Executive Summary

5G networks put forward very aggressive performance metrics as compared with existing 3G/4G networks. Major changes and new technologies are required to achieve the performance metrics targeted by 5G. The corresponding test and measurement technologies are critical for not only the R&D perspective but also the future network deployment perspective.

New technologies for 5G may likely include mmWave, ultra wide bandwidth, and Massive MIMO. The first step is to measure their corresponding propagation channels between UE and BS, then build mathematic models for propagation channels and use the models to define the air interface for 5G.

The air interface for 5G is also facing major changes to satisfy performance metrics. New technologies such as SDM, Massive MIMO, high frequency communication, new waveforms and new multiple access schemes are anticipated. Each new technology needs special test solutions to verify the real achievable performance and the performance optimization solutions. Take Massive MIMO for example, the test solutions need to extend to multiple channels for transmitters and receivers specification measurements, and need to deploy OTA tests for system performance verification.

5G network architecture may change significantly to satisfy extreme network demand, including ultra high rate, high capacity and low latency. Specialized test and measurement solutions must be adopted to verify new network architectures, and help to optimize the deployment of 5G networks. The challenges are that a lot of those test solutions need to support distributed and large scale measurements, and to emulate realistic control and data traffic to do perform stress tests of the network. The test of the coexistence of multiple radio access networks is another challenge to be addressed by the test solutions.

The 5G test and measurement group in FuTURE Forum 5G SIG aims to research new technologies and provide some guidelines for future test and measurement solutions. In this white paper, all aspects of 5G tests mentioned above are thoroughly discussed and carefully demonstrated. Test and measurement for 5G is feasible, yet challenging as we move forward from methodology to realization. The 5G test and measurement group welcome all parties interested in 5G test and measurement to jointly investigate and share new test solutions. It aims to develop 5G testing reference cases, which should potentially facilitate the 5G test standardization process.
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1. Overview and Introduction

5G put forward very aggressive performance metrics as compared with existing 3G/4G technologies. Major changes and new technologies are needed to achieve the performance metrics targeted by 5G. The corresponding test and measurement technologies are critical from not only the R&D perspective but also the future network deployment perspective to make sure those major changes and new technologies are able to meet the 5G performance target.

The 5G network architecture change brings new test measurement requirements and challenges. 5G network is undergoing significant changes to meet 5G network performance requirements on high data rate, guaranteed minimum data rate, high capacity, low latency etc. The major changes in the network sides include: 1) using network architecture which is beyond the traditional cell based network architecture 2) using ultra dense network 3) centralized Radio Access Network (C-RAN) and virtualized Radio access network (V-RAN) 4) separate the control plane and data plane 5) caching the content where it is more close to the user etc. 6) using software defined network to dynamically adapt the network according to the customer needs, etc.7) supporting the coexistence of 5G with existing 2G/3G/4G seamlessly. Dedicated test and measurement solutions are thus needed to check the feasibility of those changes, validate the performance of the new network architecture and also help optimize the 5G network when it is being deployed. The challenges for the 5G test solutions to test the 5G network are that a lot of those test solutions need to support distributed measurement, to be capable to perform large scale measurement and to be able to emulate realistic control traffic and data traffic to do the stress test of the network. The test of the coexistence of multiple radio access networks is another challenge to be addressed by the test solutions.

The 5G air interface brings new test measurement requirements and challenges. Besides the network architecture changes, 5G air interface are also undergoing significant changes to meet 5G performance requirements. The major changes in the air interface part include: 1) using massive MIMO technology 2) using high frequency for broadband communication 3) using full duplex technology 4) using new waveforms and asynchronous multiple access technologies 4) using new frame structure 5) using software defined air interface concept. The changes in the air interface bring a lot of new test measurement challenges. Each new technologies need dedicated test solution to check the technology feasibility, validate the performance of given technology under real usage scenarios and optimize the solution for better performance. For example, massive MIMO bring the test and measurement challenge on the cost scalability of the test solutions with regarding to the number of channels. Massive MIMO also brings the challenge on over the air performance test. Full duplex solution needs the test solutions to evaluate how the solution works under real scenarios.

