# Sustainability in 6G Networks: Vision and Directions

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***Abstract*—In this paper, we present a vision of sustainable sixth generation (6G) networks. Sustainability has become inevitable due to the strain on natural resources including materials and energy and increase in greenhouse emissions. The energy consumption and the resulting carbon emissions into the environment will be a serious concern. We cannot expect that the present exponential development will continue because of fundamental limits of nature. We first present a brief summary of system-level principles for future networks. Intelligence will be implemented using feedback loops that should be almost isolated from each other implying loose coupling and fast convergence. We next focus on sustainability challenges, including network management, network security, and network hardware. Several approaches and algorithms are highlighted for the goal-directed distributed network management perspectives of 6G sustainability. Resource consumption in network security can be minimized with enabling sleep mode in idle times, moving towards software-based security functions instead of hardware-based systems, and rethinking of encryption techniques in view of sustainability through code optimization and load fragmentation. High-efficiency antennas can incorporate biodegradable materials to build sustainable network hardware. We also introduce a new research thrust for total control of electromagnetic waves by the modular metasurface antennas making sustainable 6G radio coverage possible in various communication scenarios, e.g., small cell base stations and holographic radio coverage areas.***

***Index Terms*—6G, loose coupling, sustainable network management, sustainable security, and sustainable hardware.**

## I. Introduction

The basic reason for the present need of sustainability is the population explosion of the world and the available finite resources, especially materials and energy. Using the Earth Overshoot Day, we can estimate that already now the world population is 70% too high and with the present growth rate of 1.1% per year, the population will be doubled in 64 years. According to Ericsson (2020), Information and Communication Technology (ICT) equipment consume about 3.6% of global electricity, produce 1.4% of total carbon emissions while forming about 6% of the global economy. In communications, our focus is on the basic resources including materials, energy, information, time, bandwidth, and space [1], [2].

Sustainability means that all the basic resources are used efficiently, and contamination is reduced by recycling. The use of basic resources per bit should be minimized. Optimization of parts does not result in optimization of the whole, and therefore the conventional analytical or reductive thinking fails, and thus interdisciplinary systems thinking is needed in designing complex systems [2]. Fundamental limits of nature form constraints in optimization. For example, radio waves propagate at the speed of light, and therefore the minimum delays depend on the physical distances. Thus all communication networks are distributed in this sense, which implies in principle larger consumption of resources compared to the case where everything is done in one place. The network must be carefully designed, for example by minimizing the amount of control information and emphasizing local processing or computing everywhere.

Until about 2000, the energy efficiency of silicon electronics improved by a factor of one hundred in a decade, which made the implementation of a new generation of mobile systems every ten years possible. After about 2000, the improvement slowed down and further significant development in the 2020s is not expected. Various trade-offs are needed in optimization between the efficiency in the use of different basic resources. For example, an increase of the energy efficiency (in bit/J) usually implies decrease of bandwidth efficiency (in bit/s/Hz) and vice versa. This also necessitates a trade-off between resource consumption and performance to improve sustainability.

There are many papers on the functional and nonfunctional requirements of the 6G networks [3]. In most papers the focus is in energy efficiency, and the exponential development is expected to continue although the fundamental natural limits significantly constrain the optimization. Our approach is to use systems thinking described in [2], constrained by the unavoidable fundamental limits. In this paper, we investigate the main resource consuming services and technologies that pose major challenges to sustainability in 6G, and deliberate a way forward in this direction. Various modern standardization efforts are mentioned in the text.

The rest of the paper is organized as follows. We first introduce the reader to the general system-level principles for future networks. Next we explain the sustainability challenges in three important areas of interest, including network management, network security, and the use of network hardware. Next we offer visions to the future. Finally some conclusions are drawn.

