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Understanding 5G

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Contents

Introduction

Making up new definitions in the telecoms market is generally frowned upon and in many cases the technical definitions are overtaken by marketing and publicity definitions: ITU defined 4G to be IMT-Advanced (100Mbps when user is moving, 1Gbps when stationary) but the market has decided otherwise. LTE, and even LTE-Advanced, does not yet meet these requirements, but on the other hand, some operators called HSPA+ a "4G" technology or Long Term HSPA Evolution as an LTE technology, both for marketing and competitive reasons.

A new mobile network generation usually refers to a completely new architecture, which has traditionally been identified by the radio access: Analog to TDMA (GSM) to CDMA/W-CDMA and finally to OFDMA (LTE). So the industry has started now to refer to the next fundamental step beyond fourth generation OFDMA (LTE) networks as being "5G". It is clear that 5G will require a new radio access technology, and a new standard to address current subscriber demands that previous technologies cannot answer. However, 5G research is driven by current traffic trends and requires a complete network overhaul that cannot be achieved organically through gradual evolution. Software-driven architectures, fluid networks that are extremely dense, higher frequency and wider spectrum, billions of devices and Gbps of capacity are a few of the requirements that cannot be achieved by LTE and LTE-Advanced.

This paper will review the technology and society trends that are driving the future of mobile broadband networks, and derive from here a set of future requirements. We will then look at the key technical challenges and requirements, and some of the research subjects that are addressing these. Examples of this include Cloud-RAN, massive MIMO, mmW access, and new air interface waveforms optimized for HetNet and super-dense networks.

The paper will then review the impact of these 5G developments to the test and measurement industry. We will look at both how the 5G technology will change the requirements and parameters we will need to test, and also at how the 5G technology will be used by Test and Measurement to align the test methods to network evolutions.

The final section of the paper will take a more in-depth review of some specific waveforms being evaluated for air interface access. We will study the theory and objectives for the waveforms, and then see how the waveforms can be simulated and analyzed using test equipment. Such an exercise is important as these tests need to be made early in R&D to evaluate the impact and inter-action of the waveforms onto real device technology, to evaluate the real performance. This will also inform closely the level of device technology development needed to support the widespread deployment of the different types of waveforms.

5G Mobile Broadband Objectives

The definitions of "5G", like the previous "4G" networks, is as much a marketing activity as it is a platform for the introduction of new technologies into the networks. This paper will study the different technologies and concepts being proposed for 5G networks, and review them together with the different test methods and techniques that may be required to support them. This paper will not cover in detail the business case or investment justifications for 5G, beyond the simplistic need to reduce costs for an operator and to match the cost of a service offered to the value that the user will perceive from the service. Equally, the strict definitions (such as those from ITU) of 5G networks will not be debated in detail, but rather the general industry trends and activities that have been associated with "5G" will be covered.

The concept for "5G" is both an evolution of wireless networks to meet future demands for data, and a revolution in architecture to enable a flexible and cost efficient network that can be efficiently scaled. These are the network operator operational demands on the network and technology, but they are driven by the demands for the type user experience which should be offered. These user experience demands that provide the underlying requirement for "5G" are:

Capacity

Perception of infinite internet: The 5G network should give the user the perception that the capacity of the network is infinite, that is there is always enough capacity available for whatever data transfer is required. This means in effect that there should be enough capacity for the services being run, at the time place that the service is being used. So if the network is flexible in how the limited resources/ capacity are deployed in both time and space, then the network can react to local data demands and give enough capacity. Thus the network does not need to have an infinite capacity, but enough finite capacity and flexibility to meet the real time needs of the services being run.

In terms of targets and headline figures, the general consensus is 10 Gb/s peak data rate for static users (i.e. indoor areas) and 1 Gb/s for low mobility users. As a low end limit, no less than 100 Mb/s shall be reached in urban areas. Massive scalability for millions of devices belonging to the widely known IoT or D2D markets will be demanded, which will consequently be leading to a capacity 1000x times bigger than current networks.

Coverage

A consistent user experience at any time/place is needed. This means that in effect the network coverage can provide always enough performance for the use cases at any location. As the network is expected to have flexibility in how resources are configured and deployed, the dynamic selection of different radio resources will be used to provide coverage based on service needs.

Convenience

The parameters defining convenience are split into two key types, depending on what type of interaction is taking place; either human interaction of machine interaction.

For human interaction the requirement is for a "Tactile internet", providing real time inter-active applications (1mS response/latency, Round Trip Time RTT) where the response time of a cloud service is real time to the user. This is required to deliver a true "multi user" experience where several users inter-act on the same service simultaneously (.e. multi-user games, augmented reality). A very optimistic target that requires high levels of integration between the 5G access network, core networks, and application servers and environments.

For machine to machine interaction, one of the key requirements is for a long battery life for embedded machines (typically required 10 years). This is required to support the typical operational life of embedded "smart meters" and monitoring applications. To achieve this, new techniques to minimize the "on" time of the power consuming radio circuits is required, plus simplified and robust protocol procedures to minimize processing requirements.

In overall, 5G will strongly highlight itself as a greener technology, aiming to reduce up to 90% of the power consumption in devices and network centers. This is a very optimistic target that will require a strong effort from OEMs and mobile firmware developers. There is strong user demand to reduce power consumption of devices, to extend normal battery life beyond just a day. But increasingly there will be demand to reduce power consumption for the network, both from an environmental point and also from a cost of energy point that drives cost of running the networks.

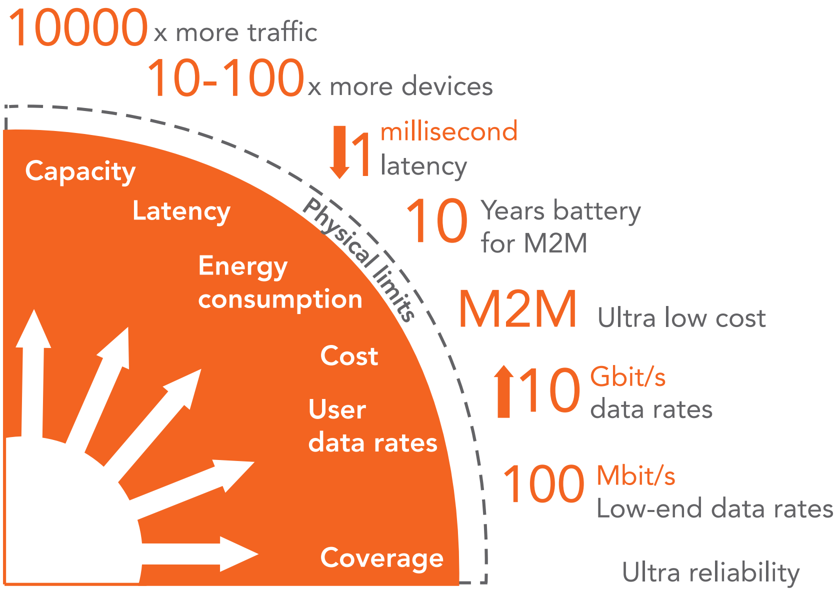


Fig 1 - 5G Mobile Broadband Objectives

Looking in the past: Cellular Generations

It is well understood now in the industry that the "mobile phone" business has gone through a complete transformation over the last 20 years and through the evolution of 3G and 4G. Where it had started as a "telephone" device centered around making and receiving voice calls, with any supplementary data services as a side activity, today the smartphone is seen as very much a data centric device giving access to a full range of data based services and applications, as well as being a platform for many local applications and services that may not even rely on cellular data services (e.g. camera, personal navigation, fitness monitor). This trend has given rise to the great increase in volumes of data being transported across telecom networks, in particular video content being a user of high data bandwidth whilst also being easily consumed and discarded by users.

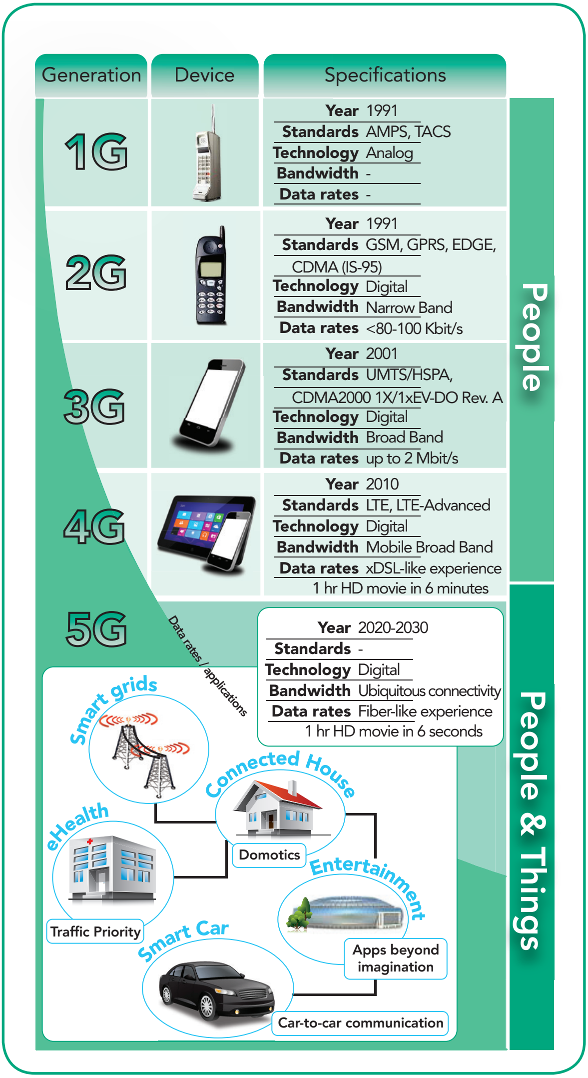


Fig 2 - Mobile Communications: from 1G to 5G

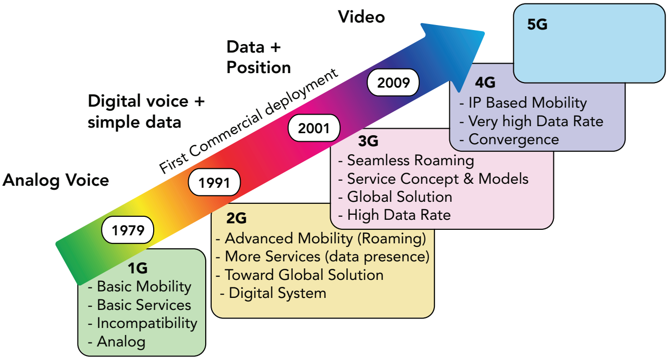


Fig 3 - Evolution of standards in mobile technology

From 1979 with the 1G commercial deployments, a new technology has emerged every 10 years. The second generation, first digital mobile technology and first approach to a global solution was commercially launched on the GSM standard in Finland in 1991, introducing relevant benefits such as a significantly more efficient spectrum or new data services like SMS text messages.

2G Target

2G focused on voice availability and basic SMS support

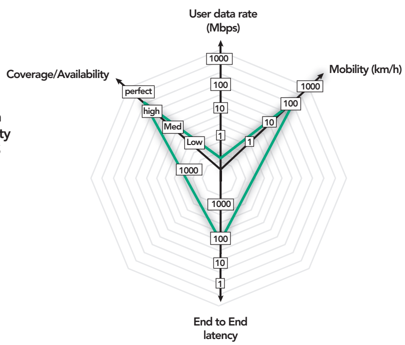


Fig 4 - 2G Target

Introduction of data packet (GPRS/EDGE)

2.5G Targets

2.5G focused on data trading off with efficiency/ availability

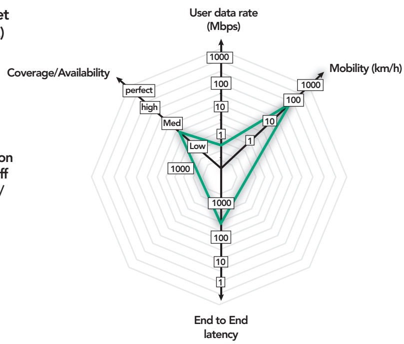


Fig 5 - 2.5G Targets

Nevertheless, this second generation did not fulfill the emerging demand for Internet access in mobile phones. This reason lead to the development of 3G, released in 2001, which was specified from ITU-R (IMT-2000) and was considered as a revolution in mobile data rates, seamless roaming and new service concepts and models.

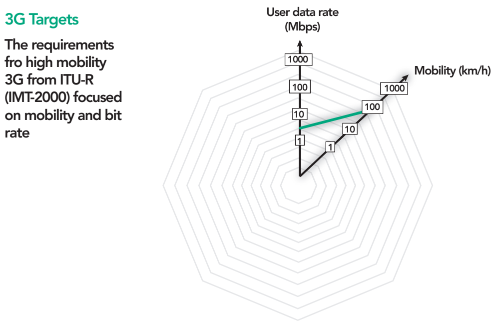


Fig 6 - 3G Targets

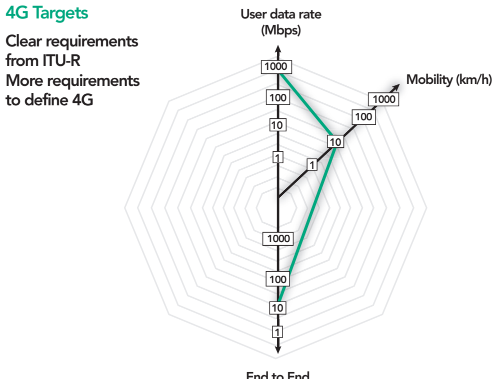
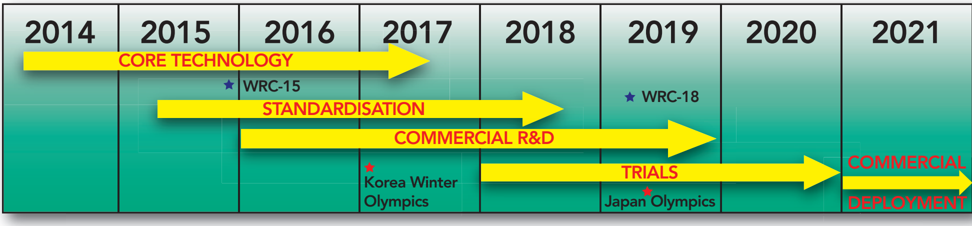


Fig 7 - 4G Targets

The last step was held in 2009, with 4G technology principally aiming for the all-IP mobile network, a very high data rate and the convergence of all services into a much simpler architecture. 4G was aiming very much on higher data rates and lower latency compared to 3G, and also to the simplified all IP architecture that gave more deployment flexibility compared to 3G. However, 4G did not address the needs for denser networks and capacity demands exploding at an unforeseen rate, as the "smartphone revolution" had not started when the 4G requirements and technologies were selected.

So "5G" is setting out to provide a technical solution to the problems of today's 4G networks that cannot be easily addressed using the existing technology, problems that have arisen from the changing demands on the telecom network over the last 8 years as 4G was defined and developed. But also, 5G is attempting to look 8 years into the future (year 2022 is a typical schedule for when 5G networks may be deployed in large scale) and trying to predict both the requirements on telecom networks at this time, and the technologies which may be required to meet this.