The 5G devices bring new test and measurement requirements and challenges. 5G devices are undergoing some major changes to meet 5G performance requirements. The major changes in the 5G devices are the following: 1) besides the human devices, there are a huge amount of machine devices. The machine devices bring in other dimensions of performance to be tested for other industry application. For example, some of those devices need to be able to last for many years, which needs to be validated through test. 2) The devices are getting much smarter about the network and service surrounding it. It can choose the network and service smartly. The network can also dynamically reconfigure to support the customer needs. The service can be delivered from either the network or by some devices nearby. Dedicated solutions are needed to validate whether the device is smart enough to and also validate how the device can co-work with the network to achieve the service performance it needs. 3) more challenging RF technologies on 5G devices. It might have both lower frequency and high frequency radios, which covers a wide frequency span and broad bandwidth with more number of channels. Dedicated solution is needed to check how those different radio technologies coexist.
The 5G applications bring new test and measurement requirements and challenges. 5G aims to provide very different user experience for different applications targeting not only wireless communication industry but also other industry like automotive, health, education, gaming, consumer electronics, etc. The different applications have different end to end user experience requirements and require different test solutions to validate that. For example, for health industry, the robustness and low latency of the wireless connection and the overall application can be critical. It needs specific test to make sure the performance requirements can be met always. On the other hand, for the massive machine to machine communication application in the consumer electronics, how the system performance scales with the number of devices can be very important to test.

5G also results in more needs for in field test. For 5G, most of the new technologies and changes are happening in the network side. It is thus very important to perform the in field test to validate that the network performance is as expected. 5G network will coexist with 2G/3G/4G network for quite a long time and serve the customer based on their requirements on the service. In field test is important to check how the 2G/3G/4G network serves the customer. A lot of 5G key technologies are highly dependent on the channel characteristics, for example massive MIMO, full duplex etc. It is thus important to do the in field test under different scenarios to evaluate the technology’s performance under different channel scenarios etc.

5G also results in a lot of changes in the way the test will be done. The major drive for such kind of change arises from the following aspects: 1) the architecture and interface change of the device of test (DUT) make the traditional way of test not feasible any more. For example, massive MIMO system performance test requires over the air test instead of the cable conducted test. 2) The scale of measurement required to perform the test for the new network requires innovative new test method. 3) The enhanced contrast between the increased system complexity and dropped test cost per device or channel requires innovation in the test and measurement solutions to make it sustainable.

The test solutions are highly depending on the DUT architecture and test interface available. To effectively address the 5G test and measurement challenges, close collaboration among the 5G industry is very important. The test and measurement challenges if addressed efficiently via industry collaboration and standardization can greatly accelerate the maturity of 5G technology.

2. The Channels: Requirements for Channel sounding and modeling by Spectrum Strategy

With its aggressive performance goals, the emerging 5G standard will almost certainly incorporate a combination of millimeter-wave (mmWave) frequencies, ultra-broad bandwidths, and massive multiple-input/multiple-output (MIMO) methods. Although each of these adds difficulty to the design of transmitters and receivers, the most significant unknowns are in the over-the-air radio channels between user equipment (UE) and base station (eNB). To fully characterize the channel, it is necessary to create mathematical models of channel performance and use them to define new air-interface standards for 5G.

The successful deployment of mmWave-based systems requires a solid understanding of channel conditions. Currently, attention is being focused on radio-wave propagation at a variety of possible carrier frequencies in the spectrum above today’s densely populated 6 GHz band. Detailed characterization of the propagation channel is vital to enable the air-interface design that will support the data rates, spectrum flexibility and ultra-broad bandwidth
envisioned for 5G. Channel sounding is a necessary step towards understanding the channel. A variety of measurement methods are available, and each has strengths and weaknesses.

2.1 Wireless Radio Channel Characteristics

The detailed knowledge of the radio wave propagation channel is a prerequisite for the design of a new physical layer in 5G for the mm-Wave frequency range. Higher frequencies and wider bandwidths, together with large antenna arrays in terms of number of elements and in terms of physical size with respect to the wavelength, is the main propagation challenge. The aim of channel sounding is to characterize a radio channel by decomposing the radio propagation path into its individual multipath components. Channel sounding is a measurement technique that mimics the operation of any wireless communication system. Referring to Fig 2.1-1, a transmitted signal travels through the air, is affected by channel conditions, and then reaches the receiver. By applying signal processing in the receiver, a measurement system can extract the characteristics of the wireless channel at a frequency of interest.

\[ y(t) = h(t) \otimes x(t) \]

\[ R_{xy}(\tau) = E[x^*(t)y(t-\tau)] = h(t-\tau) \otimes R_x(\tau) \]

The channel modeling procedure is shown in Fig 2.1-2.