## II. System-level principles for future networks

Complex systems are always hierarchical. Self-organizing systems are some of the most complex of all technical sys-

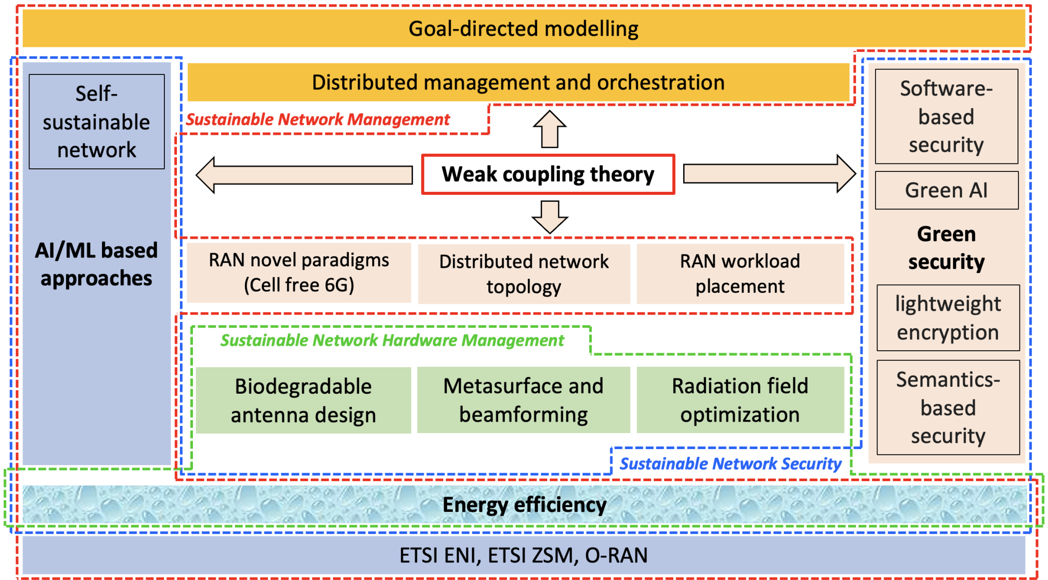


Fig. 1: Conceptual research focus for 6G sustainability.

tems [2], [4]. In the network layer we have a network manager, which controls the use of the basic resources to minimize interference and guarantee fairness in the use of resources.

Modern communication networks use feedback that consists of sense, decision, and act blocks. Sensing results are received from the next layer below about the state of the network. Next a decision is made about how to move the state of the network towards improved performance using the act block, and finally the loop is closed by sensing the next state. The feedback loops have a potential to become unstable, and the behavior may be chaotic if the network is not carefully designed.

Loose or weak coupling is known to be an efficient approach to implement hierarchy and to avoid instability [2]. Our system model combines centralized and distributed control. In communications, such a combination is called the hybrid self-organizing network (hybrid SON) [4]. The loose (i.e., slow) centralized control helps us to optimize the network and make its behavior predictable, see [5] and the references therein. On the other hand, almost autonomous distributed control can improve scalability and reactivity to external disturbances and reduce the need for control information. Thus we combine the benefits of both centralized and distributed control (see Fig. 1). The computing-communication trade-off must be taken into account since communications are expensive in terms of energy, time, and bandwidth, and thus as much local computing as possible is used in distributed systems.

Loose coupling is used in biological systems in the form of near decomposability, which implies that such systems are highly efficient. There are various practical communication applications of loosely coupled systems including cross-layer design, Internet services, and interworking architectures. Loose coupling should be used both vertically between different layers and horizontally between subsystems in the same layer. Ideally, the feedback loops are isolated from each other so that their stability is guaranteed and the loops converge as fast as possible. The vertical coupling between the layers is loose since the higher layers control the lower layers only slowly. The horizontal coupling between the loops in the same layer are also avoided. In the physical layer the coupling may be in the form of interference between users, and this is avoided by using orthogonal signals. The convergence of mutually coupled or interfering feedback loops may slow down or they may behave even chaotically. For example, the power control loops of two transmitters may be coupled when they interfere each other.

If the physical distances in the network are large, the delays in the loop may be long, and the convergence of the loops must be slowed down. Usually the higher layers have longer delays than the lower layers. Therefore, to avoid stability problems in the network, there must be time-scale separation between the layers so that the higher layers are slow and lower layers are fast. The delays may be significant for example when using cloud servers for computing. Long delays may be avoided by using local processing so that the lower layers are almost autonomous, and the layers exchange a minimum amount of information. Delays can be reduced by edge computing close to the devices at the edge of the network. An example of the use of feedback loops is the Open Radio Access Network (O-RAN). Three different time scales are used, below 10 ms, 10 ms - 1 s, and above 1 s.

