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Full Network Sensing: Architecting 6G beyond Communications

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Abstract—As requirements for 6G systems start being shaped, we propose the provoking vision that the future generations of mobile networks shall reach beyond their traditional role of enablers for communication services. In fact, mobile networks have an impressive untapped potential for dual use as a pervasive remote sensing platform, which, if duly exploited, can support compelling original applications across a variety of domains. Unlocking this capacity requires a systematic end-to-end integration of sensing functionalities in the mobile network architecture beyond radio access, on a level and in synergy with classical data transport operations. In this paper, we formalize the vision above as the *full network sensing* paradigm. We discuss representative use cases for full network sensing, and requirements towards its implementation. We lay out a conceptual model for the integration and management of sensing functionalities into modern mobile network architectures, and present open technical challenges to realizing the full network sensing vision. These contributions lay the very first principles to a disruptive paradigm that can unlock new markets for mobile network providers, and support innovative remote sensing services that benefit the society at large.

Index Terms—Mobile networks, 6G, remote sensing, full network sensing.

INTRODUCTION

Mobile networks have been designed and deployed for almost forty years with the objective of enabling anytime and anywhere communication services. The evolution of such services, summarized in Figure 1, has been astounding: gigantic leaps have been made since the undependable and expensive voice calls of the 80's, all the way to today's wide range of apps and connected objects.

The attention of the research community is now shifting to the future sixth generation (6G) of mobile networks, via the definition of reference use cases, relevant Key Performance Indicators (KPIs) and their associated targets, as well as technological innovations capable of meeting them. Early contributions agree on several important facets of 6G, like the utilization of sub-THz and Visible Light Communications (VLC), the need for three-dimensional cell-less coverage, the extensive integration of network intelligence for zero-touch network and service management (ZSM), or the reduced communication power requirements to boost device battery lifetime [1], [2].

Still, current proposals for 6G remain strongly bounded to the classical recognition of mobile networks as distribution systems for data traffic exchanged with mobile devices. The services they enable –although increasingly complex and creative– are invariably communication-based, *i.e.*, rely on the network infrastructure exclusively to transfer the information they generate. While there is no question about the paramount utility of mobile networks as a pillar of ubiquitous communications, a transition between generations represents an opportunity to introduce more disruptive ideas that part from such a conventional understanding.

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This paper sets forth a groundbreaking and likely controversial vision for 6G systems as globally pervasive, high-resolution, privacy-preserving and cost-effective platforms for remote sensing. We formalize this vision as the *full network sensing* paradigm, to disambiguate from the current acceptation of network sensing as a radio-access-only capability focused on localization. Indeed, our proposal has a much wider scope, and aims at a systematic integration of sensing functionalities across all domains of the mobile network architecture, allowing services to tap into the rich metadata that flow in the *whole* network infrastructure.

As illustrated in Figure 1, full network sensing would allow 6G to support a completely new family of services in the remote sensing domain. Rather than relying on mobile networks as the transport system for their data like traditional mobile applications, such services would leverage mobile networks as a *source of heterogeneous data* to fuel knowledge discovery and informed policy-making in a variety of contexts beyond classical telecommunications.

MOBILE NETWORKS AS DATA SOURCES

Mobile networks produce vast amounts of in-network traffic that is presently regarded as communication overhead. Layered protocol headers as well as signalling and control traffic embed raw data that outline, *e.g.*, the location of each mobile device, the end hosts and requirements of the services it runs, or its interactions with other user equipment. These metadata are essential to the network operation, and enable functions like paging, resource allocation, control plane orchestration, or accounting. However, the same metadata also contains rich information about the mobility, activities, habits and relationships of people, which are generated ceaselessly and with nearly ubiquitous coverage.

As a result, the data available within the network infrastructure has significant applications across a variety of knowledge domains. In sociology, it helps revealing

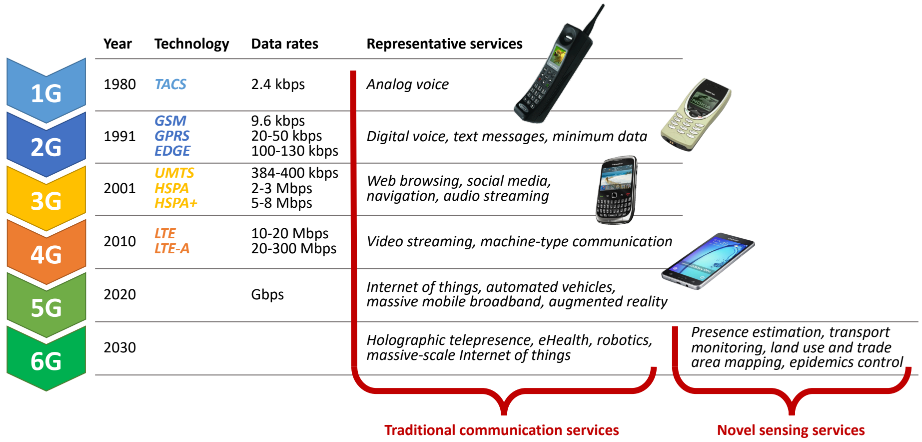

Fig. 1: Evolution of mobile network technologies through generations, with representative applications. Our vision for 6G is that traditional support for communication services is extended to remote sensing services, de-facto doubling the purpose of the network infrastructure.

