High-Efficiency Device Positioning and Location-Aware Communications in Dense 5G Networks

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***Abstract*—In this article, the prospects and enabling technologies for high-efficiency device positioning and location-aware communications in emerging 5G networks are reviewed. We will first describe some key technical enablers and demonstrate by means of realistic ray-tracing and map based evaluations that positioning accuracies below one meter can be achieved by properly fusing direction and delay related measurements on the network side, even when tracking moving devices. We will then discuss the possibilities and opportunities that such high-efficiency positioning capabilities can offer, not only for location-based services in general, but also for the radio access network itself. In particular, we will demonstrate that geometric location-based beamforming schemes become technically feasible, which can offer substantially reduced reference symbol overhead compared to classical full channel state information (CSI)-based beamforming. At the same time, substantial power savings can be realized in future wideband 5G networks where acquiring full CSI calls for wideband reference signals while location estimation and tracking can, in turn, be accomplished with narrowband pilots.**

***Index Terms*—5G networks, 2D/3D positioning, beamforming, location-aware communications, mobility management, tracking**

I. INTRODUCTION

FUTURE 5G networks are expected to provide huge improvements in the capacity, number of connected devices, energy efficiency, and latencies when compared to the existing communications systems [1], [2]. These features will be enabled by the combination of higher bandwidths, advanced antenna technologies, and flexible radio access solutions, among others. Especially in urban environments, 5G networks are also expected to consist of densely distributed access nodes (ANs) [2] located, e.g., in lamp posts above the streets as illustrated in Fig. 1a. Consequently, a single user equipment (UE) in such dense networks is within coverage range to multiple closely located ANs at a time. Such short UE-AN distances provide obvious benefits for communications, e.g., due to lower propagation losses and shorter propagation times, but interestingly can also enable highly accurate UE positioning. Altogether, 5G networks allow for many opportunities regarding acquisition and exploitation of UE location information in unforeseen manners [3], [4]. This is the leading theme of this article.

One of the improvements in 5G networks concerns the positioning accuracy. It is stated, e.g., in [5]–[7], and [8][1], that 5G should provide a positioning accuracy in the order of one meter or even below. That is significantly better than the accuracy of a couple of tens of meters provided in long term evolution (LTE) systems by observed time difference of arrival (OTDoA)-based techniques. The required positioning accuracy in 5G networks will outperform also commercial global navigation satellite systems (GNSSs) where the accuracy is around $5\,\mathrm{m}$, and wireless local area network (WLAN) fingerprinting resulting in a $3\,\mathrm{m}$–$4\,\mathrm{m}$ accuracy. Another improvement that 5G networks may provide concerns the energy efficiency of positioning. This stems from the common assumption that 5G networks will exploit frequently transmitted uplink (UL) pilot signals for channel estimation purposes at the ANs. These signals can be used also for positioning in a network-centric manner where the UE location is estimated either independently in the ANs or in a centralized fusion center, assuming known AN locations, and thus no calculations are needed in the mobile UEs. Note that this is a considerable difference to the device-centric positioning, e.g., GNSS, where the mobile UEs are under heavy computational burden. Therefore, network-centric positioning techniques provide significant power consumption improvements and enable ubiquitous high-accuracy positioning that can run in the background continuously. Such a functionality decreases also the signaling overhead when the location information is to be used on the network side, but on the other hand, requires additional care for privacy as the positioning is not carried out at the UEs themselves. As a third improvement in 5G-based positioning, regardless whether it is network- or device-centric, location information can be obtained in complete independence of UE-satellite connections everywhere under the network coverage area, including also challenging indoor environments.

The aim of this article is to discuss the technical enablers

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[1]See also 3GPP technical report 22.862, v.14.1.0.