In addition to stability and efficiency, loose coupling has various other benefits including scalability, reliability, and agility. Scalability is improved since the system is flexible enough so that it can adapt to future needs and larger number of users. Reliability is improved since errors do not propagate easily because of loose coupling. The systems are agile since they can adapt to fast changes in the environment because of decoupling of various feedback loops.

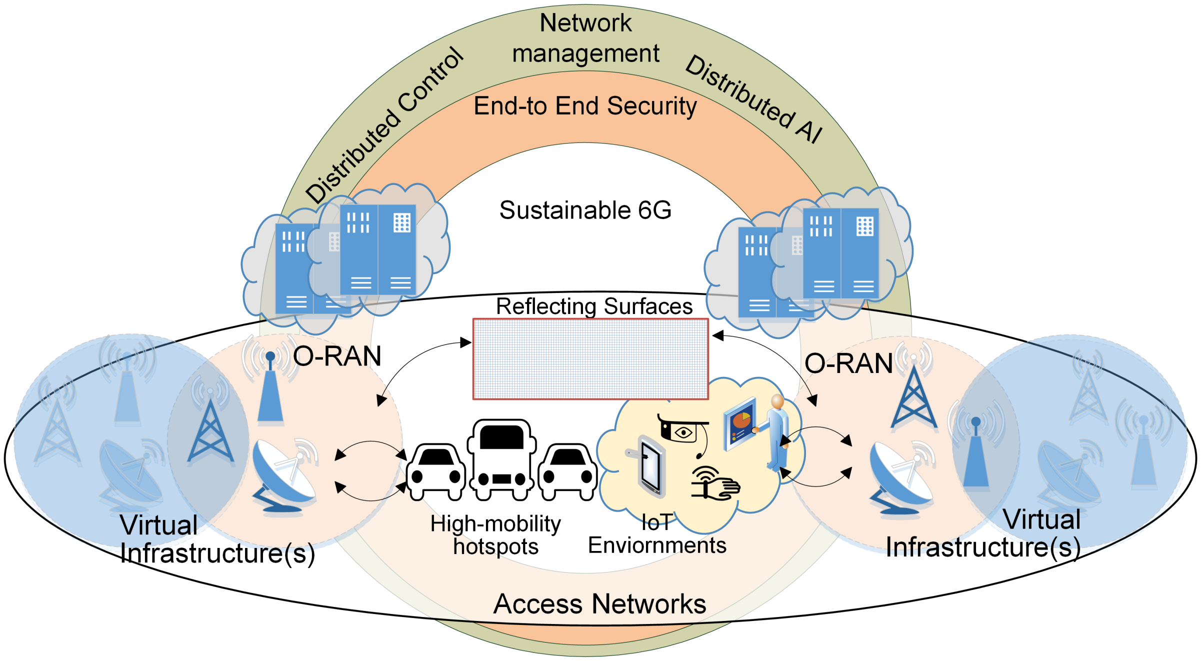


Fig. 2: High level network architecture of sustainable 6G networks, where different network layers, components, and perimeters including diverse types of RATs cooperate and have feedback, loosely coupled, systems (circular shape represents feedback system, conceptually borrowed from sustainable circular economy).

## III. Sustainability Challenges of Future Networks

6G networks are being developed to meet the increasing demands for high volume, large bandwidth, and low-latency (i.e., low-delay) data transmission with multi-radio access technologies (RAT), heterogeneity, and ultra-dense attributes, as shown in Fig. 2. The overall network is loosely coupled where diverse RATs, backhaul, and core networks, consisting of physical and virtual infrastructures work in unison. Systems thinking forces us to understand the whole network since otherwise we would be limited to local optimization that does not result in global optimization. The limitations of the physical layer must be taken into account. The physical layer in the new frequency bands may cause more problems than the network layer. For ensuring future 6G network sustainability, the network should be adaptive, autonomous, intelligent, and secure from the perspective of new material design, implementation, operation, and management. The networks will use feedback as an integrating concept, and therefore loose coupling principles are mandatory. In this section, we focus on sustainability, especially on autonomous networks, its security, and materials. Our principles are explained in this section and summarized in Fig. 1 which is concept driven, in Fig. 2, which is topology driven, and in Table I presenting the main challenges and solutions in the three areas covered.

