Bharat
6G VISION

Taskforce Report
Multi-platform Next Generation Networks

सत्यमेव जयते
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6G Taskforce Report:
Multi-platform Next Generation Networks

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1. Background

Task Forces under Technology Innovation Group on 6G (TIG-6G) were constituted vide DoT Letter No.6-1/2021-IC dated 30th Dec 2021 for inputs to TIG-6G. One of the Task Force was on "Multi-platform Next Generation Networks".

The terms of reference of this Task Force are as follows:

- Development of Network Elements of Multiplatform Next Generation Networks
- Integrated Optical and Wireless Network (referred to as Wireless GPON)
- Spectrum Hyper-Efficiency in Networks
- Tactile Internet Remote Operation (referred to as remote near-physical activity)
- Space-Terrestrial Integrated Network (referred to as LEO Satellite Overlay/ Geo Synchronous Satellite based Overlay)
- Drone Communications/ High Altitude Platforms technology
- Any other items in the scope of 6G activities and overall deliverables

2. Executive Summary

The Task Force deliberated extensively on the current global thinking regarding evolution of telecom network in the year 2030 and beyond. The strands were evaluated in the context of India's own future needs and growth trajectory over the next decade. Depending on the degree of relevance of each of these strands in our context, the Task Force has emphasized some of the possible evolutionary paths. While evaluating the strands, it emphasized on those that appeared more realistic and promising in a ten-year timeframe.

The importance of a dense optical network in homes and offices cannot be over-emphasized. This takes time and resources to build, and the wireless network continues to not only serve the needs of a mobile user but nomadic or static user as well. Going forward, a seamless integrated optical and wireless network, with wireless fiber-like segments wherever appropriate, is imperative. Sufficient attention will have to be paid to GPON network engineering in rural areas.

The explosive growth in data volumes, multiplicity of access technologies, deepening of the optical access network, proliferation of edge clouds, and increasing need for content and user-awareness will lead to a more decoupled core and network architecture, and increased use of AI/ML in optimization and intelligent network operations.

As spectrum gets more heavily used, ever-higher frequency bands are being explored primarily due to the large bandwidths available and ever-improving operating frequencies of semiconductor technologies, despite the challenging propagation conditions at these frequencies. Mitigatory techniques such as Intelligent Reflective Surfaces may provide some workarounds of poor propagation at very high frequencies as well as massive MIMO with cell-free operation. The Air Interface may move radically to a virtualized user-defined mode enabling the radio to support the specific user requirements for a given wireless channel, moving away from the hitherto conservative design for the worst-case wireless channel. The wireless transceiver in many cases may additionally play the role of a radar sensor to capture the ambient environment around the transceiver.

While the remote operation of machines and robots may be attempted even with 5G networks in the coming years, the Tactile Internet for Remote Operations is a serious possibility after a decade from now. This capability may be used not just for high-end applications such as remote robotic surgery, but for a host of mundane applications in a similar way to multimedia communications is used today with the smartphone for all kinds of applications. This may require good support from edge computing clouds that run ML/AI algorithms and will leverage a user-defined radio interface to ensure high reliability. The growth of Industrial IoT in the coming years will drive the growth of remote operations even if much of it is simply automation and not tactile. Digital Twins of complex, real physical systems and networks running in the edge clouds will enable automated control of the real system by predictive analysis of future events based on AI and other techniques.

With the increasing cost-effectiveness of Low Earth Orbit satellites and new technologies such as HAPS, it is likely that non-terrestrial wireless networks will finally get integrated with the terrestrial network to offer ubiquitous coverage not only on ships and aircraft but in the Indian context, to rural areas under-served by the terrestrial network. The explosive growth forecast in drone usage will necessitate drone communications to be supported by the integrated space-terrestrial network in a reliable and secure manner.

The very high data rates supported by the next-generation network are likely to provide a platform for realistic e-meetings where holographic-type or AR/VR technologies are deployed along with multi-gigabit-per-sec tether-less links to provide a near-physical experience. User-defined virtualized air interfaces will enable such platforms to be invoked even by a mobile user based on the ability to set up a sufficiently fast, low-latency, low-jitter, reliable link, leading toward what could be described as hyper-personalized wireless networks.

