6G-enabled Integrated Sensing and Communications to Tackle Climate Change: The Geothermal Sensing and Monitoring Model and Its Implications

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***Abstract*—Climate change-induced natural disasters are seriously affecting the planet's ecosystem and disrupting the socio-economic development of humanity. This exigent issue leads to the developing of novel technologies and methodologies to utilize sustainable energy sources such as geothermal energy for energy generation. However, geothermal reservoirs are highly location-specific and identifying the potential zones is a daunting task for reservoir engineers. Moreover, the geothermal energy density of a place can change over time due to various environmental factors; therefore, it is crucial to monitor and assess its changes periodically. Concurrently, the accelerating advancements in the research of sixth-generation (6G) wireless networks and their possible disruptive technologies, such as integrated sensing and communications (ISAC), have recently received much attention from the broader research communities. In this article, we envision and introduce the general concept of a generalized geothermal sensing and monitoring (GeoSM) model and explore the role of the ISAC system in the localization and periodic monitoring of geothermal energy. Specifically, we illustrate the envisioned system architecture for the GeoSM model, present a general framework of the 6G-enabled ISAC system, and suggest possible enabling technologies to facilitate the distributed sensing and monitoring of the geothermal energy zones. Then, we describe the geothermal heat network as a prospective use case of the GeoSM model. Following that, we present a preliminary case study on the waveform optimization of our proposed ISAC framework of the envisioned GeoSM model for a specific application scenario. Finally, we outline the open research challenges and discuss possible future research directions.**

***Index Terms*—Climate change, geothermal energy, 6G, integrated sensing and communications, machine learning, passive optical networks, wireless communications, wireless underground sensors.**

I. Introduction

DURING the second decade of the current century, we have experienced the warmest climate ever since the record-keeping of the weather started in 1880 [1]. That is a shred of irrefutable evidence that the impact of climate change has reached a new deleterious level. The main driver for this drastic climate change is the emission of the greenhouse gas, such as carbon dioxide (CO_2), which is produced when fossil fuels are burnt for the energy generation [2]. The CO_2 is transparent to the visible sunlight; however, it absorbs the reflected infra-red rays and prevents its escape from the surface of the earth. That gradually heats the earth's surface and results in a phenomenon known as global warming. As part of the global response to minimize the CO_2 emissions, there have been significant efforts made worldwide to accelerate the transition from fossil fuels to renewable energy sources for energy generation. For example, geothermal energy, a type of renewable energy taken from the earth's internal heat, is recently attracting growing attention to use as an energy source [2]. This choice of utilizing geothermal energy is driven by the need to transition to cleaner energy sources and reduce reliance on fossil fuels.

Geothermal energy is a sustainable energy source, unlike wind and solar energy; nevertheless, it has a single most significant disadvantage: it is highly location-specific [2]. This constraint limits the deployment of geothermal energy plants in geographic locations where the energy is easily accessible. The location constraint of geothermal energy necessitates the development of low-cost and feasible techniques for sensing the geothermal potential zones. Earlier efforts were based on perforations made through the drilling process to measure the subsurface temperature [2]. However, the significant cost associated with the drilling operation limits its practicality. Recently, some researchers considered using remote sensing data combined with a geographic information system to locate the geothermal energy potential zones with a considerable compromise on the spatial resolution [3]. Besides the location constraint, the periodic monitoring of geothermal zones is crucial since the geothermal energy density of a place can change over time due to various factors, such as natural geological changes like tectonic plate movements, natural depletion or recharge, climate change, and natural events like earthquakes or volcanic eruptions [4].

Like the recent coronavirus pandemic, climate change can be a major calamitous event and may result in a substantial economic crisis. To us in the broad science and engineering community, the fact that communication and sensing technologies have a pivotal role in mitigating climate change issues should enhance our social responsibility and professional values [1]. The foreseeing climate change-induced threats to humanity prompted us to integrate various emerging advancements in the broad areas of science, engineering, and