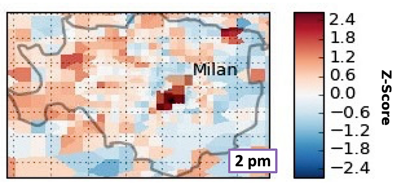

Fig. 2: Example of dynamic population density estimation with mobile network metadata. The plot shows a map of the z-score of the population density in Milan, Italy, at 2 PM on April 25, 2015. Dark regions denote a significantly increased human presence along the course of a public march in the city center, whose number of participants can be also inferred with network metadata. Figure from [9].

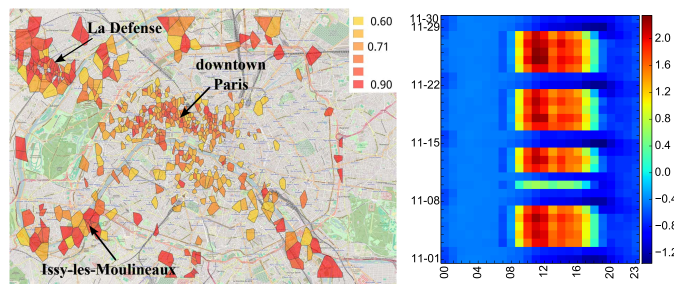

Fig. 3: Sample outcome of exploratory factor analysis of mobile network metadata for land use mapping. The map (left) highlights geographical regions in Paris, France, that are dominated by an office land use, with darker colors denoting a higher prevalence of businesses. These areas are strongly characterized by a high normalized network activity during work hours only (right – hours from 0:00 to 23:00 are on the abscissa, and days during four weeks are on the ordinate). Figure from [10].

personal communication structures [3], or mapping social segregation [4]. In economy, it allows characterizing trade areas of commercial activities [5]. In transports, it can expose origin-destination matrices [6] or road traffic conditions [7]. In epidemiology, it enables modelling the spreading process of infectious diseases, and the consequent development of techniques for their containment [8], whose significance is demonstrated by the COVID-19 outbreak. In all these scenarios, mobile network metadata emerge as a very effective enabler for sensing tasks that are otherwise expensive, impractical or technically convoluted to perform at scale. We provide below three practical examples of such a capability.

Dynamic population density estimation

The distribution of people over a territory is typically expressed in terms of dwelling units, *i.e.*, structures used as a domicile by persons, and is traditionally obtained via costly, labour-intensive surveys. Recent solutions in geoinformatics apply machine learning to high-definition satellite images to automate the process. However, they only detect household densities and their variations at timescales of months. Instead, they cannot track the changes of population presence caused, *e.g.*, by regular daily human activities like commuting, which occur at order-of-minute timescales.

Mobile network metadata about the location and communication activity of users can make the accurate estimation of dwelling unit density inexpensive; more importantly, these data also allow sensing much more rapid variations of population densities. Multivariate models in the literature take advantage of such information to achieve 10% error in estimating populations within the coverage area of each base station on an hourly basis [9], as illustrated in Figure 2.

However, these performance figures are still far from those needed for a practical sensing service. As indicated in Table 1, urban planners would require a spatiotemporal resolution of the population estimate in the order of tens meters and minutes, updated in quasi real-time on network metadata available within minutes from their generation.

Land use mapping

Urban land use describes the socioeconomic utilization that is made of the city territory. It tells apart, *e.g.*, areas that are characterized by residential and industrial usage, cultivated fields, or green zones in a city. Even within cutting-edge initiatives such as European Union's LUCAS, land use mapping is presently performed mainly by surveyors on

Sensing service	Information	(metadata)	Accuracy	Latency	Methods
Dynamic population density estimation	Mobile subscriber presence Activity level	(location) (per-user traffic)	10 m / 5 min	minutes	Multivariate model [9]
Land use mapping	Mobile service demands	(geolocated data traffic volume)	50 m / 10 min	days	Exploratory Factor Analysis [10]
Multimodal transport flow detection	Mobile subscriber position End terminal displacement	(location) (signal strength)	1 m / 1 s	seconds	Hidden Markov Model [11]

TABLE 1: Representative examples of services enabled by network sensing, along with their requirements in terms of input information and underlying metadata, spatial and temporal accuracy, and information provisioning latency. The last column reports state-of-the-art models for such services.

the field, which is an extremely time-consuming approach. In-progress investigations that leverage satellite imagery to fulfil this challenging task are also bound to produce a zoning limited to the macroscopic land usages listed before.

