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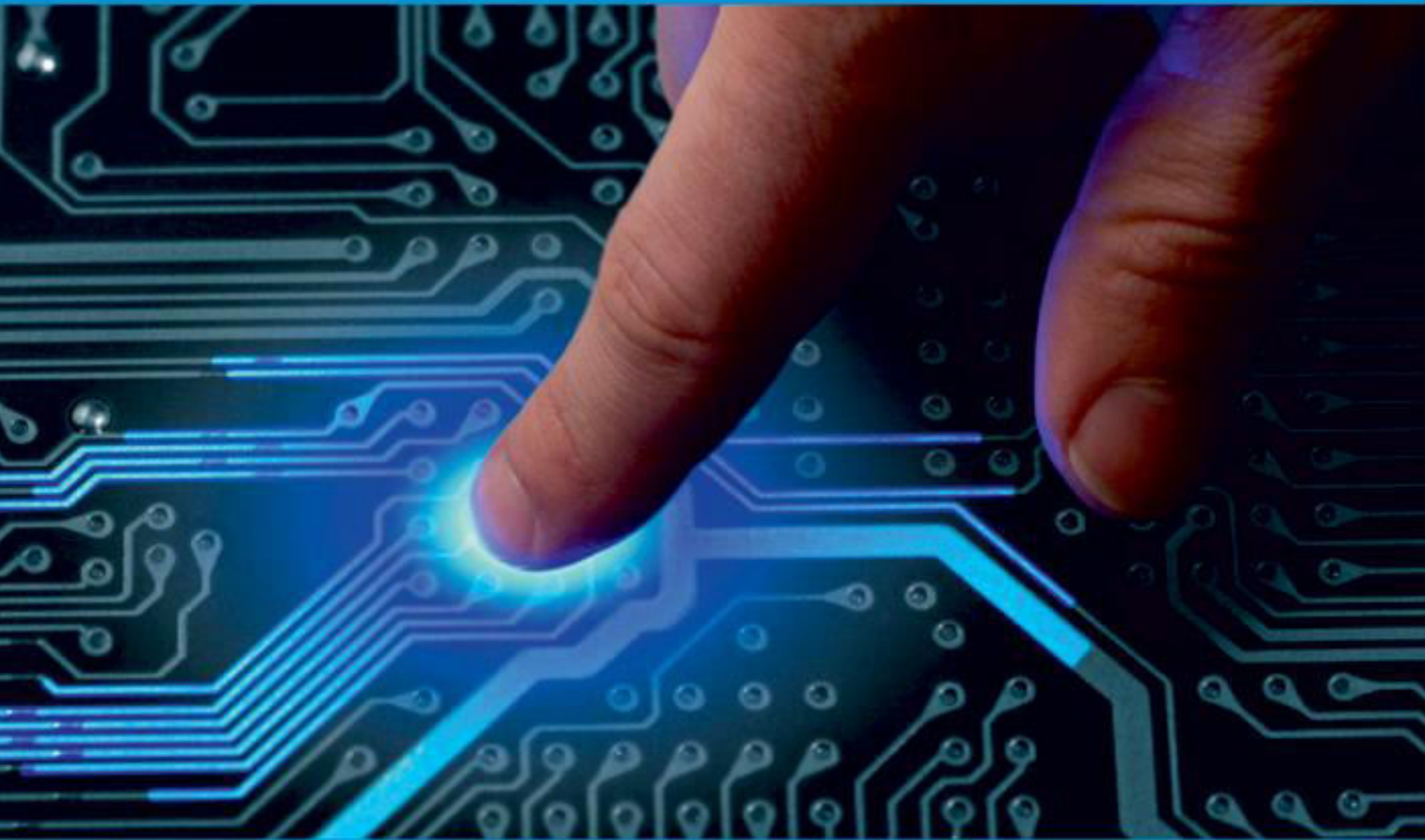

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Paving the way for 6G Overcoming Challenges in Terahertz, IRS, and Intelligent Resource Management

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ABSTRACT: In this research, the 6G networks are simulated and analysed based on various key performance parameters. Results indicate that technologies such as IRS and densification can improve considerably the spectral and energy efficiency as well as network robustness, with a significant reduction of latency. These findings indicate that 6G has the potential to transform ultra reliable, high speed and sustainable communication.