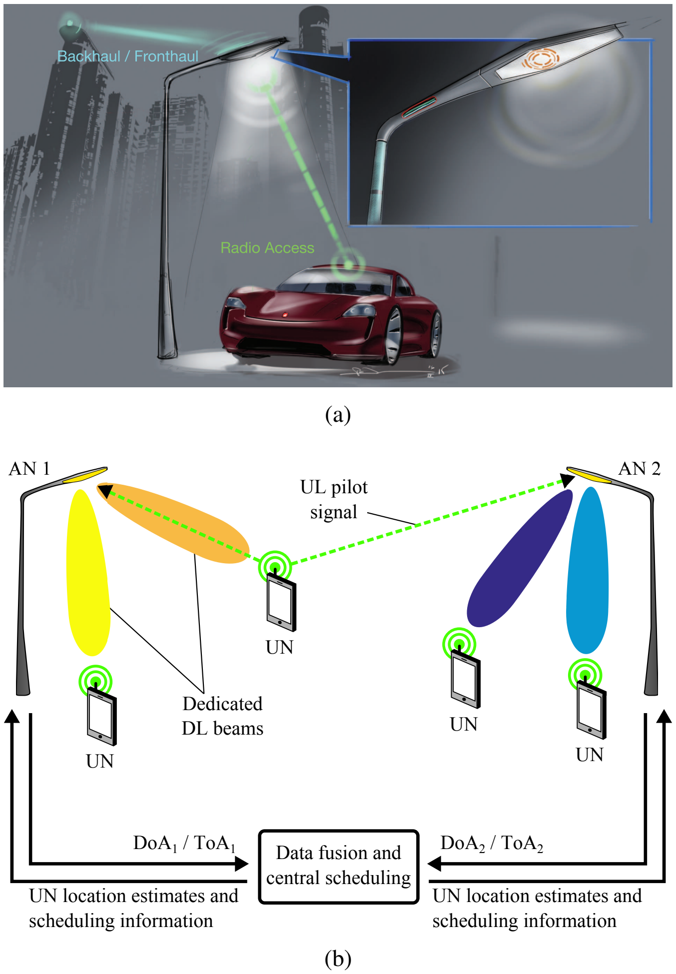

Fig. 1: Illustration of a 5G network where (a) AN, deployed in a lamp post, provides a LoS connection to a nearby UE and (b) ANs estimate DoAs/ToAs of the UEs based on UL pilot signals. The obtained estimates are then communicated to a fusion center providing the final location estimate which, in turn, enables geometric DL beamforming.

of envisioned device positioning in 5G networks, and to promote the prospects of the obtained location-awareness. In this regard, focus is given to location-based communication and network management techniques such as location-based beamforming as well as mobility and radio resource management (RRM) [9][2]. We recognize that UE location information can be exploited by the UE itself as well as shared with third parties, thus allowing for innovative location-based applications to emerge. Particularly, we will focus on the connected car application, being identified, e.g., in [5] as one key application and target for future 5G mobile communication networks, with a minimum of 2000 connected vehicles per km^2 and at least $50\,\mathrm{Mbps}$ in downlink (DL) throughput. Now, facilitating such greatly enhanced connected vehicle applications, having a 5G network with built-in capability to localize and track vehicles is a very tempting prospect. Furthermore, location information is a central element towards self-driving cars, intelligent traffic systems (ITSs), drones as well as other kinds of autonomous vehicles and robots which are envisioned to be part of not only the future factories, but the overall future society within the next $5-10$ years.

[2]See also the WHERE and WHERE2 projects at http://www.ict-where.eu/ and http://www.ict-where2.eu/

II. 5G Networks and Positioning Prospects

A. *Technical Properties of 5G Radio Networks*

Generally, it is expected that network densification will play an important role in achieving demanding requirements of 5G networks. The inter-site distance of ANs in such ultra-dense networks (UDNs) is envisioned to range from a few meters up to a few tens of meters, e.g., assuming several ANs per room indoors and an AN on each lamp post outdoors [1]. Moreover, these 5G ANs are expected to be equipped with smart antenna solutions, such as antenna arrays supporting multiple-input multiple-output (MIMO) techniques [6]. Such antenna technologies are suitable for effective communications as well as accurate direction of arrival (DoA) estimation, which in turn allows for high-accuracy positioning. Furthermore, it is argued that devices tend to be in line of sight (LoS) condition with one or multiple ANs due to network densification, which is a favorable condition not only for communications but also for positioning purposes.

It is commonly agreed that 5G technologies will require wide bandwidths in order to meet the envisioned capacity requirements. Therefore, 5G networks will most likely operate at higher frequency bands, including millimeter waves (mmWaves), where the availability of unallocated spectrum is considerably higher. Such high frequency bands together with UDNs can provide very high overall system capacity and enable an efficient frequency reuse [6]. However, with the envisioned high frequencies, the propagation conditions become more demanding due to, e.g., larger propagation losses. Hence, the effective range between transmitting and receiving elements is relatively short which also emphasizes the importance of expected UDNs. Furthermore, the utilization of effective antenna solutions become more practical as a result of shorter wavelengths, and consequently due to smaller physical size of antenna elements. In addition to the potential frequency bands above $6\,\mathrm{GHz}$, also frequencies below $6\,\mathrm{GHz}$ are expected to be used in 5G networks [5]. Apart from a communication perspective, the envisioned wide bandwidths enable also very accurate time of arrival (ToA) estimates which in turn provide an opportunity for positioning with remarkably high accuracy [3].