To create the desired mathematical model, a variety of channel parameters need to be estimated, which can be cataloged into three groups:

- Channel Impulse Response (CIR).
- Instant parameter
  - Angle of Arrival (AOA)
  - Angle of Departure (AOD)
  - Doppler shift;
  - Power delay profile (PDP) (which includes absolute delay and path loss).
- Statistical parameters and modeling elements
  - Angular spread (AS) of AOA and AOD;
  - Power Angular Spectrum (PAS);
  - Doppler spectrum;
  - Correlation matrix;
  - Rician K factor.

The channel modeling procedure is shown in Fig 2.1-2.
A channel sounding system captures data from antennas with necessary processing, then streams and stores the measurement data. The resulting data can be used for post-processing analysis of other channel measurements. For detailed post-processing analysis of acquired signals, the channel parameters can be extracted using different schemes. With enough measurement, the estimated channel parameters can be used create channel models.

2.2 Wireless Channel sounding for 5G

The technical choices for new 5G mmWave air-interface designs create a baseline that sets the requirements of the measuring system:

- Ability to handle carrier frequencies ranging from 10 to 100 GHz and perhaps higher
- Ability to support bandwidths from 500 MHz to 2 GHz, and possible beyond
- Ability to handle multiple simultaneous or near-simultaneous channel measurements thus emulating massive MIMO antenna configurations
- For the channel sounding measurement, all the channel characteristics in time domain (absolute and relative Power Delay Profile, including path loss and path delay), frequency domain (Doppler frequency) and spatial domain (Angle of Arrival and Angle of Departure) are necessary.
- To enable absolute PDP and Doppler frequency measurement in channel sounding, synchronization of Transmitter and Receiver of the channel sounding system are necessary.

To enable AoA and AoD measurement in channel sounding, either MIMO channel sounding system with antenna array or SISO channel sounding system with directional antenna and turning table is needed. Channel sounding with different methods should be completed within the coherent time of measured wireless channel.

These requirements lead to six crucial technical challenges, as illustrated in Fig 2.2-1.
Fig 2.2-1: The five technical challenges affect the overall need to define the most effect approach and architecture for a channel-sounding measurement system.

Starting at the top of the diagram, the overarching challenge is selecting the most effective approach and architecture for the channel-sounding system. The other crucial technical issues that must be resolved include:

- Finding RF and mmWave test equipments that provide sufficient performance when used in concert with mmWave up-conversion (signal generation), down conversion (signal analysis) or switching.
- Providing the necessary bandwidth in signal generation, acquisition, and analysis. This affects the necessary clock rates and bit depths (i.e., dynamic range and resolution) in the analog-to-digital converter (ADC) and digital-to-analog converter (DAC) technologies.
- Achieving very fast data streaming and managing large data storage to accommodate long-duration sounding measurements at high sampling rates and across many channels.
- Getting adequate accuracy in parameter-estimation algorithms to handle the required path-delay resolution and inter-path phase difference.
- Enabling accurate synchronization and calibration of all included measurement hardware, thereby ensuring precise and repeatable results.

### 2.3 Comparing existing sounding technique

There are at least three basic sounding approaches to measure the propagation characteristic is to conduct channel sounding measurement campaigns in order to collect data for the detailed analysis of the radio transmission channel in all possible environmental conditions. One of them belongs to frequency domain measurement approach, the other two belong to time domain measurement approaches.

1) Measurement of the complex frequency response with sweeping CW signals:

This method can be performed using a vector network analyzer. It provides the CIR as the Inverse Fourier Transform of the measured complex frequency response. However, this method is suitable for indoor campaigns only, since it requires transmitter and receiver phase synchronization. Furthermore it is limited to time invariant channels due
to the limited speed of the required signal sweeping process. Nevertheless, this method is not limited with respect to the channel bandwidth.

2) Time-domain measurement of the channel impulse response with sliding correlation method:

This is a direct CIR measurement, compared with the indirect CIR measurement method mentioned before. It is based on the transmission of a wideband signal with good autocorrelation characteristics (e.g., Pseudo Noise sequence, etc.) as the sounding stimulus signal. At the receiver side, the known sequence is generated as the reference sequence at a symbol rate that is slightly different to the transmitting sequence generated at the transmitter. The received signal is multiplied with the local reference sequence, then performs narrow band filtering and envelope detection; the output directly yields the channel impulse response with relatively low sampling rate. The diagram of sliding correlation method is shown in Fig. 2.3-1. The sliding correlation method reduces the requirement for digitization speed, while the measurement speed slows down due to the sliding correlation processing. Thus it is also limited to time invariant channels measurement.