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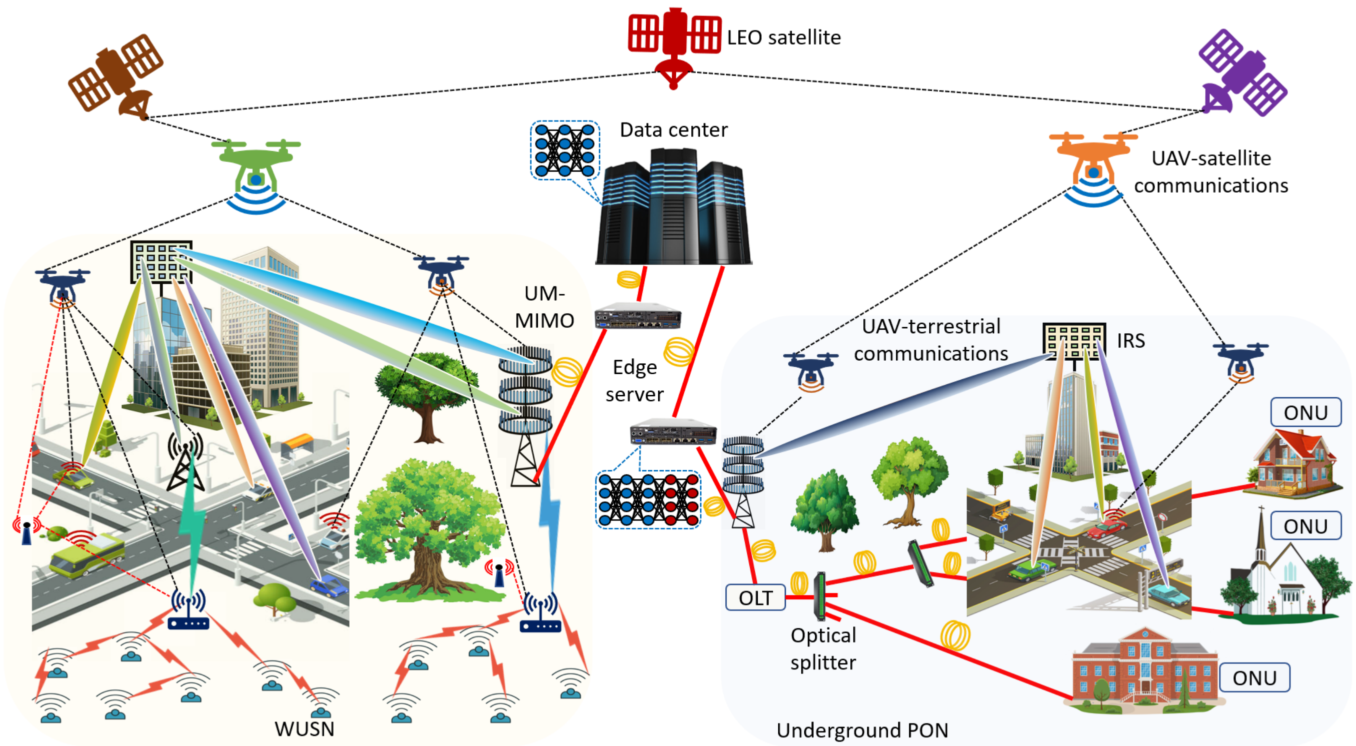


Fig. 1. Illustration of the envisioned 6G-enabled ISAC system landscape for geothermal energy sensing and monitoring. LEO: low earth orbit, UAV: unmanned aerial vehicle, IRS: intelligent reflecting surface, UM-MIMO: ultra-massive multiple-input multiple-output, WUSN: wireless underground sensor network, PON: passive optical network, OLT: optical line terminal, and ONU: optical network unit.

technology to tackle the socio-economic disruptions that those threats may cause [1]. For example, it is imperative that the emerging sixth-generation (6G) mobile cellular systems will have the ability for localisation and sensing using the existing network infrastructure on par with the communication and information transfer [5]. That is called integrated sensing and communications (ISAC).

The ISAC system has been widely recognized as a key technological advancement in the upcoming 6G era. This has already been acknowledged as a subject of research by both academia and industry. The projected gain in terms of efficient spectral resource utilization, complemented by the reduced hardware cost and power consumption, makes the ISAC system an ideal enabler for emerging applications requiring energy-efficient wireless connectivity combined with high-precision sensing and systems demanding optimal performance in a dynamic, resource and cost-constrained environments. Another motivating factor for choosing ISAC in 6G is the potential mutual benefit between the communication and sensing signals, achievable through the proper design of the joint system. The ISAC system has been critically evaluated across diverse 6G research domains, including but not limited to smart transportation, smart homes, smart factories, smart healthcare, smart cities, and environmental sensing for climate change mitigation.

The earlier implementation of the ISAC system was based on an opportunistic spectrum sharing where the communication system transmits the signal when the space and frequency spectra are not in use by the radar system. Nevertheless, this spectrum-sharing approach restricts the simultaneous signal transmission by the two systems. As a progression of this method, waveform optimization techniques have been applied through the joint design of the radar beamformer and the covariance matrix of the communication signals. While such joint waveform designs are well-advanced, a notable shortcoming is that the radar and communication devices need to share the side information for effective coexistence. In contrast to these schemes, a dual-functional radar and communication (RadCom) system has been recently proposed that enables the simultaneous transmission of both radar probing signals and communication signals without requiring the exchange of side information [5]. The RadCom system seamlessly integrates wireless communication signals with radar probing signals within a unified framework, enhancing the effective utilization of the available spectrum. In our vision, the ISAC in 6G will have the ability to integrate the communication data with the sensing data from the enormous amount of distributed sensors alongside the usual meaning of joint communications and radar.

Besides the innovation in ISAC systems, machine learning (ML)/ artificial intelligence (AI) will become more fundamental in the design of 6G systems, where the unprecedented amount of network and sensor data serves as fundamental resources that need to be exploited for improved system performance [6]. The central theme of our work is to introduce the general framework of a geothermal sensing and monitoring (GeoSM) model that utilizes the existing deployed sensor network and integrates them with the 6G-enabled ISAC system and a highly interconnected spider web of communication devices and technologies. We believe that the existence of such an information model can assist the applications that use geothermal as the energy source to make informed decisions on the geographic locations of the geothermal source, foster sustainable geothermal resource management, renewable energy development, early detection of geothermal activity, and continuous monitoring of the geothermal density over an extended geographic area. Fig. 1 illustrates our envisioned general framework of the 6G-enabled ISAC system of the GeoSM model for sensing and monitoring the potential geothermal zones. We anticipate that the innovative technology infrastructure of the 6G combined with the ML/AI can fulfil the massive connectivity requirements of the hyper-connected world while simultaneously collecting and processing the enormous amount of localization and sensing data to identify and monitor the potential geothermal energy zones.

