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JOINT COMMUNICATION AND SENSING TOWARD 6G MODELS AND POTENTIAL OF USING MIMO

M.SUGAVANAM[1], ANITHA M[2]

[1]*Students, Department of CSE, KINGSTON ENGINEERING COLLEGE, VELLORE - 632 059,TamilNadu,India*

[2]*Assistant Professor, Department of CSE, KINGSTON ENGINEERING COLLEGE, VELLORE - 632 059,TamilNadu,India*

ABSTRACT

The sixth-generation (6G) network is envisioned to integrate communication and sensing functions, so as to improve the spectrum efficiency and support explosive novel applications. Although the similarities of wireless communication and radio sensing lay the foundation for their combination, there is still considerable incompatible interest between them. To simultaneously guarantee the communication capacity and the sensing accuracy, the multiple-input and multiple-output (MIMO) technique plays an important role due to its unique capability of spatial beamforming and waveform shaping. However, the configuration of MIMO also brings high hardware cost, high power con Sumption, and high signal processing complexity. How to efficiently apply MIMO to achieve balanced communication and sensing performance is still open. In this survey, we discuss joint communication and sensing (JCAS) in the context of MIMO. We first outline the roles of MIMO in the process of wireless communication and radar sensing. Then, we present current advances in both communication and sensing coexistence and integration in detail. Three novel JCAS MIMO models are subsequently discussed by combining cutting-edge technologies, i.e., cloud radio access networks (C-RANs), unmanned aerial vehicles (UAVs), and reconfigurable intelligent surfaces (RISs). Examined from the practical perspective, the potential and challenges of MIMO in JCAS are summarized, and promising solutions are provided. Motivated by the great potential of the Internet of Things (IoT), we also specify JCAS in IoT scenarios and discuss the uniqueness of applying JCAS to IoT. In the end, open issues are outlined to envisage a ubiquitous, intelligent, and secure JCAS network in the near future.

Index Terms: Communication and sensing coexistence, communication and sensing integration, joint communication and sensing (JCAS), multiple-input and multiple-output (MIMO), radar sensing.

1. INTRODUCTION

COMBINING communication and sensing in wireless networks has recently attracted great attention. It not only allows for more efficient spectrum usage but also provides efficient dual-function services for many applications, e.g., intelligent transportation [1], smart factories [2], and the Internet of Things (IoT) [3]. This has made joint communication and sensing (JCAS) a promising candidate for future networks. The early motivation of JCAS comes from the scarcity of spectrum resources [4]. With the increasing requirements of high-resolution sensing and high-rate communication, communication and sensing systems are constantly expanding and merging their frequency bands. For example, it has been reported by [5] that the global system for mobile communication shares the same spectrum with high UHF radars and that the long-term evolution (LTE) and the WiMax system partially occupy the spectrum of S-band radars. In addition, for the shake of the efficient usage of the wide bandwidth, spectrum sharing is also extended to the mmWave band [6]. Serious mutual interference motivates communication and sensing systems to cooperate. Since wireless communication and radio sensing both use radio signals to carry information, the idea of integrating them into one platform naturally arises. Such an integrated communication and sensing system has incomparable benefits of low cost, low power consumption, and compact volume. This brings new opportunities to those applications that require both communication and sensing services, but their platforms are incapable of supporting the both. To achieve this kind of JCAS, researchers have made considerable efforts. The radar-centric schemes try to use radar platforms to achieve communication functions. The communication-centric schemes try to extract target information from communication signals. To achieve balanced communication and sensing performance, devising a novel dual-function.