![Diagram of sliding correlator based channel sounding system](image)

Fig.2.3-1 Diagram of sliding correlator based channel sounding system

3) Time-domain measurement of the channel impulse response with wideband correlation method:

This is also a direct CIR measurement method. It is also based on the transmission of a wideband signal with good autocorrelation characteristics (Pseudo Noise sequence, linear frequency modulation signal, etc.) as the sounding stimulus signal. Different to sliding correlation method, at the receiver side, the received signal is directly captured by wideband digitizer to get wideband IQ data, then the correlation with known reference sequence is performed which directly yields the channel impulse response. Wideband correlation method is more complex, but much faster.

Considering the measurement speed needs to match with the time variant properties of channels, especially for 5G channel sounding (higher frequency, higher Doppler frequency), the wideband correlation method is more suitable due to its fast measurement speed.

### 2.4 Assessing channel sounding methods

Multiple channel sounding methods exist to provide the essential information for channel modeling, this chapter assesses the different methods.
- Use parallel transmitting and receiving, as shown in Fig 2.4-1. While the all-parallel approach is the fastest, it introduces cross-interference between the various transmitting channels, potentially degrading the performance of sounding measurements.

![Parallel transmitting and receiving approach](image)

**Fig 2.4-1 Parallel transmitting and receiving approach**

- Use switching on both the transmitter and receiver sides, as shown in Fig 2.4-2. All switched approach doesn’t have the problem of cross-interference, and it only needs single signal source and single receiver so the system complexity is relatively low. However the measurement speed is the lowest among these three approaches.

![All switched approach](image)

**Fig 2.4-2 All switched approach**

- Use switching at the transmitter and perform parallel receiving as shown Fig 2.4-3.

![Switched transmission/parallel receiving](image)

**Fig 2.4-3 Switched transmission/parallel receiving**

- Use SISO channel sounding setup with modifications on the Rx antenna position.
Figure 2.4-4 shows the principle of a SISO channel sounding setup that can provide angular information (angle of arrival) with high resolution. The signal source for the Tx is a wideband Signal Generator. The test equipment for the Rx side is a wideband, high frequency Signal Analyzer.

- Use SISO channel sounding setup by moving the omnidirectional Rx antenna and creating a “virtual antenna array” on Rx side to provide angular information measurement.

SISO approaches is less complex for system setup, but measurement speed is too slow to catch up with the channel variation due to they need physical antenna movement.

Switched transmission/parallel reception is much faster than having to switch both the transmitted and received multi-paths. With its speed advantage and freedom from cross-interference, the switched/parallel method thus emerges as the better choice.

An example architecture for channel sounding system is shown in Fig.2.4-6, where the system uses wideband correlation as the baseband sounding technique and switched-transmit/parallel-receive for assessing MIMO multiple paths for data capture. This provides three important technical advantages: fast measurement speed, MIMO sounding capability, and excellent measurement performance (with minimal cross-channel interference).
On the left of Fig 2.4-6, the transmitter side includes a single-channel wideband signal generator and mmWave switch; On the right, the receiver side provides parallel signal acquisition with a wideband multi-channel receiver that can be implemented using high-performance digitizers or wideband vector signal analyzers.

![Block diagram of switched-transmit/parallel-receive architecture](image)

**Fig 2.4-6:** This block diagram illustrates the basic implementation of the switched-transmit/parallel-receive architecture.

### 2.5 Ensuring measurement accuracy

To achieve precise results, system synchronization and calibration are required. The channel-sounding system must be capable of measuring and characterizing its own phase and amplitude impairments and compensating for the following issues:

- Inter-channel phase errors
- Antenna errors in amplitude and phase
- I/Q mismatch errors
- Spectral flatness errors

### 2.6 Channel parameter estimation

The various channel parameter estimation algorithms can be categorized to 3 types, summarized in Table 2.6-1

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Example</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamforming Based</td>
<td>Bartlett, Capon</td>
<td>Simple for implementation</td>
<td>Poor performance,</td>
</tr>
<tr>
<td>Subspace Based</td>
<td>MUSIC, ESPRIT</td>
<td>● High accuracy</td>
<td>Maximum number of path limited by the number of Rx</td>
</tr>
<tr>
<td></td>
<td></td>
<td>● Low computing load</td>
<td></td>
</tr>
<tr>
<td>Maximum Likelihood</td>
<td>SAGE</td>
<td>● High accuracy</td>
<td>Iteration needed, large computing load</td>
</tr>
<tr>
<td>Based</td>
<td></td>
<td>● No limitation for maximum number of path</td>
<td></td>
</tr>
</tbody>
</table>
The ML based algorithm (e.g. Space-Alternating Generalized Expectation (SAGE)) is well accepted and widely used due to its high estimation precision and its capability of joint parameter estimator for multiple channel parameters, what’s more, the maximum estimating path number is not limited by the number of antenna array elements.

