \ldots, \tau_3$. In particular we are interested in the estimation performance of τ_1, corresponding to the serving BS. The flat fading coefficients α_p and consequently the CRLB are random. For this reason we use the 90%-variance as performance measure. The CRLB is lower or equal to that value with probability 0.9. Fig. 4 shows the square root of these variances vs. the transmit power P_{TX} at each BS. The estimation performance without exploiting position information (dashed graph) is our reference. Compared to the ideal case where no interference is present from BS_2 and BS_3 we obtain a degradation in terms of Tx power of about 0.4 dB.

Now let's assume that there is an estimate $[\hat{x}, \hat{y}] = [x, y] + [\epsilon_x, \epsilon_y]$, which is the true MT position plus an additive Gaussian error with zero mean and variance $\mathrm{E}\left\{\epsilon_x^2\right\} = \mathrm{E}\left\{\epsilon_y^2\right\} = \sigma_{\mathrm{pos}}^2/2$. With that knowledge about the MT position we can relate the different propagation delays to each other. As a result the Fisher information about the propagation delays τ_p increases and the CRLB improves as the positioning error σ_{pos} decreases [16]. The results show that up to 8 dB in Tx power can be gained with accurate knowledge ($\sigma_{\mathrm{pos}} \to 0$) about the position of the MT.

VII. CELLULAR HETNETS: LOCATION-BASED LONG-TERM POWER SETTING

In heterogeneous co-channel deployments of macro base stations (MBSs) and femto base stations (FBSs), inter-cell interference coordination (ICIC) appears as a proper way to secure the MBS traffic. Priority should be put on minimizing the interference created by FBSs on MBSs while maintaining a reasonably high FBS throughput inside the home. Besides, due to the high number of FBSs, ICIC minimizing the MBS-FBS exchanges is desirable. In the downlink, the impact of interference generated by a FBS on mobile terminals served by a MBS (MMTs) depends in particular on the power received by each MMT around the FBS from its serving MBS and surrounding base stations. Based on this received power in-
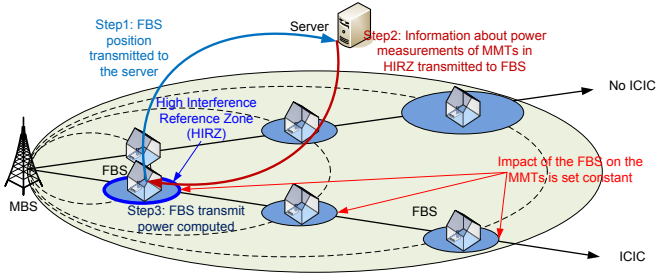
Fig. 5. ICIC providing macro-degradation equalization (single cell, no shadowing).
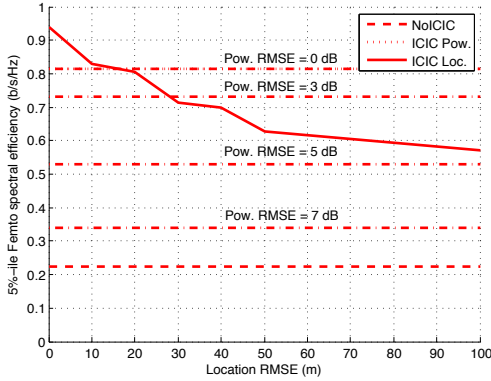

Fig. 6. Localization error effects: Femto performance for 10% cellular cell-edge decrease with 125 FBS/km2.

formation, location-based long-term power setting [19] ensures that the FBS impact on surrounding MMTs is independent of its location within the MBS coverage, as depicted in Fig.5. Using the MMT and FBS location information, together with an appropriate database, benefits the ICIC power adjustment, by providing precise information on received powers at MMTs surrounding a given FBS. The geo-referenced database is built thanks to MMT reports to their serving MBS, containing received power from neighboring MBSs and FBSs and the MMT location. Upon installation or reinitialization, a FBS transmits its location information to the server maintaining the database. This server can reply appropriate information about MMTs located around the FBS. This information allows more accurate power setting at FBS, compared to the non-location-based approach where the FBS sets its transmit power without any external knowledge, measuring received powers by itself and assuming that they properly approximate received powers at surrounding MMTs. Focusing on a reasonable 10% macro spectral efficiency loss compared to the case without FBSs, Fig.6 shows that even with location errors the location-based approach (ICIC Loc.) provides a gain against the non-location-based approach (ICIC Pow.), especially if the FBS power measurement is erroneous due to the decorrelation between indoor and outdoor shadowing.

