6G Radio Requirements to Support Integrated Communication, Localization, and Sensing

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***Abstract*—6G will be characterized by extreme use cases, not only for communication, but also for localization, and sensing. The use cases can be directly mapped to requirements in terms of standard key performance indicators (KPIs), such as data rate, latency, or localization accuracy. The goal of this paper is to go one step further and map these standard KPIs to requirements on signals, on hardware architectures, and on deployments. Based on this, system solutions can be identified that can support several use cases simultaneously. Since there are several ways to meet the KPIs, there is no unique solution and preferable configurations will be discussed.**

I. INTRODUCTION

6G will support extreme use cases, requiring gigabit-per-second peak data rates with millisecond end-to-end (E2E) latency [1]. Secondly, 6G will rely on a variety of new enablers at the physical layer [2], including the utilization of frequency bands in the upper millimeter-wave (mmWave) range (100–300 GHz), novel radio frequency (RF) architectures, exploration of hardware-friendly, energy-efficient waveforms and beamforming, and the use of distributed large MIMO system and reconfigurable intelligent surfaces (RISs). Finally, 6G will feature a tight integration among communication, localization, and sensing [3], [4]. Integration will not only enable exciting, but challenging, new use cases, but also improve communication functionality as well as other services [5]. Use case requirements are generally specified in terms of key performance indicators (KPIs), which in turn impose requirements on the signals (e.g., bandwidth, waveform, and modulation) [6], the hardware architectures (e.g., carrier, channelization, array type, output power) [7], and deployments (e.g., placement of (distributed) base stations (BSs) and RISs) [8].

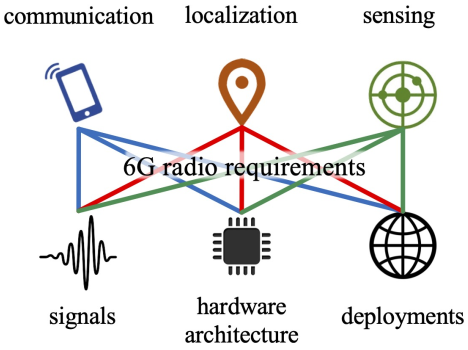

Fig. 1. Communication, localization, and sensing each impose requirement on signal, hardware architectures, and deployments, which should be met by 6G radio.

In this paper, we investigate the requirements on signals, hardware architectures, and deployments for 6G integrated communication, localization, and sensing. Starting from several 6G use cases, we state expected KPIs, list the possible options in terms of signals, hardware architectures, and deployments, followed by discussing how they should be determined to support the considered use cases. As there is no unique solution to this design problem, several alternatives are discussed, with the aim of finding commonalities and possibly a joint design that can serve several 6G use cases simultaneously. The main contribution of this paper is to provide both a methodology for determining such requirements, as well as listing initial solutions. We also highlight several of the (sometimes subtle) synergies and trade-offs that should be considered in overall 6G radio.

In terms of structure, this paper starts with a recap of 6G use cases and KPIs (Section II), followed by a brief overview of the components of the radio channel (antennas, RF technology, and wave propagation) at upper mmWave frequencies (Section III). Section IV describes the identified degrees of freedom in terms of signals, hardware architecture, and deployments. Then, in Sections V–VII, the specific requirements are determined, needed to support the use cases from Section II. We conclude the paper with Section VIII.

II. 6G USE CASES AND KPIS

In this section, we recap several 6G use cases and list their KPIs, for all three considered applications: communication (C1–C2), localization (L1–L3), and sensing (S1–S2).

A. Communication

Following [9], we propose two communication system design scenarios corresponding to 6G use-cases with advanced design requirements. *Very short-range wireless access (C1)* 100 Gbps per-user rate, 0.1–1 ms E2E latency, 10 m link range. *Short-range wireless access (C2)* $10\,\mathrm{Gbps}$ per-user rate, $<1\,\mathrm{ms}$ E2E latency, $100\,\mathrm{m}$ link range.