The research efforts over the next few years should be aligned toward realizing one or more of the highly promising, scalable, and feasible (with high probability) technologies/platforms outlined herein. All of these are of great relevance in the Indian context and also have global applicability. Advances made in any of these areas will not only serve our needs but also give India an edge, globally. India can use this decade to realize its aspiration of being a net global provider of telecommunications technology.

2.1 Development of Network Elements of Multiplatform Next Generation Networks

The 5G core network architecture having well-defined virtualized network elements enables support for increased throughput demand, reduced latency, and increased reliability as per requirements of various applications and services that 5G must support. The new 5G core utilizes cloud-aligned, service-based architecture (SBA) that spans across all 5G functions and interactions including authentication, security, session management, and aggregation of traffic from end devices. The 5G core network has been designed from scratch to include Service Based Architecture, network slicing, mobile edge computing, etc. that bring flexibility, easy integration with third-party software, easy provision of services belonging to different verticals, improved QOS, etc. It will enable mobile operators to serve IoT (Internet of Things) use cases, ultra-reliable, low latency connections as well as use cases pertaining to enhanced mobile broadband.

The 5G Radio Access Network caters to multiple categories of applications that require high reliability and low latency using the Ultra-Reliable Low-Latency Communication (URLLC), Massive Machine Type Communications (mMTC), and Ultra Mobile Broadband (eMBB). It employs massive MIMO extensively to achieve high spectrum efficiency. For the first time, the 5G network forays into the mm-wave band with wideband channels having a bandwidth of 400 MHz While the radio propagation characteristics in this band are not as favorable as in the lower bands, the antennas do become smaller enabling very large number to be deployed in an array, and the data rates achievable are impressive.

The next-generation (6G) network is anticipated to make several major leaps forward, and the network elements belonging to multiple platforms such as RAN, Cloud, Edge Cloud, optical network, terahertz wireless nodes, and new user device types will be required to inter-operate seamlessly to make the new applications and use cases a reality. In 6G, Multi-platform Network elements have to work at very high frequencies, bandwidths, and data rates, provide ultralow latency where needed, support programmability, and provide high computational power, high reliability and security. These are dealt with extensively in the following sections dealing with specific capabilities envisaged in the next-generation 6G network.

2.2 Integrated Optical and Wireless Network

The network architecture currently in vogue uses an optical fibre network for backhauling the data to the routers and data centres, and a wireless network for mobile subscriber access. Optical fibre is increasingly being extended for providing higher data-rate connectivity not just in offices, but in homes too using Gigabit Passive Optical Network (GPON) technology. Within offices and homes, Wi-Fi provides tether-free access to users. While optical fiber backhaul from cellular base stations is the preferred mode due to the ever-increasing data rates supported by the wireless systems, wireless backhaul continues to be used where optical fiber connectivity has not yet been provided.

As data consumption by users grows exponentially, the desired network configuration is an optical fiber in every office/home and ultra-high-speed / reliable / low-latency (all three desirable features or some combination thereof) wireless access for mobile users. Given the ever-increasing user appetite for data, it is wise not to overload the mobile access network with indoor users who could very well be served by an optical network reaching into the office/home. Since densification of the optical network takes time, wireless access continues to serve indoor users as well in many homes and offices.

One of the thrust areas for the future network is maximal optical fiber penetration in offices, shops, and homes. When water, electricity, and even gas are being piped to every home, there is no reason not to extend optical connectivity too. However, the outdoor plant engineering for the last-mile OFC with terminations every 10-15m, and with sufficient robustness against frequent digging, construction activities, etc, remains to be fine-tuned. Just as electricity is supplied with overhead cables in certain areas, the last-mile overhead OFC deployment option must also be engineered in a robust fashion (e.g., new fiber designs with a low bending radius could be developed). A decision has been made to take OFC to every village in the country. It is the right time to work out the best-engineered solution to extend GPON to every home in the village including the dwellings build under the Pradhan Mantri Awas Yojana.