5G Project Summary



Technology

5G PPP
METIS
5GIC

Industry R&D

StandardiZation

NGMN (requirements)
ITU
3GPP (beyond Rel 12/13)
IETF
IEEE

New Spectrum Allocations

WRC-15
- more mobile broadband frequencies
- Harmonize 700 MHz bands

WRC-18
- more bands needed for 5G

Fig 8 - Expected timeframe for 5G

5G development, as any other technology, can be scheduled into 3 main stages: firstly, the definition of requirements and key technologies, secondly the development and standardization processes, and eventually real demonstrations plus further commercial deployments.

During 2015, concepts, vision and requirements for 5G will be defined. Selection of key technologies and demonstrations as proof of concepts will emerge by this year as well. R&D on the core technology will continue evolving from the work pieces carried out during previous years and may last until the first half of 2017. Within this period, international groups such as 5G Public Private Partnership (5G PPP) belonging to Horizon 2020 European research program, ARIB 2020 ad hoc group in Japan or IMT2020 and Beyond promotion group in China will drive the bases for the new technology. Other national groups like 5G Innovation Center based at Surrey University in UK or New York Wireless University consortium are also important technology hubs contributing in the 5G approach.

The standardization process may start at the end of 2015 due to the fact that WRC discussion is set at this time, which could already establish more mobile broadband frequencies or harmonize 700MHz bands for next generation. Development, writing and approval of standards may last until the first half of 2018, so in parallel we will see a huge effort in R&D against these emerging standards.

As with 2G, 3G and 4G, there are likely to be several different competing standards for the networks, coming from different standards bodies, as well as some more proprietary technologies looking to be defined within the standards. It is therefore possible that several standards appear in parallel, and no dominant standard may appear for some time (e.g. GSM vs IS-54 vs IS95, UMTS vs CDMA2000, LTE vs WiMAX). The interesting note is that for 4G the industry was much quicker to settle onto a single standard and there was less interest in multiple standards simultaneously. The various factors influencing this include the cost scales of volume and the need for global roaming. If this remains true for 5G then we are likely to see a quick convergence onto a single set of 5G standards rather than several different sets of standards.

In 2018, the Winter Olympics taking place in South Korea could mean a good chance to launch trials or demonstrations of standards based networks in real scenarios. A second WRC meeting will be set between the end of 2018 and the beginning of 2019, which could also close all the open discussions for new frequency bands allocations. Finally, Japanese Summer Olympics in 2020 looks set to become a starting point for a real live demonstration of 5G that could lead to the commercial deployment.

ITU project to define spectrum usage worldwide, WRC15 and WRC18.

One of the fundamental needs of 5G is the requirement for more RF spectrum, to be able to carry the ever increasing volume of data being transmitted wirelessly across the networks. This applies to the need for wireless backhaul (a key enabler for some of the deployment scenarios), as well as to the well-publicized need for more capacity on the air interface for delivery of data to the terminals/devices. Global spectrum usage and allocations are agreed under the World Radio Council (WRC) as part of the International Telecoms Union (ITU). In this forum, global agreement on the allocation and purpose of different frequency bands is made. Within the purpose, there is then defined limitations on the licensing, types of waveforms (but not specific selection of particular standards), and usage. This covers all types of applications such as public broadcast, mobile phone and data services, military use (radio, radar, etc.), satellite services, public emergency services, unlicensed services (e.g. Wi-Fi, garage door openers, remote control toys, walkie-talkie). The change of most types of broadcast from analogue to digital broadcast has freed up much spectrum due to the higher spectral efficiency of digital formats. However, the amount of freed spectrum is not enough to meet the growing data capacity needs of telecoms networks. Hence, there is a need to allocate (or re-allocate) some other spectrum bands to the purpose of mobile phone networks. Telecom network services have traditionally preferred frequency bands in the range 450 MHz to 2.6 GHz, as this gives the best performance in terms of range (propagation through atmosphere and buildings) and cost of technology to implement it. However, such low frequencies have limited amount of MHz of bandwidth available. To find more bandwidth requires the move to higher frequencies, where more spectrum is available, but with the trade-off of lower coverage and higher cost technology in the terminals/devices.

So a number of research projects are looking at either re-using the lower frequency spectrum to get more capacity from these preferred frequency bands. Other projects are looking at how to overcome the propagation and cost barriers to using the higher frequency spectrum. In parallel, the higher frequency spectrum is already used for wireless backhaul links (where directional antenna are used to overcome propagation issues), and further research is being made to increase capacity of these links. There is also research to implement "non line of sight" data links to overcome one of the principle weaknesses currently in high frequency backhaul links that of requiring direct line of sight between the two antennas in the data link. This obviously limits the deployment scenarios that are possible, making indoor or city/urban use almost impossible, and requiring specific antenna masts to be erected in almost all deployments today.

5G Requirements

There are several projects and groups working worldwide to define 5G needs, technology requirements, user requirements, and other views on what 5G should be. The mobile network operators have built up an eco-system community called Next Generation Mobile Networks (NGMN) which is creating a requirements document from the perspective of wireless network operators. NGMN had previously written requirements for 4G networks, and selected LTE as a preferred technology. The NGMN is an operator led forum, but with participation from the equipment/network vendors and supply chain, to try and align the industry needs.

Technical Challenges and Targets

There are several key challenges to be met with future 5G networks, looking at the performance needs of future networks and identifying affordable technologies which may be developed to support these.

5G Targets by use case

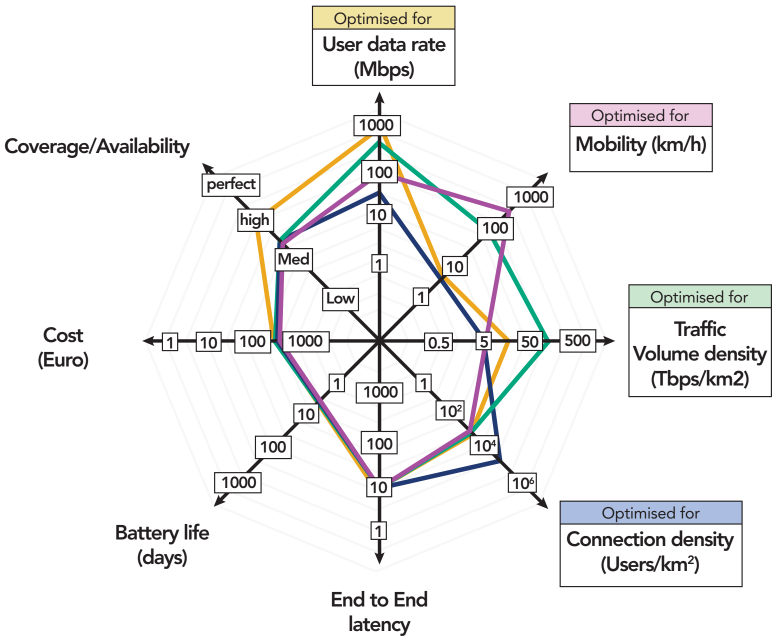


Fig 9 - 5G Targets by use case

5G is promoting targets in all different service layers, it is an all-optimized network designed to support the highest user data rate with unlimited coverage and within challenging mobility scenarios, capable for a massive number of connections per km^2 but also reducing the latency to the "immediate" feeling and the cost and power consumption of devices to their minimal possible figure. Ensuring all these premises would transform 5G into the most complete wireless network ever seen, tremendously attractive for automotive, M2M and even upcoming futuristic applications. This is what we call "Performance oriented" use case.

5G Targets by use case

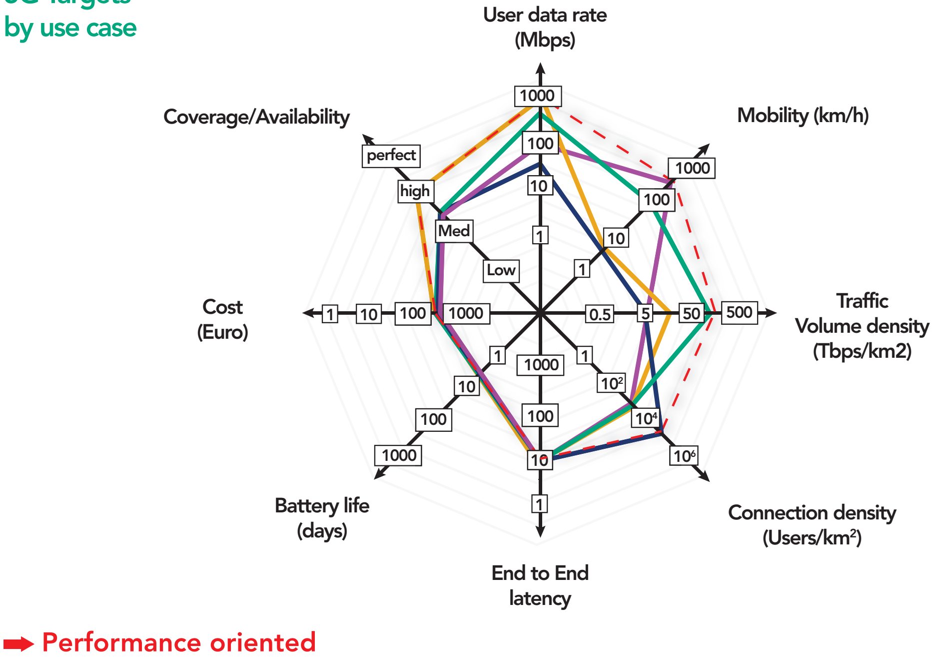


Fig 10 - 5G Targets by use case: Performance Oriented

This use case can be applied to multiple upcoming and demanded services, such as 3D videos in 4K screens, augmented reality, work and play in the cloud or, simply a highest possible data throughput (Gigabytes in a second) performance.

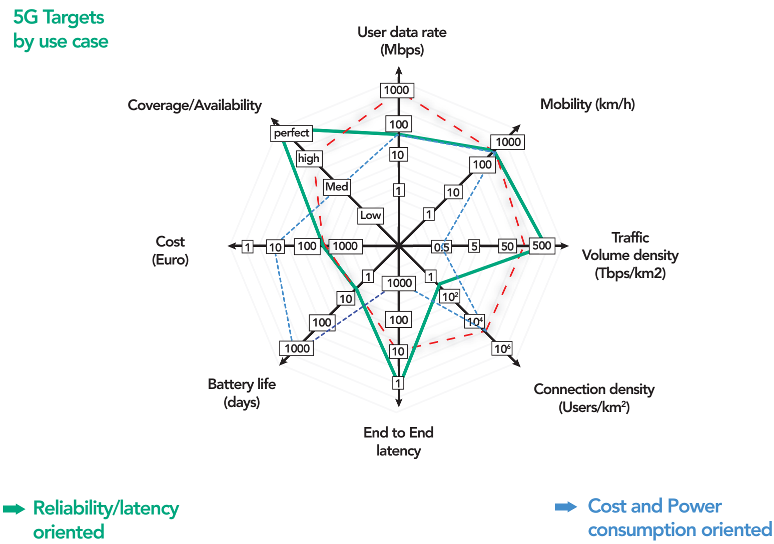


Fig 11 - 5G Targets by use case: Reliability/Latency and Cost and Power oriented

5G will also look at a "Reliability/latency oriented" use case, which will fit into the needs of services like Industry automation, critical information broadcast or self-driving cars. In this case, 5G technology should adapt itself to a much optimized network in terms of coverage, latency and mobility. The connection density for Industry automation or critical information broadcast is not important, as they will not represent a high amount of users concentrated in a specific area. Even for self-driving applications, should not be a restricting parameter because these users will be moving, thus driving importance to mobility optimization.

Eventually, there is a third use case in which the low cost and long battery life are the most important premises. 5G will fulfil the requirements for millions of smart devices entering into the network and building a huge "Sensor network" interconnecting the cities around the globe. This use case will have to consider a high connection density profile as well, as some urban areas could be intensively invaded by thousands of devices.

From the different key targets and use cases, some of the targets creating the technical challenges are as follows:

Internet of Things (IoT) capacity requirements

The IoT is predicted to create a massive increase in the number of devices/ connections across wireless networks. It is envisaged that many billions of devices will be connected to the networks, although many of them will be only sending/receiving data on an intermittent of very low data rate. This will create new demands in terms of the capacity of the network to transmit data, but also the capacity in terms of number of connected users that can be managed by the network. In current 3GPP based networks there are limits on numbers of users that can be connected to specific network nodes, and this limit may be insufficient for future needs. The capacity requirement is expressed both in terms of number of users connected (registered) to the network, and also in terms of number of users active (making simultaneous data transactions) on a specific network node.

Volume of data

Data will be one of the key drivers for 5G. Firstly, continuing the legacy from LTE, voice will be totally handled as an application simply using the data connectivity provided by the communication system and not as a dedicated service. This is an additional increase in a data growing pace of between 25% and 50% annually and is expected to continue towards 2030 due to the increase in size of content and the number of mobile applications requiring high data rates, the rise in screen resolution with the recent introduction of 4K (8K already in development and expected beyond 2020) and the developments in 3D video.

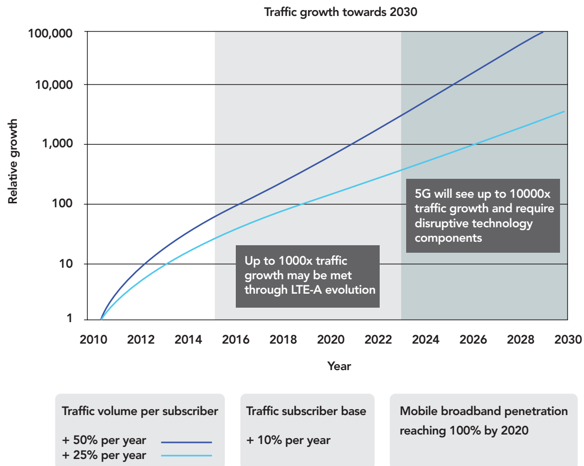


*Fig 12 - Predicted traffic volume towards 2030 * (Figure from Nokia 5G white paper)*

Types of data

It has been widely discussed and seen in the industry over the last 5 years that there is a need to increase the capacity of the network without increasing the cost. Users are consuming increasingly more volume of data (mainly through video services) but are reluctant to pay 100x more subscription costs to cover the 100x volume of data they use. So there is a major challenge to increase the capacity of the network (both volume of user plane data, and volume of control plan data and attached devices to be managed). One technology already being developed in 3GPP for LTE networks is to separate the distribution of control and user data planes to align to data requirements. One typical example is to provide the control plane signalling to a wide area using a macro cell, and then user plane data via small cells within the coverage of the macrocell. This enables a higher capacity of user plane data within the area, due to higher frequency re-use of the small cells, without the added complexity of requiring control plane function and co-ordination across many small cells (which then requires a high amount of backhaul capacity to carry this inter-cell control information).

A second evolution in the network design, complementary to the user/control plane separation, is the move towards cloud services and cloud RAN. In this concept, some of the function of the RAN network (e.g. eNodeB in LTE networks) is moved from the cell site or eNodeB back into a cloud service. This provides a key technology platform to them support scaling and economy, leading to deployment flexibility, and easier re-configuration. This is because now the core signalling and intelligence is held within the cloud, and the only localized physical elements are the RF transceivers to connect to users. This reduces the cost/complexity of the localized elements, giving better flexibility and scalability of deployment.