Recent technological advancements in distributed sensing (DS) via wireless underground sensor networks (WUSNs) allow acquiring the measurement data, which are spatially and temporally distributed over a wide geographic area [7]. The WUSN plays a crucial role and acts as a sensing arm for the Internet-of-Things (IoT) and serves as a laying stone for the convergence of the 6G and IoT [7]. Distributed fiber optic sensing (DFOS) by reusing the existing buried passive optical networks (PONs) is a rapidly evolving field that can be effectively used for temperature and acoustic signal sensing in urban areas [8]. From [9], it is clear that the upcoming 6G era will see the migration of the existing intensity-modulation/direct-detection (IM/DD) PON to the coherent PON (Coh-PON) to meet the higher capacity requirements in the last mile connections. In our envisioned ISAC framework in the 6G era, the integration of the WUSN with the Coh-PON can be considered a unified sensing infrastructure to enable the wide-area sensing of the geothermal energy potential.

In this article, we introduce the general framework of the GeoSM model and explore the vision of holistically integrating various 6G technologies and existing communication and sensing infrastructures to enable ISAC for the sensing and monitoring of the geothermal energy zones. We start with a generalized block schematic of the envisioned GeoSM model, including the proposed ISAC framework and various enabling technologies for realizing the ISAC system. Then, we describe the geothermal heat network (GHN) as an example of a prospective use case of the GeoSM model and include a proof-of-concept case study where we consider the waveform optimization problem of our proposed ISAC framework for a specific application scenario. Finally, we identify open research challenges, discuss possible future research directions, and conclude the paper.

II. Role of 6G in Climate Action: Envisioned GeoSM Model and Enabling Technologies

While the industry and academia are relentlessly working to roll out the 5G technology globally, the telecommunications research community has already started the research toward 6G. One of the main foundational visions of 6G is to develop systems and technologies that can support positive social and environmental change [10]. In recent years, the rapid development of wireless communication technologies and the ubiquitous deployment of smart devices and sensors have steered the requirement for massive mobile connectivity. The consolidation of the mobile broadband access platforms with the low earth orbit (LEO) satellites can be considered a key enabler to tackling the large-scale mix of the communication and DS data along with providing sensing and monitoring of the geothermal data. Furthermore, flying base stations such as unmanned aerial vehicles (UAVs) can also be considered for the DS of the potential geothermal zones to deal with climate change and provide seamless connectivity for the large-scale distributed sensors. Alongside the aforementioned technology platforms, the ML/AI-enabled communication technologies of enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communications (URLLC) will make use of the underpinning communication infrastructures of 6G such as intelligent reflecting surfaces (IRSs) and ultra-massive multiple-input multiple-output (UM-MIMO) transceivers to handle the ISAC data effectively.

Fig. 2 illustrates the envisioned GeoSM model for geothermal energy sensing and monitoring. In this model, apart from the usual meaning of joint communications and radar, the ISAC system suggests utilizing a multitude of mobile broadband access entities, 6G specific communication technology platforms, and the widely deployed WUSN and PON (this can be extended to Coh-PON in the 6G era) infrastructures to realise a multi-static sensory mesh network for sensing and monitoring of the geothermal energy over an extended geographic area[1]. Considering the heterogeneity of the various communication network entities and the statistical heterogeneity of data, such as the non-independent and identically distributed nature of the sensing data generated from the sensing nodes, we recommend incorporating the AI/ML functionalities into the envisioned GeoSM model. More specifically, we proffer the idea of employing the personalised federated learning approach, such as federated transfer learning (FTL), to effectively deal with heterogeneity. The details of the terminal, the edge, and the datacenter levels of the envisioned GeoSM model are given as follows.

1) Terminal Level: The terminal level of the envisioned GeoSM model can consist of the interconnected and widely spread network of WUSNs and the live traffic-carrying PONs to aid the distributed sensing of geothermal energy. The permanently deployed WUSN arrays can be an effective solution for the sensing and monitoring of geothermal energy with reduced land impact and rapid operation in the data acquisition and processing [7]. Similarly, the PON is the most common network topology to deliver broadband network access in the last-mile connection between the central offices and the end-users [8]. It follows a point-to-multipoint topology in which a single fibre serves multiple endpoints using a passive optical splitter. The PON technology is proven to be the cost-

[1]Note that the extent and reach of the WUSN and PON networks in a given geographic location decide the geographic boundary of our envisioned GeoSM model.

