On Prospects of Positioning in 5G

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***Abstract*—Technologies envisaged for a 5G communications system provide interesting prospects which are beneficial for cooperative positioning. Since 5G development is in the early stages, there is a unique opportunity to develop and integrate mobile radio based positioning technology in 5G from the beginning. In this paper we discuss 5G concepts to ensure seamless positioning by cooperative positioning. In cooperative positioning, mobile terminals (MTs) collaborate to help each other to determine their own position. We address key 5G prospects like smaller cells, higher MT densities and the capability of device-to-device (D2D) communication to enable cooperative positioning. By using the Cramér-Rao lower bound we investigate cooperative positioning performance for signal propagation delay based pseudo ranging in an exemplary typical urban environment. Numerical results for an exemplary environment have shown that with MT densities $D > 1100$ MTs per square kilometer sub-meter positioning accuracy with outage probabilities converging to zero can be achieved.**

I. Introduction

Position information has become a key feature in recent years to drive location and context aware services in mobile communications. Providing position information with sufficient accuracy, high availability and coverage is still a challenging task. Global satellite navigation systems like the US Global Positioning System (GPS) or the European satellite navigation system Galileo provide accurate position information in suitable environments [1] like outdoors with clear view to the sky, meaning that there are line-of-sight signal propagation conditions between mobile terminals and the satellites. However, in environments like urban or indoors such systems provide a poor performance due to weak signals, multipath or non-line-of-sight signal propagation. Mobile radio communications systems provide signal structures and capabilities for the determination of the mobile terminal position. Systems of the 3$^{\text{rd}}$ and 4$^{\text{th}}$ generation, like UMTS* and 3GPP-LTE†, provide signal bandwidths and power levels which are attractive for mobile terminal positioning, even in urban and indoor environments. Mobile radio positioning and its combination with complementary positioning methods like satellite navigation [2], [3] and inertial navigation is a promising approach for providing position information with high accuracy, availability and coverage.

Currently operating 2G, 3G and 4G cellular wireless communication standards specify a variety of mobile terminal (MT) positioning methods. These methods infer position information from received signals and include cell-ID, received signal strength (RSS) as well as time difference of arrival (TDOA) based methods. All these methods have in common that they use downlink signals. Propagation delay based methods like TDOA require signal reception from 3 base stations (BSs) in order to calculate a 2D MT position as shown in Fig. 1. In many environments the probability of receiving signals from 3 different BSs with sufficient quality has shown to be quite low. For increasing adjacent BS hearability the IPDL (Idle Period Downlink) has been implemented in the 3G standard UMTS [4]. LTE has addressed this problem since its Release 9 with the specification of positioning reference signals (PRS) [5]. However, multipath and non line-of-sight (NLoS) propagation are still present and potentially cause severe positioning performance degradations. Usually, the probability of receiving signals under LoS condition decreases with increasing distance between BS and MT [6]. Applying appropriate multipath estimation algorithms may combat positioning errors due to multipath propagation. A bias caused by NLoS propagation cannot be mitigated by such algorithms. For signals received under NLoS conditions these unknown bias terms have to be estimated in addition to the MT position, and therefore, increase the number of unknowns. However, if the unknown MT positions and NLoS biases at different time instances show sufficient correlation, the problem becomes solvable, e.g., by applying sequential Bayesian estimation algorithms [7], [8], [9]. Cooperative positioning [10] exploits a mesh network structure to estimate the position of sensors (similar to the proposed MTs with only one radio air interface in this paper). With the concept of cooperative positioning a MT additionally

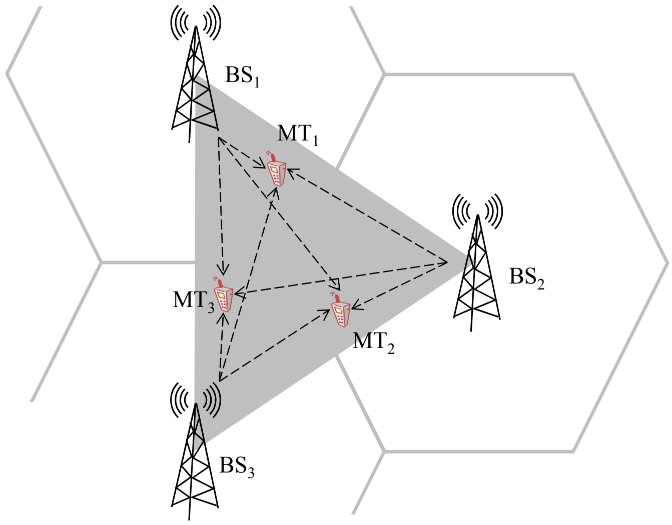

Fig. 1. Today's cellular mobile communication system, where MTs require signals from at least 3 different BSs in order to calculate their position in 2D. For positioning the MTs operate independent from each other without any cooperation.