2.7 Summary

With its aggressive performance goals, the emerging 5G standard will incorporate a challenging combination of technologies. With these present challenges are in the design of transmitters and receivers, one of the most significant unknowns is in the over-the-air radio channels at mmWave carriers. To fully characterize and understand these unknowns, it is necessary to create mathematical models and use them to define a new air interface standard.

An effective channel-sounding system enables more exploration in less time, deeper understanding of the channel, and ultimately, a 5G air-interface that provides the best possible user experience while taking care about highest RF performance/signal quality.

3. The Air Interface: Measurements Requirements for Software Defined Air Interface

3.1 Massive MIMO Test

Massive MIMO is widely regarded as one of the key technologies to enable the 5G vision and is getting tremendous attention in research. The intent is to make full use of spatial diversity to improve system capacity, energy efficiency, and spectral efficiency. Given the large requisite increase in the number of channels, the likely use of higher frequency bands (and the associated higher data transmission rate), massive MIMO test and measurement systems also face a great challenges. Because of the complexity of the Massive MIMO system and multiple possible implementation methods, the challenge of a cost- and time-efficient test and measurement solution and definition of the most important valuable test metrics are critical for the realization of massive MIMO for 5G.

Having in mind these Massive characteristics the economic and practical test and measurement solutions should be evaluated: how to decide the balance point between RF path number, baseband processing, test time, and cost?

As a reference in LTE technology in 4G, Test Specifications from 3GPP exist for conducted test (e.g. for LTE TS36.141 Tx tests, Rx tests, performance tests). All test limits are defined for conducted tests, i.e. the Test Equipment is connected to the antenna connector of the Base Station via a RF cable. So far there are no clear Test Specifications available for Over-The-Air (OTA) tests available from a standardization body like 3GPP.

Active Antenna Arrays are needed for transmission in very high frequency bands (e.g. in 5G technologies) to provide a highly directive beam transmission (high antenna gain) in order to counteract the bad propagation conditions (high path loss) in these high frequencies. But also in existing frequencies (e.g. 2.6GHz, 3.5GHz, etc.) and existing technologies like LTE / TD-LTE antenna arrays are coming up to allow for 3-dimensional beamforming to not only provide horizontal and vertical sectorization but to provide also means to up-tilt a beam e.g. to the upper floors of a high-rise building.
The following Fig 3.1-1 shows the principle of a typical antenna array:

![Antenna Array Diagram]

Figure 3.1-1 principle of a typical antenna array

In this example 64 typically cross-polarized antenna elements (128 in total) are shown. The number of antenna elements varies and is implementation specific.

Due to the high number of antenna elements it is clear that there will not be any antenna connectors in the finally assembled antenna array. In earlier phases of the product design antenna elements are typically accessible with connectors to verify the proper design of the antenna.

Chapter 3.1.2 will describe details about conducted and OTA test of antenna arrays.

### 3.1.1 Massive MIMO Test Methodology

The following figure 3.1-2 shows the simplified typical Product Development Process of an antenna array of an infrastructure supplier. The different phases in this product development process require and allow for different measurement and verification methods and the various approaches to realizing a Massive MIMO system could require different test interfaces. So, the first issues that should be addressed are:

- How to define and select the system-level test metrics for a massive MIMO system?
- How to define and select the test metrics and performance requirements on each test interface?
- How to select the different test interfaces for specific and sub-system-level test and measurement purposes, for example, phase and amplitude misalignment, blocking performance, etc.?
- How to decompose the system metric to different interfaces to meet overall massive MIMO system performance?
- What is the relationship between the performance of each antenna element and the performance of the antenna array as a whole?
Fig 3.1-2 Product Development Process of an antenna array

Fig 3.1-3 Massive MIMO system and possible test points

Fig 3.1-3 shows a possible block diagram of a Massive MIMO system and possible test points. Traditionally, the tests performed on LTE systems include conducted and over-the-air (OTA) tests. Performing these tests on a system employing massive MIMO presents a number of new challenges due to the potential of a large number of antenna connectors employed and the required integration of power amplifiers with the antennas. As a result, the process of selecting appropriate reference points must be carefully studied.

