Characterization of Multi-Link Propagation and Bistatic Target Reflectivity for Distributed ISAC

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Abstract—Integrated sensing and communication (ISAC) qualifies mobile radio systems for detecting and localizing of passive objects by means of radar sensing. Advanced ISAC networks rely on meshed mobile radio access nodes (infrastructure and/or user equipment, resp.) establishing a distributed, multistatic MIMO radar system in which each target reveals itself by its bistatic backscattering. Therefore, characterization of the bistatic reflectivity of targets along their trajectories of movement is of highest importance for ISAC performance prediction. We summarize several challenges in bistatic modeling and measurement of extended, potentially time-variant radar targets. We emphasize the specific challenges arising for distributed (hence multi-link) ISAC networks and compare to the state of the art in propagation modeling for mobile communication.

Index Terms—Integrated sensing and communication, distributed MIMO radar, bistatic target reflectivity, propagation measurement and modeling.

I. INTRODUCTION

ISAC is considered to be one of the key features of future 6G mobile radio. Despite of different interpretations, we understand ISAC as a means of radar detection and location of passive objects (“targets”) that are not equipped with a radio tag. These targets reveal their existence and position by radio wave reflection only when properly illuminated. In contrast to well-known radar systems, ISAC exploits the inherent resources of the mobile radio system on both the radio access and network level. In its most resource efficient operational mode, ISAC reuses the signals originally transmitted for communication purposes at the same time also for target illumination. This scheme resembles and extends the well-known passive radar principle. We introduced the term “cooperative passive coherent location (CPCL)” [1], [2] for it. In case of this communication centric version of ISAC, the radio access modes defined for communication are also used to radar sensing. This includes the waveform (usually OFDM and derivatives), its numerology, multiuser access (OFDMA, TDMA), pilot schemes, channel state estimation and synchronization, channel state signaling for predistortion and link adaptation, and eventually also for resource allocation. With the ubiquitous availability of the mobile radio access, we immediately have a distributed network of radar sensors at hand. The same network is also used for data transport and data fusion. With the computing facilities of the mobile edge cloud (MEC) we have all resources at our disposal, which we may need to apply machine learning (ML) and artificial intelligence (AI) for adaptive resource allocation, target parameter estimation, and scene recognition. This way, ISAC will become a ubiquitous and cognitive radar sensing network. As we know very well from mobile radio performance prediction, the knowledge about the multipath radio propagation is very important. Channel measurement and modeling always stands at the very beginning of the definition and standardization of new radio access schemes. In this paper, we ask the question: “What are the differences and challenges of propagation research for ISAC as compared to plain mobile radio communication?” We will find out among other things that the knowledge about single, i.e., solitaire objects that are identified as radar targets, is most important. This includes bistatic target reflectivity, how it evolves if the target is moving, and how it can be characterized if it is inherently time-variant. Besides of conceptual issues, we for the first time introduce a new measurement range for the bistatic reflectivity of extended objects up to the size of a passenger car. This unique measurement range, which we call BiRa (Bistatic Radar), is capable of real-time wideband measurements of time-variant targets. Hence, we can analyze the bistatic micro-Doppler response of extended targets [3].

II. MULTI-LINK ISAC SYSTEM ISSUES

A typical ISAC system consists of either one stand-alone or several meshed radio nodes acting as transmitter (Tx), receiver (Rx), or both. In case of an infrastructure based setup, these can be single or distributed base stations consisting of several synchronized remote radio units (RRUs). A single base station case corresponds to a stand alone radar. The gNodeB (gNB)

Fig. 1. Infrastructure based sensing using a single base station that is equipped with an antenna array
must be capable of full duplex radio access and needs to be equipped with an antenna array for direction of arrival (DoA) estimation. The target bearing line will be a circle around the gNB and the target location is given by joint DoA and time of flight (ToF) (resp. range) estimation, see Fig. 1. In radar terms, this is referred to as “monostatic”. The challenge is the full duplex operation of the radio interface, which is not yet standard in communications. The distributed equivalent is depicted in Fig. 2. It resembles the passive radar case and, hence, also our CPCL scenario [1]. The estimated parameter is the excess ToF delay of the sensing link relative to the direct line-of-sight (LoS) link. The resulting target bearing line is as an ellipse with the Tx and Rx positions as its focal points. Obviously, we would need multiple measurements, hence additional radio nodes, to achieve a unique and unambiguous location estimate in 2D or even 3D. DoA estimation, hence antenna arrays, are not necessary. However, beamforming can be additionally applied, e.g., for filtering undesired multipath (clutter). This distributed Tx/Rx geometry is obvious and self-evident for communication centric ISAC. In radar terms, it is referred to as “bistatic”. In this case, we do not need a full duplex air interface and we may have further advantages in spatial diversity as will be discussed below.