*Universal Mobile Telecommunications System
†3$^{\text{rd}}$ Generation Partnership Project - Long Term Evolution

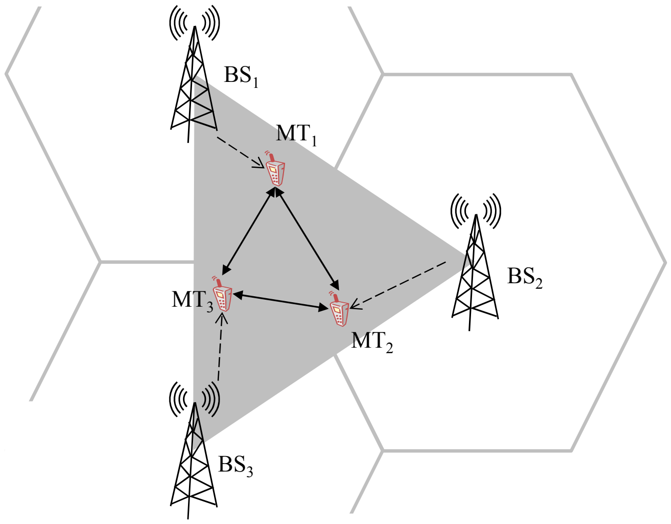

Fig. 2. 5G envisages D2D communications, where MTs may cooperate with each other for positioning. If the mesh of D2D links is sufficient, positioning works even if there are less than 3 BSs visible to individual MTs.

observes signals transmitted from other MTs in its neighborhood. If reasonably connected, cooperative positioning is possible even if there are less than 3 BS visible at each MT, which is intuitively shown in Fig. 2.

Theory about cooperative positioning is well understood. The authors of [11] provide a detailed analysis for cooperative positioning based on Fisher information and the corresponding Cramér-Rao lower bound. In [10] the authors describe cooperative positioning algorithms, providing significant performance gains compared to non-cooperative methods. These algorithms are capable of working decentralized with only little required overhead in communication. Investigations on location aware communications and mobile radio based cooperative positioning with focus on indoor environments have been addressed in the EU FP7 project WHERE2 [12]. A set of heterogeneous radio air interfaces with different capabilities, such as communication range, used bandwidth, and available connectivity, etc. promises a seamless positioning and tracking of MTs in cellular networks.

Cooperative positioning requires direct transmission and reception of signals among MTs. This direct signal exchange on the one hand enables the determination of distances in form of e.g. pseudo ranges between MTs. On the other hand relevant information for cooperative positioning algorithms can be directly shared among the MTs. So far, cellular mobile communication systems are based on communication links between MTs and their serving BS only. Especially when operating in frequency division duplex (FDD) mode, today's MTs are usually transmitting in the uplink and receiving in the downlink bands only due to RF front end constraints for instance. Therefore, MTs cannot directly observe their transmitted signals mutually. Note in time division duplex (TDD) transmission uplink and downlink share one frequency band and mutual signal observation is inherently possible. Recent developments in 3GPP-LTE include enhancements which are key enablers for cooperative positioning. With Release 12 so called Proximity Services (ProSe) are supported [13], [14]. In ProSe, MTs in close vicinity directly communicate with each other, and thus provide the prerequisites for cooperative positioning. Such device-to-device (D2D) communication requires discovery mechanisms. ProSe discovery can work directly at the MTs without network support. For network assisted discovery, MTs register their position in a central server or the network tracks the MTs [15], [16]. MTs in close vicinity are informed by a central network entity about ProSe capabilities. Thus, discovery mechanisms of ProSe can also benefit from information provided by cooperative positioning.

In this paper we discuss the prospects of cooperative positioning based on signal propagation delay estimation for a wireless communications system of the 5^{th} generation. We use the Cramér-Rao lower bound for cooperative positioning and assess cooperative positioning in a cellular mobile communications environment. For these investigations we use large scale signal propagation model developed within the WINNER II project [6]. Numerical evaluations provide lower bounds on the achievable positioning accuracy with respect to parameters like cell size, the user density, etc.

II. Positioning in 5G

Currently, the question how a communication system of the 5^{th} generation will look like is intensely discussed. Insights into research and development towards 5G can be found for example in [17], [18], [19], just to mention a few. The trend here is clearly that 5G won't be an incremental evolution of 4G, in particular LTE. By using new technology and paradigms as well as seamless integration of radio access technologies 5G aims to provide 10-100x higher user data rate, 1000x higher mobile data volume per area, 10-100x higher number of connected devices, 10x longer battery lifetime and 5x reduced end-to-end latency [19]. Besides requirements related to communications, mentioned above, the authors of [20] have addressed that in 5G network based positioning should be supported with accuracy of 10 m down to less than 1 m in 80 % of occasions and less than 1 m indoors.

So far, positioning has been an add-on feature to mobile phone standards. Having realized that mobile radio based positioning accuracy does not achieve appropriate accuracy, technology improvements have been included in later versions of standards. Examples for that are the IPDL in UMTS and the PRS in LTE, which we already have mentioned. Since 5G development is in the early stages, there is a unique opportunity to develop and integrate mobile radio based positioning technology in 5G from the beginning. With an initial integration of appropriate positioning technology the impact on communication can be minimized and synergies between communication and positioning can be exploited. Missing this opportunity, there is the risk that the integration cost will be higher, positioning coverage and accuracy will be limited, and the communication system will not be able to fully benefit from position information. Ultimately, potential economic gains from location-based-service will be drastically reduced.