### A. *Sustainable Network Management*

It is expected that future world will be hyper-connected, and the upcoming network generation must act as a communication and information backbone, allowing anything to communicate anywhere and anytime while maintaining a low carbon footprint. Present network management lacks of self-management and network control intelligence for highly complex and variant environment to maintain sustainability. This motivates researchers to investigate the new scope of sustainable network management by enforcing the migration from an environment-adaptive self-organizing networks towards a self-sustainable network to maintain its key performance indicators in the dynamic and highly complex environment for new applications.

In self-sustainable network, many services will go across different network functions and domains in the network which require to work in unison to ensure end-user experiences. Thus, the traditional service and network management solutions may not be sufficient. The appropriate implementation of distributed management and orchestration solutions are required to automate the life cycle management workflows. This shift will boost the flexibility and efficiency of service delivery and reduce the operating expenses through self-management capabilities, e.g., self-configuration, self-healing, self-optimization, and self-protecting. The self-sustainable network management will be envisioned by developing goal-directed modeling of service orchestration through automation, softwarization, and intelligence inspired by European Telecommunications Standards Institute (ETSI) specification groups, i.e., Zero Touch Network and Service Management (ZSM) and Experiential Network Intelligence (ENI) architectures.

The ZSM architecture is developed to specify an end-to-end network and service management reference architecture

TABLE I. SUMMARY OF SUSTAINABILITY CHALLENGES AND POTENTIAL SOLUTIONS

| Sustainability Target | Sustainability Challenge | Sustainability Solutions |
|---|---|---|
| Network Management | Self-management and network control intelligence | Goal-directed modeling of service management and orchestration |
| | Fully distributed architecture | O-RAN complemented by loose centralized control |
| | Cell-centric approach | Goal-directed and distributed RRM algorithms |
| Network Security | Hardware-based security | Security softwarization and virtualization |
| | Resource depleting encryption and packet labelling | Load fragmentation, code optimization, and use of semantics |
| | Economic denial of sustainability attacks | Energy fingerprinting and monitoring |
| Network Hardware | Use of plastics | Biodegradable and recyclable materials |
| | Large number of base stations | Intelligent reflective surfaces, holographic beamforming |
| | Less coverage | Beamforming and smart metasurface technology |

enabling agile, efficient, and qualitative management and automation of emerging and future networks and services [6]. This framework is envisaged as a next-generation management system. The ENI architecture uses control-loop artificial intelligence/machine learning (AI/ML) mechanisms to improve the operator experiences based on context-aware and metadata-driven policies [7]. This model is foreseen to provide actionable network management by adjusting network services and resources based on user demands and environmental conditions. However, these architectures are not fully aligned with sustainability requirements of goal-directed modeling on service orchestration.

In practice, goal-directed management uses rules to govern behavioural choices whilst satisfying the goals of the system. Certain attributes should be tackled, i.e., behaviour is independent from a service model, and the models are independent from software. It should be adapted with changing situations and network complexities by taking intelligent policies. To the best of the authors' knowledge, the goal-directed approach and refinement has not been researched so far from the network management, automation, and intelligence perspective. We believe that by applying the loose centralized control to ZSM and ENI architectures, the networking approaches (e.g., planning and design, delivery, deployment, provisioning, monitoring and optimization) will be changed from reactive allocation towards a closed-loop-based proactive allocation.

*Directions –* To implement fully self-sustainable network management, the embedded intelligence must be used in every layer of the network while having a loose centralized controller in every layer including the radio access network. Most of efforts are concentrated on the "non-radio" sections while the deployment, optimization and operation of the RAN components generally accounts for approximately 70% of the entire network cost. Consequently, a more open, intelligent and software based RAN architecture can increase the network sustainability. The O-RAN Alliance was formed to bring the flexibility and agility of the RAN architectures by introducing new entities, i.e., near-real-time and non-real-time RAN intelligence controllers [8]. These entities including AI/ML frameworks increases the possibility of RAN automation, reduces manual intervention, and saves operational expenses while avoiding human errors. Hence, self-sustainable network complemented with an O-RAN based architecture and AI/ML based frameworks will benefit from combined monitoring of performance and automation at various levels such as for workload predictions, optimization, and controlled RAN protocol performance by RAN workload placement. The O-RAN architecture improves network resource efficiency and performance due to a continuous monitoring that enables close-loop control of resources with reduced human intervention. However, the current resources are managed based on a cell-centric approach which is not sustainable. Therefore, novel approaches could be designed to enable goal-directed and distributed radio resource management (RRM) algorithms implementation in order to facilitate a fully user-centric network architecture, i.e., cell-free networks.