The ISAC architecture can also comprise multiple units of mobile UE in the UL or DL, resp., see Fig. 3. This corresponds to a multiuser scenario, which we call a multisensor scenario in ISAC terminology (the figure shows only one UE). The difference to Fig. 2 is that the sensor may now be mobile which has influence on Doppler processing. Moreover, as the sensor is the UEs, the direct wireless link is necessary for Tx/Rx synchronization and to make the transmitted signal available at the sensor as a correlation reference. In contrast to passive radar, the CPCL receiver is prepared to generate a clean replica of the transmitted waveform [1].

The radar architecture made up from multiple, widely distributed radio nodes is called distributed MIMO radar (as opposed to co-located) [2]. The generic distributed multiple-input multiple-output (MIMO) radar setup shown in Fig. 4 involves some issues and challenges. Obviously, the full $\#\text{Tx} \times \#\text{Rx}$

MIMO matrix requires monostatic radio interfaces at all nodes. Moreover, the multiple Tx/Rx links would require some coordinated access, which includes sensor broadcast (with multiple simultaneous DL measurements at several Tx) and the orthogonal multisensor case that can be used for UL and DL sensing). Joint transmission can be implemented in the DL with noncoherent and coherent superposition at the place of the target. Moreover, heterogeneous links can make sense. However, further discussion is beyond the scope of this paper. Obviously, distributed MIMO radar includes several synchronization issues. It allows unambiguous 3D location and dynamic state vector estimation (which includes the velocity vector and perhaps higher derivatives) if there are enough orthogonal Tx/Rx links available. An excess number of measurements will increase the reliability of detection and estimation. Reason is that the bistatic view offers a considerable target related backscatter diversity gain. This applies also to velocity estimation. While single radar (monostatic or bistatic) is “Doppler blind” if the target moves tangential to the range bearing line, a distributed geometry can avoid Doppler blindness [3]. For dynamic targets, it is important to gather these multiple measurements in a short enough time interval in order not to lose the geometric consistency of the parameters.
Moreover, it seems that Doppler estimation plays a specific role here for target dynamic state estimation, since correct Doppler estimation requires coherent sampling on some slow time interval. This presumes that the spatial sampling interval should normally be less than half the carrier wavelength. This is important not only for unambiguous speed estimation. It is also crucial for achieving a valuable radar integration time in connection with correlation processing. The resulting signal-to-noise ratio (SNR) gain is an important advantage of ISAC vs. communication. While the radar equation seems to penalize ISAC vs. communication with respect to coverage distance, correlation gain can compensate a lot of the additional propagation loss.

### III. Multipath Propagation and ISAC Performance Evaluation

From mobile radio research we already know that the knowledge about propagation phenomena is of highest importance for system design and performance assessment. For instance, only the idea to exploit rich multipath propagation brought the breakthrough for capacity efficient MIMO communication. We have learned that performance evaluation of communication systems on the link and system level has to consider realistic radio propagation models. Consequently, advanced sounding and propagation modeling methods were required to provide us with a deeper understanding of the relevant propagation phenomena and to deliver a modeling kernel to be used in more comprehensive system simulation frameworks. A similar situation we expect for performance assessment of ISAC systems. While basic ISAC system design approaches assume clear LoS propagation situations, the reality is more complicated. Propagation phenomena will, for instance, have influence on visibility of targets, as the target can be hidden by obstacles. Multipath reflections from the environment will further add, which may be considered as some kind of interference (called “clutter”). On the other hand, multipath can be exploited to support target illumination and visibility. Eventually, the scattering statistics of a target is of highest importance for predicting detection probabilities and, hence, for a meaningful information- and estimation-theoretic performance assessment of the whole ISAC system. Therefore, propagation models for ISAC systems have to reflect already the key ISAC system design issues. However, we may ask, if the same models that were developed for communications technology can be reused for ISAC or what are the differences and are there specific requirements?

Just like the communication channel, also the sensing channel is composed of multiple propagation paths attributed to direct LoS propagation and deflected paths resulting from interaction with the environment. However, a communication channel exploits all the energy, which is transmitted from Tx to Rx to transport information, regardless on which path it propagates. In ISAC it is different. Here the Tx-to-Rx path that is routed via the target is most interesting as it carries the information about the target’s position and dynamics. The remaining multipath constitutes the clutter, see Fig. 5.