Several technologies envisaged in 5G in order to meet the challenging requirements related to communications are beneficial for positioning as well:

a) Dense Networks: A denser grid of base stations reduces distances between MTs and BSs. With lower BS-MT distances the probability of line-of-sight (LoS) signal reception increases. This reduces the risk of positioning errors due to the NLoS bias. Further, the multipath components are less harmful and reduce the need for mitigation technologies to resolve the individual signal propagation delay.

b) Higher Frequencies and Signal Bandwidths: Higher signal bandwidths allow a better resolution of the wireless channel in time, and therefore, more accurate estimation of multipath components, in particular their signal propagation delays. This reduces positioning errors caused by multipath biases. Using higher carrier frequencies, in particular in the mm-wave spectrum, increases the probability of LoS reception conditions as any NLoS condition is likely to be blocked. This reduces the risk of positioning errors due to the NLoS bias. Further, higher frequencies together with massive MIMO schemes allow to track the individual terminals by the beam pattern of the antenna array more accurately. Therefore, LoS propagation conditions are more likely and ease the determination of the distance between MT and BS.

c) Device-to-Device Communications, High Number of Connected Devices: D2D communications extract advantages from the high density of connected devices. There are two benefits to improve the performance of positioning.

First the numerous additional links provide additional signal observations that can be exploited to determine pseudo ranges between MTs. With the implementation of D2D communication capabilities, MTs are inherently receiving signals from each other. Signal processing entities for D2D communications, in particular synchronization and channel estimation units, could be reused for signal propagation delay estimation. D2D communication provides a meshed network structure rather than the star shaped one for today's mobile cellular systems. Assuming a fully connected mesh as a best case the number of D2D links is $N_{\mathrm{MT}}\,(N_{\mathrm{MT}}-1)$, and therefore, grows quadratically with the number of mobile terminals, N_{MT}. As the number of unknown positions increases linearly with N_{MT}, D2D links provide significant redundancy in the number of observations to either neglect links which are under disadvantageous propagation conditions like low SNR, NLoS, severe multipath, bad geometry, etc., or even estimate additional unknowns like NLoS bias terms.

Second the additional D2D communication links between MTs could be used to directly exchange necessary data for cooperative positioning. The exchange of common physical layer estimates could be used to accelerate local decisions. Further, higher layer information could be exchanged such as position estimates (including the uncertainties of the estimate) between MTs or mobility information about the neighboring MT itself. Such information is relevant to improve the convergence time of estimation processes in the MT.

III. Environment

We consider a general cellular layout with MTs being located in an area between 3 closest BSs, as shown in Figs. 1 and 2.

A. Signal Model

At BS_b, located at a known position $(x_b^{\mathrm{BS}}, y_b^{\mathrm{BS}})$, we transmit a baseband signal $s_b^{\mathrm{BS}}(t)$. We assume a synchronized network of BSs. The received signal at MT_m transmitted from BS_b is

$$r_{b,m}^{\mathrm{BS}}(t) = \alpha_{b,m}^{\mathrm{BS}}\, s_b^{\mathrm{BS}}\left(t - \frac{1}{c_0}\left(c_0\,T_m + d_{b,m}^{\mathrm{BS}}\right)\right) + n_{b,m}^{\mathrm{BS}}(t), \quad (1)$$

where T_m is the time offset between the time bases of MT_m and the network. $n_{b,m}^{\mathrm{BS}}(t)$ is additive white Gaussian noise (AWGN). Large scale flat fading between BS_b and MT_m is taken into account with the scalar factor $\alpha_{b,m}^{\mathrm{BS}}$. The distance $d_{b,m}^{\mathrm{BS}} = \sqrt{(x_m - x_b^{\mathrm{BS}})^2 + (y_m - y_b^{\mathrm{BS}})^2}$ between BS_b and MT_m as well as the speed of light c_0 determine the signal propagation delay between BS and MT. The quantity

$$\tilde{d}_{b,m}^{\mathrm{BS}} = c_0\,T_m + d_{b,m}^{\mathrm{BS}} = c_0\,T_m + \sqrt{(x_m - x_b^{\mathrm{BS}})^2 + (y_m - y_b^{\mathrm{BS}})^2} \quad (2)$$

is called the pseudo range between BS_b and MT_m.

Similarly, we transmit a baseband signal $s_n^{\mathrm{MT}}(t+T_n)$ at MT_n, where we again take care of a time base offset T_n at the transmitting MT_n and get

$$r_{n,m}^{\mathrm{MT}}(t) = \alpha_{n,m}^{\mathrm{MT}}\, s_n^{\mathrm{MT}}\left(t - \frac{1}{c_0}\left(c_0\,(T_m - T_n) + d_{n,m}^{\mathrm{MT}}\right)\right) + n_{n,m}^{\mathrm{MT}}(t), \quad (3)$$

for the received signal at MT_m transmitted from MT n, where

$$\begin{aligned}\tilde{d}_{n,m}^{\mathrm{MT}} &= c_0\,(T_m - T_n) + d_{n,m}^{\mathrm{MT}} \\ &= c_0\,(T_m - T_n) + \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \quad (4)\end{aligned}$$

is the pseudo range between MT_m and MT_n. $\alpha_{n,m}^{\mathrm{MT}}$ accounts for large scale flat fading between these MTs. The transmitted reference signals from both BSs and MTs are assumed to be orthogonal. This can be achieved by using orthogonal resources in time and/or frequency direction within a communication frame.

TABLE I. Large scale channel model parameters for a typical urban macro cell (WINNER C2).