New types of services

Highly reliable communications links are an emerging trend for cellular network systems. Medical monitoring solutions are also moving increasingly to use wireless networks, to provide remote patient monitoring/care as well as greater access for remote support to medical staff. Emergency services, (e.g. police/fire/ambulance) provide critical services that require high reliability voice links, without issues of call drop, busy network etc. Today's solutions provide high reliability by having dedicated networks, but with limited data capacity or performance, and requiring high cost investments to provide even reasonable coverage. Future requirements are for high data rate, and real time interaction, so these critical services can respond faster and with more immediate remote connections.

Real time and Virtual Reality services. As augmented reality becomes deployed into portable/personal devices, so the demand on network performance is dramatically increased. One key aspect is that the latency (delay) must be very small to enable true inter-action between the real and virtual environments. The human brain is very sensitive to time delays when processing visual data, due to the processes in the brain to convert eye image patterns into images we "see" in our mind. If the network cannot interact with our eye/brain process in real time then a true virtual reality service can not be delivered. The key to delivery of such a service is latency, and so each step in the link between device as server must be optimized for latency, and we need to test/measure not only the end to end latency (Round Trip Time, RTT) but also the latency in each link, and have methods to investigate the cause of excessive delays/failures.

There is much discussion in the wireless communications industry about Machine to Machine (M2M) communication being a big driver for future growth, as an enabling transport technology for the Internet of Things (IoT). Although there are many case studies and potential business models being developed, there is one segment of the industry which is already pushing forward in this area, the automotive business. There are a number of automotive applications already under development or in early trials/deployment:

- In-Vehicle infotainment drives mobile wireless link capacity to the "vehicle as a hub".
- Use of vehicle as base station or relay node due to enough battery power.
- Intelligent Transport Systems (ITS) creating demand for Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and generic Vehicle to other devices (V2x).
- Autonomous driving, convoy driving, safety alert and traffic management.

One area that has been traditionally outside of cellular network communications is Device to Device communications, that is direct links without relay of information through the base-station or network. Such traditional "walkie talkie" systems have been in existence for a long time, using limited access control to prevent interference or overlapping of messages. However, the ability to transmit data is severely limited, and the need to have a separate device for this walkie talkie mode versus a conventional cellular device has become a user issue. Previous cellular networks have developed "push to talk, PTT" technology to deliver a similar user experience where a voice message is delivered to all users on the same frequency/network (like a walkie talkie), and this has been shown to be technically feasible. The limitation is still that the cellular infra-structure is required to relay the messages, and for critical communications (e.g. emergency services) then it can not be relied that there is working infra-structure with sufficient coverage when it is needed (e.g. earthquake disaster zone). Hence the development of Device to Device (D2D) to allow direct communications. This technology is already being developed in LTE-A, but is expected to have a much more robust implementation in 5G where the network is already designed/optimized to carry this type of communications.

5G will introduce more requirements of the transport network and overall architecture in order to ensure support for any-to-any communication, so not only device to device but also node to node self-backhauling. Intelligent Transport Systems (ITS) for traffic control and passenger safety purposes could also benefit from this kind of communication technology.

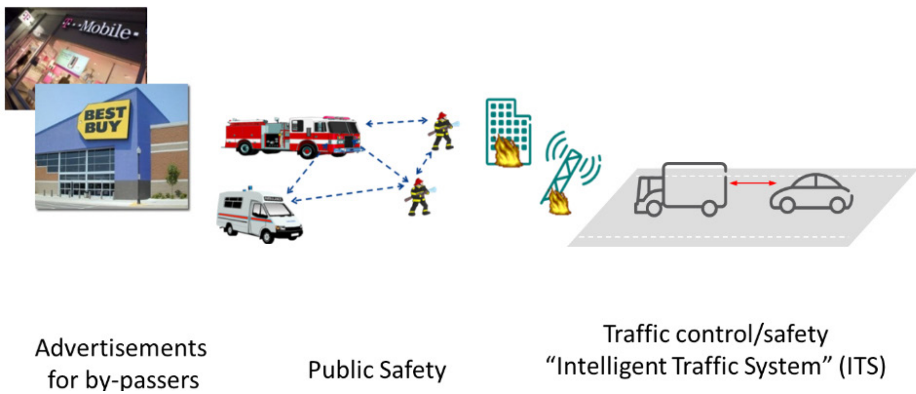


*Fig 13 - Device to Device Communication *(Picture from Ericsson Research Blog: "D2D Communications – What Part Will It Play in 5G?")*

5G architecture will support D2D better than LTE can do nowadays. However, D2D communication still implies new challenges for devices design, security or interference and mobility management, between others. D2D would also influence new breakthroughs in backhaul design, which will be required to enable very dense networking of radio nodes. Nodes with 'plug-and-play' techniques to access and self-organize available spectrum blocks for backhauling will be key for enabling high-frequency spectrum radio access.

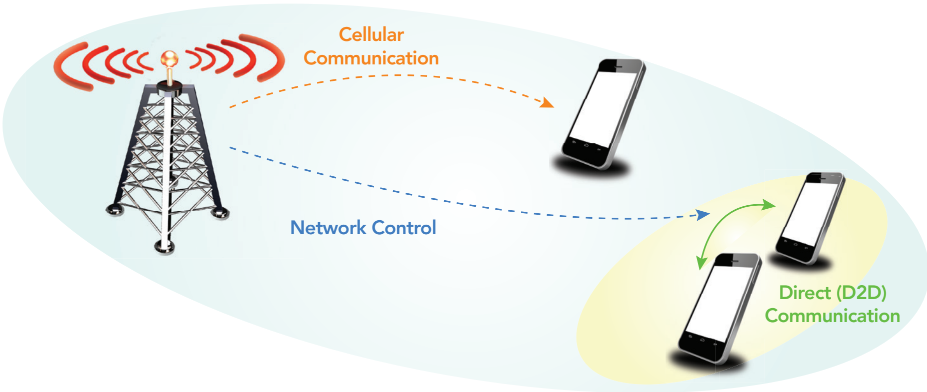


Fig 14 - Device to Device and Cellular communications share the same radio resources

**(Picture from Ericsson Research Blog: "D2D Communications – What Part Will It Play in 5G?" - The network controls and optimizes the use of the resources for both Cellular communication and D2D, resulting in enhanced performance and quality of service.)*

All of the above challenges are now starting to drive the areas of research, highlighting the limitations of current networks and the envisaged requirements of future networks. Current technology developments and user demands are merely providing a glimpse of the nature of 5G networks. At the moment, cost is not a major driver of 5G technology discussions, allowing a much wider list of candidate technologies to be considered. In order to discuss these technologies meaningfully, cost is also ignored in this article. It is the radical and disruptive changes to the existing network that are outlined.

It is clear that a new air interface will be needed. Some R&D work goes as far as to suggest that a 5G network will consist of several air interfaces coexisting in the same network. From a theoretical perspective, this is ideal (e.g. OFDM does not lend itself to small cells and HetNets and there are other, better candidates), but from an operational and economic perspective, this would mean significant development costs and deployment effort.

Research subjects

The academic community, and industry research programs, are currently investigating a number of subjects to identify and develop key technologies. The research subjects are based around the generic technical needs for 5G to meet the objectives and targets previously outlined.

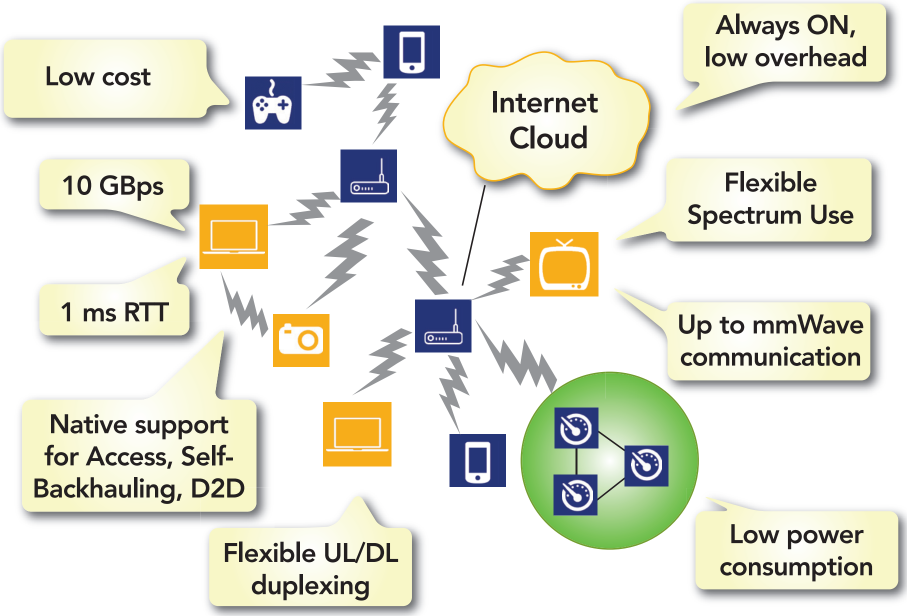


Fig 15 - Research Subjects for 5G

Extreme densification

Network densification is not new. As soon as 3G networks were congested, mobile operators realized the need to introduce either new cells into the system or more sectors. This has evolved to include many flavours of small cells, which essentially move the access point much closer to the end user. There is simply no other way to increase the overall system capacity of a mobile network significantly. 5G networks are likely to consist of the several layers of connectivity that HetNet architecture is currently suggesting: a macro layer for lower data speed connectivity; a very granular layer for very high data speeds; and many layers in between. Network deployment and coordination are major challenges to be addressed here, as they increase exponentially with respect to the number of network layers.

As we have indicated already, 5G networks would be principally designed for data-centric applications rather than voice-centric applications. Network densification is very suitable for increasing the capacity and data rate to meet the future demands. With the increasing density of networks, also the backhaul will become more heterogeneous and possibly also scenario dependent. The high data rates of 5G would imply that the backhaul/fronthaul would need to be fiber optic to achieve the data rates required (i.e. 1-10Gb/s per sector). Nevertheless, Millimeter wave backhaul/fronthaul is another attractive option, probably cheaper and surely easier to deploy than fiber, but technological and regulatory challenges are yet to be addressed. In addition, the connectivity among the network nodes should allow for fast direct exchange of data between them, which will be challenging in Ultra Dense Network (UDN) deployments. The radio access networks will also be impacted by the heterogeneous backhaul structure, e.g. latency differences on different types of backhaul links will impact inter cell coordination and cooperation algorithms.

It is likely that the cost implications of developing an entirely new backhaul network will instead drive the industry to develop new technology that is able to use existing IP network technology and infrastructure in a better way. Already in 4G there was a migration to "all IP" networks and support of IPv6 signalling. This has also evolved to provide better use of MPLS technology for IP routing in the network. As cloud services, NFV and SDN evolve in current IP networks, it is expected that these become key technologies to resolve the gap between the cost and performance of current mobile network backhaul versus the ideal new 5G backhaul.

The new network architecture may be focused also into the public concern about EMF induced by wireless networks. By reducing the distance between receivers and transmitters, small cells enable the minimization of the power emitted by the mobiles devices and the total EMF exposure. 5G architecture combining small cells, heterogeneous networks and offloading should inherently enable minimizing both the human EMF exposure and the power consumption of the network.

Air interfaces for higher data rates and higher capacity

In current 4G LTE (OFDMA) networks we require self-interference avoidance, which is strictly a timing based approach, and this causes higher power consumption and significant waste of control plane signalling resources. Interference resistant access schemes in 5G that could replace the currently used OFDM are under intensive evaluation. More efficient orthogonal schemes such as FBMC, UFMC or GFMD, which introduce a better use of the spectrum are excellent candidates for the upcoming 5G access waveform. Generally, orthogonal transmission can avoid self-interference and this leads to a higher system capacity. However, for rapid access of small payloads, the procedure to assign orthogonal resources to different users may require extensive signaling and lead to additional latency. Thus support for non-orthogonal access, as a complement to orthogonal access, is being considered as well. Examples include Non-Orthogonal Multiple Access (NOMA) and Sparse-Code Multiple Access (SCMA).

Multi-carrier waveforms will still remain as the preferred scheme because they fit very well with MIMO techniques, which will be massively deployed. UL/DL full duplex and simultaneous transmission along with wider bandwidths from 100 MHz onwards will drive the air interface to support higher data rates.

On the other side, millions of low data rate devices for Machine Type Communications (MTC) may require new interfaces with much lower network capacity demand, but high robustness, in order to ensure connectivity at any time. Device to Device communications, especially thought for public safety and services applications, would also join this group. The first steps to this are being taken in LTE-A, being categorized as "Category 0" devices, where the air interface and network signalling and supported features/data rate are minimized in order to provide lower power consumption of devices and lower cost of devices.

A further development for the air interface is the area of Cognitive Radio. This is the capability for a device to sense the RF environment and make configuration decisions based on the local RF characteristics. Examples of such functionality are the sensing of unused RF spectrum (so called 'white spaces') and then the temporary use of these unused frequencies for data transmission. A more advanced example is in the area of Software Defined Radio (SDR), where the radio modem is able to re-configure itself to support the protocols and RF transmission formats being used locally, basic on generic Tx/Rx circuits and then software based modem functions that are dynamically set to match local protocols. The device will first sample the local RF environment, and then based on evaluation of the RF characteristics, a suitable modem configuration and protocol stack is loaded from memory (or from the cloud) to support the local network.

Cell coverage improvements

The concepts of Macro cell and Smart cell, emerging previously in LTE-A, will grow in importance for 5G. Complex heterogeneous networks will appear as a huge amount of small cells will operate with a single carrier waveform serving small areas. We will see not only multiple-antenna systems providing Spatial Multiplexing techniques, i.e. transmitting different data streams through each element and, consequently increasing the data rate, but also beamforming antenna techniques for improving the quality of transmission or the signal-to-interference-plus-noise ratio (SINR), which have already become popular from TD-LTE deployment. "Massive MIMO" or dense antenna arrays composed by, for example, 64x64 elements, will suit to mmW systems due to the small physical size and precise focusing they can offer.

Co-operative antenna techniques refers to the capacity of handling the information received from spatial distributed antennas belonging to different nodes in a wireless network. Single User MIMO (SU-MIMO) has been the first appearance of these techniques in LTE-Advance. In this case, apart from the Base Station, different antennas belonging to the network and not to the user behave as relays in order to build the distributed multi-antenna scenario. On the other hand, co-operative MIMO or distributed MIMO groups multiple radio devices (including users' devices) to form virtual antenna arrays so that they can cooperate with each other by exploiting the spatial domain and improving coverage and cell edge throughput. Some devices can also be treated as relays to help the communication between the network and device. This is considered as one of the new emerging technologies in 5G, thus many research challenges in cooperative antennas have to be addressed before the wide deployment.

Key technologies

Based upon the research subject areas discussed, there are a number of specific technology needs which are currently being investigated to identify specific solutions and candidate technologies to be used within 5G networks.

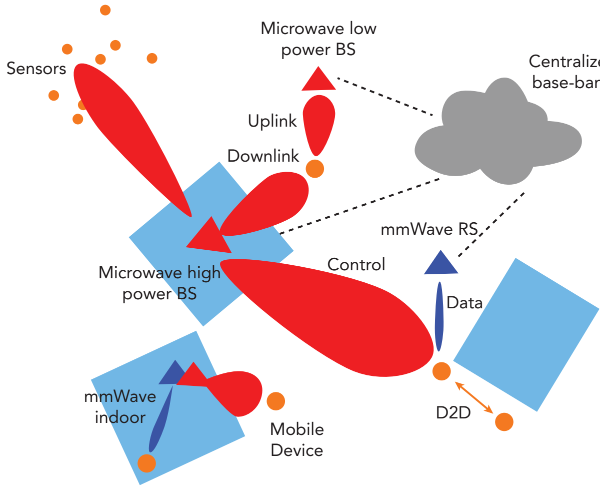


Fig 16 - Key Technologies for 5G

Network design

A parallel evolutionary trend to 5G is software virtualization and cloud services, where the network is driven by a distributed set of data centers that provide service agility, centralized control, and software upgrades. SDN, NFV, cloud, and open ecosystems are likely to be the foundations of 5G and there is an ongoing discussion about how to take advantage of these architectures.