In contrast to the earlier cell-centric architectures, it is currently under discussion whether 5G networks will be developed in a more device-centric manner. Moreover, it is envisioned that 5G networks could also provide improved quality of experience (QoE) at cell borders with only a minimal system-performance degradation compared to earlier systems [10]. This development enables tailoring of a particular communication session and the functions of the associated ANs to a connected device or service instead of obtaining services from the AN commanding the specific cell. In such device-centric architecture, a given device can periodically send UL signals to connected ANs in which UL reference signals are used for channel estimation, but they can also be employed for network-centric positioning as illustrated in Fig. 1b. Furthermore, future 5G networks are expected to operate with relatively short radio frames resulting in availability of frequent location information about a transmitting device.

B. Leveraging Location-Awareness in 5G Networks

Continuous positioning provides awareness not only of the current but also of the past UE locations and thus the network is able to carry out UE tracking. When the UE location and movement information is processed by predictive algorithms, the network can even predict the UE locations to some extent. Availability of such location information in turn enables a wide selection of entirely new features and services in 5G networks. First, location-awareness can be used for communications purposes by enhancing the utilization of spatial dimension, e.g., by geometric beamforming [11] and sophisticated spatial interference mitigation. These features allow for multiplexing a high density of UEs and provide significant throughput improvements for high-mobility UEs, as illustrated in Section IV. Second, a combination of location information and measured radio parameters over a long time period enables the construction of radio environment maps (REMs), depicted in Fig. 2a, which, in turn, can open many opportunities in terms of proactive RRM [9]. Particularly, knowledge of large-scale fading and location-based radio conditions can be utilized for *RRM purposes* without the need of knowing the instantaneous channel information between the AN and UE. Therefore, the network is able to carry out proactive allocation of active UEs to nearby ANs such that, e.g., power consumption, load balancing and latencies are optimized as depicted in Fig. 2b. Location-awareness can improve network functionalities also by enabling proactive location-based backhaul routing such that the UE-specific data can be communicated with a high robustness and low end-to-end latency.

The obtained location-awareness can be exploited also in the UEs as well as by third parties for providing other than purely communications type of services. Taking traffic and cars as an example, up-to-date location information and predicted UE trajectories can provide remarkable improvements, e.g., in terms of traffic flow, safety and energy efficiency. When comprehensively gathered car location information is shared with ITSs, functionalities such as traffic monitoring and control can be enhanced. Accurate location information is needed also in the cars themselves, e.g., for navigation purposes, especially when considering autonomous and self-driving cars. Location-awareness is required also for collision avoidance. Within communications range cars can report their location directly to other cars, but when the link between the cars is blocked, location notifications are transmitted in collaboration with ITSs as illustrated in Fig. 2c. Naturally, the demands and functionalities regarding self-driving cars cannot be met everywhere and at all times by existing communications systems and satellite-based positioning. Consequently, advanced communications capabilities and network-based positioning in 5G is likely to play an important role in the development of self-driving car systems.