2. LITERATURESURVEY

Paper	Year	Topic[1]	Focus	Main contribution
Han*et al*[7]	2013	C&S integration	system prototype and pe formance	A survey specialized in the dual-function system, the system architecture and performance under different waveforms are the main covered issue
Hassanien*etal.* [8], [9]	2016, 2019	C&S integration	embedding schemes	A survey specialized in signaling integration strategies of radar-centric C&S
Zheng*et al*[4]	2019	C&S coexistence and integration	communication and sen ing coexistence	A survey specialized in C&Scoexistence,covering spectrum sharing scenarios three typical
Mishra *et al*[6]	2019	C&S coexistence and integration	signal processing	A survey specialized in mmWave JCAS, mainly reviewing the mmWave characteristics and signal processing techniques for C&S coexistence and co-design
Feng*et al*[10]	2020	C&S coexistence and integration	comprehensive overview	A comprehensive survey on the state-of-the-art JCAS, from coexistence, cooperation, co-design to collaboration
Liu*et al*[5]	2020	C&S coexistence and integration	detailed working regime	An overview of the state-of-the-art techniques and a detailed case study on the working regime of the DFRC
Zhang *et al*[11]	2021	C&S integration	signal processing	A survey specialized in the signal processing of C&S integration, with balanced coverage of T&R techniques
Zhang *et al*[12]	2021	C&S integration	perceptive mobile netwo	A comprehensive survey on the perceptive mobile network, mainly covering the issues of framework design, system evolution and key technologies

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Wild*et al*[13]	2021	C&S integration	cellular-basedC&Sintegration	A survey on specialized in cellular-based C&S integration, with the focus on the issues of waveform candidates, parameter selections and resource allocation
Cui*et al*[14]	2021	C&S integration	IoT scenarios	A macroscopic description of the motivations, applications, trends and challenges of JCAS in IoT
Liu*et al*[15]	2022	C&S integration	comprehensive overview	A comprehensive survey on C&S integration, mainly including the issues of background, key applications and state-of-the-art approaches
Liu*et al*[16]	2022	C&S integration	fundamental limits	A specialized survey on the fundamental limits of sensing and C&S integration, including the device-free and device-based cases
This survey	2022	C&S coexistence and integration	JCAS MIMO	A survey specialized in JCAS of using MIMO, discussing basic models, potential and challenges of JCAS MIMO designs

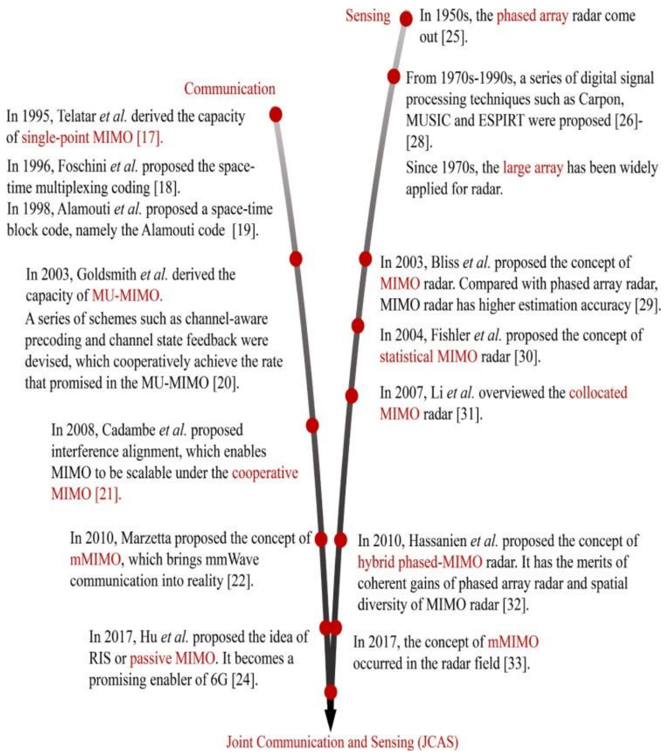

Fig (a)