While building such a deep and dense OFC network, it is to be expected that providing 100% Optical connectivity may not be technically or economically feasible in certain areas or sections at a given point of time. This is where tightly integrated optical and wireless networks play an important role. New wireless technology in the mm-wave, E, V, and terahertz bands is expected to provide multi-gigabit speeds akin to optical systems. It is also fairly easy to "drop" multiple links on a wireless "bus" similar to GPON. It is worth noting that GPON itself is evolving to higher rates such as XGSPON (10 Gbps) and HS-PON (50 Gbps). There is great interest globally in an integrated optical and wireless network (see, for example, https://iowngf.org/) which is managed and re-configured intelligently along with a host of distributed computing resources. Thus, a judicious combination of ultra-high-bitrate wireless technology in new mm-wave and terahertz bands and optical technology, designed to interoperate seamlessly, can provide India with the flexible and cost-effective solution to take broadband to every home and office within the next ten years.

It is also anticipated that quantum communication techniques will become more common-place in the ever-expanding optical network to provide an enhanced level of security.

2.3 Core Network

In conjunction with the proliferation of the mobile cellular network in the country, there also has been tremendous growth in mobile data consumption. The key factors that drive this growth in the country are increased usage of smartphones, availability of a variety of mobile applications, and limited deployment of fixed-line infrastructure. Mobile phones are the primary or only means of data consumption even from the home or workplace. Even a conservative estimate indicates a huge consumption to the tune of a few exabytes per day by 2030, when the deployment of IMT-2030 or the

6th Generation mobile communications system (6G) may start. In order to support the very large number of users including machines, and to support extremely large data transfer volumes, we will need an immensely flexible and scalable core network as an integral part of the 6G system.

The 5G core network has been designed from scratch incorporating technologies and design principles such as Software-Defined Networking (SDN), network function virtualization (NFV), network slicing, service-based architecture (SBA), and control and user plane separation. Among other capabilities, these technologies and principles bring flexibility, platform independence, cloud-native deployment, easy integration with third-party software, provisioning of services belonging to different verticals, and support for diverse QoS requirements of applications and services. The 5G system also has a converged core with a common interface between the access and the core network enabling easy integration of diverse access technologies within a single 5G network. While these techniques would continue to be the bedrock of the 6G core, the core network may need to evolve further in order to support the emerging diversity and the required data volume in the 6G network.

The recent advent of cloud computing and network functions virtualization has resulted in the emergence of network cloudification. Furthermore, with the proliferation of edge computing, computing resources inside a network now extend from a centralized cloud to the network edge, providing almost ubiquitous computing power. However, the computing capability of a single network edge site is normally limited and cannot be flexibly expanded. Future networks may require multiple distributed network edge sites to interconnect and collaborate with each other. Orchestration capabilities that are computing-aware will need to be supported.

With the advent of social media platforms, AR/VR use cases, etc., the users are also more content-aware. IETF has proposed Information-Centric Networks (ICN) as a paradigm to make networks content-centric than the current approach of being host-aware networks are expected to improve the network efficiency and satisfy ever-growing data demands of the users.

Design principles and technologies such as disaggregation, edge computing, incorporation of diverse and complementary access technologies, user-centric design enabling concurrent usage of a large number of access links/technologies, and usage of AI/ML techniques are likely to play a significant role in this evolution. The 6G core is likely to be integrated with an ever-larger number of access technologies, terrestrial and non-terrestrial, unicast and broadcast, licensed and unlicensed access, etc. The usage of technologies, that support network softwarization, such as SDN, NFV, SBA, network slicing etc. will gain further momentum. These will be complemented by AI/ML technology, which is likely to play an important role in the performance optimization of the 6G core. AI/ML-driven protocol and network design will impart greater flexibility. In addition, the enablement of localized (or edge-based) service delivery with a reduced number of network functions in the data path (possibly involving only access network functions) is expected to be an important design principle for the 6G core. It leads to a decoupled access and core network architecture, unlike the existing 5G architecture, and may bring immense benefits both in terms of reduced end-to-end latency and improved scalability of the core network.

As networks become increasingly flexible and the complexity of network functions grows, the introduction of intelligent operation capabilities in future networks will be of great importance.