B. Localization

Following [10], we divide localization scenarios into three categories, with KPIs derived from [5]. *High-accuracy positioning (L1)* for very fine maneuvers or coordination. An example in this category is *augmented reality*, with $1\,\mathrm{cm}$ location accuracy, $1\,^\circ$ orientation accuracy, $100\,\mathrm{Hz}$ update rate, and $10\,\mathrm{m}$ link range. *Low-latency positioning (L2)*, for example for *collaborative robot localization*, requiring $10\,\mathrm{cm}$ location accuracy, $1\,^\circ$ orientation accuracy, $1\,\mathrm{kHz}$ update rate, and $30\,\mathrm{m}$ link range. *Low-complexity positioning (L3)* for Internet of Things (IoT) localization with reduced capacity (RedCap) devices. An example is *remote sensing*, with 1–10 m localization accuracy, 1 Hz or lower update rate, and more than $1\,\mathrm{km}$ link range.

C. Sensing

A natural breakdown is into monostatic and bi-/multi-static sensing. *Monostatic sensing (S1)* involves a transmitter and receiver are co-located, sharing common knowledge of the data and have a shared clock, and provides radar-like mapping (e.g., for automotive applications), with $10\,\mathrm{cm}$ distance accuracy, $0.04\,\mathrm{m/s}$ velocity accuracy, $3\,^\circ$ angular resolution, $0.2\,^\circ$ angular accuracy, maximum range of $50\,\mathrm{m}$, and $25\,\mathrm{Hz}$ update rate [11, Table C2]. This application is similar to the *sensor infrastructure web* use case from [5]. We only consider monostatic sensing with communication signals, not dedicated sensing waveforms. *Bi-/multi-static sensing (S2)* involves physically separate transmitters (Txs) and receivers (Rxs), e.g., for *robotic object sensing*, with $1\,\mathrm{cm}$ localization resolution, as well as angular resolution below $1\,^\circ$, $0.1\,\mathrm{m/s}$ velocity resolution, and up to $1\,\mathrm{kHz}$ update rate.

III. RADIO CHANNEL AND RF TECHNOLOGIES

The radio channel is composed of antennas/arrays connected to RF transceivers at ends of the link, with the multipath wave propagation channel between them. Combined, they determine the practical link performance within the constraints imposed by the wave propagation and semiconductor/material physics. The following summarizes some viewpoints about them, focusing on upper mmWave frequencies.

A. Antennas and Arrays

At both lower and upper mmWave, most likely hybrid architectures of analog RF and digital baseband beamforming will be used to support a massive number of antenna elements in the array. Due to challenges in integrated designs of an antenna array and its feeding network for RF phase shifting, practical implementation of an integrated phased antenna array may need a compromise in a beam scanning range and some extents of grating lobes. Lens antennas and radomes, despite bulkiness, allow improvement of the beam scan range of antenna arrays, e.g., [12], and are applicable to upper mmWave RF. The knowledge of radiation patterns of antennas and arrays is essential in localization and sensing, while it is less important in communications but would enhance the link performance in, e.g., beam searching. Antenna and array calibration methods, in an anechoic chamber or over-the-air, would be an important technical element [13].

B. RF Technology

Array performance is dependent on the amplifier performance both in transmit and receive side. The former defines the largest possible output power while the latter minimum noise figure. Both are to certain extent bandwidth dependent and even more carrier frequency dependent. Fundamental limits stem from the properties of semiconductor technologies and wiring losses. Silicon and compound semiconductors including different transistor types, sizes and technology nodes determine maximum operating frequency as maximum unilateral gain ($f_{\max}$) or transition frequency. As carrier frequency gets higher, the gain, fundamental requirement of RF processing, approaches unity while available output power decreases and noise increases rapidly. Recent example of a state-of-the-art $290\,\mathrm{GHz}$ amplifier in SiGe BJT process demonstrates more than $10\,\mathrm{dB}$ of gain at $2/3$ of $f_{\max}$ at the cost of significantly lowered dynamic range compared to a low frequency counterpart using the same technology [14]. RF transceivers for single link have been demonstrated at frequencies above $200\,\mathrm{GHz}$ for short range ($1\,\mathrm{m}$) communications trials achieving $100\,\mathrm{Gbps}$ [15].