![Fig. 5. Geometric structure of the ISAC multipath channel consisting on target and clutter paths.](image)

A measured power delay profile (magnitude squared impulse response) is shown as an example in Fig. 6. The figure exemplifies how dominating the clutter can be in a practical situation. The scenario was a street with office buildings at both sides and some lamp posts. The target was a car sensed via bistatic LoS response from two other cars (Tx and Rx, resp.). The energy reflected off the target almost disappears in the clutter. However, as the target car is moving and the clutter is static, the target reveals itself as some small ripple in Fig. 6. Therefore, we can apply background subtraction or identify the target in the range-Doppler plane. The separation of clutter vs. target response is a major task of radar signal processing. The procedures applied typically rely on spatial/directive filtering or exploit the different dynamic of the target and the environment (static vs. time-variant scattering or different Doppler shift).

Target estimation procedures that exploit the multipath propagation are also interesting. On the one hand, multipath contributes to target illumination (if there are multiple bounce reflections). This increases the energy that falls onto the target and brings similar diversity gain as already discussed in relation with Fig. 4. The potential benefit is a better location
performance. The target can be localized even if the number of illuminators is too low to deliver the necessary geometrical degrees of freedom. It becomes also possible to locate objects in shadowed areas [6], [7]. However, the position of the dominant interacting points multilink of the environments need to be known. An alternative is to apply machine learning from reference scenarios [8], [9] with known target positions, e.g., for supervised learning.

Yet another approach that exploits multipath relies on target link adaptation. If we can estimate the Tx-to-target link, it becomes possible to pre-distort the transmit signal by convolving it with the time axis mirrored channel response. This method is called time reversal [10]. As a consequence, several copies of the Tx waveform, which arrive over multiple propagation paths, coincide at the target in time and perhaps also with the same phase (non-coherent and coherent superposition). This makes sure that all transmitted paths arriving at the target contribute to the target illumination (hence increasing reflected energy) and do not need to be separated as LoS vs. clutter illumination. A similar predistortion, related to orthogonal time frequency space (OTFS) modulation can be carried out in the Doppler domain, thus matching the Doppler shifts over all illumination paths. This would considerably decrease the effective target Doppler spread, simplify target estimation and tracking and allow longer coherent radar integration intervals.

A. Challenges in Multi-link Propagation Modeling

Since the target state vector (position and target dynamics) is directly estimated from multiple distributed sensing link parameters, it becomes obvious that the channel model has to be geometrically relevant. This is somewhat in contrast to geometrically based statistic channel models (GBSCMs) that are used in mobile radio communications. GBSCM represent the multipath geometry only in some statistical sense, e.g., to reproduce joint delay and angular statistics. For ISAC we need deterministic models with more physical relevance. This applies most of all for target modeling, but may also apply for the multipath propagation if multipath is exploited. Only remaining (not used) clutter can be modeled in a statistical sense. Deterministic geometrical relevance includes “spatial consistency” which means that the geometric parameters that are relevant for target location change in a consistent way in all multiple Tx/Rx sensor links and over time according to the trajectory of Tx, Rx, and target. This is somewhat opposed to the random drop based modeling approach applied for a sequence of GBSCM impulse responses in communications.

The consistent, contiguous change of geometry requires a corresponding variation of the geometric parameters. These are bistatic ToF and directions of propagation paths at both sides of the link (DoA and direction of departure (DoD)). However, Doppler, which is also geometry related, plays a more special role. First of all, Doppler shift is important for estimation of the dynamic target state vector and for tracking. However, Doppler is much more sensitive to movement as it relates to carrier phase. On the other hand, ToF, DoD, DoA are much more coarsely resolved because of the limited observation aperture in frequency (bandwidth) and space (array size) and therefore the corresponding resolution in delay and direction. Doppler processing would always need some coherent processing interval along slow time. The length of this interval determines Doppler resolution or the coherent radar averaging time, respectively. As the spatial sampling distance should be smaller than half the carrier wavelength, the required spatial update rate may sound incredibly high. However, a viable balance of effort can be achieved if we combine different track scales. This may be important for both measurement and modeling. In sounding measurements we can take coherent sequences of impulse responses in intervals that are sampled fast enough to meet the Nyquist criterion in the Doppler domain and long enough to get reliable joint range/Doppler-estimates. In ray tracing simulation we can generate sequences of impulse responses that keep pace with spatial carrier phase rotation for a fixed set of ToF, DoD, DoA path parameters (assuming that these geometric parameters do not change within the coherent processing interval). Hence, path search needs to be carried out only once for any coherent processing interval.

In total, a propagation channel model for ISAC should be geometrically correct for multiple simultaneous sensor links (for a meshed network) and reproduce a moving target in a spatially consistent way along a track, which includes phase continuity.