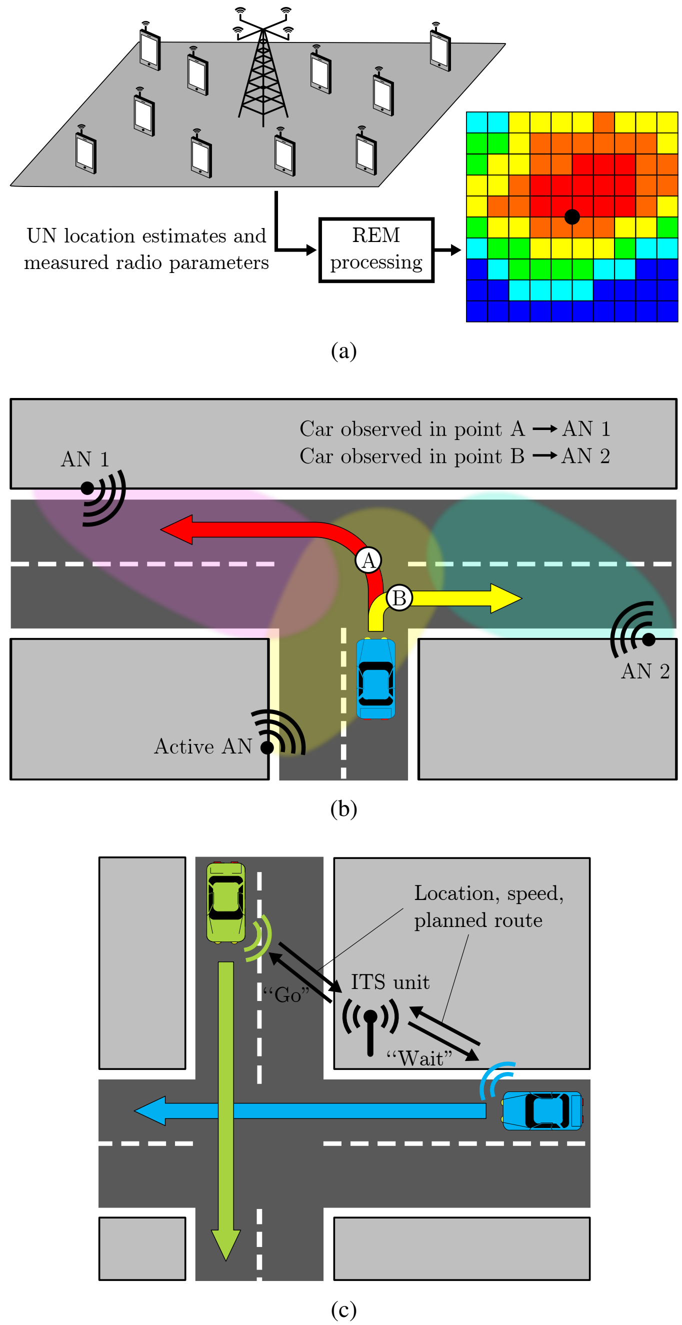

Fig. 2: Illustrations of selected positioning prospects in 5G a) REM generation, b) proactive RRM for a car whose location is being tracked, and c) ITS-based traffic control and collision avoidance with self-driving cars.

III. Enabling Technologies for High-Efficiency Network-centric Positioning

A. State-of-the-Art

Dense networks are characterized by radio channels that are dominated by the LoS-path. For example, the typical Rice-factor, being a power ratio between the LoS component and all other propagation paths, in urban micro-cell environments is around 10 dB, even in sub-6 GHz [12]. Additionally, network densification increases the LoS probability between UEs and ANs. As an example, 3GPP employs a channel model based on extensive measurements in which the LoS probability is higher than 0.7 for a maximum UE-AN distance of $35\,\mathrm{m}$.

Determining the ANs that are in LoS condition to a given UE is important since it allows estimating and tracking the directional parameters of the LoS-path, in addition to the time-of-flight and clock-offsets, thus greatly improving the UE positioning accuracy. Particularly, the LoS condition of a radio link may be assessed by estimating the corresponding Rice-factor. A multichannel observation is obtained for each UL reference signal given that a multicarrier waveform and multiantenna ANs are employed. Sequential estimation of the Rice-factor can be accomplished, e.g., with a particle filter due to the non-Gaussian nature of the amplitude distribution of the UL multicarrier channel. Finally, LoS detection can be accomplished using a likelihood-ratio test, or a model selection technique. In case all ANs are in non line of sight (NLoS) to the UE, coarse network-centric positioning can still be achieved using radio frequency fingerprinting, received signal strength indicator and cell-identifier, among others [9].

Multicarrier waveforms offer a versatile approach for estimating ranges between a given UE and multiple ANs [9]. Relying solely on UL reference signals makes it possible to synchronize the ANs as well as the UE, in addition to estimating the ToAs of the LoS-paths [3], [4]. The actual sequential estimation of the ToAs and clock-offsets can be accomplished with different Bayesian filters either in a cascaded or fully centralized manner depending on the network architecture, baseband processing capabilities of the ANs, and backhaul capacity. Note that the UL reference signals can also provide additional information for UE positioning when utilized, e.g., for tracking Doppler-shifts.

ANs with multiantenna transceivers allow for estimating the DoA of the LoS-path from UL reference signals, and such an information can be used for UE positioning. Planar or conformal arrays, such as circular or cylindrical antenna arrays, make it possible for estimating elevation and azimuth arrival angles, and enable 3D positioning. Bayesian filtering techniques can also be employed for tracking the DoAs of the LoS-paths from mobile UEs as well as fusing the ToAs and DoAs in order to allow for joint UE positioning and network synchronization [3], [4]. ANs with analog beamforming structures and sectorized antennas can also be exploited for UE positioning and tracking [13].

Due to the non-linear nature of the involved state-space models, estimation and tracking can be carried out with different non-linear Bayesian filtering techniques. In this article, the tracking processes are carried out using the extended Kalman filter (EKF) due to its highly accurate estimation performance and low computational complexity compared to, e.g., particle filters and the unscented Kalman filter (UKF). In general, within the EKF, the state of a system is first propagated through a linearized state evolution model and this prediction is, thereafter, updated using the obtained measurements and a linearized measurement model, through which the state is associated with the measurements [4].

Finally, the techniques overviewed in this section for UE positioning can also be employed for estimating the locations of the ANs. For example, a few well-surveyed ANs can be used for finding the locations of neighboring ANs, which in turn may be used as new anchors. Such a procedure is useful since surveying all ANs would increase the deployment cost of UDNs significantly. Alternatively, joint UE tracking and ANs positioning can be achieved using techniques stemming from simultaneous localization and mapping (SLAM) [14]. These techniques are versatile but the cost is an increase in computational complexity due to the large number of parameters to be estimated.