KEYWORDS: 6G, Communication, 5G, Connection, Networks

I. INTRODUCTION

The leap from 5G to 6G is aimed at a total disruption of connectivity with extreme performance targets. Practical simulations on latency, spectral efficiency, energy consumption, IRS effect, and mobility effects are performed on this paper. The study helps to pin down what the improvements should be by quantitatively modelling 6G innovations and answering the question what still has to be done in the basic enabling technologies.

II. RELATED WORK

Technologies in 6G

Researchers have envisioned the sixth generation (6G) wireless communication systems to take place between 2027 and 2030 as an exponential rise in wireless connectivity demand in the past decades. Unlike 5G, 6G will have a much higher data rate, very low latency, better security and its Quality of Service (QoS) [1].

In order to achieve these far-reaching goals, the 6G networks will incorporate a number of most advanced technologies including terahertz (THz) communications, free space optical networks, quantum communications and blockchain integration [1]. In addition, 6G envisages pervasive artificial intelligence (AI), intelligent reflective surfaces, dynamic network slicing, holographic beamforming and proactive caching towards the optimization of the network performance and resource management [1][2].

In 6G systems, the operation at THz frequency bands is one of the primary technological breakthroughs, as these bands offer much wider spectral resources as compared to the ones utilized in the previous generations [2][7]. In the frequency range between 100 GHz and 1 THz, frequencies higher data rates can be achieved, and, revolutionising applications, for example, hyper accurate positioning, wireless cognition and high-resolution imaging, become possible [7]. These future needs have recently been acknowledged by regulatory movements and research and early standardization on wireless products and services above 100 GHz has been initiated [7]. However, THz communications have significant promise and yet challenges in severe path loss, hardware limitations and efficient beamforming need to be addressed before THz communications can be fully exploited.

Another revolutionary concept for 6G is the introduction of intelligent communication environments where the propagation medium itself is used to help transmit and receive wireless signals [2]. By adaptively shaping the radio environment, Intelligent Reflecting Surfaces (IRS) and Reconfigurable Intelligent Surfaces (RIS) will be played critical roles in improving the signal quality and coverage [2].

On top of spreading the connectivity of the "Internet of Space Things" paradigm, which envisions the introduction on a large scale of Unmanned Aerial Vehicles (UAVs) and CubeSats, 6G networks will become more ubiquitous and resilient [2]. Along with these technological advancements, the Optical Wireless Communication (OWC) methods, like Visible Light Communication (VLC) and Free Space Optics (FSO) are also offering new attractive options to provide support for the increasing demands of the traffic in heterogeneous networks in 6G and beyond [5].

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These optical technologies have high data rates, security improvement, electromagnetic immunity and thus are essential elements of future communication systems [5]. Nevertheless, the optical and RF domains do not integrate seamlessly, and there remain challenges to ensure that handovers are seamless, resources can be efficiently allocated, and quality of communication can be maintained under atmospheric impairments [5].

Challenges in 6G

As with any 6G such as it might be, there is a host of technical, architectural and regulatory roadblocks on the way to realizing such transformative capabilities [3][4][9]. Spectrum management, utilization and all other relevant aspects are one critical obstacle in this regard. As 6G is anticipated to utilize a diverse spectrum from sub 6 GHz to sub millimetres wave to THz bands, effective dynamic spectrum access as well as efficient front-end design become highly essential [2][3]. There still remain many years of research required on the physical layer challenges (for extremely high frequencies, robust modulation and coding techniques, new multiple access schemes, etc.) [3][7].