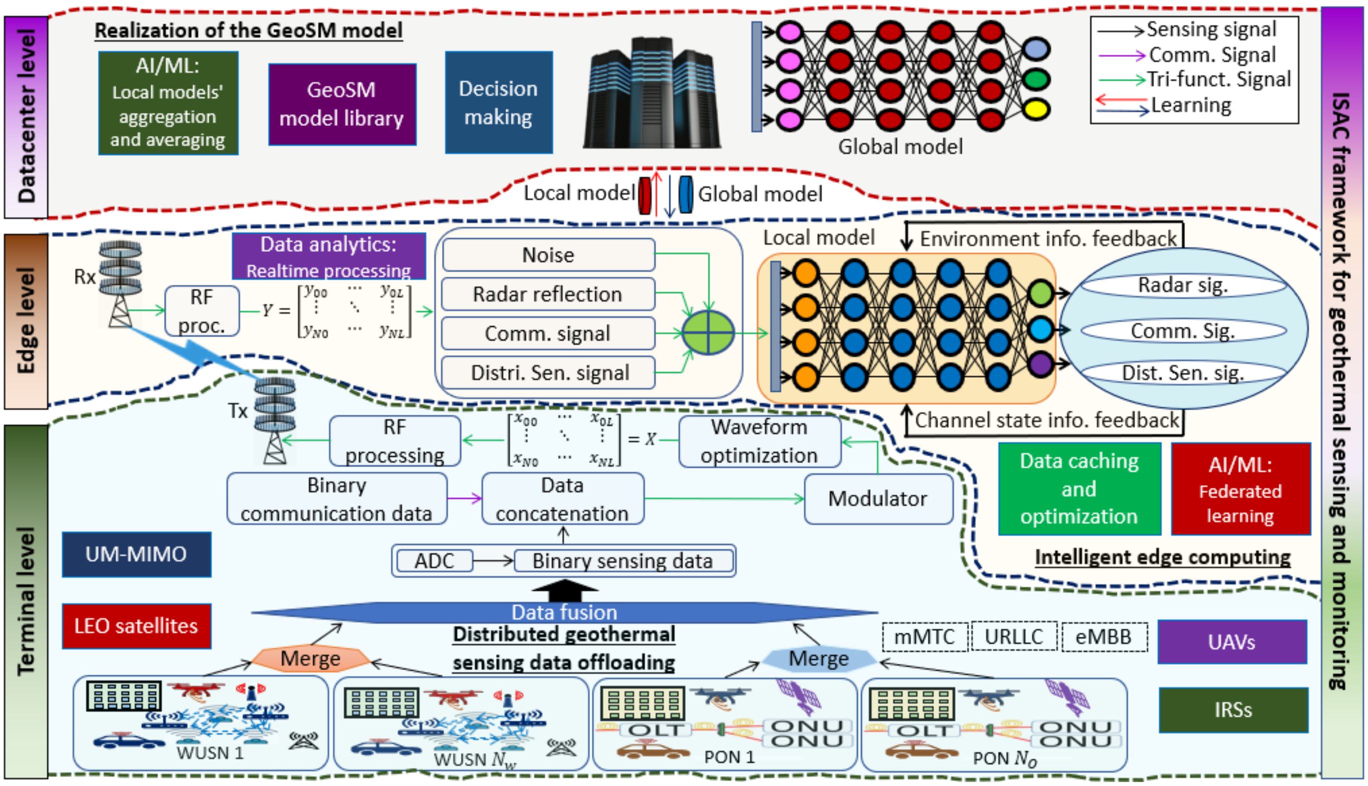


Fig. 2. The block schematic of the envisioned GeoSM model in the 6G era, where X represents the transmitted tri-functional signal matrix, Y denotes the received tri-functional signal matrix, N is the number of MIMO antenna elements, and L is the length of the data frame. ADC: analog-to-digital converter, RF: radio frequency, Tx: transmitter, and Rx: receiver.

effective broadband service provisioning widely deployed in urban areas. This ubiquitous deployment of the PON networks can be utilized for a cost-effective distributed sensing of the geothermal energy potential. Our idea is to assess and monitor the geothermal energy potential using the Brillouin backscatter mechanism of the existing underground optical fibre network. By utilizing both WUSNs and PON networks, our proposed GeoSM model can enable the collection of geothermal sensing data over a wider geographic area. These collected sensing data from the WUSNs and PON networks are merged independently before carrying out the data fusing operation to enable an accurate, comprehensive, and reliable representation of the geothermal sensing data.

Different from the dual-functional RadCom system proposed in [5], the sensing part of our proposed ISAC framework consists of two distinct sensing signals: (i) the radar probing signals and (ii) the sensing signals from the geographically distributed sensors. That constitutes a new system framework incorporating the three functionalities, such as distributed sensing, radar, and communication signals, which we call a tri-functional SenRadCom system. To the best of our knowledge, this form of tri-functional ISAC system has not been considered yet in the literature. The terminal level in Fig. 2 illustrates the signal processing flow in our proposed tri-functional SenRadCom system. The fused sensing data is first converted into the digital domain using an analog-to-digital converter. The binary sensing data is then concatenated with the binary communication data and passed to the modulator for signal modulation. The modulated signals are optimized by the waveform optimization techniques introduced in [5] before being directed to the radio frequency (RF) processing block for transmission via the MIMO antenna arrays. The optimized transmitted signal matrix X is the unified waveform for the tri-functional SenRadCom system consisting of the distributed sensing signal, radar, and communication signals.