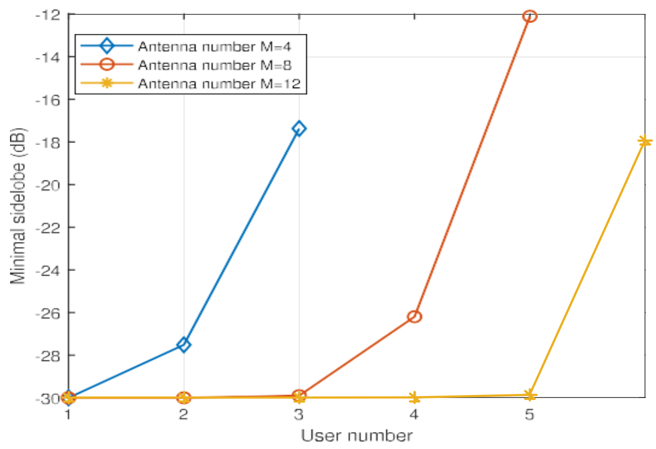

Fig (b)

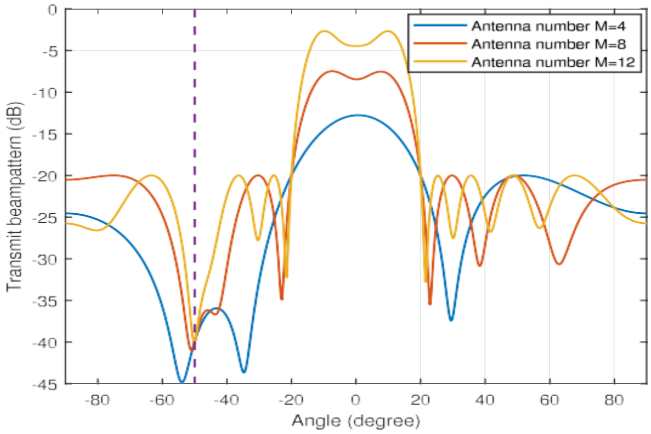

Fig (c)

A. **JCAS With Cooperative MIMO**

B.

Cooperative MIMO refers to applying distributed nodes to transmit or receive signals, and these signals are jointly processed in a central unit. As for the communication side, a well-conditioned channel matrix could be constructed by selectively activating an dmuting different nodes at different times. Benefiting from multi-perspective observations, thesensing accuracy canal so get great improvement. In addition, we could assign different nodes with communication only.

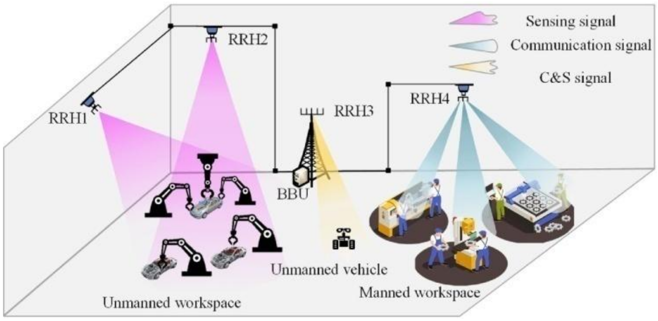

Fig (1)

sensing-only tasks so that the incapability of using onewave form for two uses is downplayed. In short, the macro diversity not only improves individual communication and sensing performance but also gives the system more choices to configure the two functions in a more compatible manner. In the literature, Ahmed et al. considered a distributed DFRC system and proposed a power allocation scheme. The sensing performance is greatly improved by jointly processing the echoes from all DFRC nodes[127].Sansonetal. considered a vehicle network and devised a cascading information fusion method to improve the resolution of the multi-target detection. Results show that, enhanced by the cooperative MIMO,theoriginallyindistinguishabletargetsaredistinguishable.Theauthors also conducted practical experiments to verify their results[128].

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B. JCAS With Dynamic 3D MIMO