B. Tracking of Directional Parameters using EKFs

We start by demonstrating the performance of EKFs in tracking the directional parameters of the LoS-path. We consider the case where both the ANs and UEs are equipped with multiantenna transceivers. Two schemes are considered, namely a network-centric approach and a decentralized scheme. In the network-centric approach, the arrival and departure angles of the LoS-path between a UE and an AN are tracked jointly at the AN[3]. The UE transmits periodically UL reference signals from all of its antenna elements. Each UE antenna element is assigned a single subcarrier, which is different from those used by the other antennas. The departure angles are transmitted to the UE on a DL control channel.

The decentralized scheme consists in tracking the double-directional parameters of the LoS-path independently at the AN and UE. Such a scheme is based on narrowband UL transmissions from a single antenna element of a UE. This allows the AN to track the arrival angles of the LoS-path. These arrival angles are used for designing a beamforming weight-vector that is exploited by the AN to transmit a beamformed DL reference signal towards the UE. This makes it possible for the UE to track the arrival angles, and thus design the receive beamforming weight-vector. The transmit and receive beamforming weight-vectors designed in this fashion are compared to CSI at transmitter (CSIT)-based precoding schemes in Section IV.

The performance of both network-centric and decentralized approaches have been analyzed with a time division duplex (TDD) based 5G simulator. In particular, we have considered a UDN composed of 74 ANs with a deployment identical to that illustrated in Fig. 3. The ANs are equipped with circular arrays composed of 20 dual-polarized 3GPP patch elements $5\,\mathrm{m}$ above the ground. The UEs are equipped with circular arrays composed of 4 dual-polarized elements (cross-dipoles). The transmit power budget of the UEs is $10\,\mathrm{dBm}$ while that of the ANs is $23\,\mathrm{dBm}$. The UEs take different routes through the Madrid grid (see Fig. 3) with velocities of $30\,\mathrm{km/h}$ to $50\,\mathrm{km/h}$. The carrier-frequency is $3.5\,\mathrm{GHz}$ and the METIS map-based ray tracing channel model [12] has been employed. An orthogonal frequency division multiplexing (OFDM) waveform is used in both UL and DL. The subcarrier spacing is $240\,\mathrm{kHz}$ and the transmission time interval (TTI) equals $200\,\mu\mathrm{s}$. The UL and DL reference signals are Zadoff-Chu

[3]The departure angles can only be retrieved from the arrival angles if the orientation of the UE's array is known. The network-centric approach requires that the calibration data of the UE's array is acquired by the AN, e.g., over a UL control channel.

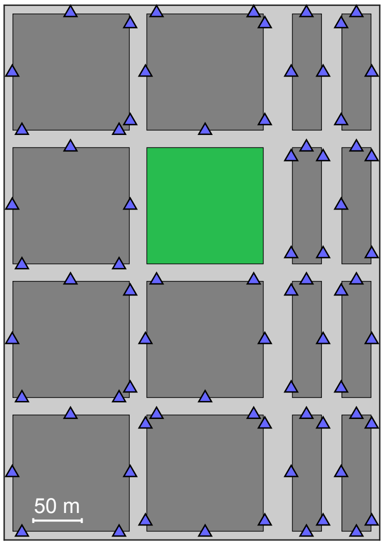

Fig. 3: METIS Madrid grid layout, from [12], where ANs (blue triangles) are distributed densely along the streets.

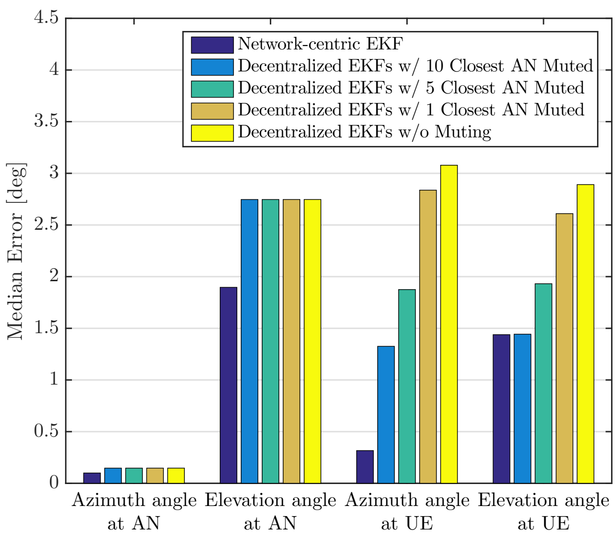

Fig. 4: Accuracy of tracking the arrival and departure angles with EKFs in terms of the median error. In network-centric EKF, the UE transmits UL reference signals from all antenna elements and the AN tracks both arrival and departure angles of the LoS-path. In decentralized EKF, the UE transmits UL reference signals from a single antenna element which is used by the AN to track the arrival angles of the LoS-path with an EKF. Such directional parameters are employed in order to design a DL beamformed reference signal that then allows the UE to track and design a similar receive beamforming vector.

sequences, similar to those used in LTE. The pilots employed by the network-centric and decentralized EKFs for tracking the double-directional parameters are transmitted on a single subcarrier in a frequency-hopping manner spanning $10\,\mathrm{MHz}$. Such UL and DL pilots are transmitted on every 500^{th} TTI. Hence, the UL and DL beaconing rate is $10\,\mathrm{beacons/s}$. The latency between UL and DL pilots in the decentralized scheme is 2 TTIs.