Instead, information extracted from mobile network metadata can bring land use mapping to a whole new level, thanks to the fact that subscribers consume mobile services in different ways depending on their current activity. As exemplified in Figure 3, experiments with data traffic volumes recorded at each base station on an hourly basis demonstrate that exploratory factor analysis on such metadata can tell apart much more nuanced urban functions, including transportation hubs, commercial zones, education infrastructures, sports facilities, or urban areas that are especially popular for work lunches and nightlife [10].

Still, attempts at metadata-driven land use mapmaking presently suffer from a low geographical resolution, due to the large coverage areas of individual base stations, which span from hundreds of square meters to square kilometres.

Multimodal transport flow detection

Transportation solutions in cities are increasingly dense, complex and interdependent, with a growing offer of modes that includes the likes of walking, scootering, biking or driving, as well as public vectors such as subways, buses, and light trains. This fosters multimodal mobility, *i.e.*, transport mode changes within a same trip. Monitoring and unravelling multimodal travel is a difficult and open problem, whose solution has significant applications in, *e.g.*, transport planning or social segregation mitigation.

Legacy approaches based on, *e.g.*, ticketing, traffic counts, or, more recently, digital data about shared vehicle usage can only monitor users within a single transport mode. Solutions based on mobile network metadata remove this barrier, as they can follow individuals across modes, hence enabling the tracking of major multimodal flows in metropolitan regions. Attempts at large (*i.e.*, citywide) scale have been carried out using Hidden Markov Models on location observations mapped to a multi-layered representation of the communication and transportation networks [11].

Depending on the transportation mode, current solutions achieve a variable recall and precision in the 40%–85% range, when the mobile subscriber location is sampled at every 15 minutes. These numbers are hardly suitable for a production service, which, as per Table 1, would achieve near 100% accuracy by leveraging high-resolution data with spatiotemporal granularity close to the meter and second.

NETWORK METADATA FOR REMOTE SENSING

Those above are just three examples of the many compelling remote sensing services that mobile networks could potentially nourish, yet they yield needs that can hardly be met by today's mobile networks. Unsatisfactory error levels, insufficient spatiotemporal resolution of the output, and lack of support for real-time operation are barriers that relegate all studies conducted to date on sensing applications based on mobile network metadata to the status of academic exercises that are not transferred into production systems despite their relevance to varied application domains.

Requirements of full remote sensing

The needs of full remote sensing can be unfolded in terms of quality, provisioning and privacy of the metadata provided by the mobile network, as follows.

Network metadata quality and scope. The accuracy and precision of sensing services primarily depends on the quality of the metadata provided by the network. Most studies proposed to date rely on scant metadata, typically in the form of Call Detail Records (CDR) that log geo-referenced and time-stamped interactions of the end terminals with the network infrastructure occurring during calls, text messages and possibly data traffic sessions. CDR are easily accessible since they are maintained in curated databases for accounting purposes, but they only capture superficial information, with poor cell-level spatial resolution and sparse, irregular sampling in time due to the inconsistent activity of users. The improving monitoring capabilities of mobile network infrastructures are making richer metadata more accessible: leading operators are presently deploying a variety of probes tapping at the interfaces of network entities and gateways that can gather detailed information about user movements and service usage [12].

Still, even state-of-the-art metadata collection platforms have limited spatiotemporal resolution, *e.g.*, to the level of cells covering hundreds of square meters each and with infrequent location updating for idle devices. Moreover, existing platforms are completely focused on network operation, gathering hundreds of KPIs about resource utilization or Quality of Service (QoS): while paramount to the management of the infrastructure for traditional communication-based services, these KPIs are irrelevant to or not directly usable by remote sensing, which would instead require accurate metadata about, *e.g.*, user presence or demand patterns. Obtaining these metadata is presently a cumbersome and ad-hoc effort of processing raw KPIs in the attempt to align them to the requirements of sensing services.

Network metadata collection and provisioning. Many sensing applications need live information to be effective, which calls for real-time metadata collection. Most of the scientific literature building on network metadata relies on historical information that is provided weeks after collection, upon sanitization and aggregation processes; while data gathered in this way can be replayed for proof-of-concept investigations, they are clearly unfit to operation in production. State-of-the-art live network monitoring systems can provide KPIs in near-real-time, *e.g.*, with sub-second delays within RAN equipment; however, the latency tends to grow substantially as the consumer is located farther from the end terminals, and easily reach tens of minutes for over-the-top tenants –violating the specifications of many sensing applications, such as the multimodal transport flow detection presented before.