Propagation Condition	Applicability Range	A	B	C	$\sigma_{\mathrm{SF}b,m}$
LOS	$10\,\mathrm{m} < d_{b,m} < 48\,\mathrm{m}^2/\lambda_c$	26	39	20	4 dB
	$48\,\mathrm{m}^2/\lambda_c < d_{b,m} < 5\,\mathrm{km}$	40	12.4	6	6 dB
non-LOS	$50\,\mathrm{m} < d_{b,m} < 5\,\mathrm{km}$	35.7	42.6	23	8 dB

B. Signal Propagation Model

1) Propagation between Base Station and Mobile Terminal: For describing the signal propagation between a BS_b and a MT_m we use the typical urban macro cell channel model developed within the WINNER II project [6]. We focus on large scale flat fading parameters. The *path loss*

$$\mathrm{PL}_{b,m}\,[\mathrm{dB}] = A\,\log\left(d_{b,m}\,[\mathrm{m}]\right) + B + C\,\log\left(\frac{f_c\,[\mathrm{GHz}]}{5.0}\right), \quad (5)$$

is a deterministic figure. It depends on the distance $d_{b,m}$ between BS_b and MT_m as well as the carrier frequency f_c. *Shadow fading*

$$\mathrm{SF}_{b,m}\,[\mathrm{dB}] \sim \mathcal{N}\left(0, \sigma_{\mathrm{SF}_{b,m}}\right) \quad (6)$$

is a random process. It is drawn in dB from a normal distribution with zero mean and standard deviation $\sigma_{\mathrm{SF}_{b,m}}$.

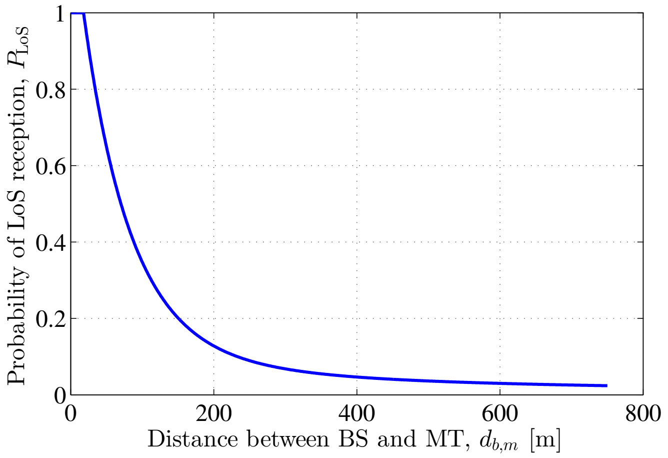

Fig. 3. Probability for LoS propagation between BS_b and the MT_m vs. their distance for the WINNER C2 Typical Urban Macro Cell channel model.

The corresponding channel model parameters are summarized in Tab. I. The model parameters have been calculated for the default heights of the BS ($h_{\mathrm{BS}} = 25\,\mathrm{m}$) and the MT ($h_{\mathrm{MT}} = 1.5\,\mathrm{m}$). There is a breakpoint distance, which separates two applicability ranges with different path loss parameters. This breakpoint distance is calculated from carrier wavelength $\lambda_{\mathrm{c}} = \frac{c_0}{f_{\mathrm{c}}}$ as shown in Tab. I. For simplicity we assume that shadow fading is mutually uncorrelated.

The model distinguishes between LoS and NLoS propagation conditions. The probability for LoS propagation between BS_b and the MT_m

$$P_{\mathrm{LOS}\,b,m} = \min\left\{\frac{18\,\mathrm{m}}{d_{b,m}}, 1\right\}\left(1 - \mathrm{e}^{-\frac{d_{b,m}}{63}}\right) + \mathrm{e}^{-\frac{d_{b,m}}{63}} \qquad (7)$$

is dependent on the distance $d_{b,m}$ between BS_b and MT_m. Fig. 3 shows that the probability of LoS reception quickly drops down to ≈ 0.13 within the first $200\,\mathrm{m}$. We relate the path loss and shadow fading to the flat fading coefficients $\alpha^{\mathrm{BS}}_{b,m}$ in Eq. (1) as

$$\alpha^{\mathrm{BS}}_{b,m} = 10^{-\frac{\mathrm{PL}_{b,m}+\mathrm{SF}_{b,m}}{20}}. \qquad (8)$$

2) Propagation between Mobile Terminals: For D2D links between MT_n and MT_m we assume free space path loss without shadow fading. In this case the path loss is [6]

$$\mathrm{PL}^{\mathrm{free}}_{n,m}\,[\mathrm{dB}] = 20\,\log\left(d_{n,m}\,[\mathrm{m}]\right) + 46.4 + 20\,\log\left(\frac{f_{\mathrm{c}}\,[\mathrm{GHz}]}{5.0}\right) \quad (9)$$

The flat fading coefficient in Eq. (3) then becomes

$$\alpha^{\mathrm{MT}}_{n,m} = 10^{-\frac{\mathrm{PL}^{\mathrm{free}}_{n,m}}{20}}. \qquad (10)$$

IV. Cramér-Rao Lower Bound for Cooperative Mobile Terminal Positioning

The Cramér-Rao lower bound is a well known and easy to handle method for lower bounding the variance of unbiased signal parameter estimates. Subsequently, we'll use this bound for performance assessment of cooperative positioning in a cellular mobile radio environment. The Cramér-Rao lower bound is obtained by inverting the Fisher information matrix (FIM).