The mobile communication infrastructures and technologies of the terminal level can work in alignment to carry out an efficient maneuver of the communication and sensing data to the higher levels for further processing. Enabled by the massive surge of applications requiring extremely low latency, ultra-high reliability, high capacity, hyper-connectivity, scalable, ubiquitous, and distributed communication models, the 6G research has been focused on a holistic approach. This includes integrating diverse communication technologies such as eMBB, MTC, and URLLC with potential infrastructures like UM-MIMO, IRSs, UAVs, LEO satellites, and so forth.

2) Edge Level: The edge level can consist of various base stations (BSs) and mobile edge servers to effectively deal with the ISAC data. Furthermore, it supports a range of data analytics tasks, including real-time signal processing and data caching, leveraging the power of advanced AI/ML techniques. The BSs can use the ISAC technique to transfer information with various communication equipment/entities and acquire the geothermal sensing data from WUSNs and the PON-based distributed sensors. In our proposed ISAC architecture, the sensing data is integrated with the messages originating from many communication devices and infrastructures that differ in their technology, hardware architecture, network conditions, power levels, and channel conditions. A practical solution to this heterogeneity is using AI/ML techniques with a personalised learning framework. Specifically, we suggest using an FTL approach between the edge and the remote datacenter that jointly trains a model by aggregating locally trained models in the edge. At the edge level, after the RF processing, the received signal matrix Y, encompassing the radar reflection, communication signal, distributed sensing signal, and noise, is forwarded to the FTL network for further processing. The FTL network offers intelligent nonlinear signal classification to effectively separate the three signal components within the received tri-functional signal waveform. This is achieved by leveraging the feedback from the environmental information and the channel state information, resulting in reduced computational load and processing delay. After training the local model, the model parameters are sent to the datacenter level for constructing the global model.

3) Datacenter Level: The datacenter level can consist of several interconnected physical and virtual clustered servers to efficiently process the digital information transferred from the edge level. The servers in the datacenter have high computing power and massive data storage capacity. The core servers in the datacenter can be used to aggregate the model parameters of the locally trained FTL model in the edge and average them into a global model to send back to the edge level. This process of exchanging the model parameters between the edge and the datacenter levels repeats until it converges after a few number of iterations. Thus, a highly effective global model can be developed and then transmits the model parameters to the edge for further personalization. The trained global model can be tailored to integrate the geothermal sensing information obtained from different geographic locations after effectively separating it from the communication and radar signals. Based on this model, the core servers can build a GeoSM model library, assisting the decision-making on selecting the appropriate geographic area with geothermal potential. The GeoSM model library may help construct the profiles of the geothermal energy hot spots and can act as a base model to study and predict the seasonal trends and the relationship between the subsurface depth and temperature of the potential geothermal zones. This may also help monitor geothermal energy zones for responsible and sustainable development and harness the full potential of geothermal energy as a clean and renewable energy source.

It is worth mentioning that our proposed ISAC framework can be easily adapted to any diversified application field that involves extensive environmental sensing and monitoring. For example, in underground mining operations, the networked sensor systems are used for various applications such as excavation, process automation, remote operation, and ensuring the occupational health and safety of the mine operators. In this scenario, our proposed ISAC system can be effectively applied for the sensing and monitoring of the ambient mining environment attributes for the applications mentioned above and generate a global profile of the mining sites to study and predict their climate change-induced dynamic evolution.

III. An Example of a Prospective Use Case

It is well reported that the primary sources of CO_2 emissions are surface transport, manufacturing, electricity supply, fuel supply, buildings, aviation, waste, and agriculture sectors [11]. In recent years, the efforts of applying various policies and methodologies have succeeded in decarbonising most of the sectors mentioned above. However, the flatlining of the CO_2 emissions from buildings that use electricity as the energy source for heating, ventilation and air conditioning (HVAC) system slows down the overall decarbonisation efforts [11]. It has been shown recently that the geothermal heat pump (GHP) system, an energy-efficient HVAC system using geothermal energy, helps to reduce CO_2 emission from buildings to a great extent [12].

The GHN or the district heating that uses GHP as the key technology can be considered a feasible solution to eliminate the CO_2 emission from the buildings in a much wider geographic area, such as a metropolitan city or a local neighbourhood, and avoids the requirement of having electric heaters or boilers in every building or household [13]. The GHN are particularly attractive in densely populated areas and some rural off-gas grid households [14]. The GHN can deliver various environmental benefits and offer attractive economic benefits to its consumers by cutting down energy bills [14].

Considering all the GHN advantages, identifying a suitable geographic location can pose several challenges and considerations, such as geological suitability, distance to demand centers, environmental impact, and seasonal variation of the geothermal energy gradient. In this application scenario, we believe that our envisioned GeoSM model can play a crucial role in identifying suitable locations for GHN systems by providing valuable data and insights. By bringing together the wealth of geothermal sensing and monitoring information, the GeoSM model can assist decision-makers, investors, and governmental organizations in identifying geothermal locations more efficiently and confidently. Such a model can accelerate the development of sustainable, low-carbon HVAC solutions and promotes the adoption of geothermal energy.

Our proposed GeoSM model stands at the intersection of the advancement in 6G technologies and the utilization of existing distributed sensor network infrastructures to accelerate the efforts towards climate change mitigation. We envision that the seamless integration of these two distinct entities, harnessing the immense capabilities of the upcoming 6G disruptive technologies and the ubiquity of worldwide deployed WUSNs and PONs, will improve the real-time monitoring of the geothermal potential zones and the efficient utilization of the geothermal energy while establishing a GHN or district heating networks.