Fig. 4 illustrates the performance of both network-centric and decentralized EKFs in tracking the double-directional parameters of the LoS-path in terms of the median error. In the network-centric EKF, the UL beacons received at the ANs are impaired by uncoordinated interference due to UEs transmitting simultaneously roughly $250\,\mathrm{m}$ away from the receiving ANs. The performance difference in azimuth-angle estimation at the AN and UE is due to the larger array aperture of the former. However, the elevation angle estimates at the UEs outperform those obtained at the ANs. This is explained by the highly directive beampatterns employed at the ANs which decrease the effective aperture of the ANs' arrays in the elevation domain. In particular, the beampatterns of the 3GPP patch elements composing the arrays at the ANs are characterized by a large attenuation at the poles, thus decreasing the estimation accuracy that can be obtained for the elevation angles.

In the decentralized EKF, the ANs transmit DL reference signals to 8 UEs simultaneously ($20\,\%$ of the spatial degrees-of-freedom). Such DL reference signals are impaired by similar pilots transmitted by neighboring ANs (unless being muted). Results in Fig. 4 show that muting neighboring ANs leads to improved performance on the azimuth and elevation angles at the UEs due to reduced DL interference. Such an interference coordination does not influence the performance of the estimated azimuth and elevation angles at the ANs since these parameters are estimated from UL reference signals. The network-centric EKF outperforms the decentralized EKF since all parameters are estimated and tracked jointly. The cost is an increase of the computational complexity and required control channel capacity.

C. *Positioning Accuracy using Cascaded EKFs*

Next we assume that the DoAs and ToAs are acquired using the network-centric EKF-based approach deployed at ANs as described in Section III-B with more details available in [4]. These spatial and temporal estimates from all the LoS-ANs can be thereafter fused into 3D UE location estimates using an additional positioning and synchronization EKF, thus assembling a cascaded EKF solution within a network as a whole [3], [4]. In addition to 3D location estimates, the latter EKF can be simultaneously used for tracking the valuable clock offset estimates of unsynchronized UEs and LoS-ANs. In order to demonstrate the performance of the cascaded EKF, two alternative scenarios for synchronization are considered. In the first scenario, the UEs have unsynchronized clocks with drifts whereas the ANs are assumed to be synchronized among each other. In the second scenario, the ANs have also mutual clock-offsets, which are not fundamentally varying over time, whereas the clocks within the UEs are again drifting as mentioned above. Such scenarios are later denoted as Pos&Clock EKF and Pos&Sync EKF, respectively [4].

Considering the radio interface numerology described in Section III-B and exploiting a constant velocity (CV) motion model for the UEs attached to vehicles with a maximum speed of $50\,\mathrm{km/h}$, the performance of the Pos&Clock and Pos&Sync EKFs are compared with the classical DoA-only EKF using both $4.8\,\mathrm{MHz}$ and $9.6\,\mathrm{MHz}$ reference signal (RS) bandwidths. Since only automotive applications are considered here, more appealing 2D positioning approach was used in the evaluations. The 2D positioning results in terms of cumulative

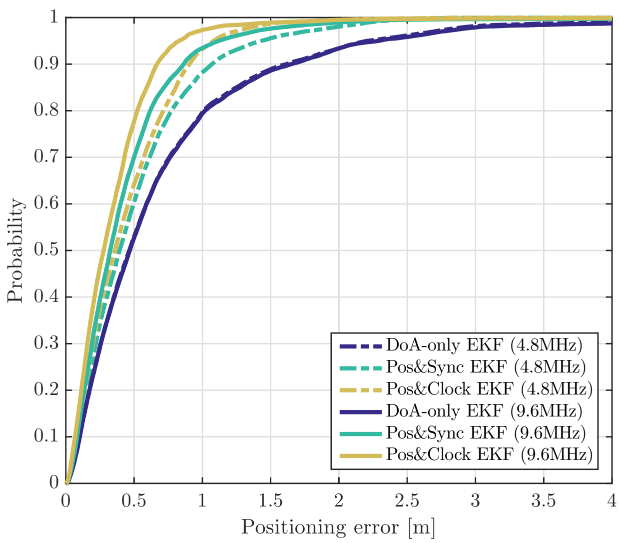

Fig. 5: CDFs for 2D positioning errors with $4.8\,\mathrm{MHz}$ and $9.6\,\mathrm{MHz}$ RS bandwidths over random routes through the Madrid map. Pos&Clock EKF refers to synchronized ANs whereas Pos&Sync EKF refers to unsynchronized network elements.