A. Fisher Information

For AWGN signal models, the FIM components are [21]

$$\mathbf{F}_{u,v} = 2\,\mathrm{Re}\left[\frac{\partial\,\mathbf{s}^{\mathrm{H}}}{\partial p_u}\,\mathbf{C}^{-1}\,\frac{\partial\,\mathbf{s}}{\partial p_v}\right], \qquad (11)$$

in case the AWGN covariance $\mathbf{C}$ does not depend on the parameters we wish to estimate. The superscript $(\cdot)^{\mathrm{H}}$ denotes the Hermitian of a vector or matrix. We assume that signal observations according to the signal models in Eqs. (1) and (3) are available sampled at time instances $t = k\,T_{\mathrm{S}}$.

All these observed signal samples $r^{\mathrm{BS}}_{b,m}(k\,T_{\mathrm{S}})$ and $r^{\mathrm{MT}}_{n,m}(k\,T_{\mathrm{S}})$ are collected in a vector $\mathbf{r}$ and their corresponding means $\alpha^{\mathrm{BS}}_{b,m}\,s^{\mathrm{BS}}_b\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}^{\mathrm{BS}}_{b,m}}{c_0}\right)$ and $\alpha^{\mathrm{MT}}_{n,m}\,s^{\mathrm{MT}}_b\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}^{\mathrm{MT}}_{n,m}}{c_0}\right)$ in vector $\mathbf{s}$. Matrix $\mathbf{C}$ denotes the covariance of $\mathbf{r}$. In our AWGN case, this matrix is diagonal. The diagonal elements are the corresponding AWGN variances $\left(\sigma^{\mathrm{BS}}_{b,m}\right)^2 = \mathrm{E}\left\{\left|n^{\mathrm{BS}}_{b,m}(k\,T_{\mathrm{S}})\right|^2\right\}$ and $\left(\sigma^{\mathrm{MT}}_{n,m}\right)^2 = \mathrm{E}\left\{\left|n^{\mathrm{MT}}_{n,m}(k\,T_{\mathrm{S}})\right|^2\right\}$. Let us formally define a vector

$$\mathbf{p} = \left[p_1, \ldots, p_{3N_{\mathrm{MT}}}\right]^{\mathrm{T}} = \left[x_1, y_1, T_1, \ldots, x_{N_{\mathrm{MT}}}, y_{N_{\mathrm{MT}}}, T_{N_{\mathrm{MT}}}\right]^{\mathrm{T}} \quad (12)$$

which contains the parameters we wish to estimate, i.e., the unknown locations of the MTs (x_m, y_m) as well as their time base offsets T_m. In order to simplify the notation we do not further distinguish whether a signal is transmitted from a BS or a MT and skip the superscript for the moment. So, we generally state that a signal is transmitted from a transmitter ℓ, which can be a BS or a MT. However, when building the FIM, we are aware that positions of base stations as well as their time offsets are known. With these additional assumptions and properties Eq. (11) rewrites to

$$\mathbf{F}_{u,v} = 2\,\mathrm{Re}\Bigg[\sum_{\ell,m}\frac{\alpha^2_{\ell,m}}{\sigma^2_{\ell,m}} \times \times \sum_k \frac{\partial}{\partial p_u}\,s^*_\ell\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}_{\ell,m}}{c_0}\right)\frac{\partial}{\partial p_v}\,s_\ell\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}_{\ell,m}}{c_0}\right)\Bigg] \quad (13)$$

According to the signal models, the transmitted signals depend on the unknown parameters p_i solely through the corresponding pseudo ranges. With this property and by applying the chain rule we obtain

$$\frac{\partial\,s_\ell\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}_{\ell,m}}{c_0}\right)}{\partial p_u} = -\frac{1}{c_0}\,\dot{s}_\ell\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}_{\ell,m}}{c_0}\right)\frac{\partial}{\partial p_u}\tilde{d}_{\ell,m}, \qquad (14)$$

where $\dot{s}(t) = \frac{\partial}{\partial t}s(t)$. With the gradient operator $\nabla_{\mathbf{p}} = \left[\frac{\partial}{\partial p_1}, \ldots, \frac{\partial}{\partial p_{3N_{\mathrm{MT}}}}\right]$ we can express the FIM in compact form as

$$\mathbf{F} = \sum_{\ell,m}\nabla^{\mathrm{T}}_{\mathbf{p}}\,\tilde{d}_{\ell,m}\underbrace{\left(\frac{2\,\alpha^2_{\ell,m}}{\sigma^2_{\ell,m}\,c_0^2}\sum_k\left|\dot{s}_\ell\left(k\,T_{\mathrm{S}} - \frac{\tilde{d}_{\ell,m}}{c_0}\right)\right|^2\right)}_{=\tilde{\sigma}^{-2}_{\ell,m}}\nabla_{\mathbf{p}}\,\tilde{d}_{\ell,m} \quad (15)$$

or

$$\mathbf{F} = \mathbf{G}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{G} \qquad (16)$$

if we collect the gradient vectors for P pseudo range observations in a $P \times 3N_{\mathrm{MT}}$ matrix $\mathbf{G}$ and the corresponding P pseudo range variances $\tilde{\sigma}^2_{\ell,m}$ in a $P \times P$ diagonal matrix $\mathbf{\Sigma}$.