In the scenario where we are monitoring a network for impairment (or potential impairment) for example, it is common that multiple sensors will be measuring numerous parameters and the key performance indicator is 'network health'. These sensors tend to measure independently of one another and are not always working together in a system wide manner. Thus, a comprehensive unified, multi-level, and deeply correlated analysis of measurements is needed to accurately pinpoint root causes of alarms and instantly invoke automatic recovery mechanisms

2.4 Spectrum Hyper-Efficiency in Networks

Deploying nano/dense small cell networks overlaying the conventional macro cell networks is widely regarded as a key step towards network architecture revolution for improved spectrum and energy efficiency. This includes evolution of transport network to support such dense deployments. Obviously, if there is dense cellular network with small cells that are sized in the tens of meters range, one needs a dense optical network for the backhaul aided by ultra-high bitrate wireless links in the mm-wave bands and beyond (see Section 2.2). With such a dense network of small cells, the concept of cell-free communications between handset and base stations using massive MIMO, with a very large number of antennas that are not co-located, becomes attractive. Here there is no geographically contiguous cell served by a single base station. Rather each handset sends to and receives signals from multiple cell sites based on the channel conditions. Both capacity and coverage can be enhanced greatly using this approach.

Another holy grail in improving spectrum efficiency is full-duplex communication, which has been around for a long time in wired telephony. It is much harder to implement in wireless systems, but the reward is a doubling, over and above all other improvements, in spectral efficiency. Steady progress has been made over the years, and it is expected to become a reality sooner than later.

Despite the advances made in every generation of cellular wireless technology leading to Gigabit-per-sec speeds in 5G, the cellular system continues to be designed to ensure a minimum acceptable level of service to the worst-situated user in a cell. All the mandatory requirements to be met by the system are specified in terms of this worst-case performance, with opportunistic best-effort enhanced performance for the users who have better links to the cell site. Taking advantage of the vastly improved processing and computing power at the base station and handset, one can conceive of a "horses for courses" approach in the future, wherein multiple waveforms and link protocols are made available to users. Each handset will select the waveform and protocol best suited for its instantaneous channel conditions and user requirement (reliability/data rate/latency). This concept is being explored by several research groups (see, for example, 6G: The Personal Tactile Internet—And Open Questions for Information Theory in IEEE BITS Sep 2021), as provisioning in the same system of an optical-fiber-like high data-rate, low-error-rate, low-latency wireless connection over a relatively benign channel differs considerably from that of a low bit-rate, low-energy-consuming, robust link over widely-varying channel conditions. This idea can be refined further, and one can migrate to a completely "user-defined" dynamic radio layer determined by the current radio environment experienced by the user and the performance attributes sought by the user. This is explored further in Section 2.8.

As optical-fibre-like speeds are being approached in wireless systems, and the semiconductors used to build the systems perform better and become most cost-effective and reliable at ever increasing frequencies. there is great interest in moving to higher frequency bands where spectrum is also more easily available. In 5G, the first foray was made into the mm-wave band and over the next few years we will learn about the nuances of deploying in this band, outdoors in the rain and fog, as well as indoors, particularly in factories and stadiums. Similarly, the E-band and V-band at still higher frequencies are attractive, particularly for integrated optical and wireless networking. These bands are roughly at twice the frequency of the 5G mm-wave bands, and the learnings from the mm-wave band can be carried over in time to these bands.

Even as the semiconductor frontiers at very high frequencies are conquered, the challenge of overcoming the channel conditions at these frequencies remains. Wireless propagation at mm-wave and beyond suffers from high rain and fog attenuation and is more ray-like and less diffractive than at lower frequencies. The built environment, therefore, poses a significant challenge to the deployment of wireless systems in these bands. In an attempt to convert the light-like characteristic of propagation at terahertz frequencies to an opportunity, Intelligent Reflective Surfaces are being investigated as a way of "channelling" the signal toward the desired direction. These surfaces are massive reflective arrays placed on building facades with individual control of the reflective elements. By forming the beam appropriately, it is proposed to steer the terahertz signal around buildings, for example, and overcome one of the limitations of mm-wave-and-above propagation.