distribution functions (CDFs) are depicted in Fig. 5 after averaging over multiple random trajectories on the Madrid grid. Based on the results, the cascaded EKFs can provide extremely accurate location estimates for the UEs even in the case of unsynchronized ANs. As expected, Pos&Clock and Pos&Sync EKFs outperform the DoA-only EKF due to the additional ToA estimates. Because of a better time resolution, $9.6\,\mathrm{MHz}$ RS bandwidth implies more accurate ToA estimates, and consequently, more accurate positioning can be obtained. Despite the fact that the Pos&Clock EKF is more accurate than the Pos&Sync EKF due to the synchronized ANs, both methods can achieve the envisioned sub-meter positioning accuracy of future 5G networks [6], [7] with a probability of at least 93% when using the $9.6\,\mathrm{MHz}$ bandwidth. In addition to high-accuracy positioning performance, both Pos&Clock and Pos&Sync EKFs are able to track also the clock offsets of the UEs and ANs with an extremely high accuracy. Finally, due to being able to estimate both azimuth and elevation DoAs in addition to ToAs, the positioning EKF can also facilitate 3D and single AN based positioning[4].

IV. Location-Based Geometric Beamforming and Mobility Management

Network densification and accurate UE positioning in 5G will open new opportunities also for RRM and MIMO. Especially multi-user MIMO (MU-MIMO) is seen as a promising solution for 5G as it enables MIMO gains also with simple single antenna UEs. As discussed in Section III-A, UEs in UDNs are close to an AN with a high LoS probability. This makes it possible to design and adopt geometric beams at transmitters without the need to estimate the full-band CSIT [9]–[11]. This is enabled by using the estimated elevation and azimuth angles relative to the AN's coordinate system. The synthesized multi-user multiple-input single-output (MU-MISO) matrix can then be formed comprising only LoS-paths for all served UEs. One significant benefit of such beamforming scheme is that full-band UL reference signals, traditionally employed for obtaining CSIT, can be replaced with narrowband UL pilots. This will allow for substantial energy savings, especially on UE side, which is a very important aspect in future wide-band 5G networks. In addition to transmit beamforming, the location-based approach can be used also for calculating the receive filters at UEs when high-accuracy DoA estimates of the desired signals are available.

In addition to MU-MIMO beamforming, accurate positioning is also a key enabler for paradigm shift from classical cellular networks towards device-centric borderless networks with centralized control entities. When the network is constantly keeping track of UE locations, it can assign a set of serving ANs for each UE. Then data for each UE is partially or fully available at some small set of nearby ANs as also outlined in [2]. This enables ultra-short latencies and borderless QoE with seamless mobility decreasing handover latencies [10]. Furthermore, such device-centric mobility approach can reduce the energy and resource consuming cell measurement and reporting burden of legacy cellular systems.

A. Evaluation Setup

We consider a similar setup as in Sections III-B and III-C, with 43 ANs, user density of $1000\,\mathrm{users/km^2}$, and all users are dropped with a uniform distribution on the simulated street area. To follow the 3GPP requirements and scenarios for next generation studies [8], a single unpaired $200\,\mathrm{MHz}$ TDD carrier is assumed and $30\,\mathrm{km/h}$ velocity is used for the UEs. Additionally, the ratio between DL and UL is configured to $4.7:1$ in the employed 5G TDD frame structure [11]. Every DL transmission is assumed to start with a precoded DL pilot and maximum ratio combining (MRC) is used for calculating the receive filter according to the measured DL pilot. In case of location-based receive beamforming, estimated elevation and azimuth angles relative to UE's coordinate system are used for calculating the receive filter towards the serving AN. For both location-based transmit and receive beamforming, a 2 degree measurement error in addition to the UL pilot measurement aging in both elevation and azimuth angles is assumed. UL pilots used for CSIT estimation and positioning are scheduled according to the round-robin scheme. Hence, in the simulated scenario the average CSIT latency is $\sim 3.3\,\mathrm{ms}$. UEs are assigned to be served by the closest AN, i.e., a centralized mobility management scheme based on estimated UE locations is assumed.