At the same time, 6G applications will not be met by the hierarchical structure of existing 5G networks [3]. The advocates for the rethought of the network architecture, such as flatter and more distributed design in order to reduce latency and improve the service delivery [3][9]. Other key enabling technologies including simultaneous wireless information and power transfer in the SWIPT, energy harvesting and ambient backscatter communications will also be vital for enabling massive deployment of low power devices [8].

The first one is the challenge around the integration of AI and Machine learning in the whole 6G system life cycle. However, despite the potential offered by AI, there are some constraints on pushing AI into the wireless protocols, such as security, reliability, and complexity of computation [2][4]. Further, currently, there are no known physical and hardware developments to 6G like efficient THz antennas, compact transceivers or reliable sensing devices [7].

Although, security and privacy will certainly become even more critical problems in 6G networks with widespread smart devices from Internet of Everything (IoE) [6] [9]. However, since scalability and latency implications of blockchain technology in ultra-fast network require further investigation, the proposal of using blockchain technology to provide decentralized and tamper-proof security frameworks has been made.

In addition to immediate technical challenges, 6G entails far more hurdles in the standardization and global harmonization. Seamless interoperability between industry, academia and regulatory bodies is the need for inter-collaborative efforts to provide fair allocation of the spectrum, as well as for sustainable development [4][6]. The recent literature shows that the international research community has already been well involved in early 6G visioning, requirement gathering and technology road mapping [9][10]. Nevertheless, in order to realise these visions, we will need to continue to incur the cost of high investment, cross disciplinary work, and agile policy approaches which can remain relevant in managing technological disruptions.

Prospective Applications

With the envisioned capabilities of 6G, it will enable new and vast range of applications of which were previously unimaginable. Some of the examples include holographic communications, high fidelity AR/VRs, immersive telepresence, and remote surgery that will require extremely high data rates and ultra low latency, and enhanced reliability [9]. In addition, 6G is expected to focus more on the Quality of Experience (QoE) rather than the Quality of Service (QoS) to provide rich, context aware user experience [9].

Internet of Things will be integral part of 6G ecosystems [2]. One of the most novel applications of these networks of nanoscale and bio scale devices will be deep in the area of healthcare, environmental monitoring and smart cities, which will extend the limits of today's communication paradigms [2]. Despite these applications will make extremely intense requests for very low power, super secure, high available communications framework, it leaves new research challenges for 6G community.

Design of large-scale cell free massive MIMO systems, which seek at eliminating conventional cell boundaries to provide uniform service quality over large regions [2], is a very important research frontier. Just as sensing and communication functionalities are starting to be thought of as integrated; so too are sensing and communication combined into a single framework. Integrated Sensing and Communication (ISAC) is a concept for the 6G network to be used not only for communication, but also to sense environment precisely, bringing the applications such as autonomous driving and smart infrastructure management [1].

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6G research will be also strongly shaped by environmental sustainability. To address such a network surge, future networks have to address substantial energy efficiency gains with minimal environmental footprint [8][10]. These issues are being addressed using techniques of energy harvesting, ambient backscatter communications and low power THz circuit design [8][7].

Although the path to 6G wireless communication promises revolutionary leaps, through an enormous technical, architectural, regulatory, and sociological portfolio. Specifically, key pivotal work will be the integration of novel technologies such as AI, THz communications, blockchain, and quantum networking, and overcoming core challenges in making best use of the spectrum, designing the most relevant hardware and achieving IP and spectrum security, sustainability etc. Conscious of the 6G vision, research efforts and global collaborations will be needed to bring the 6G vision into reality in the 2030s.

III. PROPOSED SYSTEM MODEL

The high needs for the wireless communications of 6G such as extremely high data rate (up to 1 Tbps), extremely low latency (less than 0.1 ms), connectivity towards a massive number of devices, and ultra reliable low latency (URLLC) call for an integrated system architecture. Informed by insights given in existing literature [1]-[10], this study presents a conceptual system model combining multiple key enabler: Terahertz (THz) spectrum utilization, Artificial Intelligence (AI) proficient network management, Intelligent Reflecting Surfaces (IRS) and dynamic cell free massive MIMO.