ThefactthattheantennasofterrestrialBSsaredownwardto cover ground users limits the BS view for sensing. Aerialplatforms, such as UAVs, airships, and even balloons, are nec-essary to provide complementary observations. In particular,by leveraging the maneuverability of UAVs, they could beflexibly deployed to provide on-demand services. When theUAV flies high, the wide sensing beam could be used to illu-minate thewholearea,andwhenthe UAV is closeto thetargetortheuser,thedirectionalpencilbeamcouldbeusedto refine the sensing resolution or improve the communicationrate. Considering the whole flight of the UAV, the communi-cation and sensing signals could be flexibly scheduled amongdifferent time slots. As shown in Fig. 6, we depict a task exe-cution process of a UAV. In time slot 1, the UAV takes offaccordingtoapredefinedroute.Itarrivesatagivenposi-tionandflieslowtoescortthefleet.Thedual-functionbeamis used to satisfy the communication demand and simulta-neously monitor the navigation environment. In time slot 2,terrestrial BSs are available to serve this fleet. The UAV thuslifts its altitude and uses wide sensing beams to patrol mar-itime IoT. Then, in time slot 3, the UAV flies back and takesover the fleet from the terrestrial BS. It serves this fleet untilthe fleet leaves out its jurisdiction. Then, the UAV returns tothe ground, offloading the collected data and replenishing itsenergy.Aswecansee,thisprocessrequiresthejointdesignoftheUAVtrajectoryandthesignalingstrategy.Butinreality,most UAVs cannot calculate the next-step strategy in a timely manner. Offline optimization is more practical by considering the energy limitations of UAVs. In this sense, when we plan the actions of UAVs, timely CSI is not available [129]. This makes the JCAS design under dynamic MIMO characterized by predictive and process-oriented traits[62].

In the literature, Meng et al. investigated a joint trajectoryandradioschedulingschemefortheUAV-enabledcommunica-tion and sensing integrated system, where the communication occupies the whole signal frame and the detection task only.

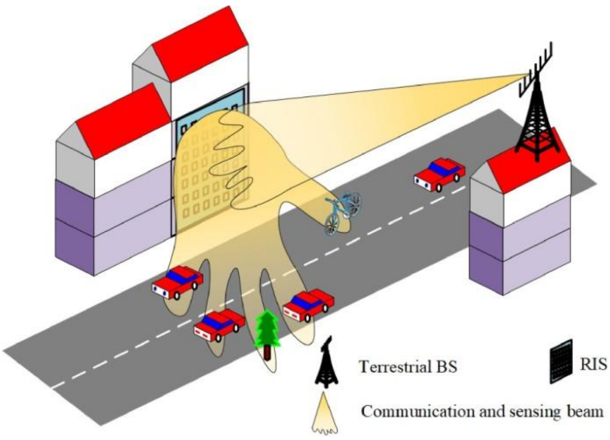

Fig (2)

Illustration of an RIS-assisted communication and sensing wave-form shaping. The RIS helps amplify the main lobe of sub-beams and surpass the side lobe between adjacent sub-beams. The primary webbed waveform is refined into a hand-like pattern by the RIS. uses a proportion of the signal frame. Through joint optimizing the transmit precoding, the UAV trajectory and the sensing start time in each frame, the userrate was maximized under the constraint of the sensingbeampatterngain[130].Lyuetal.investigated a joint beamforming and static deployment ordynamic trajectory scheme. The problem is highly complexthat the location/trajectory variables are exponent parts of thesteering vectors. In return, the corresponding scheme ownsgreatflexibilitytobalancecommunicationandsensingbyadjusting the beam pattern threshold [131]. Moreover, UAVclusters support multi-scale sensing. This further improves thesensingresolution.Chenetal.[132]evaluatedtheperformanceof a cooperative sensing UAV network (CSUN), where UAVssimultaneouslyemitorthogonalbeamsfordownwardsens-ing and horizontal communication. A novel metric named thecooperative sensing coverage area was proposed and evalu-ated.Usingthismetric,theJCASCSUNdemonstratesa66.3%improvement compared with the communication and sensingseparateCSUN.Inshort,theJCASwithdynamicMIMOexploits DoFs in both the spatial and temporal domains. Thecommunication and sensing functions are expected to be deli-cately arranged on the timeline and jointly optimized with theUAV's deployment. The joint optimization in both the spatial and temporal domains brings doubled DoFsbutalsomakesthe optimization complexity exponentially increased. The energyand hardware limitations of UAVs require the corresponding design to be simple. Compared to exhausting every DoF to chase the optimum, more robustness should be reserved to combat high dynamics.