B. Performance Results and Comparison of Location-based and CSI-based Beamforming

In [11], it was observed that both matched filter (MF) and zero forcing (ZF) precoders work rather well in UDNs, where LoS-paths are dominating over reflections and diffractions. Hence, for this study a block diagonalization (BD) algorithm [15], which can be understood as an extension of ZF, is

[4]Video of 3D and single AN-based positioning is available at http://www.tut.fi/5G/COMMAG16.

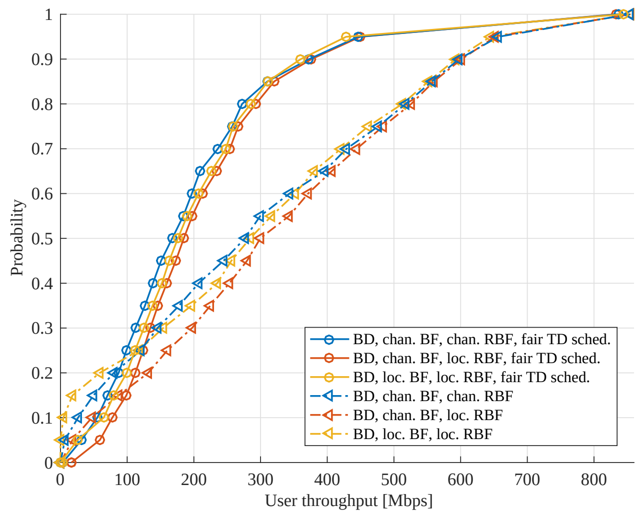

Fig. 6: DL user throughput CDFs, over random routes through the Madrid map, with channel/CSI and location-based MU-MIMO transmit beamforming (BF) and receive BF (RBF). Relying only on location information is better on average than using only CSI measurements. The best overall performance is obtained by using channel-based BF and location-based RBF.

chosen instead of conventional ZF. Especially attractive feature in BD is that the beams can be optimized for multiantenna receivers enabling better performance of receive filters.

In Fig. 6, CDFs of user experienced DL throughputs are shown with both CSI-based and location-based transmit and receive beamforming schemes. Due to high LoS probability and dominance of LoS-paths, both CSI-based and location-based beamforming schemes obtain rather similar performance over the whole distribution. Additionally, focusing the receive filter only to LoS-path with location-based receive beamforming outperforms DL pilot based receive beamforming. Furthermore, 100% increase in 5-percentile throughput can be obtained when compared to the CSI-based approach. Since ANs are using same physical resources for transmitting beamformed DL pilots, DL pilot contamination degrades the performance of CSI-based receive beamforming. In case of transmit beamforming with ZF-based precoders like BD, better performance at 5-percentile can be obtained with channel-based transmit beamforming due to the fact that there are still a few UEs in NLoS condition towards the serving AN. Thus, the best overall performance is obtained by using channel information for transmit beamforming and location information for the receive filter. Note that the pilot overhead is here the same for all beamforming schemes. However, if pilot overhead caused by full-band reference signals needed in CSI-based beamforming was reduced in the corresponding location-based schemes, the performance would improve in terms of the mean throughput and area capacity as shown in [11]. This is because location-based beamforming schemes do not require full-band reference signals, while narrowband, even single-subcarrier, pilots suffice.

In this example, in order to increase fairness of BD precoding and to reach the throughput requirement of $50\,\mathrm{Mbps}$ for all users all the time, stated in [5], the scheduling method introduced in [10] is used. This fair time domain (TD) scheduling approach is applied in a way that in every other subframe only a subset of users is chosen as scheduling candidates, in particular the users with the lowest past average throughput. In other subframes the number of simultaneously served users is maximized to increase the total system throughput. The results in Fig. 6 indicate that such scheduling provides less variation in throughputs across the UEs. Moreover, the fair TD scheduling with channel-based transmit beamforming and location-based receive beamforming decreases the simulated area throughput from $1\,\mathrm{Tbps/km^2}$ to $0.65\,\mathrm{Tbps/km^2}$. Hence, when more fair TD scheduling is applied, the total system throughput suffers to a certain extent from favoring users with poor channel conditions over users with high signal-to-interference-plus-noise ratio.

V. Conclusions and Future Work

In this article, the prospects and enabling technologies for high-efficiency device positioning and location-aware communications in dense 5G networks were discussed and described. It was demonstrated that very high accuracy 2D/3D positioning and tracking can be accomplished, by adopting DoA and ToA estimation in the ANs together with appropriate fusion filtering in the form of EKF, for example. In general, outdoor positioning accuracies below one meter were shown to be technically feasible. It was also shown that location information can be used efficiently in the radio network, e.g., for geometric location-based beamforming, where the needed pilot or reference signal overhead is substantially smaller compared to the basic CSI-based beamforming approaches. Thus, extracting and tracking the locations of the user devices in the 5G radio network can offer substantial benefits and opportunities for location-based services, in general, as well as to enhanced and more efficient communications and radio network management.

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