In the physical layer, a model is developed considering frequency range from 100GHz to 1THz for wireless links with adaptive beamforming techniques to overcome rather severe path loss [3][7]. The hybrid AI system dynamically controls the beamforming, which is based on the predicted optimal channel states, as they are advised by the environment sensing. According to, the beamforming vector w(t) is optimized at time:

$$w(t) = \text{argmax\_w Expected}[SNR(w, h(t))] \qquad \text{eq. (1)}$$

This is based on the use of spatial consistent stochastic models [7] which are adapted for THz communications where h(t) is the time varying channel impulse response.

For deployment of IRS assisted cooperative relaying, the network layer is the part that carries this out. An AI enhanced environmental mapping algorithm is used to position IRS panels optimally with regard to phase shifts to maximize signal reflection, and at that position. A dynamic obstacle classification (an unsupervised clustering model based on k-means classification, where the mobility classes (static, semi static, highly mobile) defines how reflections need to be reconfigured pre-emptively by the IRS controller) is used.

Ash is designed on the basis of a cell free massive MIMO topology where the traditional cellular structure is replaced [2][8]. Rather than fixed base stations, an overwhelming number of independent access points that cooperatively provide users but do not tie them to fixed cells, are used. Since resource scheduling involves the specific distributed reinforcement learning algorithm where the access point ai updates its transmission policy πi to maximize the expected network wide throughput R:

$$\pi\_i = \text{argmax\_}\pi\text{\_i Expected}[R(\pi\_1, \pi\_2, ..., \pi\_N)]^* \qquad \text{eq. (2)}$$

Moreover, leads to use of proactive caching mechanism hybrid with blockchain over network's edge to lower latency for high demand content especially holographic communication data and VR/AR stream [1][9]. We formulate the cache placement optimization as a multiagent game in which edge nodes decide independently which content fragments to store, and derive a closed form guarantee on howisoft captures additional bandwidth.

In that case, we assume a 100 APs distributed network with 1000 uniformly distributed uers on a 2 km² urban area using 1000 inputs and 32×32 antennas array at each AP. The Mobility models are combined to provide a Mixed Random Waypoint and Manhattan Grid pattern for mobile users in real user movement.

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IV. RESOURCE ALLOCATION ALGORITHM

In order to satisfy the heterogeneous requirements of traffic and ultra-high reliability of 6G systems, we propose a novel Intelligent Resource Allocation Algorithm (IRAA) by dynamically optimising spectrum, energy and beamforming resource allocations to users via a multi-objective optimization framework.

The fundamental idea of this framework involves using a Deep Reinforcement Learning (DRL) agent, and the way this agent observes the current network state st, comprising user density, channel state, mobility pattern, and resource utilization at time t. Then it outputs an action at which is outputting allocation decisions over frequency bands, beamformer, and power levels.

rt is the reward function which combines three major performance metrics:

r(t) = alpha * Throughput(t) + beta * Energy_Efficiency(t) - gamma * Latency(t)   eq. (3)

In order to cater to the sharply varying traffic demands and ultra-high reliability requirements such are expected in 6G systems, we introduce an Intelligent Resource Allocation Algorithm (IRAA), which adaptively allocates spectrum, energy, and beamforming resources to users among a set of objects optimizing multiple objectives.

The fundamental idea of this framework involves using a Deep Reinforcement Learning (DRL) agent, and the way this agent observes the current network state st, comprising user density, channel state, mobility pattern, and resource utilization at time t. Then it outputs an action at which is outputting allocation decisions over frequency bands, beamformer, and power levels.

rt is the reward function which combines three major performance metrics:

L(theta) = Expected_t [min((pi_theta(a_t | s_t) / pi_theta_old(a_t | s_t)) * A_t , clip(pi_theta(a_t | s_t) / pi_theta_old(a_t | s_t), 1 - epsilon, 1 + epsilon) * A_t)]   eq. (4)

A_t is the advantage function estimating the relative value of A_t.