Many emerging applications (autonomous driving, but more generally situational awareness for any mobile robot) need radar sensing to comprehend the local physical environment. With spectrum becoming scarce, and the very high frequencies (>70 GHz) typically used for radar imaging also being explored for communications, one could conceive of user devices that combine radar sensing and communications functions using the same spectrum. Just as all smartphones today are location-aware using navigational aids such as NAVIC and GPS, tomorrow's devices may become ambient-aware by using its radio for radar function in addition to communications.

2.5 Tactile Internet Remote Operation

The title of this section is based on the nomenclature introduced in Representative use cases and key network requirements for Network 2030", a document produced by the ITU Focus Group on Technologies for Network 2030. It refers to use of the Internet, including mobile Internet, to remotely control a device based on real-time feedback from the device thus establishing a feedback control loop over great distances and time-varying communication link characteristics. This is a considerable challenge compared to the highly reliable, low-latency, wired local feedback loop in most control applications today.

As 5G deployment grows, Internet of Things (IoT) is expected to grow exponentially with billions of devices connected to the Internet. These will include machines in factories, hand-tools, industrial fixed and mobile robots, vehicles, drones, fixed and mobile sensors among other things. With the URLLC service in 5G, it is possible to limit the latency on certain links to less than a millisecond, though this comes at the cost of bandwidth and energy. In private 5G networks, it may be possible to limit the latency even on eMBB links to a few milliseconds. Thus, it is possible to conceive of remote control of robots /machines based on sensory feedback to the operator either from sensors on the robot / machine or around it. While automated remote-control loops may need sub-millisecond feedback, human-in-the-loop remote control systems may work quite well with multi-millisecond feedback delay. Low jitter and link reliability are important attributes that the link must possess for such remote control to work effectively.

The demand for such remote tactile control operations will grow once the techniques become robust and well publicized, even though the initial breakthroughs will come in the B2B space. Most likely, major enhancements in the QoS provided by the wireless connectivity will be identified and implemented in the next-generation wireless network before such remote tactile operations become commonplace and are used by the wider population. The potential for such technology to impact personal productivity is high, as well as its ability to make skilled expertise available remotely when it is not available locally. While the iconic application is remotely assisted surgery, there are many more mundane but economically critical use cases where the personal skills of an expert can be productively engaged remotely. A straightforward example is remote operation of rented farm equipment such as tractors and harvesters or of tower cranes at construction sites. The productivity of the expert also increases manifold as she/he wastes much less time transporting oneself from one spot to another that needs her/his expertise.

In addition to the tactile human-in-the-loop remote operations, there is an expanding need for remote control loops in Industrial IOT (IIOT). Industrial networks enabled by the Internet of things (IoT) are fundamentally different from information technology (IT) networks in terms of performance and reliability requirements. They go beyond connecting back offices to factory floors, moving towards integration from device level all the way through to enterprise business systems, resulting in the automatic operation and control of industrial processes without significant human intervention. These networks therefore need to deliver superior performance and mandate a real-time, secure, and reliable factory-wide connectivity, as well as inter-factory connectivity at large scales in the future. Factory automation and machine control applications typically demand low end-to-end latency ranging (from sub-ms to 10 ms), and small jitter (at 1µs level), to meet the critical closed loop control requirements.

At the same time, as part of the fourth industrial revolution, or Industry 4.0, operational technologies (OTs) and IT are converging. Control functions traditionally carried out by customized hardware platforms, such as programmable logic controllers (PLC), have been slowly virtualized and moved onto the edge or into the cloud in order to reduce the capital expenditure (CAPEX) and the operational expenditure (OPEX) of the system, and to provide increased system flexibility and capability to handle and analyse 'big data'. This industrial cloudification places even higher requirements on underlying networks, as the same latency, jitter, security, and reliability requirements need to be implemented at larger scales.