B. Pseudo Ranging

Using Parseval's Theorem we obtain

$$\tilde{\sigma}_{\ell,m}^{-2} = \frac{2\,\alpha_{\ell,m}^2}{c_0^2\,\sigma_{\ell,m}^2\,T_S} \int_{-\frac{1}{2T_S}}^{\frac{1}{2T_S}} 4\pi^2 f^2 \left|S_{\ell,m}(f)\right|^2 \mathrm{d}f = \frac{8\pi^2\,\alpha_{\ell,m}^2\,E_S}{c_0^2\,N_0}\,\beta_{\ell,m}^2 \tag{17}$$

$$\tilde{\sigma}_{\ell,m}^2 = \frac{c_0^2}{8\pi^2\,\beta_{\ell,m}^2\,\alpha_{\ell,m}^2\,\frac{E_S}{N_0}} \tag{18}$$

for the (inverse) pseudo range variance defined in Eq. (15). Eq. (18) can be interpreted as the Fisher information for pseudo range estimation [22]. Here, $S_{\ell,m}(f)$ is the Fourier transform of signal $s_{\ell,m}(t)$ with bandwidth $B = \frac{1}{T_S}$. The noise spectral power density $N_0 = \frac{\sigma_{\ell,m}^2}{B} = T_S\,\sigma_{\ell,m}^2 = k_B\,T$ is obtained from the Boltzmann constant $k_B = 1.381 \cdot 10^{-23}$ J/K and noise temperature $T = 300$ K. The term $\frac{\alpha_{\ell,m}^2 E_S}{N_0} = \frac{\alpha_{\ell,m}^2 P_{TX}}{\sigma_{\ell,m}^2}$ denotes the signal-to-noise (SNR) ratio at the receiver, where $P_{TX} = \frac{E_S}{T_S}$ is the transmit power. The quantity

$$\beta_{\ell,m}^2 = \frac{\int f^2 \left|S_{\ell,m}(f)\right|^2 \mathrm{d}f}{\int \left|S_{\ell,m}(f)\right|^2 \mathrm{d}f} \tag{19}$$

is called the (squared) equivalent bandwidth. For signals with uniform power spectrum density (PSD) and bandwidth B, the squared equivalent bandwidth is

$$\beta^2 = \frac{B^2}{12}. \tag{20}$$

$$\beta_{\ell,m}^2 = \frac{\int f^2 \left|S_{\ell,m}(f)\right|^2 \mathrm{d}f}{\int \left|S_{\ell,m}(f)\right|^2 \mathrm{d}f} \overset{\substack{\text{uniform}\\ \text{Spectrum}}}{=} \frac{B^2}{12} \tag{21}$$

C. Cramér-Rao Lower Bound Calculation

We obtain the Cramér-Rao lower bound matrix

$$\mathbf{J} = \mathbf{F}^{-1}. \tag{22}$$

as inverse of the $3N_{MT} \times 3N_{MT}$ Fisher information matrix. The lower bound for the variance of any unbiased estimate about the position of MT_m can be obtained from the corresponding diagonal elements of $\mathbf{J}$. Using the order of parameters, defined by parameter vector $\mathbf{p}$, we get the Cramér-Rao lower bound for MT_m, in form of the standard deviation as

$$\epsilon_m = \sqrt{\mathbf{J}_{(3m-2),(3m-2)} + \mathbf{J}_{(3m-1),(3m-1)}}, \quad m = 1, \ldots, N_{MT}. \tag{23}$$

V. Results

We consider an urban cellular mobile radio environment with 3 BSs and inter site distance of d_{BS} as outlined in Figs. 1 and 2. The BSs form an equilateral triangle with area $A_{env} = \frac{\sqrt{3}}{4} d_{BS}^2$. Within this area we uniformly distribute N_{MT} mobile terminals such that we obtain a mobile terminal density of

$$D = \frac{N_{MT}}{A_{env}} = \frac{4\,N_{MT}}{d_{BS}^2\,\sqrt{3}} \tag{24}$$

Tab. II summarizes the system parameters which we have used for our investigations. We apply the Cramér-Rao lower bound for cooperative positioning as described in Sec. IV.

TABLE II. System parameters.

Parameter		Value
Carrier frequency	f_c	5 GHz
Base station TX power	P_{BS}	30 dBm
Base station TX signal bandwidth	B_{BS}	5 MHz, uniform PSD
Mobile terminal TX power	P_{MT}	20 dBm
Mobile terminal TX signal bandwidth	B_{MT}	1 MHz, uniform PSD
Noise power spectral density	N_0	$N_0 = k_B\,T$
Boltzmann constant	k_B	$1.381 \cdot 10^{-23}$ J/K
Noise temperature	T	300 K
Propagation model BS-MT		WINNER C2 Typical Urban (large scale fading)
Propagation model D2D		free space, communication range is limited to r_{com}
D2D communication range	r_{com}	50 m
Base station distance	d_{BS}	100 … 400 m
Mobile terminal density	D	≈ 230 … 1850 km^{-2}

A. Non-Cooperative Positioning

Let's start with the evaluation of the minimum achievable MT positioning accuracy for non-cooperative positioning. It is obvious that for non-cooperative positioning the positioning performance does not depend on the MT density. Thus we uniformly distribute one MT in our area of interest between the BSs and calculate the Cramér-Rao lower bound according to Eq. (23). We evaluate the statistics in form of cumulative distribution functions (CDFs). For the generation of the CDFs we have used 10000 realizations for the MT position. Fig. 4 shows the results for different BS distances d_{BS}. The channel model we have used for the BS-MT links distinguishes between LoS and NLoS propagation conditions, as described in Sec. III. As a best case we assume that in case of NLoS propagation we do not suffer from an additional bias term (NLoS bias), i.e., we set the NLoS bias to zero. For a inter BS distance of $d_{BS} = 400$ m the positioning error is lower than 66.2 m in 95 % of the cases. This 95 % error drops to 4.3 m for $d_{BS} = 100$ m.