Future 6G networks should be capable of providing sustainable network management solutions by taking autonomous network decisions such as spectrum usage, power control, and other RRM algorithms based on the outcomes of previous operations, without communication overhead to and from centralized controllers. In addition, energy sustainability could be improved by using energy-efficiency xApps in O-RAN frameworks.

### B. Sustainable Network Security

Network security will be highly challenging in future networks mainly due to the amalgamation of a vast number of mobile services that follow users, increasingly huge number of devices with limited resources in Internet of Things (IoT), and the merger of different operators with possibly conflicting security policies [9]. The most common security approaches fall under the International Telecommunication Union-Telecommunication (ITU-T) standards and recommendations. ITU-T covers the security aspects from eight different dimensions, namely, access control, authentication, non-repudiation, data confidentiality, communication security, data integrity, availability, and privacy. Each of these have their own techniques of implementation and have resource (storage, computing, bandwidth, and energy) consumption costs. Each of these techniques requires specific changes towards green security, in other words, maintain the same level of security with comparatively less consumption of resources. For reason of brevity, we take the case of firewalls and end-to-end encryption, which are common techniques to provide a level of security. Firewalls can employ techniques for access control, authentication, non-repudiation, as well as ensure availability of services behind it. End-to-end encryption, generally, helps in data confidentiality and integrity, communication security, and privacy.

Firewalls are usually deployed at the border gateways in access and core networks. The techniques used by firewalls, e.g., for deep packet inspection (DPI) and intrusion detection/prevention systems (IDS/IPS), are highly efficient due to the emergence of fast hardware and intelligent ML-based analysis tools [10]. However, firewalls are also highly resource consuming. In traffic inspections for intrusion detection, each packet must be matched against a set of rules derived from previous experiences. The matching of the data and header parts of packets consumes resources right from packet sampling and labelling, to rule matching and temporary storage. Regardless of these overheads, the main consumption occurs when proprietary hardware runs by default even if there are no security threats.

The energy consumption of the most common encryption and hashing algorithms is evaluated in [11]. Various sets of use cases were investigated to evaluate the strength of security with comparison to its energy consumption. The results reveal that less secure algorithms consume less energy, and the energy consumption increases linearly as the load increases. However, the energy consumption can be greatly controlled with efficient software implementation by optimizing the code for energy consumption. Furthermore, load fragmentation can also be an effective technique to minimize power consumption, specifically of the central processing unit (CPU). Moreover, when techniques such as network and user zoning are used, the number of packets to be inspected can be reduced, resulting in reduction of resource consumption. Similarly, ML techniques are used that require labeling of packets and increased rounds of communications between the training systems and the data generating environments. Due to limitations of in-network resources, hardware accelerators are also required for most ML techniques. As a result, the use of ML increases the overall resource consumption footprint of security techniques.

Denial of service (DoS) and distributed DoS (DDoS) attacks overwhelm a network infrastructure with unwanted traffic or operations and stealthily consume its resources. Such attacks hinder access of resources to legitimate users. The economic denial of sustainability (EDoS) attacks [12] target cloud users to increase their consumption of resources in a leased or rented cloud environment such as the Amazon Elastic Compute Cloud (EC2). It is evident that 6G networks will use different variants of cloud platforms, including edge, fog, etc., for sensitive networks functions such as O-RAN. Thus, EDoS attacks [12] will pose significant threat to 6G networks.

*Directions –* Resource consumption in network security can be minimized with enabling sleep mode in idle times, moving towards software-based security functions instead of hardware-based systems, and rethinking of encryption techniques in view of sustainability through code optimization and load fragmentation. The role of hardware-based proprietary firewalls can be reduced by leveraging virtualization and softwarization technologies. Security functions can be virtualized into virtual network functions (VNFs) and placed in high-end servers in cloud platforms. Migrating such VNFs to different network perimeters, i.e., ingress gateways, only when there is a need, can minimize the overall resource consumption. The main reduction is through relinquishing services from purpose-built proprietary hardware that is always running once deployed. Lightweight intelligent software functions should be used whenever possible, and can be easily re-used, re-purposed, or recycled compared to hardware solutions. The challenge, however, will be related to placing security functions before an incident occurs. ML-based prediction, network zoning, and using network semantics can help overcome such challenges.