An adaptive network solution framework will become a necessity for accommodating both LTE and new air interface evolution: Cloud, SDN and NFV technologies will reshape the entire mobile network design principles. As the three-tier hierarchy (access, aggregation, and core) of network architecture is being replaced by flatter architectures, virtualized application software is replacing network appliances, and network infrastructure is becoming more 'programmable'. With SDN the network will dynamically adapt itself to provide the connectivity services that best serve the application, and a better approach will eventually produce networks that are much more flexible in providing new services and monetizing the network, as well as being more efficient in their use of resources.

Network Function Virtualization works by virtualizing the roles of the various network functions appliances into a series of Virtual Network Functions (VNF). These VNFs run on standardized servers, leading to the virtualization of the physical network infrastructure that provides a seamless deployment. VNFs are then linked together to provide a specific service for the customer, using service chaining which is configured, managed, and monitored through open-source frameworks.

Service providers can now integrate this optimized virtual infrastructure with their service orchestration systems. This allows them to integrate their OSS/BSS implementation for dynamic routing, billing and delivery of services. On the other hand, an NFV element which is added into the existing network needs advanced operational management in real time that differs significantly from the legacy systems.

Current mobile networks have evolved from a traditional Datacom network architecture, where the data is centralized and the access control is localized. This means in effect that all user data travels from one access point (where it enters the network) to a centralized location (gateways) and then back out to the access plane where it is delivered to the recipient. Similarly, access is controlled locally at a access node (e.g. eNodeB), but needs to be centrally co-ordinated so control plane messages must pass through the network. Both of these phenomena are increasing the volume of traffic that must be carried in the network. There is now research into new architectures that reverse both of these designs. Firstly then, user plane data is now considered to flow directly between access nodes, and not through a central hub, so it only travels once through the network. Similarly, if control plane/access control is centralized (e.g. by using Cloud-RAN) then the access control co-ordination information does not need to be carried across the network. So the move to a centralized control plane and a distributed data plane can offer a reduction in network traffic load for a given volume of customer data being carried. To achieve this however does require significantly higher connectivity and low latency links between all nodes, but cell densification and NFV/SDN technologies are already driving in this direction so it may be that 5G can leverage directly from this. The concept of NFV is well suited to this, as the network control functions can be virtualized and housed centrally in servers to minimize traffic flow across the network. Similarly, user plane data can enter/leave the network, and can route to any access point, by using virtualized gateway functions rather than needing to be routed to/from a centralized gateway physical element.

A parallel technology/architecture development alongside the User Plane and Control Plane routing, is also the separation of these two data types at the air interface. In current LTE networks, there is a challenge in managing the control plane signalling in "small cells" due to the interference of cells with overlapping coverage. But this overlapping coverage and deployment of many small cells is required to provide enough capacity in the User Plane for the large volumes of data. So we see that the Control Plane and User Plane have different requirements and different restrictions, which are clashing with each other. So one possible solution is to separate them on different air interface links. Thus the Control Plane can be routed to a wide coverage Macro cell, providing unified and co-ordinated scheduling and control information to all users in a particular region, whilst the corresponding user plane data is carried on localized small cells close to the user. This gives greater user plane capacity without interference problems on the control plane. This concept is a natural extension of the principles of Carrier Aggregation and Cross-Carrier Scheduling that are already introduced into LTE-Advanced networks. A second evolution of this concept is to separate downlink and uplink transmissions to separate cell sites. This has the advantage of allowing the downlink data to be routed by the network to a cell that has enough capacity for the data, but allows the user device to send uplink to a cell that is located close by, and hence reduce the amount of transmit power required by the user uplink transmission. This will reduce interference on the uplink, and allow a longer battery life "talk time" for the user device. Whilst all of these technologies offer great benefits, they do demand significantly larger volumes of control plane data in the network, to ensure all cell sites related to a single user data transmission are co-ordinated and linked together. Current LTE-A networks were not designed for such high capacity and low latency control plane data, and ask discussed previously the NFV/SDN architecture concept may be better suited to this network design idea.

So we can see that SDN, NFV, and cloud architectures will play a vital role in next generation of network architecture. It can provide an implementation model that easily and cost effectively scales with the volume of data and vast increase expected in connected devices. Secondly, it allows service providers to more easily and efficiently manage a dynamic network, with great flexibility to re-configure the network functions and capacity. Thirdly, NFV allows for a more efficient routing of both User Plane and Control Plane data, to reduce total data volume travelling across the network, and to reduce latencies with more direct routing rather than an architecture based on centralized hardware functions. This will better support the separation of Control Plane and User Plane data, and the separation of downlink and uplink data.

Cloud RAN is a specific NFV concept that is rapidly being developed and prepared for commercial deployment. This aims to centralize the functions of the RAN network (e.g. eNodeB for LTE, NodeB & RNC for 3G) within the cloud servers, such that only the physical transceiver and antenna elements of the eNode B need to be physically located at the cell site. This provides for a more cost efficient deployment, especially for "small cells" or local cell sites for limited capacity and filling in gaps in coverage. The Cloud RAN concept is taking advantage of technologies such as CPRI, that allow the baseband to TRX link of the basestation to be carried on high speed optical fibre links. This technology has already been developed for Remote Radio Head use (RRH), where the TRX/Antenna is separated from the base station baseband by several meters (top and bottom of cell site mast) up to separation of hundreds of meters or of kilometers (e.g. for in building or shopping mall deployment, where a single baseband serves all TRX/antenna sites). So Cloud RAN is extending the same concept further such that all TRX/Antenna sites in a network region can be connected by fibre to a centralized baseband server. Of course this technology currently relies on having dedicated fibre access to each cell site, and this can limit deployment in some scenarios. We will see later therefore that there is parallel research into providing a suitable wireless backhaul for Cloud RAN. The key challenge here is to have low enough latency across the backhaul, because the baseband algorithms in the NodeB require latencies of very few milliseconds in order to meet the timing requirements of the scheduler and re-transmission functions in the basestation.

Several networks are currently providing connectivity for end-user devices: cellular, Wi-Fi, mm-wave, and device-to-device are a few examples. 5G systems are likely to tightly coordinate the integration of these domains to provide an uninterrupted user experience. However, bringing these different domains together has proven to be a considerable challenge and Hotspot 2.0/Next Generation Hotspot are perhaps the first examples of cellular/Wi-Fi integration. Whether a 5G device will be able to connect to several connectivity domains remains to be seen, and a major challenge is the ability to successfully switch from one to another.

New frequencies for radio access

As the RF spectrum up to 6 GHz has been fully allocated to different uses and services, the need for wider bandwidth of radio to support higher capacity data links is pushing the industry to investigate higher frequencies. The frequencies around 3.6 GHz and 5 GHz are potential bands being investigated. For commercial deployment this of course requires formal allocation of bands, license awards by local regulators etc, but for the first step there are technical investigations to understand the capabilities and limitations of operating at such bands.

Even if additional frequency bands below 6GHz are made available for mobile communications, there are still fundamental limits on the amount of bandwidth that could possibly become available. There are, however, much wider bandwidths of spectrum in the higher spectral bands, which may reach as high as 300GHz. The fundamental physics of RF propagation means that network design for such high frequencies is much more complicated than network planners are accustomed to, as center frequency increases then building penetration becomes more difficult up to the point where a building becomes an opaque barrier for mm-wave signals. However, there is significant spectrum that could be available in these bands, and this may be used for short-range, point-to-point, line-of-sight connections, providing high speed and high capacity wireless connectivity.

Mm-wave could be used by indoor small cells to provide very high-speed connectivity in confined areas. The high-frequency nature of mm-wave means antennas can be very small with only a small impact on device form factor. A number of market analysts still believe mm-wave is a radical technology and may require many years of R&D to be cost-effective for the mass market. There are still key issues with the performance of semiconductors at these frequencies, giving an impact on the cost and power consumption of devices such as amplifiers and mixers, which fundamentally limit the range/sensitivity of radio transceivers. This technology is now evolving from specialist high cost markets to becoming affordable for high volume and low cost massed markets as the semiconductor technology is further developed.

It is interesting to note that developments in mm-wave are not new: the WiGig alliance is focusing on 60 GHz spectrum. Over the last few years there have also been a number of acquisitions of specialist mmW technology companies by major telecom players, as they seek to increase technology capability and IPR in this area. A prime target were the companies which have emerged over the last 10 years to use advances in semiconductor technology to realize cost efficient mmW circuit technology for the 60 GHz band

It is clear that 5G will need Gbits backhaul and, so far, only fibre optics and wireless can provide this service. On one side, the drawbacks of fibre are the cost and the difficulties for installation in urban locations. On the other side, wireless would need mmW band for fitting into the high capacity requirements. The disadvantage here is that mmW needs Line of Sight (LOS) operation. Technically speaking, it could be overcome by electrically steerable antennas and directional mesh for a true SON backhaul in a Non Line of Sight (NLOS) environment. In support of this, there is now a growing area of research for NLOS mmW links, which use advanced MIMO to enable high data rate links into a dense urban environment where the complex multipath environment may be used to synthesize many different spatial paths to support a dense backhaul.

Mesh networking refers to a network topology in which each node (called a mesh node) relays data for the network. All nodes cooperate in the distribution of data in the network. In a Small Cell mesh backhaul, mmW is a valuable technology because long backhaul links are not required and LOS can be satisfied. In these networks, each node establishes optimal paths to its neighbors using self-configuration techniques. When link congestion or deteriorating RF conditions occur, new paths are determined based on QoS requirements such as latency, throughput and packet-error rate and the mesh self-tunes itself to achieve optimal performance. Such a dense network is configured to have redundant links and many possible nodes, and it is this difference to conventional backhaul that gives the flexibility and enables the self-configuration capability.

We can easily see that the combination of mmW NLOS and mesh networking gives a very attractive concept for future dense city deployments. It allows for great capacity, dynamic management of capacity, and avoids the need for extensive fibre deployments and significant infra-structure projects. Instead the infra-structure is flexibly deployed and configured, and no longer is a limiting issue on the location and deployment of cells sites.

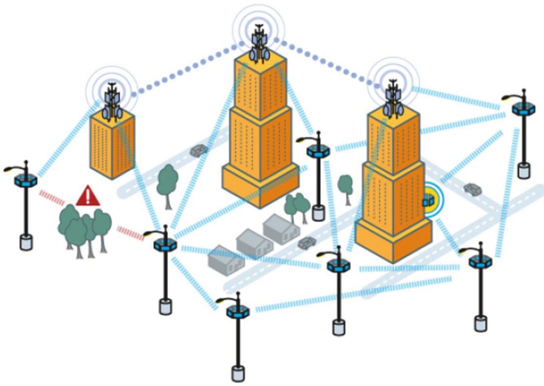


*Fig 17 - mmW multi-hop directional mesh small-cell backhaul * (Figure from "Small Cell Millimeter Wave Mesh Backhaul" white paper, InterDigital)*

Air Access and modulation schemes

Previous generation networks (2G, 3G, 4G) have been designed as "signal strength limited networks", that is the coverage of the network was defined by the area of adequate signal strength (signal to noise ratio, SNR). Advances in the air interface were designed to improve the SNR and hence increase coverage and capacity of the network, giving higher data rates available across the cell due to a higher SNR. The base assumption for this was the limiting factor is the propagation loss of the signal, and after a certain level of signal loss then the SNR no longer supports the required data channel (Shannon's law). The extreme demands on capacity of the networks have driven the architecture to implement "hyper densification" through small cells, which gives more capacity in a network given the limited RF spectrum resource available. But this has now moved the network coverage limitation from being a SNR limit to being interference limited. With many small cells deployed, there is always a good SNR available, but with many cells overlapping in coverage (heterogeneous networks) then the limitation becomes the SNR limit from interference from other cells rather than the SNR due to propagation loss. So now the network has become interference limited, and the development is now underway to look at new air interface technologies that are more resistant to RF interference, as OFDM does not offer resistance to interference from other neighbor cells. 4G/LTE is using OFDMA as the air interface access method due to its ability to easily support scalable bandwidth, leading to flexible global deployment and scalability to support higher bandwidths for higher data rates. A key issue for high bandwidth systems is linearity and distortion across the band. OFDM overcomes this by using many highly linear and highly efficient smaller sub-bands.

A key weakness has come with OFDMA however, that is not aligned with the capacity and density explosion that has hit the cellular industry. OFDMA does not readily manage interference, either external interference or self-interference from neighbor cells or overlapping coverage from small cells or local capacity hotspots. LTE (Release 8&9) has a basic frequency domain management technique called ICIC to manage this problem for user data in overlapping cells, but this does not manage the overlapping control plane data and cell broadcast/sync channels of adjacent cells. To overcome this, LTE-A has introduced a time domain management for this control signalling called eICIC and feICIC. Whilst these can succeed to manage the control/broadcast interference due to overlapping cells, they do so by limiting times for transmission and hence reduce capacity of the network.

So, the key research theme for new modulation/access schemes is to allow the flexible/scalable bandwidth of OFDMA, but to overcome the interference management issues in dense networks and Heterogeneous Network (HetNet) architectures expected for 5G without sacrificing capacity or spectral efficiency. This problem is eventually leading to new air interface technologies or modulation schemes as FBMC (Filter Bank Multi-Carrier), which improves the spectral efficiency and can dramatically reduce interference, or UFMC (Universal Filtered Multi-Carrier), which shows up more flexible to combine MTC or TDD/FDD schemes with wider bandwidths to increase peak data rates. A more detailed analysis of some candidate waveforms is presented in the later chapter where candidates are simulated and then analyzed.

In Band Full duplex

All mobile communication networks have relied on a duplex mode to manage the isolation between the uplink and downlink. There are frequency duplex – FDD (such as LTE, where uplink and downlink are separated in frequency and operate at the same time) – and time duplex schemes – TDD (where the transmitter and receiver transmit at different times but use the same frequency, as in TD-LTE). A duplex mode is necessary to coordinate uplink and downlink to prevent the transmitter saturating the receiver and blocking any signal reception, but now full duplex technologies are now being discussed. In this full duplex scheme a device both transmits and receives at the same time, thus achieving almost double the capacity of a FDD or TDD system.