Network metadata privacy. The vision of pervasive remote sensing through mobile networks raises clear concerns in terms of privacy. The metadata needed by sensing applications may include personal and sensitive information, including the movements of mobile subscribers, their interactions, or the nature of mobile services they consume. It is thus of paramount importance that network sensing abides by sound privacy-by-design practices [13].

Currently, simple practices are adopted, such as removing personal identifiers from user-level metadata or performing arbitrary aggregations, which are acceptable as long as the data does not leave the secure premises of the operators. As full remote sensing assumes that the metadata is exposed to third-party service providers, such basic approaches will need to be replaced by provably secure methods that can guarantee the privacy of the data subjects.

Remote sensing and 5G technologies

The deployment of 5G systems is making important steps towards full network sensing, introducing functionalities that will benefit our proposed vision, especially in terms of localization and metadata management. Yet, 5G fundamentally remains a communication technology that only indirectly tackles the requirements introduced above, which leaves gaps to be filled by future network generations.

Localization. 3GPP Release 16 includes specifications for mobile device positioning that are driven by sensing use cases. Targets include sub-meter resolution, 99% availability and order-of-second latencies in both indoor and outdoor conditions, to be achieved by bolstering classical approaches like observed time-of-arrival (TOA) based on timing advance (TA), time difference-of-arrival (OTDOA), or uplink time difference-of-arrival (UTDOA) with 5G radio technologies such as massive multiple-input–multiple-output (MIMO) beamforming or millimetre wave (mmWave) signals [14]. In this way, 5G addresses well the requirements of metadata quality in terms of positioning accuracy.

Metadata management. The requirements previously outlined for metadata provisioning and privacy build on a proper metadata management pipeline. The emergence of data-driven network management has fostered the standardization of structures for data collection and analytics in 3GPP standards for 5G, such as the Network Data Analytics Function (NWDAF) in the control plane and the Management Data Analytics Function (MDAF) in the management and orchestration (MANO) domain. NWDAF And MDAF collect data from generic network functions, and support analytics that transform such data into information that can be consumed by other network functions via a subscribe model. The concept behind these functions is general enough that it can be potentially extended to encompass the needs of network sensing, providing an interesting unified approach to metadata collection for both communication-based and sensing services.

Limitations of 5G for sensing. While it lays interesting potential foundations for sensing support, 5G does not fully embrace the vision of the mobile network as a remote sensing infrastructure. As a result, the requirements presented earlier are not addressed in a systematic way in 5G architectural models, and significant gaps remain.

In terms of metadata quality and scope, network sensing is understood in 5G as a positioning and spectroscopy service only [15]. Instead, *full* network sensing is a much broader paradigm that pushes high quality requirements for metadata beyond location and towards, *e.g.*, detailed user activity levels, precise mobile application usages, or high-resolution spatiotemporal demand profiles. This creates a need to evolve the whole end-to-end network, and not just part of its radio access, into a sensing infrastructure.

Concerning metadata collection and provisioning, functions like NWDAF or MDAF can exchange data and analysis results with different network and applications functions, but are still exclusively designed for communication-based scenarios. The use cases they support, such as load levels, resource status and usage, misuse of devices or QoS changes are misaligned with the needs of full network sensing, and 5G activities do not present any roadmap for extension of such use cases to remote sensing assistance. Moreover, exposure of network metadata to third-party tenants is very cumbersome, and interfaces for service providers to interact and possibly drive the metadata collection process are absent. All these are fundamental operations in full network sensing.

Metadata privacy is also not adequately supported in 5G, mainly because all data-related operations are expected to concern network management tasks and thus to stay confined within the network infrastructure. In absence of suitable routines for privacy-preserving real-time data exposure, it is easy to anticipate that little will change in 5G with respect to current practices of having only historical metadata that is sanitized offline leave the network domain for added-value applications.

All these limitations stem precisely from the fact that remote sensing is regarded as a second-class citizen in today's mobile networks. Introducing individual patches in order to support specific remote sensing applications is an opportunistic approach that cannot offer a structured support to any sensing service, and thus fails to abide by the full network sensing concept we propose.