B. Challenges in Bistatic Target Reflectivity Modeling

Besides of the more global, track related view to channel modeling for target modeling discussed above, we can also have a more local or microscopic view, which is related to the target as a single or solitaire object. For obvious reasons, the reflectivity of the target object is of outstanding importance for radar performance evaluation. For ISAC it is the bistatic reflectivity, as discussed with the system setup. For a comprehensive experimental characterization of a target object we have to illuminate it from all possible directions in azimuth and elevation (practically only in the upper half sphere) and observe it also from all possible directions. This way, we end up with a four-dimensional data structure. Since Tx (illumination) and Rx (sensing/observation) angles can take any value, we have the specific cases of 0° and 180° aspect angles included. The former corresponds to the monostatic case, whereas the latter is called forward scattering case. Forward scattering describes shadowing or obstruction of the LoS between Tx and Rx. However, it is also an interesting radar operation mode. Note that this case is not just shadowing as diffraction occurs. So it is most distance and frequency dependent.

In general, the radar target has to be considered as an extended target. This means that it is wider than a resolution cell, which is given in radial distance by the range resolution. Therefore, we have to collect multiple range bins for depth information depending on available bandwidth. The number of range bins depends on the electrical size of the object, which may be larger than the mechanical one if the target is concave.
and has structural resonances, e.g., because of cavities. This way we effectively get another dimension besides of the 4D angles. Moreover, radial distance of Tx and Rx antennas matters. In general, we are not in the far field, which is characterized by planar wave fronts along the whole size of the object. Interestingly enough, this not only true for a practical measurement setup (see next section), but also for many typical ISAC application scenarios in the field, e.g., car2car communications. Therefore, a near-to-far-field transform for model building would not suffice. We would need a model, which is scalable with Tx and Rx distance. Further issues are related to the polarimetric target response, which requires a complete $2 \times 2$ Jones matrix for any entry of the multidimensional radar reflectivity. We propose the term “bistatic radar reflectivity” as opposed to bistatic radar cross section (RCS), since RCS is usually understood as the cross section of an equivalent sphere that reflects the same power as the target in the far field. The RCS is important for radar link budget estimation using the radar equation. However, the conventional definition of RCS does not hold for extended targets. On the other hand, also the bistatic reflectivity can be calibrated in a way that it reflects the physically correct link budget.

Fig. 7 indicates the bistatic response of an extended target if illuminated and sensed by distributed Tx and Rx antennas. It becomes obvious that we can attribute a “global” Doppler shift describing the movement of the target on a track as described in the subsection above. However, what happens, if the target moves more locally? If it rotates, or if it contains rotating parts like wheels or propellers? Or if the target is a creature like a human being or an animal? There may be moving legs, arms, or wings. Or what if the target is tumbling on its track or just starting to change direction? This time variance would also cause some Doppler shift. But as it is local and independent from the track related to global Doppler, it is better called micro Doppler [3]. Related to the discussion about the bistatic reflectivity above, we regard it as the time-variant bistatic reflectivity. The signal analysis tools to be applied in order to identify the type and nature of the time variability reach from harmonic analysis over short-time Fourier transform until Wigner distribution and Wigner-Ville spectral analysis, which also includes cyclostationary spectral analysis if the time-variability is not strictly periodic but rather an almost period modulated random process.

IV. Conclusions

From the discussion above, we can conclude that for ISAC propagation research we need not only a multi-node real-time channel sounder that is capable to emulate a meshed ISAC-network in a dynamic setup (including mobile radio nodes and moving targets) [11], [12], [13]. Because of the prominent role of the target in distributed ISAC, we need also a measurement range, being capable to analyze the bistatic radar reflectivity of extended solitaire objects. First ideas of such a setup were already published in [14]. Fig. 8 shows the BiRa measurement range currently being installed at Ilmenau University of Technology. It consists of two pivoting gantries that carry a Tx and Rx antenna, resp. The object under test is placed on a turntable, which together with the gantries allows independent illumination and observation of the target object from arbitrary directions in the upper half space. The accessible frequency range covers all relevant frequency ranges from FR1 and FR2 up to 170 GHz. A remarkable feature is that besides of a standard vector network analyzer (VNA), we can use a wide-band channel sounder for illumination and sensing with an instantaneous bandwidth of 4 GHz. This does not only accelerate the total measurement time. It allows also to investigate micro Doppler of time variant targets, e.g., multi-copters with rotating propellers. Analyzing, studying, and learning the micro Doppler signature of these objects will help to classify their type and to identify and separate them in real-life multiple target scenarios.

Besides of the two measurement setups, the bistatic target reflectivity measurement and the multi-node real-time channel sounding, we need also a multipath propagation simulation framework, which is capable to generate spatially consistent and geometrically representative multiple link responses.
Thereby it seems that phase-continuous modeling and correct bistatic reflectivity modeling of moving targets poses new challenges. The long lasting discussion about stochastic vs. deterministic modeling will get a second wind. Also hybrid deterministic/stochastic modeling of targets and environment may become of interest [15]. The results gained with the BiRa measurement range will allow to deduce sophisticated scattering models of the target to be plugged into in a more comprehensive propagation simulation framework.

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