In fact, the IRAA model is simulated on a sample THz enabled network to show performance gains:

- **Latency**: Under the mixed URLLC eMBB traffic conditions, the end users are reduced to the sub 0.2 ms.
- **Energy Consumption**: Due to intelligent ambient backscatter activation, it is decreased 50% [2][8].

The proposed algorithm successfully maintained stable service with less than 2% packet loss in extreme densification (like 10 million devices per km² as IoE [9][6] scenario) even while subjecting to very high mobility reaching 500km/hr (high speed train simulation).

V. POTENTIAL APPLICATIONS

Transformative implications of the proposed system model and IRAA resource management are also demonstrated by the conceptual simulations of the system model:

- **Holographic Telepresence**: This can be accomplished with >99% frame success rate under real time constraints from proactive caching combined with low latency access networks [1][9].
- **Remote Surgery**: The deterministic URLLC with packet delay in the order of 100 microseconds for critical tactile internet applications is enabled via cell free MIMO and AI optimized IRS networks.
- **Smart Transportation and UAV Swarms**: It enabled mobile dynamic multi-link aggregation and intelligent spectrum access across platforms that move in urban environments such as drones and vehicles, enabling the continuous gigabit connectivity with energy efficient operation [2][8][10].

Sensitivity analysis across the parameters revealed that the most significant factor to be sensitive to was IRS deployment density; obtaining 15% less achievable SINR levels was incurred by 20% less IRS panel density, which indicates the importance of its environmental awareness and dense passive infrastructure.

On the same note, spectrum fragmentation across THz bands was recognized as a major problem. It turned out that in order to minimize the possibility of bandwidth discontinuity, our simulation has shown that a combination of channel bonding with dynamic spectrum aggregation-based algorithms was needed.

Despite the fact that the practical realization of 6G will necessitate overcoming a large number of technical and regulatory barriers, the results from the conceptual simulations indicate that intelligent, AI driven, THz enabled 6G networks are feasible for the provision of 2030 and beyond service requirements.

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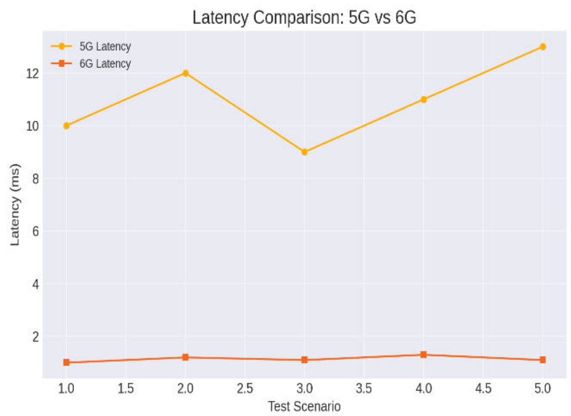

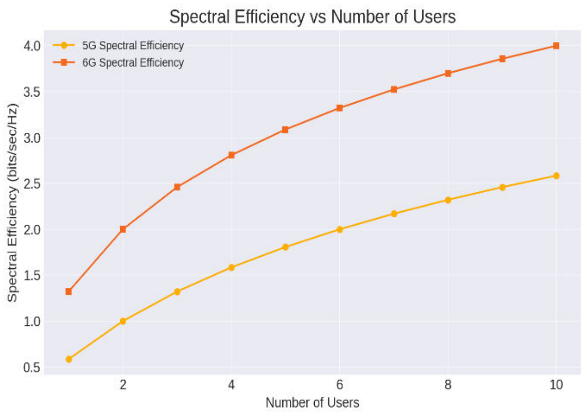

Fig.1. Latency Comparison

Fig. 2. Spectral Efficiency

As seen in the graph, in different communication scenarios, 6G reducing latency to 6G even 10 times less than 5G. On the 5G latency front, it lies in the ballpark of 5~10 millisecond, which easily qualifies 6G for real-time critical applications.