C. Wave Propagation

The most important characteristic of wave propagation is pathloss, with upper mmWave RFs showing pathloss exponents of *omni-directional channels* around 2 and 3 in outdoor cellular line-of-sight (LoS) and non-line-of-sight (NLoS) environments [16]. Even though diffraction coefficients are smaller as the RF increases, reflections on concrete walls, metal lampposts and tinted glasses can deliver power from one link end to another, making the link connectivity in NLoS feasible through one or multiple reflections even for upper mmWave. The finding of pathloss exponents does not differ from available insights for lower mmWave RF according to the comparison of indoor hotspot channels [17]. The number of multipaths or clusters is an important degree of freedom. More clusters indicate increased possibility of spatial multiplexing to send different data sets over possibly orthogonal beams. Existence of multiple clusters also implies the possibility of device localization and sensing through them. Measurements show the number of spatial clusters to be 0.69 and 1.82 for LoS and NLoS urban microcellular links [18] while channels support one to four beams in an indoor entrance hall [19].

IV. SIGNALS, ARCHITECTURES, AND DEPLOYMENTS

We describe the degrees of freedom in terms of signals, hardware architectures, and deployments. These will then be elaborated in the subsequent sections to support the use cases from Section II, and summarized in Table I.

A. Signals

The radio signals are considered to have the following 4 degrees of freedom: the *aggregate bandwidth*[1] (in Hz), the *waveform type* (examples are orthogonal frequency-division multiplexing (OFDM) [20], discrete Fourier transform spread (DFTS) OFDM [21], [22], orthogonal time-frequency-space (OTFS) [23], single carrier [24]), the *modulation type* (e.g., constant-modulus or QAM, non-coherent or coherent), the *signal shaping* (in time-frequency-space domains, including precoding, combining, pilot allocation, and power allocation).

B. Hardware Architectures

Hardware specifications originate from signal quality and range requirements. The former sets bandwidth and signal-to-noise ratio (SNR). On the other hand, underlying technologies determine minimum achievable noise and maximum transmitted power that are physics, technology, bandwidth, and carrier frequency dependent. In addition, also energy consumption and cost need to be considered carefully if we need to parallelize the signal paths. Wider bandwidth leads inevitably to higher noise and to the need to search for available radio spectrum at higher carrier frequencies. Both are impacting negatively on achievable performance. Taking these into account we have some degrees of freedom in frequency to arrange signals in *carrier, and channelization* domains [25]. In the spatial domain, we can increase the range by beamforming or the rate with MIMO, either in centralized or distributed manner. Depending on the targets we have the choice of *array type* (e.g., analog, hybrid, planar), *array size* (number of elements). RF phased arrays already exist in 5G NR operating at lower mmWave region, which are needed even in mobile equipment for decent range [26]. Careful link analysis for line-of-sight and other anticipated radio channel conditions is needed to balance all the requirements with hardware properties including antennas to evaluate the feasibility of the radio transceiver hardware for different deployments [27]. Hence, hardware architecture in digital systems needs to determine the number of parallel digitized radio channels to achieve sufficient bandwidth and then channelize it into different radio paths in frequency and spatial domain while utilizing array gain for compensating radio path loss of every available beam [19].

C. Deployments

The deployments are largely limited by cost and include the following 3 degrees of freedom: the *placement of infrastructure nodes (INs)*, including fixed and mobile base stations and RISs (number of INs and their positions and orientations),