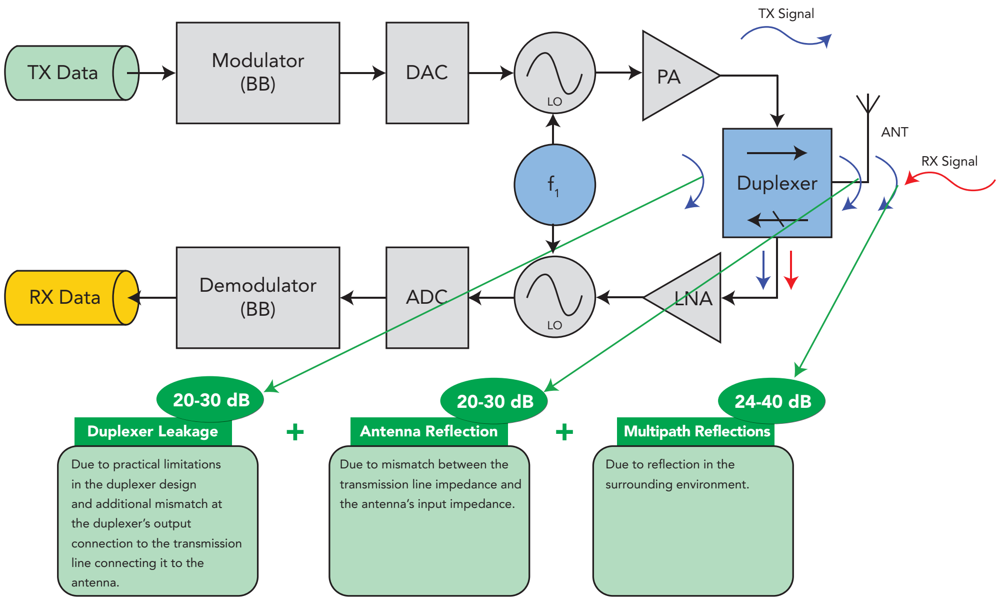


Fig 18 - Sources of Interference

There are major technology challenges to achieving what is essentially self-interference cancellation and major changes in both networks and devices are essential for full duplex. However, the potential increase in overall capacity is substantial, making full duplex a very important technology for the future of mobile networks. In a current LTE network, the transmitter at the device end may be up to 23 dBm output power, and requires below -113 dBm receiver sensitivity, so a total of 136 dB isolation would be required in the extreme case. We can see that current research has reported 110dB isolation, so it is improving but still some way off. It is therefore under study to see if a useful figure could be achieved in the timeframe of 5G deployment.

So the key to achieving higher capacity (spectrum efficiency) via "full duplex" is to solve the transmit – receive isolation problem, protecting the receiver from saturation by the transmitter. The traditional approach is to use normal circuit design principles for best possible isolation (works for duplexor leakage and antenna reflection), but this does not give enough isolation for the required receiver sensitivity, and does not protect against multipath reflections beyond the antenna that create strong interference. So the new approach to solve this problem involves added interference cancellation, so that any residual interference can be removed and the required sensitivity achieved. This cancellation is required at both the analogue stage and the digital stage, to give enough performance at an affordable size/price.

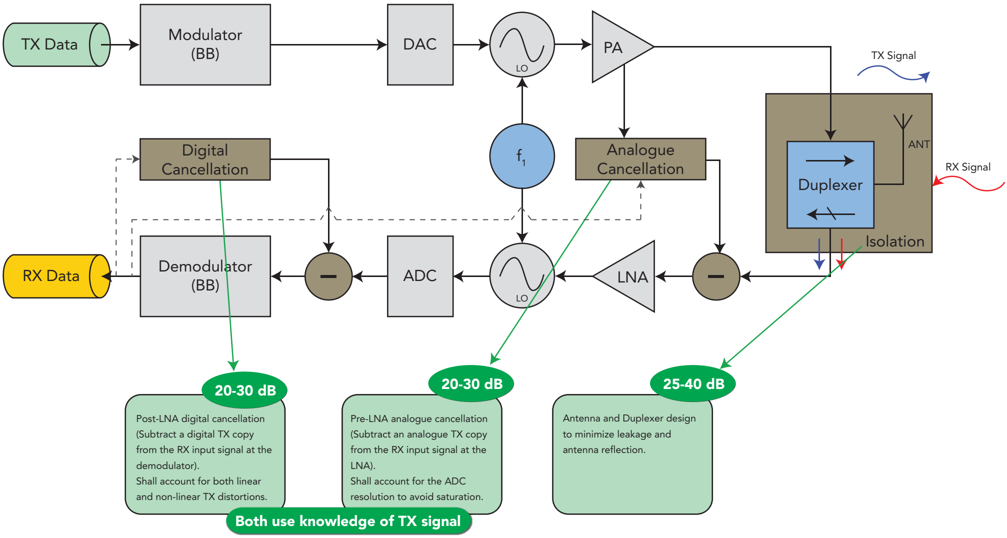


Fig 19 - Cancellation of Interference

Alongside the Tx-Rx isolation problem at each radio, there is also the need for proper access co-ordination for the multiple devices in the network. Such schemes, such as TDMA, CDMA, OFDMA are already existing. But as new and more efficient access schemes are developed for 5G, they may also have to take into account the full duplex mode when the access co-ordination methods are being evaluated. Different access schemes will change the requirements for channel measurements and cancellation algorithms, and this would directly affect the real world performance and efficiency of any full duplex modes.

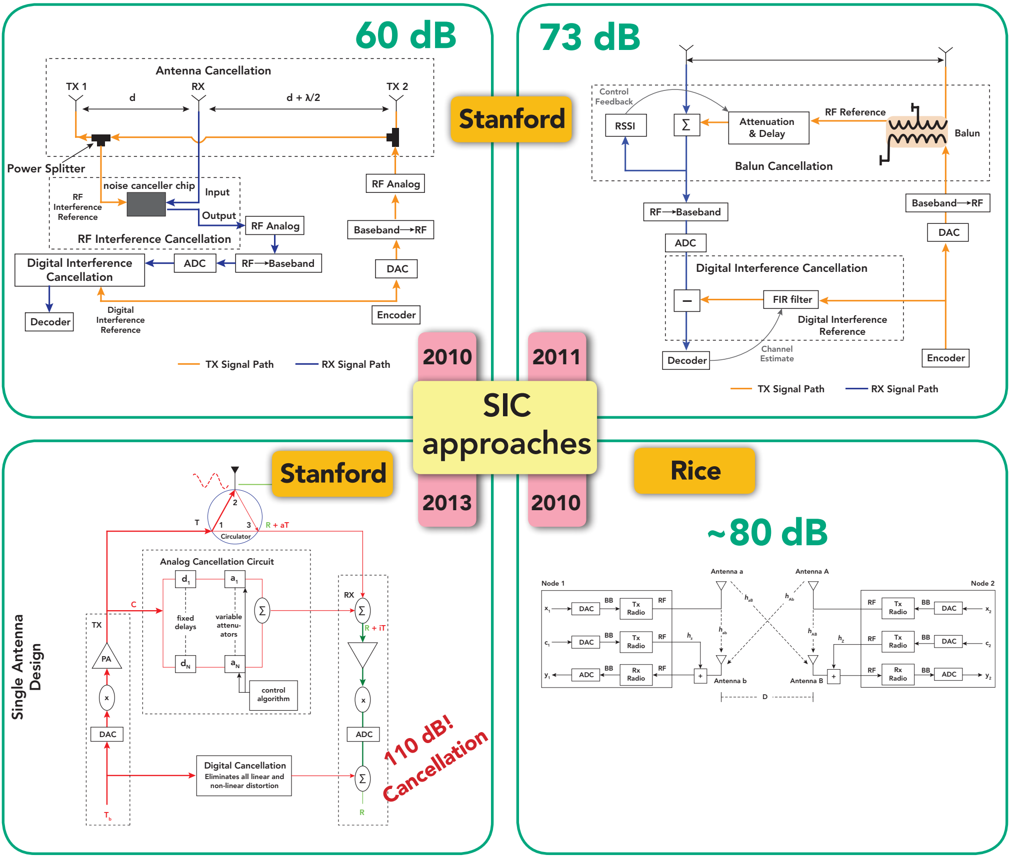


Fig 20 - Reported Performance of Interference Cancellation

Massive MIMO

MIMO has been deployed in LTE and LTE-Advanced networks, where the base station and user device uses more than a single antenna to increase link efficiency. Massive MIMO refers to the technique where the base station employs a much higher number of antennas that create localized beams towards each device. The gains in capacity are enormous but so are the technical challenges associated with this concept. A basic form of this has been introduced in LTE-A, called beamforming, but is only operational to a single device at any one time, and has only limited directivity/gains due to the limited number of base-station antenna supported in LTE-A.

Fig 21 - 128 port antenna

Massive MIMO is building upon previous research and development in phased array antennas that was principally developed for electronically steered radar systems. The basic concept is that an array of low gain and low directivity antennas are built, and then the phase relationship between the signals on each antenna carefully managed such that the composite signal from all the sub-antennas gives a high gain and directional beam that is controlled electronically by electronically

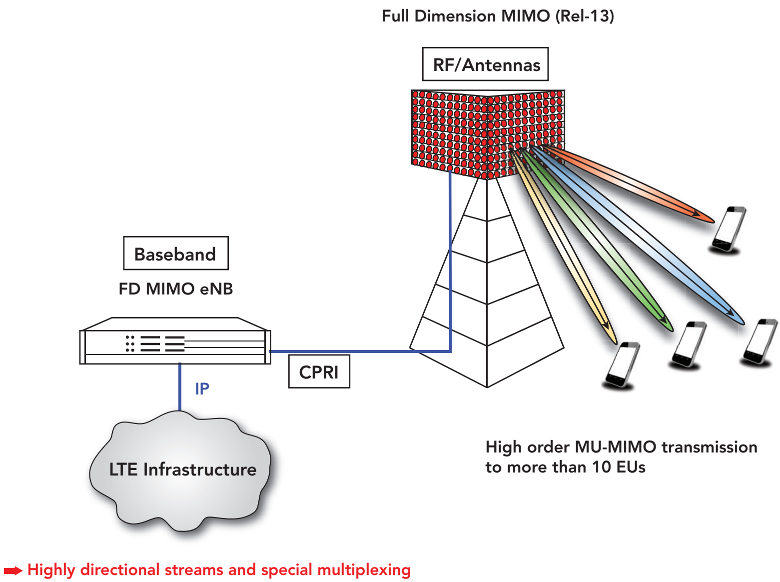


Fig 22 - Full Dimension MIMO

adjustable phase shifters. This concept is now combined with the MIMO concept, that uses baseband processing to synthesize multiple spatial paths between sets of antennas such that multiple channels of data can be transmitted simultaneously, and use MIMO spatial coding to separate the channels of data to different users according to their spatial position and the unique channel propagation characteristics of each Tx-Rx combination.

So massive MIMO now supports many separate data channels, based on the wide spatial diversity of the Tx-Rx links, and the capacity here is increased by having many Tx and Rx antennas. So where current MIMO uses 2 or 4 antennas for Tx and Rx, massive MIMO may be using 128 antennas. This will lead to much higher data capacity in a massive MIMO cell, due to the ability to synthesize many separate simultaneous data paths to individual users. This is combined with the enhanced beamforming that is possible with many more antennas, to provide highly directional beams (reducing interference and enhancing signal to noise ratio) and even 3D beamforming that enables the network to manage both near and far away devices at the same time without saturating or blocking signals.

The basic physics principles for massive MIMO are now proven, and experimental systems being deployed. Two of the key challenges to mature the technology now are to manage the amount of computing power required, and to create standardized or inter-operable algorithms so that multi-vendor and global solutions can be realized. To date, the processing power required means the massive MIMO deployment is not suitable for portable devices due to size and power consumption, and so first deployments are focused more to fixed wireless access schemes and provisioning of wireless backhaul to a dense deployment of small cells. In addition, the algorithms used so far are proprietary and very complex, and as such are only deployed into proprietary systems. To be included into a global telecoms standard then there needs to be open information on implementations such that any supplier can build either basestation or user device and be sure of interoperability of equipment coming from different suppliers.

Traffic Management

As the full deployment of IP based networks is being rolled out, already currently in LTE networks using IPv6, then the ability to offer differentiated traffic quality according to the needs of the service is being deployed. As wireless services expand, and a much wider range of services are delivered across the network, then an end to end capability for full quality of service is required to ensure the required performance level for each service. As many more real time services are deployed, taking account of the possible low latency capability, then ensuring the quality of service is critical for the applications and services to succeed. The traffic management will be required to manage the expected very high volume of traffic across the network, and must be integrated to the physical layer control procedures for each link in the network to ensure the traffic is correctly managed. This will mean that all physical links will need suitable control mechanisms, and the network will require methods to inform the individual physical links of the required quality of service. Although this capability is included in current packet data networks such as HSPA and LTE, the scheduling of data is made locally and not co-ordinated across the network in an optimum way. So NFV and C-RAN may offer more efficient platforms on which the end to end quality can be managed, as all network management and scheduling control can be centralized and shared across different network functions. So one part of 5G network research and definition will be looking at the optimisation of traffic flow, and end-to-end Quality of Service, in order to ensure that the network is delivering the required performance. Such a control system must be fully integrated to each new network element in a seamless and unified way to provide an efficient network control function.

Future Testing for 5G

As the network concepts and technologies develop for 5G, so the corresponding test methods and processes will evolve to match this. Future 5G test methods will need to provide a high confidence to operators that the technology and services are being delivered according to specification, and that the quality of service is matching to the requirements of the application or service being delivered.

A fully data-centric 5G network with a very wide and diverse set of applications to test would require a massive effort in standalone testing. Test automation, monitoring and built in test systems will be essential for analyzing properly the performance of such a network. In addition, the emergent solution to use Ultra Dense Networks (UDN) for interconnecting the radio access elements with the backhaul architecture using cloud networks will enable the development of cloud based test services for testing everything from everywhere. So, although 5G will introduce many new test requirements and challenges by the use of SDN/NFV and cloud services, this same technology can also be used for creating new test solutions that address these needs. With this in mind, cloud solutions are seen as both the new demand and the new solution for 5G network testing.

Test and Measurement challenges

One aspect that is expected to characterize 5G networks is that it is not a single technology or feature, but that it is an integrated set of technologies and features design to work together in an optimum way to support a wide range of applications and use cases. From a testing point of view, this means that as well as testing of the new technologies being implemented, there will be more of a need to test the many different combinations of technologies and network elements to ensure correct interoperability. This is of course further complicated by "virtualization" and the fact that specific network functions (the normal way in which network elements are tested) may no longer be physically realized in a specific piece of hardware, but may be dynamically moved around the network or split across different parts of the network. This virtualization of the network and its functions will require a corresponding virtualization of the testing methods and tools to be used.

We have seen in the earlier chapters the requirements on 5G networks in terms of target performance. These targets then lead us to a set of network KPI's and performance attributes to measure.

Key parameters for testing 5G.

- Traffic density Tbps/km^2.
- Connection Density. Connected users and active users. Connections/km^2.
- User data throughput at application level, both peak and average.
- Latency end to end through network, and round trip time (RTT).
- Reliability (error rates)
- Availability (coverage, handovers, mobility, capacity).
- Battery Life (mobile devices) and power consumption/power saving (network elements).
- Waveform/access spectral efficiency.
- Resource and signalling efficiency and overhead ratio.

When designing the test methods for 5G, it is necessary to pay special attention for mobility tests. There is a need to specify which parts of the network are to be used during mobility/roaming procedures, to ensure we test only these and limit the mobility combinations. This is due to the high complexity of different carriers and data links within the HetNet, meaning that not all possible data bearer combinations should be supported in all mobility test combinations. By reducing the mobility combinations, the volume of testing could be significantly reduced and maintained at a manageable level. In addition, we can see that many use cases (e.g. smart meters) will have low or no mobility requirements, but the dynamic changing of the network may result in such devices still requiring mobility across different access mediums depending on the status of the network. So mobility testing due to network configuration changes rather than device location changes may be required.