Designing mobile networks for sensing

Closing the gap between conceptual designs and operational network-driven remote sensing requires a major change in mindset: we shall stop *exploiting* mobile networks for sensing, and instead start *engineering* networks for sensing. This fundamental shift is the cornerstone of the full

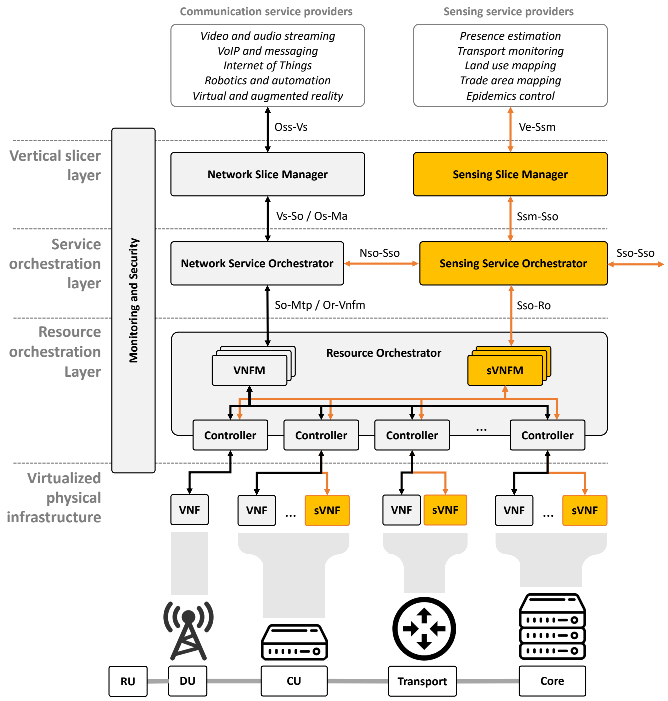

Fig. 4: Architectural concept for the integration of full network sensing functionalities in a modern sliced mobile network infrastructure.

network sensing vision we propose for 6G: probes, functions and management structures dedicated to sensing shall be *natively* integrated into the mobile network architecture, towards ensuring a systematic and comprehensive support for high-quality sensing services. Fulfilling the full network sensing vision would establishing a *dual use* for mobile networks as remote sensing platforms, and unlocking new markets for mobile network operators.

A 6G architecture for full network sensing

As a first step to close the gap above, we argue that the basis for a sensible support of full network sensing is a drastic update of the architectural design, which logically separates communication and sensing so as to emphasize the entirely different way in which such types of services use the same network infrastructure. This separation is instrumental to realize a synergic co-existence of the two purposes, by defining, implementing and managing clear priorities, and avoiding harmful conflicts in the access to resources. We thus propose a *sensing-native architecture* for 6G networks that aligns with this specification while preserving synergies between the new two purposes of the network infrastructure.

We ground our concept on a baseline 5G architecture, portrayed by the light gray boxes in Figure 4, aligned with current standardization efforts by ETSI[1], and 3GPP[2], as well as state-of-the-art research initiatives, such as the 5G-TRANSFORMER project[3]. Network sensing functionalities are integrated into the existing layering and highlighted in gold in the figure.

Sensing Slice Manager (SSM). Similarly to traditional communication-based service providers, a whole new class of verticals can now develop sensing services on top of network functionalities. The concept of slicing is very relevant to such sensing services, which call for strong guarantees on their very diverse requirements. To this end, the SSM defines a set of vertical sensing service blueprints in a catalogue to be offered to the novel verticals. The high-level sensing service description provided by the vertical is translated into low-level sensing functionalities and resource requirements by the SSM, which also map services to sensing slices. The SSM operates on very different logics than legacy NSM, since sensing slices have heterogeneous requirements that are semantically different from those of traditional network slices: for instance, traditional network KPIs are replaced by, *e.g.*, the level of aggregation, the spatiotemporal accuracy, or the update frequency of the data needed for a specific sensing service). Such new classes of requirements and need a clean-slate, dedicated translation service into logical functions and resources.

Sensing Service Orchestrator (SSO). The SSO receives requests from the SSM to create or update nested sensing services that implement the sensing slices. It is in charge of providing end-to-end orchestration of complex sensing services across multiple technological domains (*e.g.*, radio access, transport, or core) or administrative domains (*e.g.*, telecommunications networks, cloud operators, or sensing providers). Eventually, resource-related requests are generated towards the underlying layer to assign virtual resources for the actual deployment of the sensing services.

Sensing VNF manager (sVNFM). The sVNFM is responsible for managing the network, computing, and storage resources, as well as the orchestration and instantiation of Sensing Virtual Network Functions (sVNF), which form each sensing service over the physical infrastructure. In general, there will be multiple sVNFM instances acting on diverse technology domains and resource types, which sit into the overarching Resource Orchestrator (RO). Such sVNF are independent from legacy VNF, as they have to answer unique needs, such as performing distinctive data fusion on fields of control traffic headers that are unimportant to network management. Also, the separation of sVNF from VNF is instrumental to ensure full independence of operation across communication and sensing functionalities, and avoid disruption due to conflicts between the two tasks.