It is noteworthy that the ISAC system in 6G has a central role in realizing our envisioned GeoSM model. Specifically, ISAC waveform optimization plays a crucial role, enabling efficient simultaneous transfer of radar probing signals, geothermal sensing signals, and information signals in an energy-efficient manner. Waveform designs are also essential for efficient spectrum utilization, improving signal quality, reducing interference, and accommodating more complex practical

MIMO antenna arrays, geothermal sensing units (SUs), user equipments (UEs), and radar targets. To report the preliminary findings regarding our envisioned GeoSM model, we include a case study on the tri-functional ISAC waveform design in Section IV to demonstrate the feasibility of such an approach when applied to a multi-static sensory mesh network system for sensing and monitoring geothermal energy within the context of 6G.

IV. A Case Study on the ISAC Waveform Optimization

Unlike the traditional independent design of communication and sensing systems, the ISAC system aims to optimize the network resources to leverage the benefits of the joint system design. In this context, the ISAC waveform optimization plays a crucial role in minimizing the mutual interference between the sensing and communication signals, maximising the benefits of their coexistence. That is also a fundamental system design aspect central to our proposed ISAC framework of the envisioned GeoSM model (see Figs. 1 and 2).

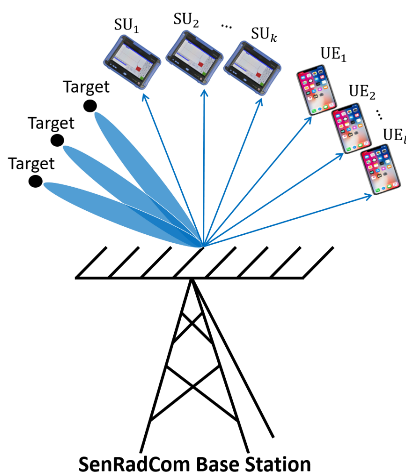


Fig. 3. The envisioned ISAC framework: tri-functional SenRadCom system for simultaneously serving radar targets, k SUs, and l UEs.

Fig. 3 illustrates the system model of the proposed tri-functional MIMO SenRadCom system in our proposed ISAC framework. As seen in Fig. 3, our proposed system simultaneously transmits the sensing signal acquired from the distributed sensors, the radar probing waveform to the targets, and the downlink communication symbols to the users. The SenRadCom base station is equipped with uniform linear array (ULA) antennas to accomplish joint communication and sensing between radar, SUs, and the UEs. In this case study, to demonstrate the potential of the proposed tri-functional SenRadCom system, we present the simulation results for a specific case where we incorporate the distributed temperature sensing (DTS) signal obtained via Brillouin backscattering from the PON network into the radar probing and the communication signals. We utilized an open-source real-time fibre-optic DTS dataset generated for georeferencing to carry out the numerical simulations[2]. In this tri-functional waveform design, the transmitted signal matrix is used as a unified waveform for the DTS, radar, and communication operations.

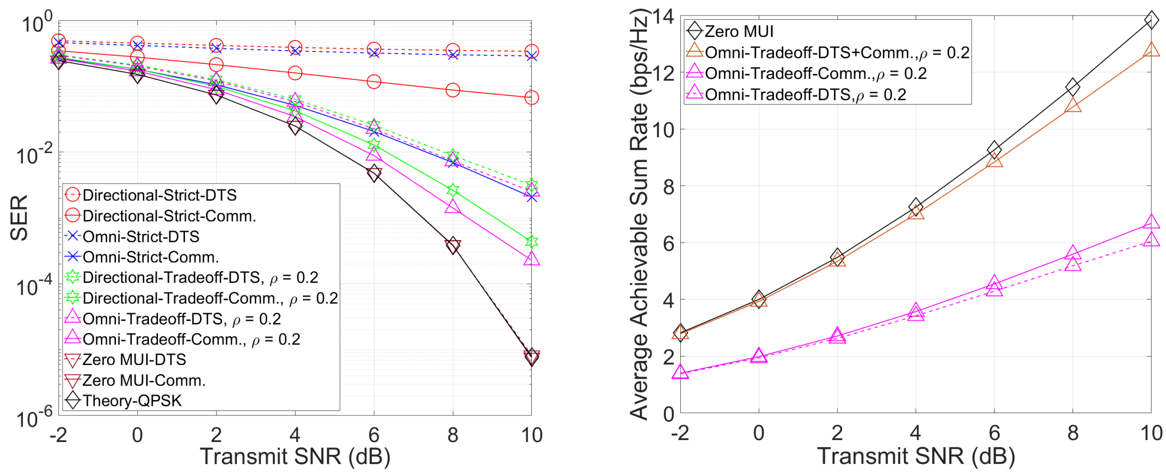
We consider similar waveform optimization techniques proposed in [5] to minimize the downlink multi-user interference (MUI) at specific UE under radar-specific constraints. That includes the omnidirectional and directional radar beampattern designs and a trade-off design with total transmit power constraint between the DTS, radar, and communication signals. The trade-off design is realized by introducing a weighting factor $0 \leq \rho \leq 1$ in the tri-functional waveform optimization problem. In this study, we assume that the weighting factor ρ is common to the DTS and the communication signals and the radar probing signal is weighted by $(1-\rho)$ in the objective function of the optimization problem. Following the naming conventions used in [5], we also denote ‘Omni’ and ‘Directional’ to represent omnidirectional and directional radar beampattern designs, and ‘Strict’ and ‘Tradeoff’ to indicate the strict total transmit power equality constraint and the trade-off designs.