It is anticipated that several of these sophisticated remote-control loops will require compute-intensive AI algorithms. For example, the remote controller may need to get a picture in real-time of the operating environment of a mobile robot or vehicle based on multiple sensor feeds. Such a picture may be obtained by data fusion using AI/ML techniques. These algorithms may run at the remote location, but this will require huge data transfers to the remote controller. A more efficient alternative would be for the remote controller to offload the AI engine to an Edge-Computing cloud provided by the network nearer the mobile robot or vehicle. Mobile Edge Computing is supported in 5G itself and will mature in a major way over the next decade.

In addition to remote control loops, there is another application with similar characteristics involving predictive analysis followed by evasive actions. A digital twin (DT) is defined as a real-time representation of a physical entity in the digital world. DTs add value to traditional analytical approaches by improving situational awareness, and further enable better responses for physical asset optimization and predictive maintenance. Facilitated by vastly deployed DTs, the digital world and the physical world have the potential to be fully intertwined, contributing to formulate a new norm of DT-enabled cyber-physical world in the near future. It is anticipated that the DTs will reside in the edge cloud, with sensor data from the physical world fed to it in real-time. It is also anticipated that ML algorithms implemented in the edge cloud will play a big role in predictive analysis at the DT to take anticipatory action in the physical world to avoid undesired situations (power tripping, traffic snarls, mob formation, are examples) from developing.

2.6 Space-Terrestrial Integrated Network (STIN)

Space-based repeaters have been used for a long time to provide communication links over great distances. While this technology overcomes the tyranny of distance, it suffers from poor spectrum re-use as the footprint of the satellite, even with modern beam-formed antennas, is quite large. Geo-synchronous satellites provide 24x7 service, but the link budget tends to be tight and the latency high. Low-earth orbiting (LEO) satellites overcome both these limitations to an extent but have to be flown in constellations since only a subset will be visible over the service area at any given time. With LEO satellites, one can even conceive of orbiting base stations and not just repeaters. Such base stations are mobile, in contrast to the fixed ones on terra-firm, and calls have to be handed over even if the user is stationary. Besides, base stations may have to serve in multiple networks as they orbit the earth to not idle most of the time.

As these technological challenges are overcome and it becomes feasible for mobile handsets to communicate with space-based base stations, one could leverage inter-connected low earth orbit (LEO) satellites and other non-terrestrial networking nodes and platforms to build a parallel Internet network that can peer with its terrestrial counterpart. With such an integrated framework, the envisaged key benefits include: (i) ubiquitous Internet access at a global scale, including rural areas like oceans, deserts, as well as moving platforms such as ships and planes; (ii) enriched Internet paths that could lead to better data delivery performance compared to those over the terrestrial Internet determined by border gateway protocol (BGP) configurations across domains; (iii) ubiquitous edge caching and computing services provided by lightweight, on-board computing and storage resources on LEO satellites.

In the Indian context where 900M users live in rural areas, and terrestrial cellular coverage remains patchy in some parts of the hinterland, a STIN can provide the ubiquitous coverage that has been sought by the country for more than two decades now. Calls from a mobile can be handed over to the space segment whenever terrestrial coverage disappears and handed back when it re-appears as one moves. Areas not served by terrestrial systems can be permanently served by the space-based network.

India has a strong space technology base, and this approach could be pursued vigorously to provide 100% universal coverage once and for all. India is also one of the few countries developing a High-Altitude Platform System (HAPS) for various applications. HAPS fly at around 20 km altitude for months together using only solar energy. They can hover (circle) over a geographical area if desired. Thus, HAPS combines the high-link-budget and low-latency benefits of LEO satellites (better actually) and the geostationary benefit of GEO satellites. HAPS platforms could be placed to serve one or more rural districts each across the country. The platforms are also immune to weather and other terrestrial disturbances and can serve the dual purpose of providing vital communications during disasters.

2.7 Drone Communications

Piloting of drones is an application in the category of Remote Tactile Operations, though the clear line-of-sight radio link in this application makes the wireless communication less challenging. While drone communications in an exclusive frequency band is fairly straightforward, implementing the same using cellular technology (4G, 5G or next generation) is a challenge. The interference environment above the cell towers is very severe though the antenna down-tilt does minimize interference among neighboring cells to an extent. By the same token, the down-tilt also makes communication with high-flying drones difficult. If the next-generation cellular systems are to be used for drones as well, these issues must be specifically addressed. Drones cannot be simply treated as one more set of mobile "users" who happen to be flying above the towers. Being an application requiring specific QoS guarantee on reliability and latency, this "above the tower skyline" application needs to be catered for with specific supporting features in the next-generation networks.