As we can see from Fig. 3 the probability of LoS propagation rapidly decreases with increasing distance between BS and MT. In a worst case we assume that we can detect NLoS propagation by appropriate methods [23]. So, we only use links which are in LoS for MT position calculation. In our case this means that if at least one of the links from the MT to the 3 BSs is in NLoS condition, we cannot calculate a position and the MT is in outage. Fig. 4 shows the corresponding results. Already for a BS distance of $d_{BS} = 100$ m, the MTs are in outage for 82.2 % of the cases. As the cell size increases, this outage probability rapidly increases to 98 % and 99.9 % respectively for the BS distances of 200 m and 400 m. In the case where we negelect NLoS links, the error performances diverge from the original graph, where NLoS bias is assumed to be zero, and quickly converge to the complementary outage probabilities $1 - P_{out}$. Note we do not have outage for our best case assumption with a zero NLoS bias.

B. Cooperative Positioning

Now, we consider cooperative positioning, where additional pseudo range observation from D2D links are available. As described in Sec. III, we assume free space signal propagation. We can expect an increasing probability of NLoS propagation

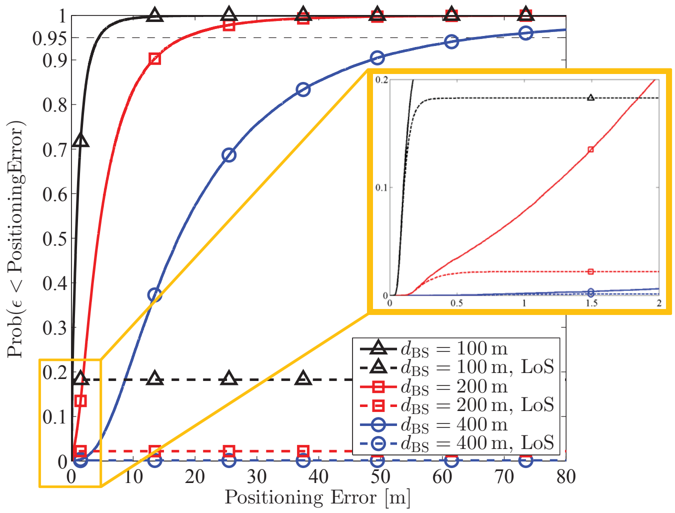

Fig. 4. CDF of the MT non-cooperative positioning error for different cell sizes. Results plotted in solid lines assume a zero NLoS bias. Results plotted in dashed lines consider only LoS reception of BS signals.

with increasing distance between MTs. Therefore, we limit the communication range to $r_{\text{com}} = 50$ m. Within this range we assume LoS propagation.

For an increasing number of MTs, we are interested in both the 95 % positioning error probability and the outage probability if we neglect NLoS links. Fig. 5 shows the error performance for zero NLoS bias (solid lines) and for those cases where we drop the NLoS links to BSs (dashed lines). The cell BS distance for this example is $d_{\text{BS}} = 400$ m. For low numbers of MTs N_{MT} we have a low probability that 2 MTs are in each other's communication range. With $A_{\text{env}} = \frac{\sqrt{3}}{4} d_{\text{BS}}^2$ as the area of interest between the 3 BSs we obtain in average

$$\bar{N} = N_{\text{MT}} \frac{A_{\text{com}}}{A_{\text{env}}} = N_{\text{MT}} \frac{4\pi}{\sqrt{3}} \left(\frac{r_{\text{com}}}{d_{\text{BS}}} \right)^2 \tag{25}$$

MTs in the communication range area $A_{\text{com}} = \pi r_{\text{com}}^2$. This quantity calculates to approximately $\bar{N} \approx 0.9 \ldots 10.9$ for the parameters shown with Fig. 5. Within this range, D2D connectivity starts and increases. With an increasing number of MTs the outage probability converges to zero. The error performance (the CDFs) for our best case and worst case assumptions inherently converge. This convergence shows that with cooperative positioning we can neglect links which are in bad propagation conditions, such as NLoS. With $N_{\text{MT}} = 96$ MTs in our example above, the outage probability is ≈ 1 % with 95 % positioning error values of 0.4 m and 0.5 m for our best and worst case assumptions.