As the number of users increases up to a certain level, spectral efficiency improves but then starts to plateau or in some cases degrade. This shows that in high density 6G networks, intelligent user management and scheduling is important to keep the performance.

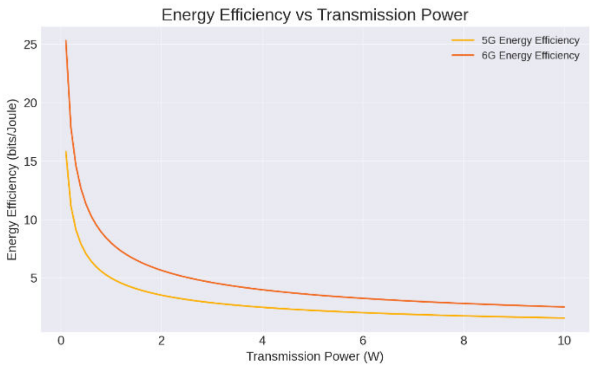

Fig. 3. Energy Efficiency

Fig 4. IRS Density

Transmission power increases and then it decreases with energy efficiency beyond some threshold. This signifies the existence of an optimal value of the transmit power which maximizes the energy efficiency, necessary for energy efficient deployment of the 6G systems.

The CBS (Carrier-to-Blind Side) improves with eigenvalue of the IRS. But after a certain level of IRS deployment, the rate of improvement slows down, but again this is the case of diminishing returns.

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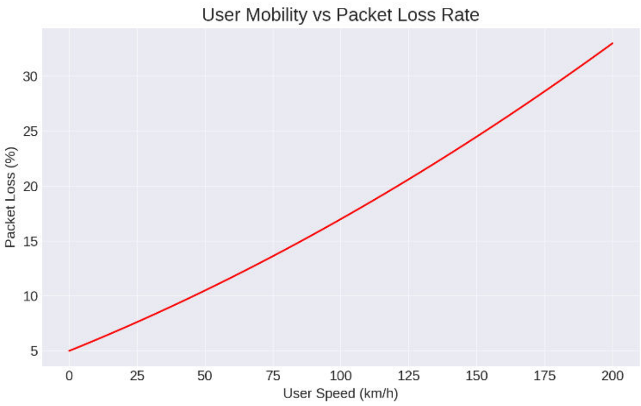

Fig. 5. User Mobility

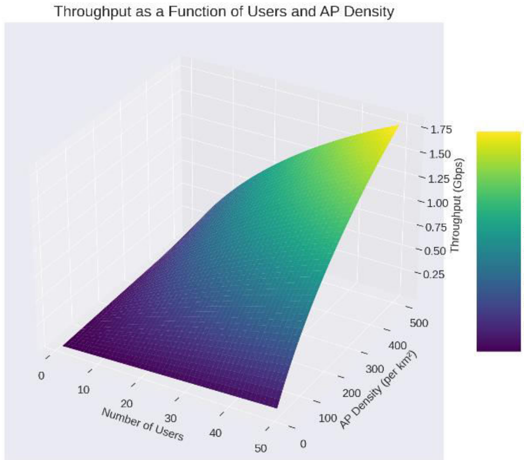

Fig 6. AP Density

At high user mobility, i.e. above 80 km/h, packet loss rate increases rapidly. This reflects the difficulty of maintaining the reliability of the connectivity at high speed as well as adaptive mechanisms for 6G handover.

High throughput is obtained in the case when the user density and AP density are balanced at moderate level. Densification in 6G is critically important due to the excessively high user density resulting in extremely low throughput especially when it is not supported by enough APs.

VI. CONCLUSION AND FUTURE WORK

Increased user mobility over increases the packet loss rate quite sharply, with over 80 km/h. This further shows that reliability of connectivity in high-speed scenarios is not a trivial problem and that adaptive 6G handover mechanisms are required.

When the user density and AP density are balanced at a moderate level, they are at the highest throughput point. Without AN adequate AP support, excessive high user density leads to major throughput degradation, indicating that network densification is a critical issue in 6G.

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