In addition for a composite conducted test, point C (antenna connector) is selected for transmitter RF parameter tests like Error Vector Magnitude (EVM) also for massive MIMO systems. If the indirect RF test method were instead used to examine baseband performance, then point E would be selected.

When massive MIMO and mmWave are combined in a system, no antenna connector is available or likely to be used due to physical size limitations and resulting insertion loss. Consequently, OTA tests (at point B or A) are selected. OTA tests revealing the three-dimensional antenna pattern can be performed either in near field (point B in figure 3.1-3) or in far field (point A). Measurements in near field allow smaller anechoic chambers for the measurement, but require an additional near-field to far-field transformation.
3.1.2 Massive MIMO Test

Stimulation of each element with the same signal but individual phase and/or individual magnitude will create a beam (the main lobe can be steered) as shown in Fig 3.1-4. Beamforming is used to establish a dedicated link to a single user while avoiding interference to other users.

![Fig 3.1-4 Theory of Beamforming](image)

With high number of antenna elements several beams can be generated to different users for better coverage in high data traffic areas. The coverage can be adjusted by the width of beam (= gain): the closer the user, the wider the beam can be. Phase modification can be done by phase shifters in the antenna feed (more static) or by direct modulation of the baseband signal (for dynamic beamforming).

It is obvious that verification and qualification of antenna arrays are very useful in all product development process phases from design over R&D up to production test, since the possibility of failures and the finally the impact of failures are significantly high.

There are three types Massive MIMO RF systems implementation – full digital implementation, full analog implementation and hybrid implementation. Massive MIMO antennas can be placed in central model and distributed model. For central model, the test and measurement solutions should handle these RF system scenarios including the RF elements test, RF test, RF system test with antenna and cable, and demodulation performance test. For distributed Massive MIMO system, each group of antenna system can be seen as massive MIMO system with a small antenna number and test solutions for each group can leverage the solution used by central Massive MIMO system.

3.1.2.1 Massive MIMO Elements RF Test

RF test including RF element test like antenna, RF test, RF system calibration.

For antenna element test, antenna connectors could still be accessible in the design phase of an antenna array. Here, measurements with Vector Network Analyzer (VNA) are recommended like e.g. S-parameters (transmission and reflection coefficients). The S-parameters contain magnitude and phase information. An example of an antenna array is shown in Fig 3.1-5 where antenna ports 1 to 8 of the first column of elements (just one polarization direction) are drawn as examples. In this example 64 antenna elements for one polarization direction can be accessed. It is obvious that for such high number of antenna elements the connectivity to antenna connectors is the main challenge. There are 2 options to address this challenge:
The RF test including lots of items, usually there are two parts for RF test, one is transmitter test and the other is receiver test. The main test items are shown in Table 3.1-1.

<table>
<thead>
<tr>
<th>Transmitter RF test items</th>
<th>Receiver RF test items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Power</td>
<td>Receiver Sensitivity</td>
</tr>
<tr>
<td>OBW</td>
<td>ACS</td>
</tr>
<tr>
<td>ACLR</td>
<td>In-Channel Sensitivity</td>
</tr>
<tr>
<td>SEM</td>
<td>Blocking</td>
</tr>
<tr>
<td>EVM</td>
<td>Receiver IP3</td>
</tr>
<tr>
<td>Spurious Emission</td>
<td>Receiver intermodulation</td>
</tr>
<tr>
<td>MIMO test</td>
<td></td>
</tr>
</tbody>
</table>

The different RF channel inconsistency will cause the main lobe gain degradation, beam bandwidth wide, and side lobe gain increase. It is necessary to introduce the RF system calibration to detect amplitude and phase misalignment and compensate channel inconsistency. There are two dominant test methodologies, traditional cable-connected test and over-the-air (OTA) test.

For cable-connected test, the reference antenna will be selected and phase and amplitude difference over the reference RF channel can be achieved. A scalable and cost-efficiency solution should be adopted, for example composite test, switch or combiner. Following is target of the calibration.