2.8 Hyper Personalized Networks

Network designs so far have focused on the Spectral efficiency improvements arising out of better coding, massive MIMO and others. As we fundamentally hit the Shannon limit (with 5G almost reaching Shannon's capacity limit for single-antenna systems) the only way to improve speeds further is to employ more spectrum, and this is available only at very high frequencies with their associated issues, as discussed above. The design-for-the-worst-case approach alluded to earlier suffers from the following infirmities:

Static and worst-case provisioning: Networks today are primarily designed for cell edge performance. The cell boundaries are static in nature since the transmit power of the power amplifiers used is typically fixed for a given base station. Since 80% of the users are never on the cell edge, the network design is thus mostly pessimistic and does not consider the average conditions. It is estimated that there is approximately a wastage equivalent to 25% of the spectrum on an average.

Limited or no sharing of spectrum: We need to leapfrog to unlock a lot of under-utilized "statically" allocated spectrum. The benefits of dynamic spectrum sharing have not been realized due to poor cognitive abilities of the transceivers to ascertain under-utilized spectrum in their respective vicinities. There is also no real-time intelligence provided to the transceivers from the spectrum licensor to better utilize the available spectrum. Since most of the communications is happening in an interference-dominated regime, the overall spectrum utilization continues to be poor. This needs to be addressed with significant changes in the regulatory and wireless system architectural frameworks.

Limited observability of the network: The common Radio Layer metrics which are observable today are not sufficient for Network Optimization. If additional metrics such as channel impulse response seen by the handset and Base Station are made observable, then it opens possibilities to perform new types of Network Optimization. The availability of such Radio Link metrics, when studied and correlated over large sample sets, can set in useful ways to exploit Machine Learning at Layer 1 and Layer 2 of the wireless network to significantly impact performance.

Instead of a fixed protocol and waveform or a limited set of waveforms, as has been the case till now, the protocol and waveform ought to be based on the specific user's location and needs, which can vary over time and space. This will result in a hyper-personalized network that has a virtualized air interface running on Software-Defined-Radios (SDR). Two possible models are envisioned for virtualization: static OpenGL-like API (as is done for Graphics), or a Java-like Virtual Machine. The different components of the Air Interface are abstracted as virtual machines on an SDR, each doing a specific radio implementation task. The advantage with either of the two approaches is that the APIs or the virtual machines are pretty much agnostic to the underlying hardware which implements them. One can visualize every waveform defined so far in 2G/3G/4G/5G as a Virtual Machine which in turn encapsulates all the required virtual machine calls.

With this approach, the RAN of the future can be enabled by defining the Virtual machine and not the waveform. Waveform synthesis is left to the Cognitive RAN synthesizer based on the local instantaneous conditions and requirements. The desired VMs are either invoked from a library or defined on the fly and uploaded to the peer entity for use to set up the link. This approach enables dynamic and localized network optimization which a digitized architecture is amenable to, rather than force-fitting on every user a design dictated by the worst-case. It opens up the doors for implementation of AI/ML algorithms based on a rich set of observable radio metrics. Some more details of the proposed Cognitive RAN approach are provided in Annexure 1.

2.9 Holographic-type communications (HTC)

The title of this section is also based on the nomenclature introduced in Representative use cases and key network requirements for Network 2030" (January 2020) referred to in Section 2.5. It alludes to an application foreseen when data rates supported by the mobile Internet reach one or two orders of magnitude higher levels than even in 5G, and when very high frequency (mm-wave and higher) wireless systems support Gigabit-per-sec links each to multiple devices in a room. While holography is a method for producing a three-dimensional image of a physical object by capturing (on a plate or film) the pattern of interference formed by a split laser beam and then illuminating the captured pattern either with a laser or with ordinary light by diffraction. However, holography technology and ecosystem are presently not mature enough for mass usage. In the next decade, the motivation of enabling a fully immersive experience will lead to the adoption of various technologies that produce augmented reality (AR) and virtual reality (VR) via head-mounted display (HMD) devices. Holographic type communications (HTC) is expected to digitally deliver 3D images from one or multiple sources to one or multiple destination nodes in an interactive manner. The ultimate aim is to produce the next generation of virtual meeting experience. Fully immersive 3D imaging will impose great challenges on future networks in terms of data rates, jitter and latency requirements.