Fig. 4 illustrates the communication and DTS performance obtained by different waveform designs in terms of the symbol error rate (SER) and the average achievable sum rate. For all the waveform designs in Fig. 4, we set the total transmit power to unity for convenience, and each term in the channel matrix follows a Complex Gaussian distribution, $\mathcal{CN}(0, 1)$ [5]. Following the approach in [5], we consider sixteen ULA antenna units with the adjacent antennas spaced at half-wavelength, two SUs, and two UEs, and the modulation format considered is quadrature-phase shift keying. Also, in Fig. 4, we have considered three radar targets with angles of $-\pi/3$, 0, and $\pi/3$, similar to the scenario considered in [5]. In Fig. 4 (a), we have included the SER performance of the zero MUI case as a function of the transmit signal-to-noise ratio (SNR) for DTS and communication signals and compared them with the theoretical SER performance for the simulation system validation. We have considered both the ‘Strict’ and ‘Tradeoff’ designs for the omnidirectional and directional waveform designs in Fig. 4 (a). It is observed that the worst SER performance for both the DTS and communication signals is for the ‘Strict’ directional waveform design technique. Noticeably, in the case of the ‘Strict’ omnidirectional waveform design, there is a significantly large performance degradation for the DTS signal compared to the communication signals. To allow a trade-off between the radar and the DTS and communication signals, we have considered the weighted optimization for the tri-functional waveform design under the non-convex power budget constraints, as given in [5]. The results of this trade-off design indicate that by introducing a weighting factor $\rho = 0.2$ [3] to the DTS and communication signals, the SER performance of the omnidirectional and directional waveform designs significantly improved; notably, the omnidirectional trade-off designs outperformed the directional ones.

Based on the finding from Fig. 4 (a), we select the omnidirectional trade-off design technique with $\rho = 0.2$ for further investigating the effectiveness of the proposed tri-

[2]The DTS dataset for georeferencing can be accessed from the following web link: https://www.usgs.gov/software/dtsgui

[3]Note that the rationale for selecting the weighting factor $\rho = 0.2$ is to make sure that the radar probing signal is transmitted at the maximum available power in practice [5].



(a) (b)

Fig. 4. Simulation results of the proposed tri-functional SenRadCom system. (a) symbol error-rate comparison, and (b) sum rate comparison.

functional SenRadCom system. In Fig. 4 (b), we plot the average achievable sum rate of the DTS, communication, and the combined DTS-communication signals as a function of the transmit SNR. We observe that the sum rate of all these techniques monotonically increases as the SNR increases. For the combined DTS-communication signals, the sum rate performance is very close to the zero MUI case in the lower SNR regime and slightly degrades for the higher SNR values. That is due to an increased level of interference between the DTS and communication signals as the signal power increases. Similarly, in the higher SNR regime, the sum rate performance of the DTS signals slightly falls behind the communication signals for the selected weighting factor $\rho = 0.2$.

While our initial focus is a system-level illustration of the proposed GeoSM model, we understand the importance of considering a more complex ISAC system for the case study. To investigate this, we have conducted a simulation study considering a complex ISAC system incorporating more SUs and UEs by fixing the number of MIMO antenna elements at 16, the number of radar targets at 3, and the SNR at 10 dB. We consider a case where SUs and UEs vary equally from 1 to 5. Fig. 5 shows the sum rate penalty, defined as the difference in sum rate when compared to the zero MUI case, of the ISAC system as a function of the varying number of SUs and UEs for the omnidirectional trade-off design technique with the power weighting factor $\rho = 0.2$. The results indicate that the sum rate penalty of the DTS, communication, and the combined DTS-communication signals monotonically increases as the number of SUs and UEs increases. Interestingly, the sum rate penalties for both the DTS and communication signals are close, with the DTS signal suffering a slightly increased penalty for more than one SUs and UEs. This warrants redefining the waveform optimization problem with the trade-off design of the tri-functional SenRadCom system by individually optimizing the weight factor for the DTS and communication signals given the radar-specific constraints.

Finally, we have conducted the energy consumption analysis of the omnidirectional beampattern design and compared it

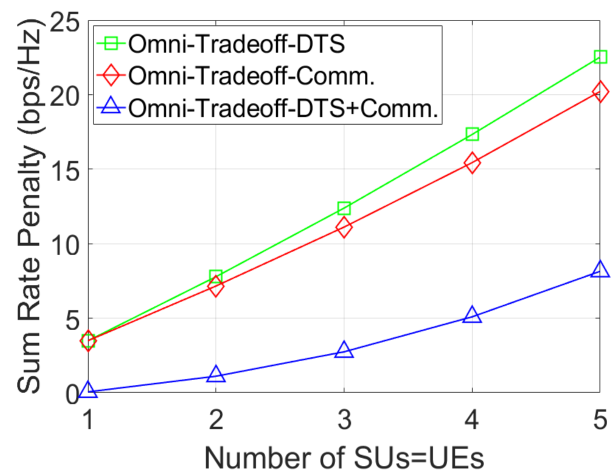


Fig. 5. The sum rate penalty of the ISAC system as a function of the varying number of SUs and UEs.