It is worth noting that sVNF and traditional VNF will ultimately *share* the physical and data management infrastructure: for instance, line-rate telemetry VNF for network monitoring and optimization shall be implemented in programmable switches along with real-time sensing data collection and preprocessing routines; or, the analysis functions for communication and sensing services may have to access the same metadata (*e.g.*, for localization) in the MDAF and NWDAF structures. To maximize synergies and avoid duplication of tasks, VNFM and sVNFM will interact through a *unified* interface with the same set of controllers and data management functions, which will then harmonize the access to the infrastructure and metadata. If needed, the RO will also provide a global coordination of VNFM

1. `https://www.etsi.org/technologies/nfv`.
2. `https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3657`.
3. `http://5g-transformer.eu/`.

and sVNFM for optimal utilization of resources across various controllers corresponding to different resource types. Besides, the RO will grant different levels of visibility of the resources through abstracted information (*e.g.*, capacities, availability, connectivity) to hide the complexity of the different technological domains.

Monitoring and security stratum. Monitoring and security services will be required that are transversal to all architectural layers above. In particular, security services shall be enacted across all layers to ensure that suitable privacy-preserving mechanisms (*e.g.*, pseudonymization, anonymization, aggregation, generalization, or equivalent transformations) are adopted as soon as possible in the data collection and processing chain that stems from the physical infrastructure to reach verticals. Thankfully, the full network sensing paradigm is inherently well suited to guarantee the privacy of data subjects and the security of the collected data. Indeed, mobile networks are physical infrastructures with clear logical boundaries and a limited set of gateways to the external world: they are *"silo"* environments, *i.e.*, an ideal milieu for proper regulation and verification of privacy-preserving data management processes. For instance, they are ideal hosts for state-of-the-art privacy-preserving data mining models where analytics (*e.g.*, for remote sensing) are fed to the data controller, and only a differentially private output is shared with the requesting party, *e.g.*, as per the OPAL model[4]. If duly regulated and standardized, mobile networks may become a privacy-friendly remote sensing ecosystem that can build trustworthiness between the data owners (i.e., operators) and the data subjects (i.e., end users), unlike what happens today with the murky data collection, protection and monetization strategies adopted by service providers that gather metadata directly from user equipment.

Open challenges towards operational sensing

The architectural concept lays the foundations to a network whose new dual use is logically separated, but it is a frame that needs to be filled with the technical innovations necessary to solve the many open challenges for the practical realization of full network sensing. Therefore, a foremost challenge is that of implementing the different architectural blocks in Figure 4, *e.g.*, by designing dedicated planning and dimensioning strategies that prioritize metadata accuracy KPIs over traditional communication-oriented KPIsl; or, by developing the needed management and orchestration routines that shall run in SSM, SSO and sVNFM, and ensure a smooth end-to-end operation of remote sensing functions. Beyond that, a number of critical technical issues arise, the most critical ones being outlined next, and portrayed in the context of the current 3GPP and O-RAN architectural model in Figure 5.

Programming the infrastructure for dual use. Dedicated privacy-preserving sVNF must be developed and deployed across network domains. These sensing-native functions shall operate as configurable monitoring probes that inspect traffic according to rules that are very different from those commonly adopted to support networking tasks like traffic engineering, load balancing, or service differentiation. sVNF may target tasks such as examining fields in protocol headers of control plane packets that are not monitored by traditional measurement platforms (*e.g.*, location identifiers in signalling traffic) or performing unconventional data de-noising and aggregation (*e.g.*, computation of idle user presence based on the most recent of location identifiers).

User plane programmability, which is expected to reach full maturity with 6G systems, may play an important role in the implementation of sVNF. Indeed, other than enabling advanced VNFs for flexible network monitoring and management, programmable switches, smartNICs and Network Processing Units (NPUs) lend themselves to implementing in-band probes that filter and capture the traffic headers and fields containing the metadata required by the diverse remote sensing applications. Also, programmable switches can be instructed to partially pre-process the collected metadata at line rate, so as to bring the provisioning of sensing information much closer to the requirement of real-time data provisioning. Finally, the technology presents clear opportunities for immediate de-personalization of the collected information: for instance, statistical aggregation enforced directly within programmable switches would ensure privacy in the data as soon as they are gathered. Yet, leveraging programmable user planes for sensing is a greenfield research subject as of today.