When we look at the area of device testing, we must now evaluate how the network simulator technology must evolve to simulate such a 5G network.

Due to the lack of available RF spectrum to meet capacity needs, there is now a strong push to utilize higher frequencies and the more available millimeter wave bands (typically from 35-100 GHz frequencies). Although individual regions have specific licensing conditions, it is generally accepted that there is more spectrum likely to be available, and specifically more contiguous bandwidth available, at these higher frequency bands. Utilization of these higher frequency bands will put further demands on the test equipment to provide corresponding support.

The test industry already has available basic RF measurement tools (spectrum analyzers etc) that support the design and test of radio units at these frequencies, and they are already in use in the industry. But, cellular network testing introduces needs for more complex network simulators and system simulators, and these have not yet been developed for such millimeter wave bands. One of the key challenges in this area is that it is expected that a 5G network will use a wide range of operating frequency bands, and may dynamically switch between them, but most user devices are expected to be optimized for specific use case scenarios. Therefore the devices will not have a standardized set of radio interface technologies, but rather each device will have a specific subset of technologies. This is similar to the 4G situation of devices having specific radio band support rather than support for all 40+ standardized frequency bands, but now with an added second dimension of millimeter wave bands and technologies to support. Network simulators have supported the sub 3 GHz band issue of having 40 different bands required by using a flexible open RF architecture, but this may not scale up to millimeter wave bands and to different access technologies.

Along with the need for more frequency bands to support, there is also a trend towards wider bandwidth channels to support higher data rates. Whilst it can be expected that the core technology for such wide bandwidths will naturally be developed for the network elements (e.g. base station transceiver technology), there are specific issues for network simulator technology in terms of having a generic capability that scales for different networks, rather than a specific implementation that is needed for real network elements. This requirement for additional flexibility in configuration becomes a key challenge in designing the RF performance and connectivity in a network simulator, being able to support the wide range of multi-carrier signals expected from a 5G network.

Massive MIMO has become a key term and attractive technology for 5G, offering significant gains in traffic density as well as data throughput peak rates. With this technology then come some key challenges for testing. A MIMO system comprises of two main elements, the baseband processing algorithms and the RF channel. The MIMO system works by having the baseband algorithm respond to the RF channel characteristics. As the baseband is split between the transmitter and the receiver, and for a cellular network these two elements come from different suppliers (infra vendor and device vendor are often different), then the full detailed operation of the parameters required for the algorithm must be specified in the technology standards documents. For massive MIMO this is likely to be a very complex and detailed specification to ensure full interoperability. So in the massive MIMO test we need to replicate each of the conditions in the massive MIMO specification, by using a fading simulator to replicate the RF channel in a controlled way and then test the response of the system. When we are testing the network then we must have a controlled reference user device, and when testing the user device we need to have a controlled reference network. As usually the most complex algorithm processing and decision making is in the network (to preserve power in mobile devices, and reduce cost impact on user devices), then the biggest challenge comes when creating a reference network simulator to test the mobile as it must have a fully open and flexible implementation for configuring and controlling the processing algorithms.

We have seen that not only is higher data rate and wider bandwidth a key feature for 5G, but hyper dense networks are also required. The limiting factor for such hyper dense deployments is the signal to noise ratio due to interference from neighboring or co-located cells. And so the ability to accurately re-create and measure performance in such a dense and complex RF environment becomes a key new test item for 5G. Alongside the creation of the complex RF environment, the hyper dense cell network testing will also require detailed testing of the RF measurements and reports from both network and devices, these are required to enable a smart access system and operation in a managed RF interference environment. This then leads to a massive increase in testing of the RF measurement and reporting functions of the network/devices, as this is the key information used to inform the network/device algorithms on how to optimize network access.

One of the most challenging technologies discussed for 5G is the concept of full RF duplex, where the frequency re-use between transmit and receive path is doubled due to simultaneous use. This offers a very attractive benefit in terms of available spectrum, but introduces some key challenges for testing and simulating. As we have seen in earlier chapters, the key to success for this technology is sufficient isolation between Tx and Rx paths. This is achieved with a combination of both RF isolation methods and IF/baseband compensation algorithms. So for testing we need to provide a very high isolation test environment that is capable to measure beyond the design specifications of the 5G system. The core technology required to implement the full RF duplex concept is expected to give enough performance for this. However, the key challenge comes in that the test equipment must usually be flexible for use in different RF bands, whereas full RF duplex technology is expected to be optimized for specific frequency bands. Therefore the test equipment must meet a critical cost/performance point in trying to implement a cost effective test solution, balancing the band specific RF needs versus the cost effectivity of a general solution. Without such a cost effective test solution, there can be significant cost barrier to having a wide deployment of the technology in the industry.

Future Test Instruments

Network test

In a higher level perspective, NFV and cloud will require more intelligence and analysis in the test instruments as the network becomes more dynamic or alive. The physical elements in the network will be split into specific/dedicated hardware such as antennas and radio transceivers, and general purpose hardware such as server/computing platforms. Each of these will have specific hardware related characteristics to be tested, such as radio emissions or sensitivity, or processor data rate or latency. The protocol aspects will be tested separately, initially in a virtual environment (i.e. inter-action of protocol stacks housed on software platforms rather than on target hardware). Finally, the integration of software/protocol onto the hardware platform needs to be tested. In SDN/NFV, this then becomes more challenging as the hardware platform will not be a specific platform optimized for the required protocol. This will mean that the performance of the network will need to be constantly verified as each virtualized network function is located or moved to different hardware elements. This type of monitoring is expected to be made using independent probes in the network, which are independent of the network hardware platforms and can quickly detect any performance issues.

As with current networks, it will be necessary the different segments in the data links, to identify any bottlenecks or restrictions in data capacity, so the overall capacity can be optimized and maintained at the required levels. But, with SDN/NFV, these statistics need to be provided in real time so that any dynamic effects due to software configuration algorithms can be detected. This is because network functions (and hence any problems) may not statically lie on a specific hardware component or use specific network links but could be software redefined by the network, and so a real-time monitoring system will be required to identify when a configuration is used that does not meet the performance requirements.

RF component and module test

5G will bring devices operating in much higher frequency bands, wider bandwidths and multi-carrier designs. More and more integrated technology is expected, which will produce a more complex analysis for interference limited devices. Generally speaking, the future RF device testing is challenging, and will ask for very precise instrumentation in order to deal with mmWave transceivers and better intelligence for Massive MIMO or AESA (Active electronically scanned array) radios. In addition, the near field effects and load pull on massive MIMO antennas in user devices will need to be fully characterized. In general, it is expected that 5G RF devices will be wider bandwidth, low distortion, and low power, to support the wide band and dense spectral efficiency of 5G waveforms. In addition, the use of full duplex RF would require significant work in the test and characterization of RF isolation and coupling between devices. These more demanding RF requirements will need to be addressed whilst aiming for higher levels of RF circuit integration to reduce cost, and in many cases these are conflicting requirements.

User device / terminal test

Testing a 5G full-capable handset may become an extensive process if we extend current handset test procedures. We can expect many more band combinations or RF duplex scenarios, massive number of transmitters and increasing types of receivers, leading to many variations in device that will constantly be increasing. User devices probably will no longer be tested using cables because 'Over The Air' (OTA) performance will be essential in the testing process, for example in Massive MIMO testing. More complex shield boxes and chambers will be required, even tunable to very different frequency bands. Alongside this, the simulation of multipath using fading simulators will grow further in importance, and also in the technical demands and capability required in such equipment. As the MIMO and HetNet algorithms become more complex and powerful, then correspondingly powerful fading simulators are required to test and verify the algorithms.

Application testing within an end-to-end environment will increase in complexity and customer experience testing may become embedded into the networks and devices, for example using smart software agents. Finding the bottleneck in the throughput, in complex QoS and multi-link transmissions, becomes far more challenging. As the uplink and downlink, control and user planes, are all separated, then the limitation in data throughput can come from any of these areas. So even when the downlink user plane has enough capacity to deliver the required data rates, the downlink control plane needs corresponding capacity and latency to schedule it, and the uplink needs low enough latency to carry the fast HARQ feedback (or similar control loop data) to maintain the high throughput.

One area of device testing that has grown significantly in 4G is User Experience Tests, and this is expected to grow further as the range of user experiences and the expectations grow based on 5G technology. One area of big concern from4G is the battery life, where a smartphone cannot be used for a single full day and users need regular access to charging points. It is expected that 5G will need to offer better battery life, but with more data processing. Test systems have evolved in recent years to provide specific and repeatable real world scenarios (e.g. browsing, email, chat) to evaluate battery life versus a reference daily set of activities. For 5G, the expected low latency of "tactile internet" is expected to give a more direct inter-action between user and apps/services, so evaluating how the air interface and modem link enables this or impairs this will be an important user experience test.

Device certification and approval, and Carrier Acceptance Testing

With the launch of 3G networks, there was an industry initiative to reduce the volume of handset testing, and repeated redundant testing, my introducing industry forums such as GCF with the concept of "test once, use anywhere" based around standardized and agreed testing. With the launch of 4G, it has been seen that the test needs for devices are diverging as carriers have significantly different network architectures due to the wide range of options. Also, 4G networks are now inter-working with non 3GPP networks (e.g. IMS, WiFi) and the separate testing regimes are not aligned so a single test plan can not cover this. So some major operators have introduced more operator specific test plans to ensure compliance to their specific network needs. Looking forward to 5G, with the much more diverse set of network connectivity from HetNet's, then extrapolating the current test methods will lead to a large increase in volume of testing. The key challenge in this is that the wide range of network flexibility/diversity required for managing a wide range of diverse use cases, would lead to a very wide range of industry standard test cases and scenarios. But moving away from an industry standardized regime to individual test plans will also increase drastically the volume of testing. So this trade-off of deployment flexibility versus standardized testing will be a key item to address in 5G network definitions.

The divergence of device types, M2M, Augmented Reality, smart meters etc. onto the network will also lead to divergent test needs and critical functionality. Some smart meter applications may prioritize battery life and cost, trading off versus data rate, latency and connection availability. Equally, augmented reality would prioritize data rate and latency above all, and critical communications (e.g. first responder, health & monitoring) may prioritize connection availability as highest priority. To handle these divergent needs and characteristics, it is likely that further classes or "class types" of user devices will need to be specified in 5G standards, so that corresponding test regimes and methods can be defined to match the different needs.

Another area of development that is becoming more relevant now in the area of 5G is that of Cognitive Radio, and Software Defined Radios. When such a device uses a general purpose RF transceiver, it is essential to ensure the required RF performance for specific protocols and modulation schemes used. Without such tests, the SDR device may produce excess interference that disrupts the network, or suffer from excess distortion/non-linearity that means data loss and communication failures. For the Protocol part of the modem, a key test is to ensure the timing requirements can be maintained, as it is implemented in non-optimized circuits and so may suffer from slow processing/response to messages.

Field Test

Testing in the field will also grow in complexity. Finding the suitable test locations in a Het Net may become a difficult or dynamic process, not only for capturing the target UL or DL stream but also for the separation between Control and User planes. This is because the HetNet itself will be dynamic in its use of available resources, and the available resources may also be a dynamic parameter.

As we have considered in the earlier technical discussions, much of the 5G HetNet will operate in an interference limited scenario (i.e. data rates and Signal to Noise Ratio are limited by interference rather than propagation losses). This will lead to a paradigm shift in how network coverage is defined and measured. Traditional coverage mapping at the modelling, planning and design stages, in field trials, and during drive testing, is based upon signal strength and assumes noise limited effects due to propagation. In 5G, we can predict that installation tests, coverage mapping, and de-bugging of issues will be much more focused on the interference environment.

Load test for HetNet, looking at capacity, throughput and latency as the main KPI's will become an ever complex issue. We can surely still use traditional drive test, and probe based network monitoring, to gather these basic user KPI's. But as we have seen, these parameters are highly variable depending on conditions in the HetNet, and any values can not be simply interpreted to establish performance and capability of the network. This is because such parameters are the result of the complex algorithms to be used for scheduling and routing of data. So, to more accurately evaluate the network capability, we may need to measure and record the values of the parameters going into these algorithms, and not only the resulting performance. So key parameters like throughput and latency will need to be defined in relation to network load, capacity, and interference levels.

Current test technology examples in early 5G development

Even in the early stage of 5G development, there are already test systems capable for evaluating the upcoming technologies. Amongst these, wide band Capture and Replay systems for IQ signal generation and analysis are important in the development of new transmitters and receivers. Using modelling software to create new waveforms and then realizing and evaluating performance in real devices is the first step before the standardization stage. This will be looked at as a worked example in the next chapter. It is used for the investigation of new waveforms, to see the spectral properties, and then to see how the waveforms are handled by real devices (e.g. harmonic distortion, non-linearity distortion etc). Similarly, new device technology is evaluated with new waveforms to see the RF performance.

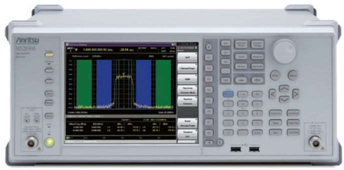


Fig 23 - MS2830A Spectrum/Signal Analyzer + Vector Signal Generator

Broadband multi-port VNA's will continue addressing the characterization of new mmW devices and MMIC's. Especially for massive MIMO, there is the need to ensure that relatively low cost and compact devices and antennas will have sufficiently stable and repeatable RF/phase characteristics. Also, as new technologies in semiconductor gates and processing enable lower cost mmW devices, these devices need detailed evaluation to ensure the RF performance is not compromised by lower cost manufacturing.

Fig 24 - ME7838A/E/D VectorStar Broadband VNA

In the network side, high speed BERTS (64 GB/channel) are used for testing next generation optical devices in fibre links and data centers. As the processing power in data centers and server farms is increased, to support cloud computing, then the inter-connect between individual server blades and server stacks needs to be high speed, low latency, and low distortion. New modulation schemes are being introduced into high speed optical communications, such as Phase Amplitude Modulation (PAM), with PAM4 and PAM8 having 4 or 8 different states possible and hence increase the data rate versus pure digital (2 state, on/off) transmission. But to enable this, the linearity of the modulators and de-modulators needs to be verified, and this is done using Eye diagrams and Bit Error Rate Tester (BERT).

Fig 25 - MP1800A Signal Quality Analyzer

100 Gb/s link analysis, traffic flow, and OTN mappings for cloud networks are also available solutions these days. It is expected that the key parameters of delay, jitter, and bandwidth will remain as in today's testing, but with the corresponding new target values.

Fig 26 - MT1100A Network Master Flex - All-in-one transport tester

Introduction to 5G Waveforms

This section introduces the reader to the different waveforms that are considered to be part of the 5th mobile generation. It highlights the advantages of FBMC versus OFDM, provides basic concepts about FBMC and demonstrates how we can load these signals into Anritsu's Signal Generators for immediate evaluation on real devices.

The 5G radio access technology (RAT) must fulfill the data traffic demand in the next years with rates above 10 Gbps and sub-ms latency. These rates can be achieved, principally, with bandwidths of at least 200 MHz, using multiple-input multiple-output (MIMO) antenna techniques and interference rejection combining (IRC) receivers. Ideally, the waveform to be used should have the specific properties, such as, limited computational complexity for the generation/detection, limited time/frequency overhead, good localization in time, good spectral containment and simple extension to MIMO, between others.