Use case	C1	C2	L1	L2	L3	S1	S2
Signals							
Bandwidth	(a) 4 GHz (b) 10 GHz	(a) 0.4 GHz (b) 5 GHz	(a) 2–4 GHz (b) 500 MHz	0.5–1 GHz	<500 MHz	(a) 2–4 GHz (b) <1 GHz	2–4 GHz
Waveform	any	any	(DFTS-)OFDM	(DFTS-)OFDM	any	(DFTS-)OFDM	(DFTS-)OFDM
Modulation	coherent or non-coherent	coherent or non-coherent	coherent	coherent	coherent or non-coherent	coherent	coherent
Signal shaping	space in some scenarios	space and/or freq. in some scenarios	freq., time, and space	freq. and space	no	freq., time, and space	trade-off with comm.
Hardware Arch.							
Carrier*	60-140 GHz	(a) sub-6 GHz (b) 60-140 GHz	(a) < 30 GHz (b) 60-140 GHz	60-140 GHz	6–30 GHz	60-140 GHz	60-140 GHz
Channelization	optional	optional	no	no	no	not preferred	not preferred
IN array type	analog or hybrid	analog or hybrid	analog or hybrid	hybrid or digital	analog	analog or hybrid	analog or hybrid
UE array type	analog or hybrid	analog or hybrid	analog or hybrid	analog or hybrid	SNR boost	analog or hybrid	hybrid or digital
IN array size (per dim.)	10-20	10-20	(a) 10–20 (b) 50–100	10–20	SNR boost	(a) 10–20 (b) 40–50	(a) 10–20 (b) 40–50
UE array size (per dim.)	4-8	4-8	10–20	10–20	SNR boost	(a) 100 (b) 10–20	100
Transmit power	medium	medium	low (see (1))	higher (small T in (1))	higher (large d in (1))	high (high path loss)	high (high path loss)
Deployments							
Placement around each device	(a) $\geq$ 1 IN multi-stream or D-MIMO (b) $\geq$ 1 IN single stream	(a) $\geq$ 1 IN multi-stream or D-MIMO (b) $\geq$ 1 IN single stream	$\geq$ 4 INs in LoS (TDoA, 3D), $\geq$ 2 INs in LoS (AoA, 3D)	same as L1	$\geq$ 4 INs in LoS (TDoA, 3D)	N/A	(a) $\geq$ 1 Rx INs (TDoA + AoA + AoD), Tx-Rx in LoS (b) $\geq$ 1 Rx INs (ToA + AoA + AoD), Tx-Rx in NLoS
Synchronization	1–10 ns (D-MIMO)	1–10 ns (D-MIMO)	100 ps (TDoA)	0.5 ns (TDoA)	1–10 ns (TDoA)	N/A	(a) N/A (b) 100 ps
IN knowledge	position: area-level	position: area-level	position: mm-level orientation: $\leq 0.1°$ (AoA)	position: cm-level, orientation: $\leq 1°$ (AoA)	position: m-level, orientation: $\leq 1°$ (AoA)	N/A	position: mm-level, orientation: $\leq 0.5°$ (AoA)

TABLE I

SUMMARIZING TABLE ON THE REQUIREMENTS ON SIGNALS, HARDWARE ARCHITECTURES, AND DEPLOYMENTS. ACRONYMS ARE DEFINED IN THE TEXT. *CAUTION: NUMBERS ARE IN REALITY TECHNOLOGY-DEPENDENT, WITH NOISE FIGURE AND MAXIMUM TRANSMIT POWER BEING FREQUENCY-DEPENDENT.

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[1] The aggregate bandwidth does not have to be contiguous in frequency and can be fragmented into multiple RF chains with separate smaller-bandwidth ADCs. For full utilization of the entire bandwidth, phase coherency should be maintained across the different chains.

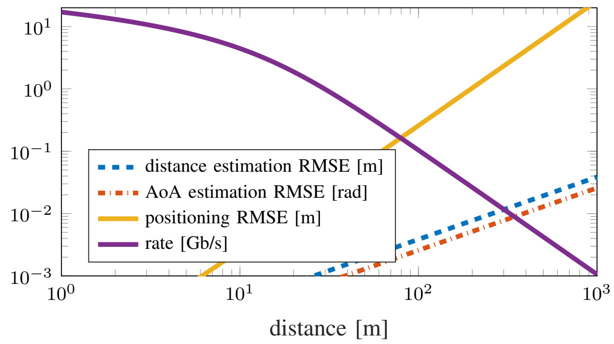

Fig. 2. Example showing how the ability to estimate distance AoA is affected by the distance between user and base station, for an uplink scenario according to [5, Annex C] using 120 OFDM symbols for localization (lasting about 125 us).

the *level of synchronization between INs* (time synchronization and phase synchronization), the *level of knowledge needed regarding the IN configuration* (e.g., location, orientation, phase center). In distributed deployments, we can split the burden to several physically separated radio units with additional cost.