VIII. MANETs: Relay Selection Policy Optimization for Two-Hop Relaying

In WLANs, it is well known that two-hop relaying can be used to improve throughput for poor links if a proper

intermediate node is used as a relay [20], [21]. In mobile networks, the mobility of nodes leads to outdated information about links' qualities and can therefore lead to suboptimal relay decisions where the chosen relay no longer delivers a sufficient QoS. If the locations of nodes and propagation characteristics are known, the QoS degradation in terms of large and medium scale path loss due to mobility and delayed information can be estimated and used to enhance the relay decision. For studying this idea, this work has considered the following simple scenario.

We consider downstream communication between a static access point (AP) and a destination node, where a set of K nodes in the vicinity can act as relay nodes. For simplicity, we consider the case with a static destination and a single mobile relay node, shown in Fig. 7. A location estimate for node R is periodically obtained using a localization system and transmitted to the AP, which is responsible for the relay decision. For a specific scenario, the AP uses a corresponding *relay policy* to map the location of the relay to a transmission mode (direct or relayed).
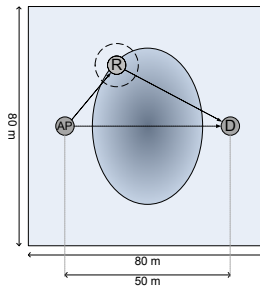

Fig. 7. System with static AP, mobile relay (R), and static destination (D). Position uncertainty is shown by the dashed circle around R.
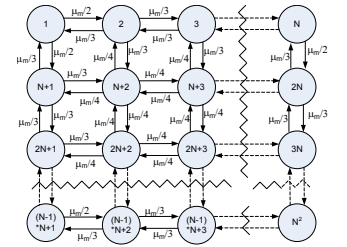
Fig. 8. Example Markov mobility model that is used in numerical results. $N \times N$ discrete grid-points represent the geographic space.

In order to investigate optimal relay policies when the location information is subject to the delays of the location update procedures, we have developed a Markov model consisting of two parts: 1) a continuous time Markov chain model for the spatial mobility of the mobile relay shown in Fig. 8; and 2) a model of location update procedures accounting for delays and losses (not shown here, but we refer to [22] for details). This model together with a novel optimization algorithm, enables policy optimization for a specific scenario, resulting in optimal relay policies that account for the risk of a suboptimal relay decision (due to outdated location information). An example of the possible improvement is shown in Fig. 9, where the avg. achieved throughput increases slightly when using the optimized relay policy.

IX. MANETs: Location Aided Attack Detection

Wireless ad hoc networks are particularly vulnerable to different threats. The so-called wormhole or relay attack is one of the most destructive. This attack is carried out by two malicious nodes that use a high-speed link (tunnel) to transparently forward data packets from one point to another (Fig. 10). Wormholes distort the network topology and disrupt
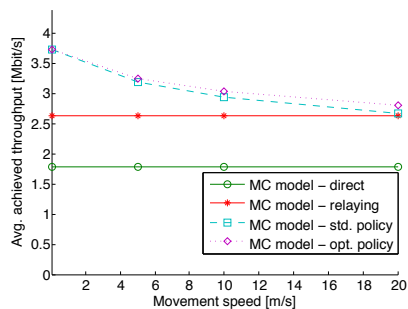
Fig. 9.   Achieved throughput for considered transmission schemes.

neighbor discover (ND) protocols, because they make distant nodes to appear as local for any node looking for its neighbors [23].
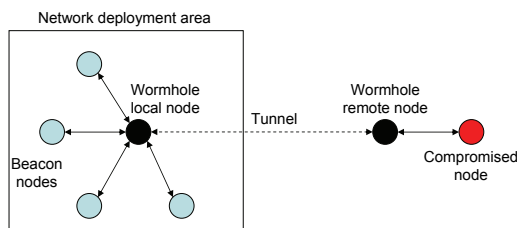

Fig. 10.   Wormhole attack.

If a set of trustworthy beacon nodes (BNs) located at reference positions are available, they can be used to effectively detect wormholes by using a two-step approach: a compromised node (CN) suspected to be the target of a wormhole attack could use the positions of the BNs along with distance related measurements, such as received signal strength (RSS), of the links between the BNs and the CN to localize itself and then report its estimated position back to the BNs; these reference nodes can, in turn, check whether the supposed position of the node is compatible with the RSS measurements of the reverse links from the CN to the BNs.

Both parametric and nonparametric localization techniques can be used for wormhole detection. Nonparametric approaches have a distinct advantage over parametric methods, because they do not require any previous calibration of the environment and are, therefore, insensitive to inaccuracies in the path-loss model parameters. To illustrate this fact, let us assume the attack model illustrated in Fig. 10, where two nodes set a wormhole to force a remote compromised node to appear as a neighbor of a set of local network nodes. As a parametric approach to secure ND, we have used a linearized weighted least-squares (WLS) approach to localize the node, followed by a likelihood ratio test (LRT) to verify the quality of the estimation, assuming a conventional log-distance path loss model for the RSS measurements. A nonparametric attack detection procedure is also implemented by using the scheme described in [24].