More work is also needed to maintain resource consumption of ML techniques. When network semantics are coupled with the data flow, the amount of labeling and its need in ML can be minimized. Similarly, efficient sampling techniques are needed for ML, resulting in lower consumption of resources, and a step towards green security. A reasonable approaches to mitigate EDoS attacks would be energy auditing, as discussed in [13] for IoT. Sustainability of different devices, which can be potential exposure points for EDoS attacks, can be achieved through fingerprinting and monitoring their energy consumption. The main lesson learned from the previous generations is that security has rarely been studied from the sustainability point of view, which must change in 6G networks.

### C. Sustainable Network Hardware Management

As discussed in the previous sections, fundamental natural limits apply to every aspect of the communication network, even to the materials used to build the infrastructure. In the hyper-connected future world, we need to be mindful that communication network infrastructure will be replaced and supplemented by the new hardware, and sustainability of the hardware is as important as that of other network aspects mentioned above.

In sub-6 GHz 5G and legacy cellular communication generations, most of the mobile phones are served by a small number of base stations covering large areas whereas moving towards 6G networks, the cell size is expected to shrink significantly due to two main reasons. The first one is the requirement of a massive number of connected devices with a twofold growth in mobile and smartphone subscriptions and a tenfold growth in machine-to-machine subscriptions predicted by 2030. Hence, small cell base stations will be better to serve all the users within a given geographical zone, including mobile networks and industrial sites. The second reason is that in addition to the sub-6 GHz and new millimeter wave (mmWave) frequency bands around 28 GHz, the 6G networks will also be using huge bandwidth available at frequencies ranging from 30 GHz up to terahertz (THz) frequencies [14]. These frequency bands will have much shorter wavelengths and higher path losses compared to lower frequencies, hence a large number of small cells will be preferred. Currently, telecom sites are crowded with equipment and waste up to 40% of the energy in heat dissipation. The push for further integration in 6G base station equipment will allow more efficient design with a potential of up to 90% efficiency. A site-level AI/ML-assisted decision-making on multi-site shutdown and adaptive power techniques will lead to up to an 8% reduction in energy consumption.

Sustainable development of a large number of base stations in a given geographical location can be achieved, not only by improving energy efficiency but also by reducing electronic waste (e-waste) and improving the recyclability of the antenna hardware. Currently, for 4G and 5G networks, the sustainability agenda is served through recycling of the radio units, but most of the existing manufacturing processes and materials used are not suited for recycling, being complicated to disassembly, and thus result in massive amounts of non-recyclable e-waste. It is estimated that 20% of e-waste is recycled and the rest of it ends up in a landfill. The situation will be further exacerbated with the expected rapid growth of base station radio units and the dismantling of the old ones.

The 6G communication systems are already envisioned to significantly rely on novel radio hardware, especially in antenna technology. In addition to base stations, it is expected to have cell-free smart surfaces at high frequencies supported by the mmWave tiny cells for mobile and free wireless access. For even higher frequencies, we may need trials of tiny cells since the path loss at THz frequencies will not support the classical cell model. For areas with weak radio coverage, we need temporary hotspots served by drone-carrier base stations or tethered balloons. For all these coverage scenarios especially at mmWave and higher frequencies, the requirements for base station radio units to maintain high efficiency poses an enormous challenge.

For 6G networks, radio units are expected to be augmented or substituted by two key enabling technologies: holographic beamforming [15] and intelligent reflective surfaces (IRS) [16] in order to ensure technological promises of Tbit/s data rate and ultra-low latency [14]. The key hardware part of these technologies can be summed up into a single term "metasurface". Metasurfaces can manipulate electromagnetic waves to provide desirable radiating features such as versatile beamforming to serve multiple data streams from a single radio unit. By arranging the metasurface unit cells, the size, fabrication complexities, and losses can be significantly reduced, making them very attractive as an enabling technology for a variety of 6G applications, e.g., high-efficiency intelligent reflecting surfaces or holographic radio technology [14], in which a radio signal can be focused at any point in space, see Fig. 3.