Cross-domain metadata collection. Remote sensing needs metadata that is often obtained by merging information available from different network domains: for instance, accurate geo-referenced demands for specific mobile applications require crossing signalling information about device locations in the RAN with traffic classification results that are only available in the core network. The gathering of cross-domain metadata is uncommon for traditional network management, where the vast majority of decisions are local and thus rely on domain-specific information. Yet, such gathering must be realized efficiently and rapidly to meet the requirements of downstream remote sensing applications. Ultimately, the metadata to support full network sensing have to be collected at and beyond the radio access, which calls for dedicated and coordinated measurements in the edge, transport, and core domains. This requires, *e.g.*, synchronization of NWDAF, MDAF and Subscribed Data Storage functions with the Data Management and Exposure function of the Non-Real-Time Network Intelligent Controller (NRT-RIC) or the Shared Data Layer (SDL) of the Near-Real-Time RIC (nRT-RIC) of O-RAN, and, again, is a vastly unexplored field today.

Structured exposure and control of network metadata. Sensing service providers must be granted immediate ways to access metadata gathered in the network, as well as to control the collection process. This calls, *e.g.*, for a redesign of the very limited capabilities of the Application Function (AF) of the 5G Service-Based Architecture (SBA) in sensing-native 6G models that create an explicit direct loop between third-party tenants and the data-related functions of the network. Sensing tenants shall then be able to use the augmented AF to subscribe to specific metadata sources, even those located deep into the infrastructure, with specified resolution of information, geographical coverage of the results and frequency of their updates. Importantly, the new AF shall allow these new tenants to parametrize the

4. `https://www.opalproject.org/`.

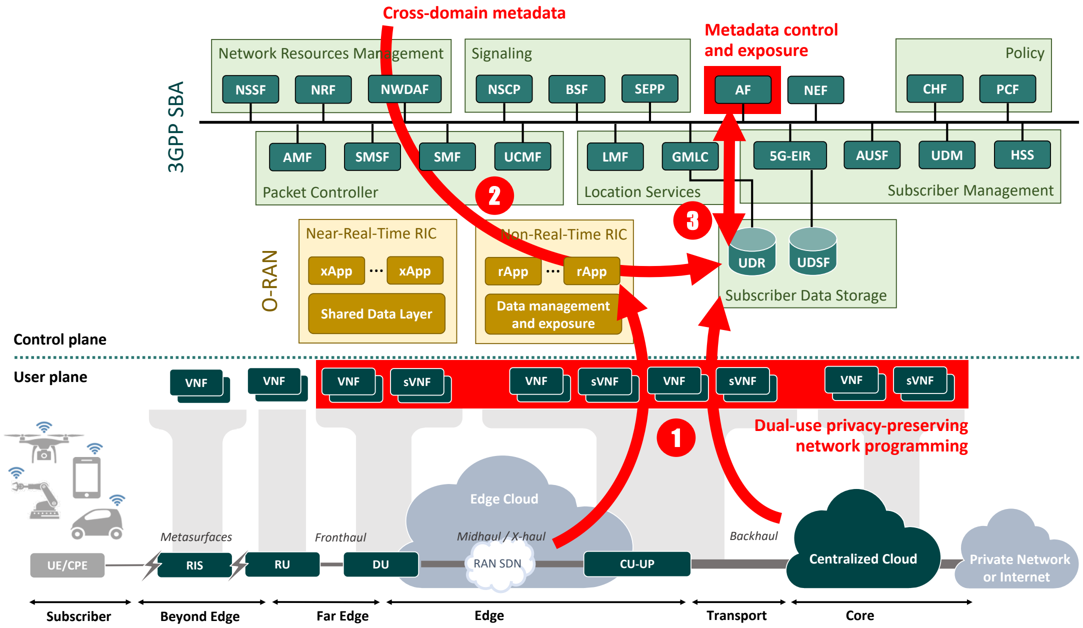

Fig. 5: Key technical evolutions within the current 5G architectural model proposed by 3GPP and the O-RAN Alliance, towards native support for full network sensing. ① Programming the infrastructure for dual use in a privacy-preserving way. ② Enabling cross-domain collection of metadata for sensing. ③ Supporting exposure and control of metadata collection by remote sensing service providers.

metadata collection, *e.g.*, by enacting proprietary policies for metadata sampling, or deciding which measurement vantage points to activate, so as to ensure an optimal use of the available sVNF. All these specifications open brand new directions for AF development in 6G.

Rentability of full network sensing. An important question is whether the foundational change presumed by the full network sensing paradigm strike a positive balance between cost and benefit for the operators. This aspect deserves thorough analysis, and calls for a planning and implementation of the whole paradigm that takes economic viability into account. At this conceptual stage, we argue that costs can be small compared to the gains. Indeed, the required modifications all build on the exact same virtualized infrastructure already employed by legacy communication-based services, hence do not introduce capital expenditure (CAPEX) overheads, which constitute the bulk of the cost for operators at the moment of deploying new technologies. In terms of benefit, the software-only modifications needed to support our full network sensing vision yield a promise to open large and brand new markets to mobile operators, allowing them to capitalize on data-based services that are today much more rentable than communication-based ones.