Orthogonal Frequency Division Multiplexing (OFDM) and Filter Bank Multi-carrier (FBMC) are considered as the most attractive candidates for a 5G waveform. The main difference between OFDM and FBMC is the pulse shaping applied at each sub-carrier. On one hand, OFDM uses the simple square window in the time domain, which leads to a very efficient implementation based on the Inverse Fast Fourier Transform (IFFT) spreading of the original block of data symbols and getting the sub-carriers orthogonal. On the other hand, in FBMC, the pulse shaping at each sub-carrier is designed in a way that some of the OFDM limitations can be circumvented, like a better frequency containment and improved system overhead (no needs of cyclic prefix), but it is more complex due to the usage of long prototype filters.

Taking into account that Anritsu provides different OFDM waveforms in its current signal packages, but nothing for FBMC ones, this guide is focused in the implementation and usage of FBMC waveforms in Anritsu's products.

Following the previous purpose, in this document is presented the most common FBMC principle, which is the OFDM/OQAM model. It means that, apart from the FBMC prototype filter applied at each sub-carrier, the modulation scheme used is of the offset-QAM type, which gives as a result the elimination of the Inter-Symbol Interference (ISI).

Filter Bank Multi-Carrier (FBMC) Concepts

The scheme of a FBMC transmitter appears in the following figure. It can be observed that it is simply formed by a Synthesis Filter Bank, whose filters are of Finite Impulse Response (FIR) type. Furthermore, only a single prototype filter is needed, so each sub-channel is filterer by same form and BW. Basically, the input information is divided in N sub-channels (typically a power of 2) and, after applying a possibly needed oversampling, are passed through the correspondent prototype filter, centered in one of the sub-carriers inside the band.

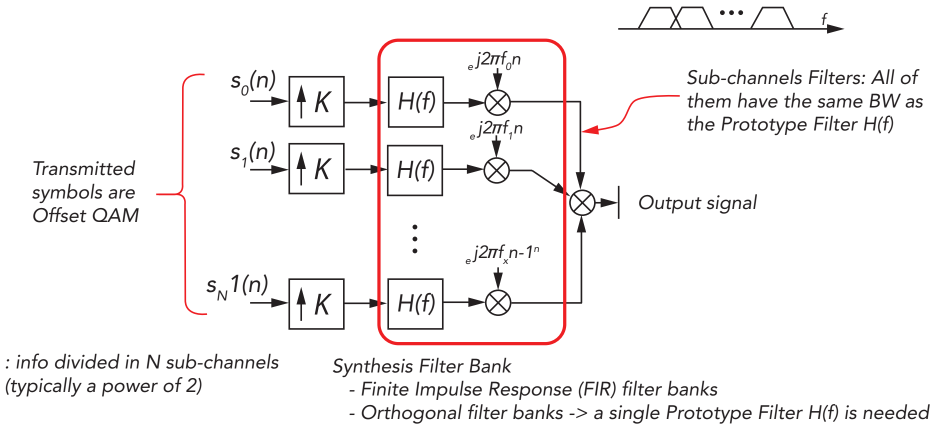


Fig 27 - Synthesis Filter Bank for FBMC Transmitters

As we introduced before, the key feature of FBMC modulators is the prototype filter applied at each sub-carrier. Thus, the definition of this filter is relevant in the design of these systems. In our case, we have chosen the Phydyas (PHYsical layer for DYnamic AccesS and cognitive radio) prototype filter [3]. This filter is designed in such a manner that only immediately adjacent sub-channel filters are significantly overlapping with each other in the frequency domain.

The next figure represents a more realistic way of our system. In this case, it can already be seen the OQAM modulation and the combination of the IFFT (for splitting the symbol energy into the different sub-carriers) and the impulse response of the prototype filter applied. OQAM makes the symbols being transmitted alternatively on the real part and the imaginary part, so In-phase (I) and Quadrature (Q) components have a time offset of half symbol interval (T/2). Once we have the baseband signal, we modulate it to RF band (fc) and transmit the real part to the channel.

In-phase (I) and Quadrature (Q) components have a time offset of half symbol interval (T/2)

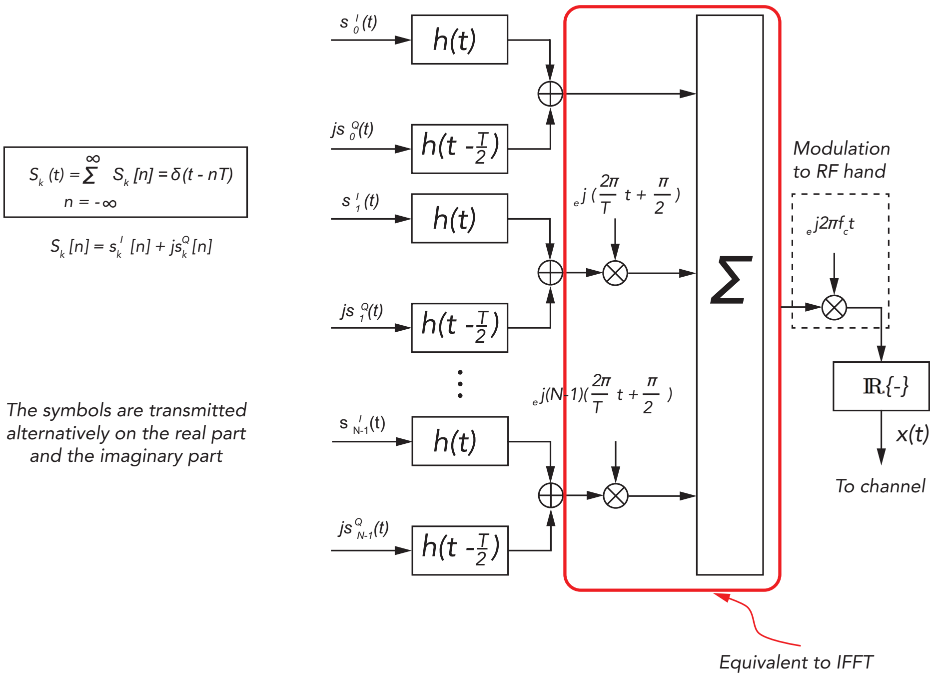


Fig 28 - Offset QAM Modulation in FBMC Transmitters

Following [5], the Prototype filter coefficients Hk are obtained and used for building the impulse response with the form:

$$h[n] = H_0 + 2 \cdot \sum_{R=1}^{R-1} (-1)^k \cdot H_k \cdot \cos\left(\frac{2 \cdot \pi \cdot k}{K \cdot N} \cdot (n+1)\right) \qquad \textbf{(1)}$$

where K is such as the filter length is L*K.

It is important to highlight that the coefficients just depend on K, but do not depend on the filter length, thus, this approach is scalable. For example, for K=4,

H0 = 1

H1 = 0.97160

H2 = √2/2

H3 = 0.235147

and these values give an iterative procedure that can be used for K>4.

Note that the bigger K, the more rejection between adjacent sub-channels and the bigger system delay. Consequently, a comprehensive value should be chosen. In our case, we will work with K=4, which will produce a difference of 40 dB between the main and second lobes of the filter's frequency response.

FBMC Modulator in Matlab

Once we have chosen Matlab as the mathematical software for programming the FMBC signals, the first target is to implement the Prototype filter based on the design we could see above.

The Prototype filter can be easily programmed in Matlab, just selecting the number of sub-carriers N and applying the impulse response formula with the filter's coefficients. Then, the time and frequency responses appear respectively in figures 29 and 30.

In figure 29 (Prototype filter's time response) we can appreciate the almost 40 dB rejection between the main and second lobes, which principally achieves the desired frequency containment that we need for future communications.

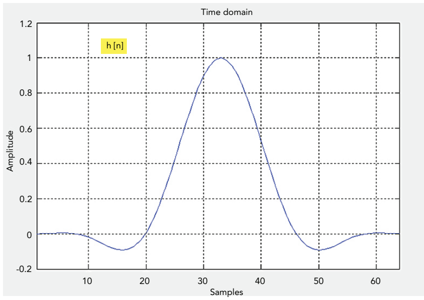


Fig 29 - Prototype filter's time response

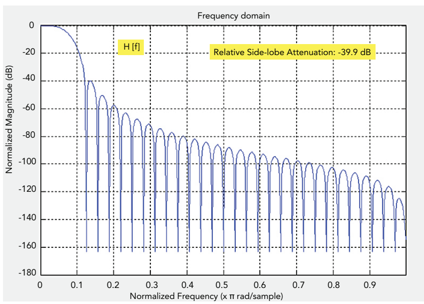


Fig 30 - Prototype filter's time response

The next step would be building the FBMC modulator. Our approach provides a tuning variable that permits the repetition of a certain number of random FBMC symbols to be transmitted. In this way, we can analyze afterwards the difference in the spectrum between a signal formed with few symbols and another one with many symbols.

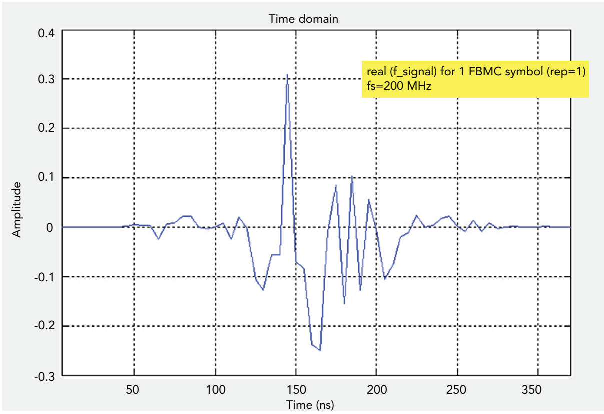


Fig 31 - FBMC Symbol in Time Domain

Firstly, we can observe the time form of a single-FBMC-symbol signal. If we analyze it in the frequency domain.

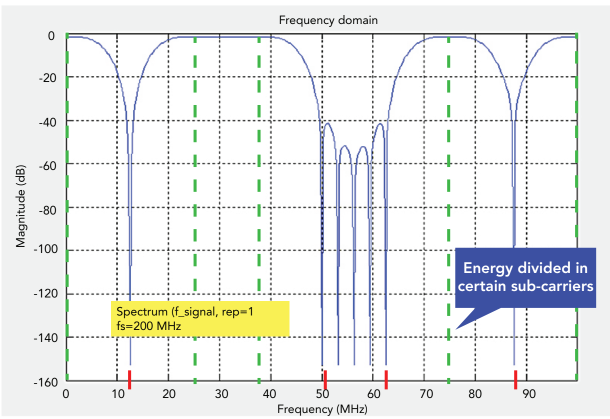


Fig 32 - FBMC Symbol in Frequency Domain

It can be observed that, with just one FBMC symbol transmitted, not all sub-carriers have been excited, but only the ones appearing in green. The different sub-carriers will be randomly excited, depending on the result of the IFFT over the O-QAM signal.

It can also be realized that only adjacent sub-carriers impacts on their correspondent neighbors, i.e. only the sum of the main lobes of adjacent sub-carriers are relevant in the spectrum. This is very important, because we could separate different signals by just one sub-carrier spacing between them and still being easily recognizable.

Only the sum of the main lobes of the adjacent sub-carriers are relevant in the spectrum

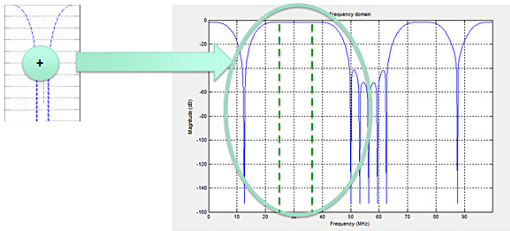


Fig 33 - Frequency relationship between FMBC signal lobes

The next scenario consists in creating a 100-FBMC-symbols signal for appreciating the difference in the spectrum with the previous one. In this case, one could expect that with 100 symbols we will have all the sub-carriers excited, thus, we will have to obtain a flat spectrum. In the next figure

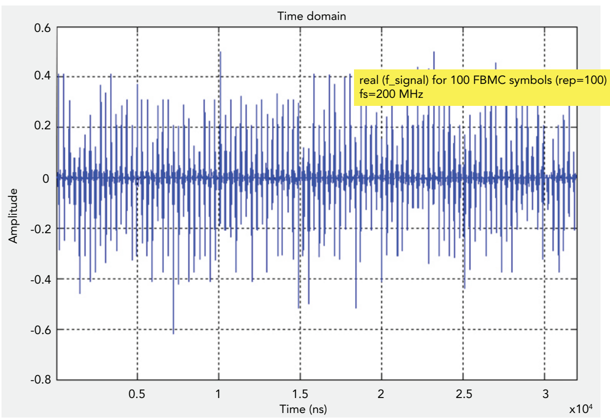


Fig 34 - 100-FBMC-Symbols signal in Time Domain

…it is demonstrated that after using 100 FBMC symbols the spectrum becomes flat, i.e. the signal energy has been divided between all the sub-carriers.

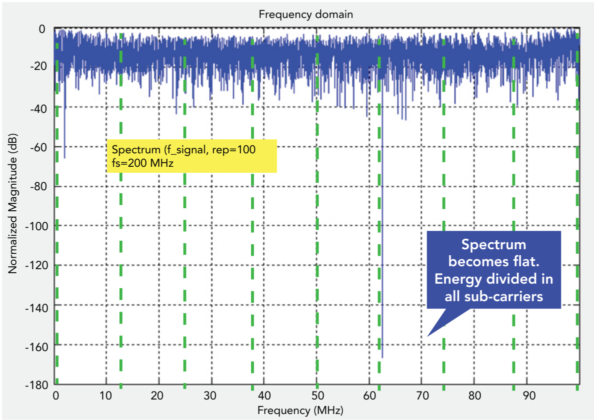


Fig 35 - 100-FBMC-Symbols signal in Frequency Domain

FBMC Waveform in MS2830A

After successfully testing the FBMC modulator in Matlab, it is time to send these signals to our SG internal memory, so we can reproduce them and use them with real devices. In this case, the all-in-one Signal Generator+Signal Analyzer+Spectrum Analyzer MS2830A has been chosen for our experiment.

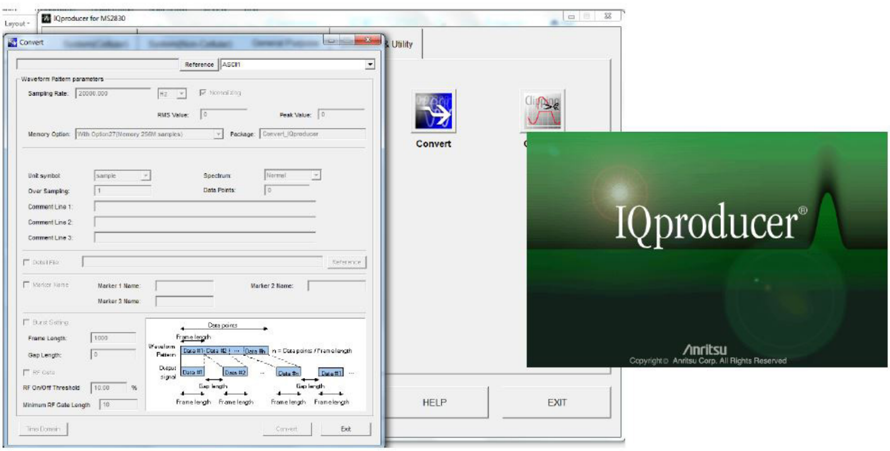


Fig 36 - Anritsu IQProducer

The MS2830A SG can read external IQ waveforms files with extensions .wvd and .wvi, which leads to the need of using Anritsu IQ Producer for converting the data from Matlab into these type of files. It will consist in saving the waveform data from Matlab into a Comma-Separated Values file (.csv) and, then, using IQ Producer for converting it into the readable waveform files.