Firstly, the time alignment should be analyzed with MIMO. Usually different antenna has its own RF path, different RF path lead to different time delay for each antenna. The multi antenna time alignment schematic diagram is shown in Fig 3.1-6.
Secondly the phase difference between multi antennas should be test. The phase difference between multi antenna lead to different transmit direction for beamforming. The basic idea about phase difference test is define one of multi antennas as the reference antenna, then display all the phase difference between the other antennas to the reference antenna. The schematic diagram of multi antenna phase difference is shown in Fig 3.1-7.

When massive MIMO and mmWave are combined in a system, no antenna connector is available or likely to be used due to physical size limitations and resulting insertion loss. Consequently, OTA tests (at point B or A in Fig.3.1-3) are selected. OTA tests revealing the three-dimensional antenna pattern can be performed either in near field (point B in figure 3.1-3) or in far field (point A in Fig.3.1-3). OTA Measurements in near field allow smaller anechoic chambers for the measurement, but require an additional near-field to far-field transformation.
Another challenge is that the performance of massive MIMO is sensitive to all kinds of factors caused by nonlinear characteristics in RF devices. The antenna gain without any distortion is shown in figure 3.1-8, while the 3D antenna gain with phase and amplitude misalignment of each channel is shown on the right. It’s clear that this impairment would lead to a gain reduction in the main lobe, as well as, an increase in mutual interference—both of which will have a tremendous impact on the system performance. It is important, therefore, that the RF test solution consider the composite spatial performance.

For over-the-air tests (OTA) the calibration of the measurement setup is of significant importance. It is clear that the effort for calibration is proportional to the number of measurement probes in the setup. The impact of long-term temperature drifts of the measurement setup (e.g. of active parts at measurement probes) has to be evaluated to be sure that measurements are reproducible. Since all these solutions have their disadvantages, combined testing may prove especially helpful. For example, conducted testing might also be performed with OTA testing.

### 3.1.2.2 MIMO OTA performance test

Over-the-Air tests are currently not standardized in e.g. 3GPP, i.e. there is not test specification available yet. Since this is a quite new field of test & measurement procedures an antenna array characterization would ideally follow a stepwise approach:

1. Static / quasi static tests: In static / quasi static tests, several beam positions should be configured for the antenna array and 3D antenna pattern should be verified. To configure these beam positions it is essential that test modes should be defined by the industry (preferably in standardization) in order to test this part of the base station separately. Another option would be to use the complete BS including baseband or predefined signal sequences to steer the relevant beams. There are multiple concepts for measuring the 3D antenna pattern:
   - Spherical scanning - using rotating positioner in a test chamber for azimuth and measurement probes at rotational arm for elevation or measurement probes in a fixed ring allocation for elevation).
   - Cylindrical scanning - using rotating positioner in a test chamber for azimuth and measurement probes moving in a vertical axis for elevation (minimizes the test chamber dimensions)
   - Planar scanning – using multiple measurement probes in a planar allocation covering a certain receive area in a test chamber
Typically the shape of the antenna pattern consists of a main lobe (that represents the gain and directivity) and some side lobes. An example 3D antenna pattern for a small array (16 elements) can be seen in Fig 3.1-9 (measured in an anechoic test chamber in near-field; after near-field to far-field transformation).

![3D antenna pattern for a small array (16 elements)](image)

**Fig 3.1-9 3D antenna pattern for a small array (16 elements)**

2. Dynamic beam steering tests: The dynamic beam movement over time should be verified, e.g. the antenna array moves the beam from position A to position B with a defined period of time. To configure this beam movement it is essential that corresponding test modes should be defined by the industry (preferably in standardization). Another option would be to use the complete BS incl. baseband or predefined signal sequences to steer the relevant beams. For this antenna array characterization a planar array of measurement probes is a promising candidate. This planar array needs to cover the complete beam range that the base station is able to steer.

3. Demodulation performance test: In order to verify UE demodulation in near real wireless scenarios and RF impairment, it is necessary to setup OTA scenarios to very verify the UE demodulation and eNB steering accuracy.

### 3.2 Test for new waveforms and multiple access schemes

A new air-interface design is driven by exploding demands in the cellar communication system. Examples include relaxed synchronism for MTC/D2D, massive number of connections, and cognitive radio for spectrum sharing. The new air interface can be divided into two research topics: new modulation techniques (mostly focused on filtered multi-carrier systems as alternative to Cyclic-Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM used in LTE), and new multiple access techniques which allow for greater flexibility in the use of the spectrum, lower latency, and higher capacity. Test and measurement solutions should verify all key technology features and guarantee these features work well in live network.