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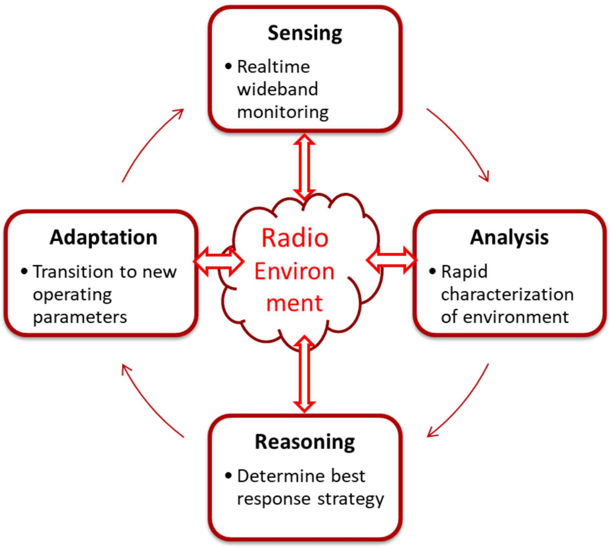
Annexure 1: Cognitive RAN - Some Details



The Cognitive RAN proposed has 4 phases of functionality comprising of Sensing, Analysis, Reasoning and Adaptation as shown in the diagram.

- Sensing Phase: In the Sensing phase the radio environment is sensed via wideband sensing/scanning as well as monitoring. In addition, the previously captured data is also utilized to find out various aspects of ambient conditions expected in the radio environment at a given time instant.
- Analysis Phase: The radio environment sensing provides information which goes through the Analysis phase to characterize and extract information on various aspects like the available radio frequency bands, licensed or unlicensed, interference power in various frequency bands, adjacent channel interference, co-channel interference, and far-off channel rejection, impulse noise, Signal to Noise Ratio, Carrier to Noise Ratio etc. It must be noted that learning algorithms can find significant use here to make use of previously existing data to infer about the radio environment.
- Reasoning Phase: In this phase the inputs from the Analysis phase are utilized to determine the best communication scheme and associated parameters required to establish successful radio links. The radio links are derived based on a chosen cost function. For a given region based on local RF terrain and geography the operator can choose the cost function of choice. As an example, some of the cost functions that can be chosen are Spectral Efficiency (Bits/Hz), Latency, reliability/graceful degradation or data security or in a combination of many different priorities like QoS/service level agreement requirements, or a certain target Bit/Packet Error rate or even frame error rate allowable by an application. Some of these cost functions could be dictated by nature of the end application which could be a voice, video, data, or a combination of those, maximum propagation distance, terrain conditions, initial hand-shake communication channel, and modulation details. Based on the chosen cost function, the reasoning phase runs an optimizer that considers the various operational constraints and then designs a modulation scheme with a desirable frame structure that can satisfy the radio link conditions. As an example, one of the operational constraints could be the spectral mask that needs to be enforced by the wireless regulatory bodies.
- Adaptation Phase: This phase takes care of transitioning the different radios on the Base Station and User Equipment side to change the existing radio link to that designed by the new radio link design and modulation scheme as designed by the output of the Reasoning Phase.

This type of RAN ensures optimal radio performance all the time for all users. The modulation and corresponding demodulation schemes are designed on the fly based on cost functions that capture the specific user's needs. In addition, this method leverages Deep Learning methods to determine the optimal use of resources to realize a waveform at Base Station and handset at a given instant. Overall, this results in a hyper-personalized network for users, rather than a one-size-fits-all approach.

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