V. REQUIREMENTS ON SIGNALS

To understand the involved trade-offs, Fig. 2 shows the performance of time-based distance, angle-of-arrival (AoA) estimation, and positioning in an uplink scenario under resolved LoS with respect to the distance, following the parameters from [5, Annex C], with a 140 GHz carrier, 2 GHz bandwidth, and 14 dBm transmit power. We see that even though distance and AoA can be well estimated at far distances thanks to the large integrated SNR, positioning (combining distance and angle) quickly degrades. The rate, assuming perfect beam alignment at the BS, degrades with distance.

A. Communication

Assuming single-stream spectrum efficiencies of 2–6 bps/Hz and 1–4 parallel spatial streams (depending on the array and spatial richness of the channel), the *aggregate bandwidth* requirement for supporting C1 is 4–10 GHz, whereas it is 0.4–5 GHz for C2. The choice of *waveform type* and *modulation* is largely dependent on the choice of hardware architecture, but in general waveforms with low envelope variations and inherent robustness to RF impairments are preferred. Waveforms based on OFDM have benefits in terms of backward compatibility and adaptability. Finally, if multi-stream transmission is to be employed, beamspace *signal shaping* is required for both C1 and C2; furthermore, flexible frequency-domain multi-user allocation may be of importance for C2, whereas it can be deemed of lesser importance for C1.

B. Localization

The *aggregate bandwidth* plays a role in terms of delay/distance resolution and accuracy. For L1, a cluttered environment and high accuracy demand a bandwidth on the order of 2–4 GHz if the resolution is to be achieved in the delay domain, while it can go down to 500 MHz when resolution is achieved in the angular domain (see later in Section VI-B). For L2, a bandwidth of 0.4–1 GHz is sufficient. To meet the L2 update rate requirement, the E2E latency should be below 1 ms, which can be met with the considered bandwidth, though 1 GHz is preferred.[2] Under L3, a bandwidth of less than 400 MHz is sufficient. The *waveform type* is largely irrelevant for localization, provided it can be flexible in duration and has a suitable ambiguity function with narrow main lobe and suppressed sidelobes. In terms of *modulation type*, since localization is based on pilots, low-order constant-modulus signals are preferred for L1–L3. Communication should be coherent for L1 and L2 to achieve accuracy beyond the resolution limit, while L3 can rely on more simple non-coherent measurements. To optimize tracking performance, *signal shaping* should be employed in L1 and L2, both for delay estimation (shaping in frequency, leading to a preference for OFDM-like signals) [28] and angle estimation (shaping in beamspace) [29].

C. Sensing

To support cm-level ranging accuracy and resolution in S1 and S2, the *aggregate bandwidth* should be on the order of 2–4 GHz. Similar to localization, the *waveform type* affects the sensing performance only through the main-lobe and side-lobe characteristics of the corresponding ambiguity function. Multi-carrier waveforms, such as OFDM and OTFS, have the advantages of lower side-lobe levels [30] and greater flexibility in signal shaping [31] and removal of the transmit data, over single-carrier ones, at the cost of being less hardware-friendly. With regard to the *modulation type*, sensing requires constant-modulus signals to have favorable side-lobe behavior. S1 relies on both random data and pilots (constant-modulus), while S2 uses only pilots. Hence, S1 can be more sensitive to the modulation type than S2. To achieve high range and angular accuracy in S1 and S2, both use cases should employ coherent measurements. Finally, for the *signal shaping*, pilot allocation could be crucial for S2, while for S1, there are trade-offs between communication rate and sensing performance [28]

VI. REQUIREMENTS ON HARDWARE ARCHITECTURES

The larger bandwidths identified in Section V are available at the upper mmWave and terahertz frequency range. High propagation loss per patch type antenna element at these frequencies drastically limits the signal transmission distance and communication coverage range. In this case, Txs with high output power using antenna arrays is of particular importance, because the degradation of transmitted signal power due to high-frequency hardware technologies highly limits performance. The key hardware impairments include nonlinear distortion (due to power amplifiers, leading also to intermodulation products outside the channel bandwidth), phase noise (induced by RF oscillators at the Tx and Rx chains), quantization noise and mutual coupling between antenna ports.