Some simulation results are presented in Fig. 11, where 20 BNs are deployed in a square room of 400 m^2. We can see that the parametric approach performs better than the nonparametric scheme for moderate shadowing losses, but quickly deteriorates if the channel model parameters are not
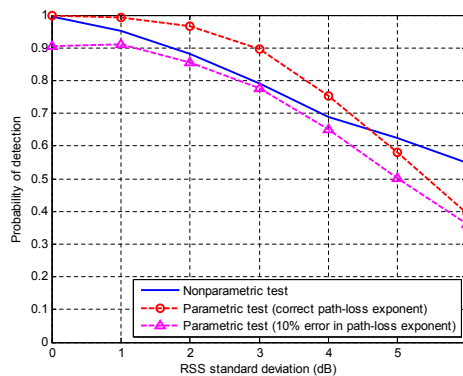

Fig. 11.   Performance of parametric and nonparametric wormhole detection schemes.

accurately estimated.

X. LOCATION AIDED COGNITIVE RADIO

A. Single Receive Antenna Case

Underlay Cognitive Radio (CR) is a popular CR design problem, in which a secondary network is allowed to operate in the presence of a primary system with interference limits at the primary Rxs, and this without any collaboration or even awareness of the primary system. To make underlay feasible, the exploitation of position information to determine attenuations constitutes probably the only realistic approach. In the MISO case, the location information could also be translated to Direction of Departure (DoD) based ZF BF. The cases of LOS and NADA need to be explored.

B. Multi-Antenna Cognitive Radio Paradigms

The extension of a number of standard cognitive radio paradigms to the multi-antenna case is not as straightforward and unambiguous as it may seem at first. In [25] we proposed some possible multi-antenna extensions for these paradigms.
Spatial Overlay: MISO/MIMO Interference Channel
In the overlay paradigm, primary and secondary collaborate. This collaboration could be interpreted at multiple levels, at the level of an exchange of Tx signals (as in network MIMO), or just at the level of CSIT, which in the single antenna case translates to coordinated power control. In the case of multiple antennas, if we limit cooperation to CSIT, this would lead to the exploitation of the multiple antennas for coordinated BF to achieve parallel interference-free channels. Coordinated BF applies to multiple antennas at the Tx side (MISO IC). In the case of multiple antennas at the Rxs, we can have coordinated Rxs. The case of the coordination of the multiple antennas on both sides corresponds to the (noisy) MIMO IC which was discussed earlier in the multi-cell setting. The recent Authorized Shared Access (ASA) proposal by Qualcomm and Nokia-Siemens Networks fits in the realm of overlay cognitive radio.
Spatial Underlay:
In the underlay paradigm, interference caused by a secondary Tx to a primary Rx is acceptable as long as the interference

remains under a maximum tolerance level. One possible definition of spatial underlay then would be that the primary Rx equipped with multiple antennas allows primary interference as long as it has enough antennas to handle it. Hence the primary Rx needs to be active. So, the primary Rx allows an interference subspace of maximum dimension equal to the excess of its number of antennas over the number of primary streams it needs to receive. The primary system is secondary-aware. Of course, the secondary Txs need to align the interference caused to primaries in subspaces of limited dimension.

Spatial Interweave:

In the interweave paradigm, the primary system should not be disturbed at all, and is not required to exhibit any cooperation with the secondary systems. So in a spatial interweave version, with multiple primary Rx antennas also, the secondary systems need to zero-force to all primary Rx antennas individually. In this case there is still room for secondary Tx if the secondary Txs have more antennas than the combined primary Rxs. The spatial interweave paradigm requires significant CSIT and can be reciprocity based in TDD, or location based in the case of LOS secondary-primary cross channels. In the LOS case, the number of primary Rx antennas becomes irrelevant (assuming they are in the far field from the secondary). In the case of NLOS, the secondary Tx needs to have more antennas than the number of propagation paths to all primary Rxs.

XI. COGNITIVE RADIO: LOCATION-AIDED CHANNEL ESTIMATION

Channel state information (CSI) is crucial for orthogonal frequency division multiplexing (OFDM) systems. Channel statistic information, e.g., *power delay profile* (PDP), can be exploited to enhance the estimation performance. Such PDPs can be obtained from positioning information. Alternatively, the PDPs could also be measured from past channel estimates. In cognitive radio systems, secondary users can only enter the primary network opportunistically. Since the latter method needs relatively longer time to converge, the location-aided approach is preferable in this regard.

In WHERE2, we developed a fast channel estimation algorithm based on the so-called dual diagonal LMMSE (DD-LMMSE) principle. This algorithm can achieve excellent performance with complexity of only $O(N \log N)$, where N is the number of sub-carriers. The details are reported in [26]. We also investigated the effect of PDP mismatch on the system performance in [27] based on the DD-LMMSE algorithm.