Currently, metasurface structures are produced using standard radio hardware fabrication technologies that either does not allow full recycling or the recycling process is deemed not economical as only tiny parts of the product are precious metals and most of it is composed of poorly recyclable plastics. To ensure that the environmental footprint of the metasurface used in base station antenna units is reduced, it is recommended to develop metasurfaces using as much of recycled materials as possible. In addition, metasurfaces can be developed using biodegradable polymers manufactured from bio-based materials (e.g., polylactic acid, polyhydroxyalkanoates) or fossil fuels (e.g., polybutylene adipate terephthalate, polycaprolactone), with a lower impact on the environment. Such biodegradable and recyclable materials need specialized improvement through composite manufacturing techniques to ensure that they fulfil the requirements of thermal stability, flexibility, and resilience to the external environment.

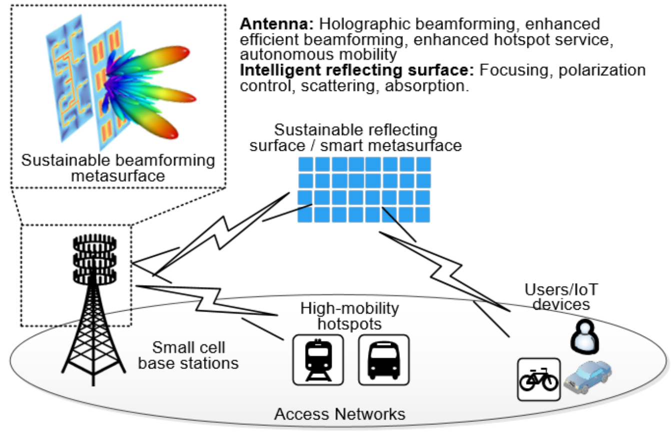


Fig. 3: Multiple operations modes of sustainable radio hardware in 6G access and IoT network.

*Directions –* Looking towards the problem from an antenna design perspective, achieving high efficiency yet compact and programmable metasurfaces is already a challenge. The task complexity increases when radiators, control circuits and reconfigurable elements are to be developed on composite biodegradable or recyclable polymers. The basic principle of operation for metasurfaces is that for a given incident field by a driving antenna in a base station, the surfaces can be realized passively by creating a distribution of miniature electric or magnetic dipoles, e.g., in [17]. This is done for maximum radiation field optimization along the intended direction of signal propagation. The same principle can be advanced to develop a high radiation efficiency intelligent reflective surfaces shown in Fig. 3. This time the signal is not driven by the local antenna but by a received signal from a base station located in the far field.

As the metasurface antennas will use a modular approach, that will enable building a sustainable antenna with the necessary performance for a given 6G communication scenario, e.g., indoor wireless access points or outdoor base station. The modular approach can ensure the re-usability of antenna units for various communication environments, for example, to build sustainable antennas for short distance communication, the metasurface with a few module units can be sufficient, whereas for long distances, the higher number of module units can facilitate better signal transmission. This in turn will reduce the number of uniquely manufactured parts and enable customised on-demand assembly and disassembly of the components of the radio unit.

## IV. Conclusion

In this paper, we first presented system-level principles to design sustainable networks. We observed that exponential development cannot continue because of constraints set by the fundamental limits of nature, and therefore the efficient use of resources is mandatory. The sense-decide-act feedback loops needed in intelligent network management must converge as fast as possible. They may become unstable or behave even chaotically unless they are loosely coupled or almost isolated. The loops form a hierarchy where the highest layers having the largest delays are slow and the lowest layers having the smallest delays are fast. The feedback loops in the same layer must not interfere with each other. The information exchange between layers is minimized and the lowest layers work almost autonomously using local information as much as possible.

Several approaches are highlighted for the goal-directed distributed network management perspectives of 6G sustainability. Different approaches are envisioned for the goal-directed management and network orchestration for the 6G application scenarios.

The wireless networks infrastructure especially the environment-facing radio hardware is required to evolve in a sustainable and eco-friendly manner to improve on previous generations. We highlight several approaches in which technological advancement in high-efficiency antennas can incorporate biodegradable materials to build sustainable radio hardware, thus forming an integral part of the sustainable hyper-connected 6G world. We also introduced a new research thrust for total control of electromagnetic waves by the modular metasurface antennas making sustainable 6G radio coverage possible in various communication scenarios, e.g., small cell base stations and holographic radio coverage areas.

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