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[2] Considering OFDM-like waveforms with 4096 subcarriers and 7% cyclic prefix overhead, OFDM symbol duration are approximately 1–10 us for bandwidths in 0.4–4 GHz. Considering slots of 14 symbols, physical layer latency with bi-directional transmission is on the order of 28–280 us.

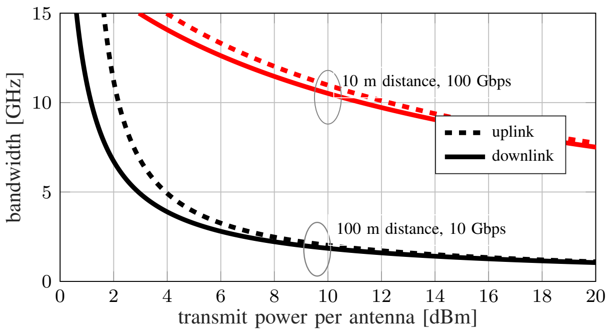

Fig. 3. Example of required bandwidth vs required Tx power per antenna element for achieving a link distance of 10 m and 100 m. A point-to-point communication link with free-space propagation at 140 GHz was considered. Other parameters: 256 BS antennas, 64 UE antennas, BS noise figure 5 dB, UE noise figure is 10 dB, pathloss exponent 2. The sum of power amplifier output back off and Rx sensitivity degradation due to implementation imperfections is 20 dB. For details of the calculation, see [9, Section 3.4.2.2.1].

A. Communication

In Fig. 3 the tradeoff between bandwidth and output power for the use-cases C1 and C2 is illustrated. For the simulation, a point-to-point communication link at a carrier frequency of 140 GHz was assumed. For C2, a bandwidth of around 2 GHz is sufficient, and that for both the uplink and downlink a saturated output power per antenna of around 5 dBm is needed. Increasing the power will not significantly reduce the bandwidth required. For realizing C1 at the same power levels, a bandwidth of around 13 GHz is needed. Note that for the uplink case the required power per element is larger since a smaller number of transmit elements is used compared to the downlink. To mitigate the need for a higher output power per element on the UE side, it is possible to use more than one IN in the uplink, distributed multiple-input multiple-output (D-MIMO) and perform multi-stream transmission. Achieving C1 with a bandwidth of 7 GHz and a single stream is very challenging due to the high output power that would be required, which is another argument for introducing multi-stream/multi-IN/D-MIMO transmission.

B. Localization

L1 and L2 require large bandwidths, which is only available at a high *carrier frequency*. *Channelization* can be used, but phase coherence must be maintained across the entire band for coherent angle and delay estimation (and thus localization). For L3, lower bands (e.g., at 30 GHz or even 6 GHz) are preferred with lower path loss. Localization relies on pilot signals, so that single-stream transmission is sufficient for broadcast signals. When dedicated pilots are used for individual devices or groups of devices, multi-stream pilots are preferred. Hence, in terms of *array types*, planar analog and hybrid structures are sufficient for L1. If stringent latency is required as in L2, digital array structure can help with multi-streams and highly flexible pilot signal design to perform localization within fewer snapshots. Regarding the use case L3, single-antenna UEs are appropriate, due to lower hardware and computation cost. In addition to the beamforming gain, the array size at the BS determines the positioning accuracy, whereas the array size at the UE affects the orientation estimation. The requirements on *array size* are thus variable: for L3, a single omni-directional antenna at the UE and an array at the INs can be sufficient. For L1 and L2, INs array sizes depend on the SNR, position resolution, and accuracy requirements, as well as the considered bandwidth. If a large bandwidth is employed (L1 and L2), this relaxes requirements on the array sizes down to 10–20 elements per dimension are sufficient, with an angular resolution of 5–10 °. With bandwidths below 500 MHz, resolution in the angular domain requires on the order of 50–100 elements per dimension in L1 (1–2 ° resolution). High orientation accuracy demands large array sizes on the user-side, where 10–20 elements per dimension should be considered. To understand the impact of the *transmission power*, it is instructive to consider a simplified 2D uplink scenario (as in Fig. 2), where the localization accuracy in uplink can be expressed as [32]:

$$\mathrm{SPEB}[\mathrm{m}^2] = \frac{N_0 B d^2}{T P_{\mathrm{tx}} \lambda^2} \left(\frac{c^2 \alpha_{\mathrm{range}}}{B^2 N_{\mathrm{rx}}} + \frac{d^2 \alpha_{\mathrm{angle}}}{N_{\mathrm{rx}}^3} \right), \qquad (1)$$

where T is the integration time (in number of transmissions), B is the aggregate bandwidth, N_0 the noise power spectral density, d is the distance between UE and IN, λ the wavelength, c the speed of light, N_{rx} the number of IN antennas, and α_{range}, α_{angle} are constants. Finally, P_{tx} is the transmit power. The first term in (1) captures the distance estimation error, while the second the angle estimation error. Hence, solving (1) for P_{tx} yields a minimum transmission power for a certain target accuracy. We see that P_{tx} can be reduced by increased number of antennas N_{rx} or longer integration times T. The latter approach places demands on the stability of oscillators. For this reason, L1 (operating at short ranges with relaxed integration times) does not require higher transmission power, while L2 and L3 do (the former due to the limited integration time, the latter due to the long link range).

C. Sensing

Both S1 and S2 require operation at high *carrier frequency* due to utilization of large bandwidths for high accuracy and resolution in range. From the perspective of frequency *channelization* [25], S1 and S2 should perform coherent processing across the entire bandwidth. In terms of *array types*, monostatic sensing (S1) can exploit (re-use) both data and pilot symbols generated by the communication system (i.e., opportunistic sensing [30]); hence, the Tx array structure will mainly be determined by the communication requirements (see Sec. VI-A), while analog and hybrid arrays are sufficient for sensing purposes at the Rx side. On the other hand, bi-static sensing (S2) favor pilot symbols due to physically separate transmitter/receiver (Tx/Rx) hardware, which might degrade the performance of range estimation (availability of a smaller portion of time-frequency resources) and angle estimation (decrease in SNR) compared to S1. Hence, S2 Rx can be equipped with a hybrid or digital array to compensate for this performance loss. Moreover, to support 1° degrees of angular resolution for S2, the Rx *array size* should be at least 100 elements per dimension (35 for S1). Contrary to the Rx side, the array size at the Tx has no impact on the angular resolution. The array size can thus vary depending on requirements on the range and angle accuracy, which, in turn, are functions of SNR, bandwidth and Rx array size. In the case of large bandwidths (2–4 GHz) and/or large Rx arrays (100 elements per dimension), small Tx arrays with 10–20 elements per dimension can be sufficient to support both S1 and S2 accuracy requirements, while for smaller bandwidths (below 1 GHz) and smaller Rx arrays (10–20 elements per dimension), S1 and S2 requires 40–50 elements per dimension at the Tx array to boost SNR towards the desired object locations. An important distinction between localization and sensing pertains to the *transmission power*. Since sensing (especially, S1) needs to combat higher path loss (d^4, where d is the distance) than localization (d^2), the transmit power should be larger for sensing. However, such high power requirements for sensing may bring additional hardware complexities. For monostatic sensing (S1), the Tx and receiver are co-located and work in full-duplex mode, which necessitates perfect decoupling of Tx/Rx antenna arrays to prevent self-interference [24], [33], [34]. On the other hand, for bi-static sensing (S2), the Tx/Rx arrays are far from each other, meaning that perfect isolation is not an issue.

VII. REQUIREMENTS ON DEPLOYMENTS

Seen from a joint communication, localization, and sensing performance perspective, the network planning problem is complex. The main reason is that multiple metrics need to be optimized simultaneously: coverage, capacity, positioning error, sensing error.

A. Communication

Traditionally, the deployment of communication networks targeted *wide coverage* and *high capacity* [35] subject to cost constraints. Except for the compulsory emergency location services provided by the cellular network operators under regulatory mandates, localization and sensing services were disregarded in the network planning phase. By contrast, the future 6G networks shall provide integrated communication and sensing services to support emerging use cases such as industrial applications, augmented reality, etc. Moreover, fulfilling challenging joint coverage, reliability and throughput requirements can be made possible by distributed deployments. The promising D-MIMO communication technology inherently implies (sub-)nanosecond synchronization among densely deployed network nodes, as well as multiple antennas both at Tx and Rx, which benefit from reduced path loss and macro-diversity mitigating shadowing/blocking.