Operators could in fact incentivize end users to opt-in for full remote sensing functionalities, in return for access to added-value services that the paradigm supports, similar to what happens nowadays with many free mobile services. Here, in fact, the more regulated and protected environment represented by mobile networks would likely foster trust and adoption of the technology by the data subject, which is often a barrier for legacy mobile services in presence of privacy-wary customers.

Ultimately, we posit that full network sensing has the potential to let operators start finally competing on more fair grounds with the large service providers that are gaining increasingly dominating positions in the telco ecosystem.

Conclusions

Full network sensing is a concept that challenges the fundamentals of past and current generations of mobile networks, with the potential to unlock new markets for mobile operators and support innovative services that benefit the society at large. Realizing this vision requires exploring new, compelling and interdisciplinary directions for research in telecommunications, towards designing 6G systems that are coherent sensing platforms in addition to high-performance communication infrastructures.

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References

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, “Toward 6g networks: Use cases and technologies,” *IEEE Communications Magazine*, vol. 58, no. 3, pp. 55–61, 2020.

[2] C. J. Bernardos and M. A. Uusitalo, “European Vision for the 6G Network Ecosystem,” The 5G Infrastructure Association, Tech. Rep., 2021.

[3] M. Karsai, N. Perra, and A. Vespignani, “Time varying networks and the weakness of strong ties,” *Scientific Reports*, vol. 4, no. 4001, 2014.

[4] D. Rhoads, I. Serrano, J. Borge-Holthoefer, and A. Solé-Ribalta, “Measuring and mitigating behavioural segregation using call detail records,” *EPJ Data Sci.*, vol. 9, no. 5, 2020.

[5] Y. Zhao, Z. Zhou, X. Wang, T. Liu, Y. Liu, and Z. Yang, “Celltrademap: Delineating trade areas for urban commercial districts with cellular networks,” in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, 2019, pp. 937–945.

[6] P. Bonnel, M. Fekih, and Z. Smoreda, "Origin-destination estimation using mobile network probe data," *Transportation Research Procedia*, vol. 32, pp. 69–81, 2018, transport Survey Methods in the era of big data:facing the challenges.

[7] A. Janecek, K. A. Hummel, D. Valerio, F. Ricciato, and H. Hlavacs, "Cellular data meet vehicular traffic theory: Location area updates and cell transitions for travel time estimation," in *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, ser. UbiComp '12. New York, NY, USA: Association for Computing Machinery, 2012, p. 361–370.

[8] A. Lima, M. De Domenico, Pejovic, and M. Musolesi, "Disease containment strategies based on mobility and information dissemination," *Sci Rep*, vol. 5, no. 10650, 2015.

[9] G. Khodabandelou, V. Gauthier, M. Fiore, and M. A. El-Yacoubi, "Estimation of static and dynamic urban populations with mobile network metadata," *IEEE Transactions on Mobile Computing*, vol. 18, no. 9, pp. 2034–2047, Sep. 2019.

[10] A. Furno, M. Fiore, and R. Stanica, "Joint spatial and temporal classification of mobile traffic demands," in *IEEE INFOCOM 2017 - IEEE Conference on Computer Communications*, May 2017, pp. 1–9.

[11] F. Asgari, A. Sultan, H. Xiong, V. Gauthier, and M. A. El-Yacoubi, "Ct-mapper: Mapping sparse multimodal cellular trajectories using a multilayer transportation network," *Computer Communications*, vol. 95, pp. 69 – 81, 2016, mobile Traffic Analytics.

[12] D. Naboulsi, M. Fiore, S. Ribot, and R. Stanica, "Large-scale mobile traffic analysis: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 124–161, 2016.

[13] Y. de Montjoye, S. Gambs, V. Blondel, and et al., "On the privacy-conscientious use of mobile phone data," *Sci Data*, vol. 5, no. 180286, 2018.

[14] S. Bartoletti, A. Conti, D. Dardari, and A. Giorgetti, "5g localization and context-awareness," in *5G Italy White Book: from Research to Market*, M. Ajmone Marsan, N. Blefari Melazzi, and S. Buzzi, Eds. Parma: CNIT, 2019, ch. 14, pp. 167–187.

[15] C. De Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E.-S. Lohan, Y. Miao, A. N. Barreto, M. R. K. Aziz, J. Saloranta, T. Sanguanpuak, H. Sarieddeen, G. Seco-Granados, J. Suutala, T. Svensson, M. Valkama, B. Van Liempd, and H. Wymeersch, "Convergent communication, sensing and localization in 6g systems: An overview of technologies, opportunities and challenges," *IEEE Access*, vol. 9, pp. 26 902–26 925, 2021.

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