Let $\mathbf{p}$ be the true channel PDP and $\mathbf{p}_{ap}$ be the available *a priori* PDP. L and L_{ap} be the true and *a priori* maximum delay spread respectively. We focus on the PDPs in the following form,

$$\mathbf{p} = [\underbrace{1/L, 1/L, \ldots, 1/L}_{L}, 0, \ldots, 0]$$
$$\mathbf{p}_{ap} = [\underbrace{1/L_{ap}, 1/L_{ap}, \ldots, 1/L_{ap}}_{L_{ap}}, 0, \ldots, 0].$$

Define a discrepancy index γ as $\gamma = \frac{L_{ap}}{L}$. Clearly, γ can be used to measure the inaccuracy of $\mathbf{p}_{ap}$ relative to $\mathbf{p}$. When $\gamma = 1$, the *a priori* PDP is accurate. When $\gamma > 1$, the channel estimation algorithm developed in [26] will try to estimate more channel coefficients than necessary, which is prone to error due to channel noise. The related performance is demonstrated by the numerical results in Fig. 12. We can see from Fig. 12 that the performance degrades moderately as γ increases. When $\gamma < 1$, the channel estimation algorithm developed in [26] will try to estimate less channel coefficients than necessary. The signals transmitted on un-estimated paths become pure interference, which cause serious performance loss as sown in Fig. 12.
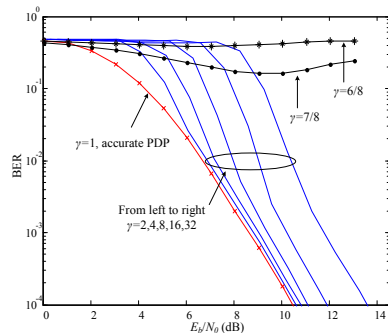

Fig. 12. BER Performances for an OFDM system with different γ. $N = 1024$, $L = 8$. Rate-1/2 $(23, 35)_8$ convolutional coding and Gray 16-QAM modulation are used.

From the results above, we observe that the *a priori* information should be used carefully. It is preferable to over-estimate the PDP length rather than to under-estimate it. This provides a useful guideline for the application of positioning information in communication systems.

XII. SPECTRUM SENSING TECHNIQUES FOR LOCATION-AIDED COGNITIVE RADIO NETWORKS

Spectrum sensing is one of the prominent techniques to enable cognitive users' opportunistic access into temporarily unused parts of the spectrum. Major challenging requirements preventing practical application of spectrum sensing are

- High sensitivity to very weak signals. For instance the signal-to-noise ratio (SNR) is required to be as small as -20 dB.
- Short observation time for measuring the spectrum. For instance the observation time is required to be as small as 1 or 2 OFDM symbols.

Spectrum sensing is an important technique that is complementary to geo-location database techniques for the opportunistic reuse of TV White Space or Authorised Shared Access (ASA). We have developed fast and high-sensitivity spectrum sensing schemes for detecting OFDM signals. The non-data-aided scheme proposed in [28], [29] offers 90% Probability of Detection and 10% Probability of False Alarm for a SNR as low as -21 dB and the observation time as short as 2 OFDM symbols. Moreover, the work presented in [30] turns out to be the best pilot-assisted spectrum sensing scheme, offering acceptable performance for a SNR as low as -10 dB.

The above results have been recently extended by considering new elements such as time/frequency diversity combining, timing and frequency synchronisation, and computational complexity. The comprehensive results can be found in [31], [32]. It has been shown that time/frequency diversity combining facilitates the non-data-aided scheme with additional 4 dB gain and the pilot-assisted scheme with additional 7 dB gain.

It is worth highlighting that the proposed non-data-aided scheme outperforms the state-of-the-art (i.e. the eigenvalue-based scheme) by 15 dB gain; and the proposed pilot-assisted scheme offers more than 5 dB gain compared to existing schemes. Such large gains come from the a-priori knowledge of OFDM waveforms including the length of cyclic prefix, number of subcarriers, pilot placement, etc. The knowledge of the OFDM waveforms can be obtained by employing location-assisted techniques with the following flowchart description:

1.	The CR obtains its position coordinates (x_0, y_0), by employing GNSS and other available positioning systems.
2.	Look up the geo-location database: ID of available access points within a range r of (x_0, y_0); what are the waveforms and relevant parameters employed by those access points?
3.	Employ the proposed spectrum sensing schemes based on the location-related waveform parameters.

Since wireless systems (such as Wi-Fi and cellular networks) normally have a large coverage (50 meter to 500 meter), the proposed spectrum sensing schemes are not demanding in terms of positioning accuracy as long as the positioning error is smaller than the coverage of the wireless systems.

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