with the directional beampattern design and a conventional communication-only zero-forcing (ZF) precoding method following the energy calculation procedure given in [15]. According to [15], the energy consumption can be estimated based on the number of complex floating-point operations (flops) required for each waveform design technique, which is approximately equivalent to the multiply-and-accumulate (MAC) operations. By using the expressions for the number of flops required for each waveform designs as given in [5], we estimate the energy consumption by specifying the energy consumption per MAC operation on a 45 nm complementary metal-oxide-semiconductor processor with 32-bit integer arithmetic. In this processor, each MAC operation consumes approximately 3.2 pJ [15]. Based on this, in Fig. 6, we have plotted the energy consumption of the waveform design methods as a function of the varying number of SUs and UEs by fixing the number of MIMO antenna elements at 16 and the length of the data frame at 30.

The results in Fig. 6 indicate that the energy consumption of the directional waveform design is significantly larger

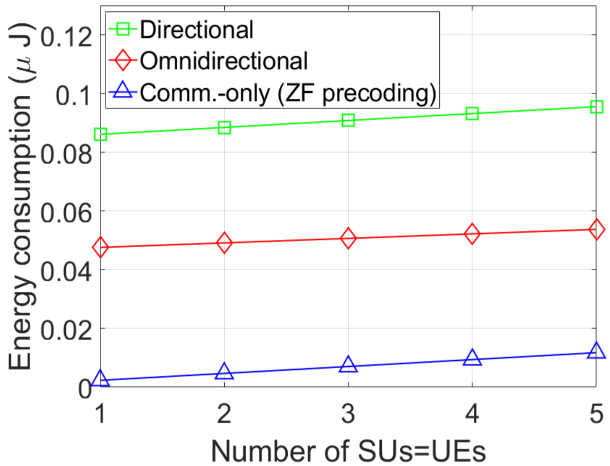


Fig. 6. The energy consumption as a function of the varying number of SUs and UEs.

when compared to the omnidirectional design and the ZF precoding of the conventional communication-only case. For example, for an ISAC system with a directional waveform design considering two numbers of SUs and UEs, the energy consumption is 0.09 μJ, whereas that of omnidirectional waveform design is 0.05 μJ, which is 80% in reduction. Also, for the same ISAC system parameters, the energy consumption of the directional waveform design is 0.08 μJ higher than the conventional communication-only case with ZF precoding.

V. Future Research Directions

Although the ISAC framework in 6G has recently attracted significant research interest, several technological issues must be addressed before its practical realization. Here, we list out the possible future research directions as follows:

- The communication and sensing networks in the 6G era will be heterogeneous in technology, resources, network topology, access methods, and infrastructure with highly dynamic channel conditions. More research is required to effectively design the ISAC system in this highly dynamic and heterogeneous scenario.
- For the case of the WUSNs, further research is required to design highly reliable and energy-efficient data collection schemes in harsh underground channel conditions. Similarly, for the Coh-PON systems in the 6G era, the practical realization of the DFOS and live traffic signals pose extreme challenges that demand further research.
- In the context of the tri-functional SenRadCom system, further research is required in efficiently fusing the sensing information from the WUSNs and the Coh-PON systems with the waveform optimization incorporating the fused sensing signal, radar probing and communication signals considering the individual trade-off designs given the radar-specific constraints.
- The design of the envisioned GeoSM model incorporating the AI/ML approaches such as FTL is an open research challenge. We believe that the framework outlined in this work, along with a preliminary case study on the waveform optimization of the proposed ISAC system for a particular application case, can fuel up further research initiatives in the effective use of the 6G ecosystem in geothermal energy sensing and monitoring to foster environmental sustainability by addressing the climate change issues.
- Beyond addressing the waveform optimization problem of the GeoSM model, a more detailed study is needed to incorporate WUSN and Coh-PON geothermal sensing data into the 6G framework, considering the necessary changes to network architecture, technologies, and functions. For example, it is imperative to investigate the potential use of disruptive 5G technologies, such as network slicing, to support the seamless integration of diverse geothermal sensing data with other 6G services, ensuring efficient resource allocation and system flexibility.
- Finally, our envisioned GeoSM model can be considered the first leap towards an extended global model for harnessing geothermal resources worldwide. However, realizing such a global model can be challenging and complex, and it may require ongoing refinement as technology and scientific knowledge emerge.

VI. Conclusion

In this article, we have opened a window for discussing the importance of using sustainable energy sources such as geothermal energy and foreseeing the role of communication and sensing technologies in contributing to climate change mitigation. In particular, we have presented the general concept of the GeoSM model and elucidated the appealing feature of the upcoming 6G mobile technology, such as the ISAC system, for sensing and monitoring the geothermal potential zones. We have described the GHN as an example of a prospective use case of our envisioned GeoSM model. We have then discussed our proposed ISAC framework and included a preliminary case study on tri-functional waveform optimization in a specific case of combining the DTS, radar probing, and communication signals. Finally, we have mentioned the future research impact of our current study and outlined possible further research directions.

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