This is the stage of the process when the user will select the sampling frequency, which will determine the signal bandwidth at RF frequencies. The software IQ Producer for MS2830A allows a maximum sampling frequency of 160 MHz, so the widest signal will have exactly that bandwidth.

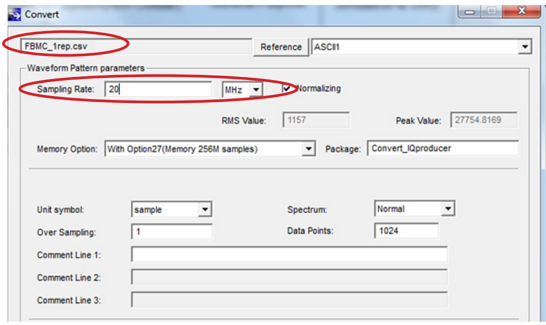


Fig 37 - Convert tool in Anritsu IQProducer

We can use the IQ Producer Time Domain application for viewing the signal loaded:

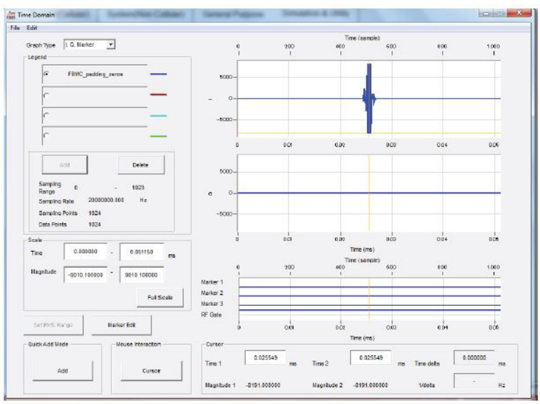


Fig 38 - IQProducer Time Domain Application

Once the waveform has been properly converted and before sending it to the MS2830A, we can use the IQ Producer Time Domain application for analyzing the form of the signal to be loaded. This software also offers FFT viewer for analyzing the signal in the frequency domain if needed.

Loading the waveform into the MS2830A is very straightforward. It is enough just creating the folder "Convert_IQProducer" in the path C:\Program Files\Anritsu Corporation\Signal Generator\System\Waveforms\ of our MS2830A, sharing it and sending there the .wvd and .wvi files. The Set Up needed for this operation consists uniquely in an Ethernet connection from the MS2830A to our Laptop (Set Up figure) and Matlab can be used again for sending these files automatically.

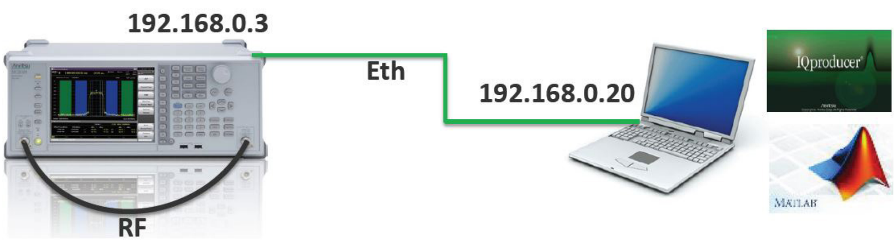


Fig 39 - 5G Waveform Demonstration Set Up

Then, going through SG/Load Pattern and SG/Select Pattern functions the waveform is easily prepared for being transmitted.

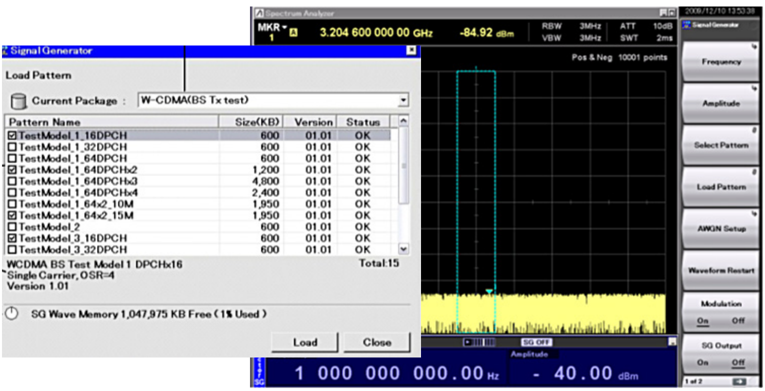
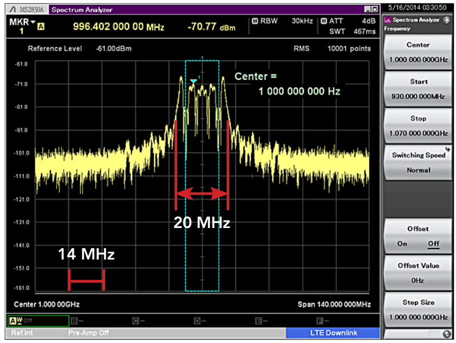


Fig 40 - Selecting 5G waveform patterns in MS2830A

Connecting the output to the input of our MS2830A, we can use the SPA for viewing the signal transmitted. In this first example, a single-FBMC-symbol signal with a bandwidth of 20 MHz can be appreciated in the figure. A good rejection at both sides of the signal is achieved, as it was expected.



- Connect the Output to the Input
- SPA
- Signal BW = 20 MHz
- Clearly distinguished sub-carrier

Fig 41 - 5G Waveform Spectrum in Spectrum Analyzer mode

The next figure shows the signal from the SA function, showing more clearly the sub-carriers that have been excited for this FMBC symbol.

- Connect the Output to the Input
- SA
- Signal BW = 20 MHz
- Clearly distinguished sub-carrier

Fig 42 - 5G Waveform Spectrum in Signal Analyzer mode

Following the same procedure with a 100-FBMC-symbols signal, we can observe the proper conversion of the signal using IQ Producer, both in time and frequency domain.

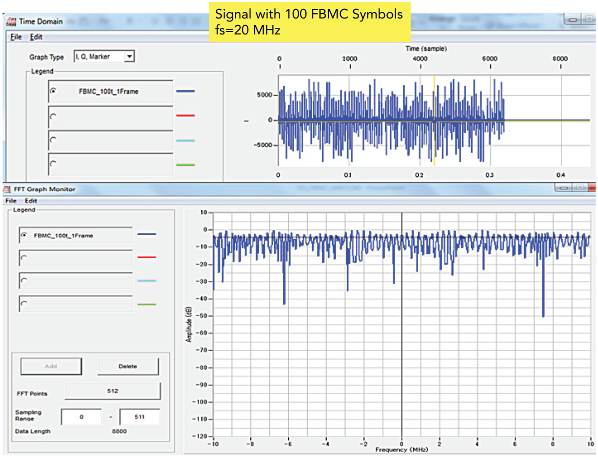


Fig 43 - IQProducer Analysis on 100-FBMC-Symbols signal

Then, once loaded into the MS2830A SG and analyzed with the SPA, the highly contained flat spectrum with more than 30 dB of rejection at both sides can be observed in this figure.

A further example consists in simulating a 100 MHz signal formed by 5 FBMC carriers.

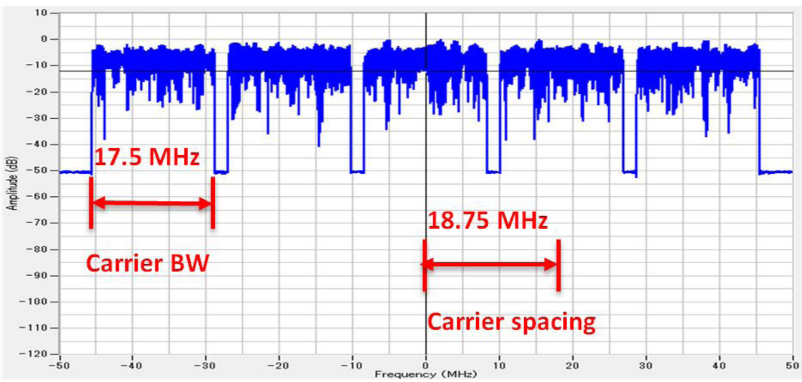


Fig 44 - Spectrum design of 5-carriers FBMC signal

In this case, considering 17.5 MHz bandwidth at each carrier, which each of them has been built with 16 sub-carriers at the same time, we could prove that a RBW around 1MHz would clearly capture the different sub-carriers being excited. This is what we represent in the following figure.

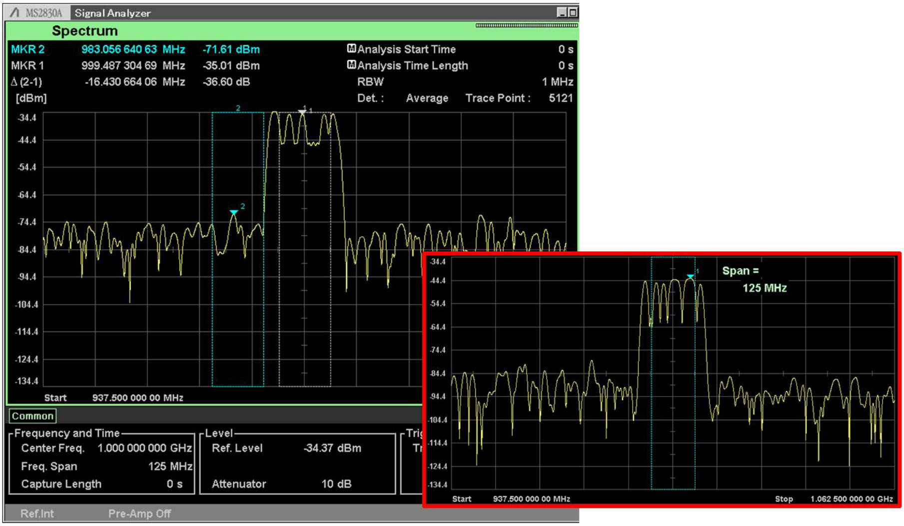


Fig 45 - Single Sweep of FBMC signal in Spectrum Analyzer

Playing with this scenario, the user can measure more complex parameters such as Adjacent Leakage Power Ratio (ACLR) in single carrier mode, multi-carrier contiguous or multi-carrier non-contiguous.

Fig 46 - ACLR Measurement on 5G waveforms

Apart from these functionalities, MS2830A can digitize these real signals into data files that can be sent back to Matlab, where they can be processed and compared with the original signals.

Fig 47 - Capturing real 5G waveforms with MS2830A

As an example, in the next figure, we can easily notice how the noise floor level of the signal coming from the MS2830A has increased in comparison with the one created originally in Matlab, mainly caused by the effect of the signal generator.

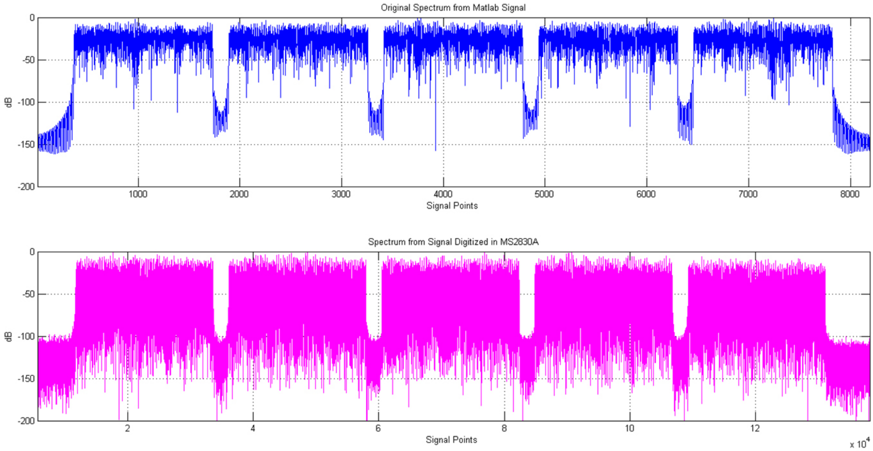


Fig 48 - Comparison of captured waveform with simulated waveform

In summary, it is possible to create almost any waveform desired without much difficulty and give the designers the chance to evaluate the performance of possible 5G communications technology. We have demonstrated how to easily load, reproduce and analyze new kinds of signals in our MS2830A.

Conclusions

We have seen in this guide that the next generation mobile broadband networks, now being called "5G", are aiming at a very diverse set of use cases and applications for mobile broadband within society. As well as meeting the constant demand for more bandwidth, higher data rates, and wider coverage, the new "5G" networks will aim to open up more use cases such as Smart Meters, First Responder, Critical Health Care, and Machine to Machine (M2M) applications by offering a network and technology suitable for this much wider set of use cases. There are a number of key new performance targets being set for 5G, matching to these envisaged use cases.

Several key new technologies are emerging as key building blocks for 5G. We have seen that cloud services, Network Function Virtualisation, and Software Defined Networks, will be the key elements to the network infra-structure, providing a more flexible, scalable, and dynamic network infrastructure that can adapt to use cases and requirements in a faster and cost effective way. Heterogeneous Networks (Het Net) are expected to be the key element for access network architecture. This uses a multi-layer approach to coverage and capacity, combining macro and pico cells, using different access interfaces simultaneously, and selecting access methods based on various parameters such as traffic type, congestion, latency etc. The result of the development of HetNet technology is that 5G is expected to not be a single access technology, but a combination of different legacy and new technologies which complement each other.

On the air interface, the key challenge is to find enough available bandwidth to meet the data capacity and performance requirements which are predicted by the use cases. Looking for new bandwidth that may become available is driving the industry to higher frequency, and to millimetre wave solutions. Here there are propagation and technology cost issues that need to be overcome. At the same time, "Massive MIMO" is being developed as an improvement to the air interface that will give higher capacity due to better spectral efficiency and spectrum re-use within a cell. There are implementation issues for massive MIMO relating to size and cost, but maturing of millimetre wave technology is helping here. For the air access method, the industry has seen that OFDMA, used in LTE, does not meet the interference handling and the spectrum density demands of future HetNet. So, new access waveforms based on improved spectrum orthogonality, or using non-orthogonal waveforms, are now being investigated for a new air access method.

For the test and monitoring industry, 5G is presenting many new challenges as well as opportunities. Testing of the core and access network elements is changing as SDN/NFV are deployed, as the test of the physical entity and test of the logical function are separated, rather than testing as an integrated network element. Device testing and certification is likely to be significantly impacted by the changes in 5G. With such a diverse range of device types, of access methods, and use cases, then the standardised testing methods based around "test once, use anywhere" will need to evolve to cover this much wider range of test requirements. In field testing and monitoring, we can see that HetNet and interference limited network performance will bring in a new set of requirements for measuring network performance, coverage, capacity etc, in order to relate the network conditions to the user experience. Alongside these new test demands, we can also see that 5G technology may also bring to the test and monitoring industry some new technologies that can also be used to implement test solutions. So cloud based systems and virtualisation may also be used to create innovative new test methods and solutions.

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