3.JCAS IN IOT SCENARIOS

In recent years, we have witnessed the fast development ofIoT. It was reported that in August 2022, the number of IoT terminal shas exceeded the number of mobile phones in China.Byinterweavingsensors,actuators,andprocessorsintoapow-erful ecosystem, IoT shows great potential to empower many novel applications. Since communication and sensing are twoimportantpillarsofIoT,itisnaturaltoconsidertoapplyJCAS to IoT. In Fig. 8, we illustrate three typical IoT applica-tions. They are smart home, autonomous driving and delivery,and environmental monitoring. It can be seen that thanks toJCAS, the isolation of communication and sensing is broken.The IoT systems have easy access to both communication andsensing resources and information. Such co-design frameworkenables both acute environmental sensing and convenient dataexchangetoempowertheseintelligentapplications.

Inthissection,weconsiderthekeyrequirementsofJCASin IoT. The discussions are from three different perspectives.The first is from the edge that BSs and radars provide com-munication and sensing services. Different from humans whoare most in cities, IoT devices distribute much wider aroundthe

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world. To provide ubiquitous services, it is necessary to extend ground techniques to airborne and space borne plat-forms. The second is from the end that IoT devices both have communication and sensing modules. The integration of communication and sensing would reduce their volume, cost, and energy consumption. But compared with edge infrastructures, their restricted hardware conditions limit the JCAS deployment. Corresponding schemes are required to be green and simple. The third is from the network perspective. The coop-eration of different nodes is the key to forming intelligent IoT systems that are capable of undertaking different complex tasks. For these reasons, we detail the issues of ubiquity, green, complexity, and cooperation for JCAS.

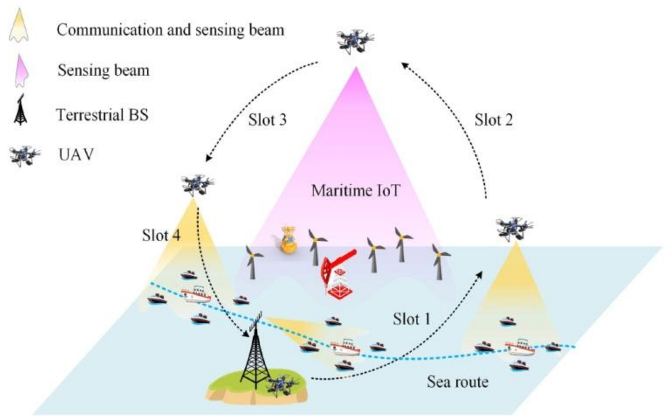

Fig (3)

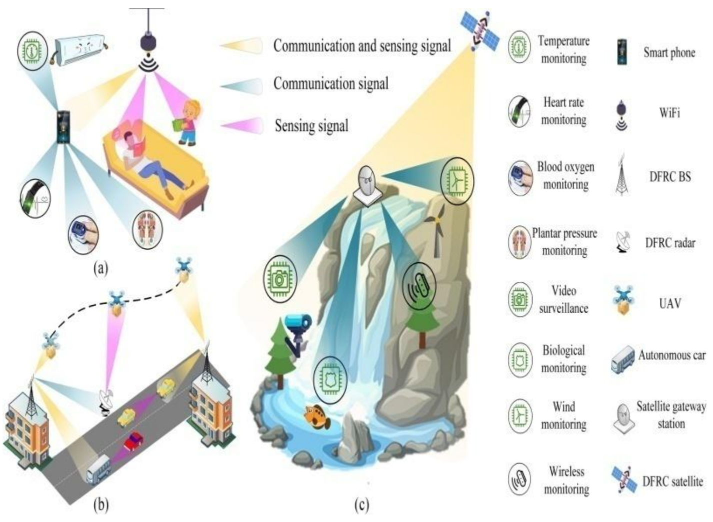

Fig (4)

4.OPEN ISSUES AND FUTURE DIRECTIONS

In this section, we briefly outline open issues and promising directions for JCAS. As the research on communication and sensing integration has just started, there is still great uncertainty on its future development. However, one can expect further works on intelligence and security. One could also envision the interplay between JCAS and other cutting-edge technologies to take advantage of their mutual benefits.