Figs. 6 and 7 summarize the outage probabilities and 95 % positioning error performances (best case). In contrast to our example above, we have plotted the graph versus the MT density D, as defined in Eq. (24). For all the considered cell sizes, the outage probability falls below 5 % for a MT density $D > 1100\,\text{MTs/km}^2$ (MTs per square kilometer)[‡]. Above that MT density, the 95 % positioning error performance reaches sub-meter accuracy. Due to convergence, the 95 % positioning

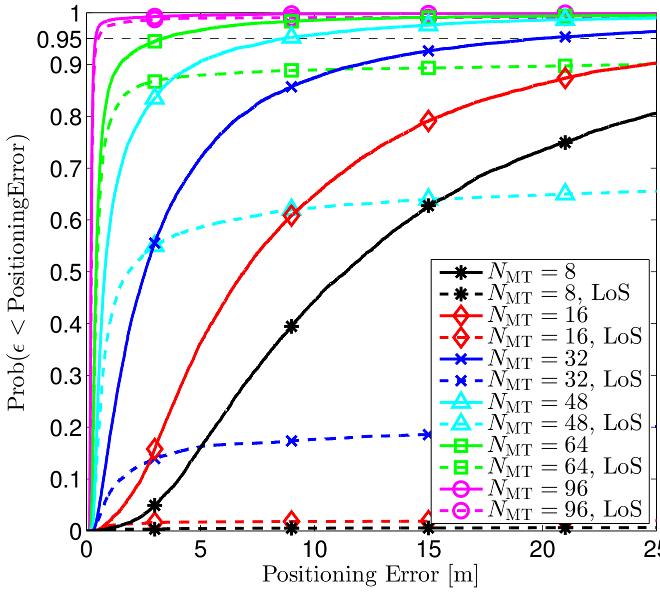

Fig. 5. CDF of the MT cooperative positioning error for $d_{\text{BS}} = 400$ m and a different number of mobile terminals N_{MT}. Results plotted in solid lines assume a zero NLoS bias. Results plotted in dashed lines consider only LoS reception of BS signals.

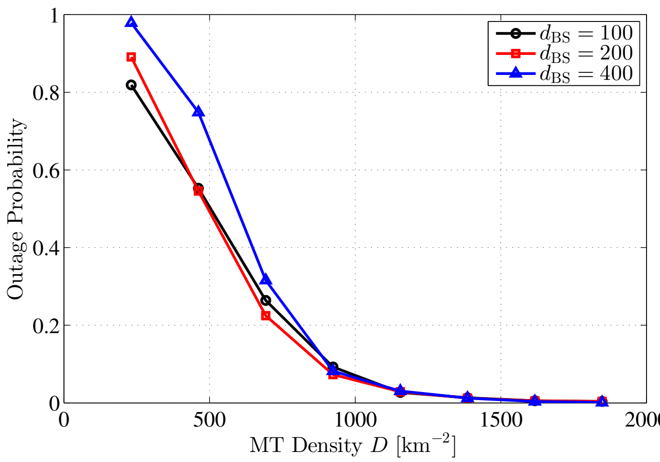

Fig. 6. Outage probability P_{out} versus the MT density for different BS distances d_{BS}.

error performance for the worst case is expected to converge to that order of magnitude as well.

VI. Conclusions

In this paper we have discussed technologies envisaged for a 5G communications system which are beneficial for the implementation of cooperative positioning in a 5G standard from the beginning. Targeting for higher carrier frequencies, higher signal bandwidths, denser networks, MIMO technologies, etc., will significantly increase the pseudo range estimation accuracy for signal propagation delay based positioning methods like TDOA. With D2D communication, MTs are capable of receiving and exploiting signals transmitted from other MTs in the neighborhood for cooperative positioning. With this principle we can estimate distances in form of ranges or pseudo ranges between MTs, which comes on top to (pseudo)

[‡]For comparison note that the mean density of players on a soccer field is approximately 3000 players/km^2.

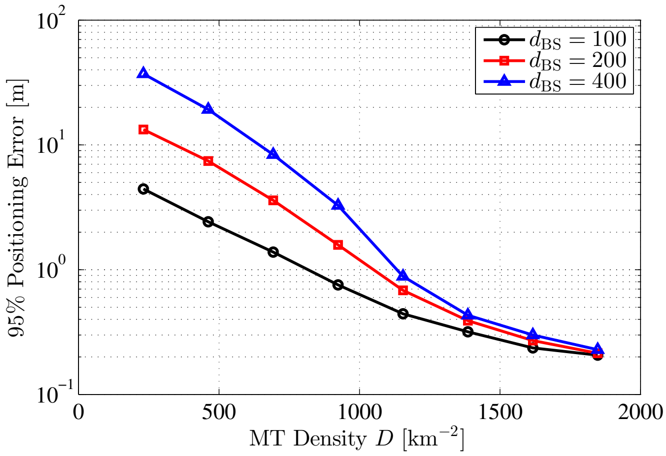

Fig. 7. 95 % positioning error versus the MT density for different BS distances d_{BS}.

ranging between MTs and BSs as it is used in today's mobile communications systems. By this we can achieve a seamless position estimation with a sufficiently accurate performance even in deep indoor areas that are not covered by state-of-the-art positioning/navigation systems today. Cooperative positioning algorithms can work centralized in the network or even decentralized and distributed among the MTs. In any case cooperative positioning requires the exchange of data between MTs and the network or between the MTs in 5G. This can be achieved by an appropriate position information exchange protocol.

By using the Cramér-Rao lower bound we have investigated cooperative positioning performance for signal propagation delay based pseudo ranging in an exemplary typical urban environment. We have discussed the prospects of 5G with respect to smaller cells, higher MT densities and the capability of D2D communication. Sufficient MT density provides enough connectivity among the MTs so that we can neglect links which are in bad propagation conditions for pseudo range estimation. An inappropriate treatment of such links yields bias terms, often in the order of tens of meters [7], which directly affect position estimation accuracy. Numerical results for our exemplary environment have shown that with MT densities $D > 1100\,\mathrm{MTs/km^2}$ sub-meter positioning accuracy with outage probabilities converging to zero can be achieved.

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