B. Localization

Similar to communications, the *placement* of localization infrastructure also targets wide coverage, but its primary goal is to minimize the localization error rather than rate. Also different from communication, localization of a device requires a plurality of INs and the corresponding performance depends not only on the SNR, but also on the relative geometry of the INs, through the so-called geometric dilution of precision (GDOP): with delay-only measurements each device needs LoS to at least 3 BSs in LoS under round-trip-time (RTT) and 4 under TDoA for UEs in the convex hull of these BSs. With angle-only measurements, at least 2 INs (2 BSs or one BS and one RIS, which is a minimal configuration). In addition to adopting multiple INs, geometry diversity can be achieved by exploiting the multipath components [36]. In this case, the surrounding environment can serve as passive INs (e.g., virtual anchors) for a better localization performance. While BS placement will be limited to existing sites or other constraints, RISs can be placed in an optimized manner to meet GDOP requirements. Based on these considerations, L1 and L2 would need at least 2 INs visible at any time, while L3 should rely on at least 3–4 INs, as long-range links rely on time-based measurements (cf. Fig. 2). The *synchronization* requirements are a function of the employed time-based measurements.[3] Time-difference-of-arrival (TDoA) requires fine timing synchronization among the INs, on the order of 1–10 ns for L3, around 0.5 ns for L2, and around 100 ps for L1. For coherent combining across different INs (e.g., using D-MIMO), synchronization requirements are even more demanding, as they relate to the signal phase. To relieve these requirements, RTT measurements can be used, which only impose local clock stability requirements, but scale worse than TDoA under high user density. Estimating the synchronization error (clock offset) during the localization phase is another option to mitigate the effect of clock drift. Finally, accurate localization requires accurate *knowledge of the locations* of the INs: both the 3D location, the 3D orientation (for AoA), and the phase center must be determined. L3 can cope with errors on the order of tens of centimeters. For L2 and L1, extreme demands are placed on calibration, which will likely require novel procedures (either offline or online). Since small orientation errors lead to large location errors (see Fig. 2), extremely precise orientation calibration is needed for INs, when UEs are farther away from the INs.

C. Sensing

In monostatic sensing (S1), the *placement* should be such that it provides sufficient coverage in the deployment region. Multiple INs need to coordinate transmissions to avoid interference. For bi- and multistatic sensing (S2), the placement problem is similar to localization (see Section VII-B with related GDOP notions), though with larger path loss. The combination of angle and TDoA (with respect to the LoS path) measurements provides a 3D picture of the environment. Statistical error bounds may be used to optimize the deployment jointly for localization and sensing in both S1 and S2. In terms of *synchronization*, S1 does not impose any requirement, while

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[3] AoA measurements only need rough synchronization to know which BS precoder or RIS configuration is used at which time.

under S2, tight inter-IN synchronization is needed when no LoS link is present between the Tx and Rxs. Finally, in terms of *IN knowledge*, S1 imposes no requirements, as sensing is performed in the frame of reference of the monostatic sensor. For S2, requirements are similar to localization.

VIII. CONCLUSIONS

6G use cases feature extreme requirements in terms of communication, localization, and sensing KPIs. The purpose of this paper was to systematically investigate the corresponding requirements in signals, hardware architectures, and deployments. From the summarizing Table I, it is apparent that to support a combination of use cases, the following combination is preferred: aggregate bandwidths around 5–10 GHz with channels of around 2 GHz at carriers above 100 GHz, flexible multi-carrier waveforms and coherent communication, with possibility to shape signals in space, relying on analog or hybrid arrays with tens of elements per dimension at both transmitter and receiver side. Transmit power requirements are moderate to high, but each user must be able to have LoS visibility to several INs, which may include RISs. Very high demands are placed on calibration in terms of location and orientation knowledge of the INs, as well the synchronization.

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