4.1 JCAS in Integrated Space–Air–Terrestrial Network

To extend the coverage of both communication and sens-ing, it is necessary to design JCAS in the space–air–groundintegrated network (SAGIN). In this scenario, the distinct rate,latency and reliability of satellite, aerial, and terrestrial linkswould render new challenges. Two kinds of integration, i.e.,communication and sensing integration and space–air–groundintegration, could couple with each other. This consequentlyposesgreatchallengestothesystemdesign.Onepossiblesolu-tionisto explore the hierarchical architecture of the hybrid system. As shown in [169], one may derive basic models forsatellite–terrestrial cooperation and treat a complicated hybridsystem as the combination of basic models. On this basis, thebasic JCAS-SAGIN model is a great breakthrough point toanalyze complex JCAS-SACINs. Each basic model containsboth minimal space–air–ground infrastructures and minimalcommunication and sensing functions. Thus, the basic rela-tion ships of different platforms and functionalities are kept in these models. The agile orchestration of these basic models would lead to various large-scaleJCAS-SAGINs.Inthisdirec-tion, both theoretical analysis and key technologies require research attention.

4.2 JCAS Using Artificial Intelligence

Applying artificial intelligence (AI) to JCAS may reduce the computing burdens of the MIMO design. A trained network could directly output the JCAS schemes by giving the input raw data. In addition, although the learning process is still a black box without explicit explanations, the output policies may be heuristic for the theoretical analysis. However, it is not an easy task to extract high-level information from massive raw data. The effective reward/cost objectives and neural network structures remain to be studied. Perhaps the model-based methods and data-based methods shall be combined.
Forexample,ifweknowtheoutputresultsaresparsebasedonthepriorknowledgeofthephysicalsystem,then euralnetworkstructure could be sensibly designed to simplify the training process.

4.3 Joint Sensing, Communication, Computing and Control

Future6Gnetworksareenvisagedtoshiftfromconnect-ing things to connecting intelligence. In other words, we wantto endow connected machines with human-like intelligence. To do so, the network needs to be aware of device status and instruct their behavior. In this sense, JCAS that makes wireless networks perceptive is the first step. We shall further investigate to build a “nerve system” for machines, where a closed loop of $\mathbf{SC}^3$ is a basic unit similar to a reflex arc. Under such closed loops, numb machines can adapt to the environment and accomplish different tasks automatically, thus releasinghumansfromallkindsofdangerousandboringjobs.However,optimization over $\mathbf{SC}^3$ closed loops covers information theory, estimation theory, control theory, etc. Aunified theoretical model is required to figure out the basic relationship of SC^3.

4.4 Security Issues of JCAS

Security is one of the key issues for JCAS. The sensing function requires signals to fully interact with the environment so that the surrounding information could be imprinted in the waveform. This increases the risk of being eaves dropped. In addition, unlike communication users, who are authenticated before access, targets are not identified and are more likely to be malicious. How to illuminate the target while limiting the information leakage is still open. Furthermore, the JCAS would bring explosive data. The balance of data security and data efficiency is challenging. We may combine JCAS with the block chain technique.

5.CONCLUSION

In this article, we have reviewed recent advances in JCASMIMO. Detailed schemes of communication and sensing coexistence and communication and sensing integration have been presented. We have also investigated three novel JCASMIMO models combined with cutting-edge technologies. In these JCAS schemes, we have found that MIMO mainly plays the role of directional beam forming for the communication function and waveform shaping for the sensing function. The main challenges lie in using restricted DoFs to balance their incompatible interests. Targeted at the dimensional problem of using MIMO, we have discussed possible solutions based on simple and robust principles. Afterwards, we have specified JCAS in IoT scenarios and emphasized the issues of ubiquity, green, complexity, and cooperation. On this basis, open issues have been outlined, with a great vision to embrace a ubiquitous, intelligent, and secure JCAS network in the upcoming Gera.

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