#### 3.2.1 New waveforms

Considering the crosstalk between different subcarriers and stringent time synchronism of CP-OFDM, current research is addressing new these design goals by experimenting with moving away from these constraints and implementing various filtered multi-carrier signal design techniques. Some examples of comprehensive proposed schemes are Generalized Frequency Division Multiplexing (GFDM), Universal Filtered Multicarrier (UFMC), Filter Bank Multicarrier (FBMC), Biorthogonal Frequency Division Multiplexing (BFDM), and Filtered OFDM (F-OFDM).
Spectral emission for these various techniques is shown in the Fig 3.1-1. Relaxed synchronization mechanisms, including frequency tracking and timing alignment verification, will be introduced in demodulation, especially for the random access (RACH) and synchronization channels for MTC, multiple point coordination and out band emission performance when this new technology is used for frequency sharing.

As we know, LTE adopts OFDM in downlink and SC-FDMA for uplink. OFDM has robust performance to combat against frequency dispersion compared to the SC-FDMA. On the contrary, SC-FDMA has robust performance to combat against time dispersion compared to the OFDM. 5G possibly introduce new waveform, for example GFDM, to mitigating the effect of frequency dispersion and time dispersion to improve oval system performance. Special test cases will be introduced to cover this tradeoff performance.

Test and measurement should consider following aspects:

- Frequency analysis: ACLR, SEM, etc.
- Baseline link level performance: Single and parallel-user links with AWGN and multipath channels should be covered to guarantee the baseline link level performance. A pre-designed test case and simulation assumptions is designed to verify the requirement of a robust synchronization mechanism. Well-designed test cases are to verify the performance to combat against time dispersion and frequency dispersion.
- Application scenarios analysis: Cognitive radio scenarios will also be introduced for fragmented spectrum sharing to detect the licensed and unlicensed frequency interference. All these cases should consider the new frame structure and modulation formats as well.
- Network coordination analysis: The performance for Coordinated Multi-point (CoMP) can be significantly improved when new waveform is introduced since this new waveform much relaxes the inter-site and/or intra-site synchronization requirement.

![Fig 3.1-1: Out band emission for different new waveform](image)

**3.2.2 Alternative Multiple Access**

The orthogonality - of the PHY layer of today’s LTE-A radio access network constitute a major obstacle for the envisioned service architecture. To address the deficiency of the OMA-based approach, the non-orthogonal based approach has been put-forward recently. Non-orthogonal multiple access (NOMA) schemes are widely known for being optimal in the sense of achieving the entire capacity region of the broadcast channel (BC) and greatly increasing the
sum capacity compared with the OMA schemes. Traditional advanced precoding for multiuser MIMO (MU-MIMO) system has been shown to achieve the sum-rate capacity of the multiple-antenna broadcast channel and the full capacity region of the Gaussian multiple-input multiple-output (MIMO) broadcast channel. However, the associated excessive overhead of instantaneous channel state information (CSI) feedback and the complicated non-causal successive encoding severely limit its practical applications. The linearly precoded MU-MIMO technique can provide enhanced multiplexing gains by allocating the same time-frequency and power resources to multiple users. Nonetheless the theoretically predicted gains rely heavily on the spatial orthogonality of the selected users, which is in general too difficult to satisfy for an insufficient number of active users in the serving cell. Furthermore, the accuracy of the transmitter CSI required by the linearly precoded MU-MIMO cannot be fully obtained in practical systems due to channel aging and high overhead of multi-users’ CSI feedback.

For multiple access channels, the non-orthogonal multiple access based approaches exhibit a significantly better spectral-power efficiency advantage over the orthogonal one for delay sensitive applications in fading environments. However, the promised gains of the general non-orthogonal scheme over the orthogonal one hinge on the optimal multiuser detector, which has exponential complexity in the number of users \( K \) and imposes a formidable challenge to practical hardware implementations for high-rate transmissions. Therefore, NOMA schemes requiring limited receiver channel knowledge and/or a low-complexity high-performance detection algorithm at the receiver are highly desirable from a practical implementation point of view for downlink and/or uplink applications.

Base on analysis above, some advanced superposition multiple access technologies via time, frequency, coding, spatial, and power domains have attracted considerable attention since they can potentially serve more users in the same frequency and time resources to enhance the system capacity and flexibility. Currently, some potential alternative multiple access schemes are being actively investigated, including Bit Division Multiplexing (BDM), Multi User Shared Access (MUSA), power domain Non-Orthogonal Multiple Access (NOMA), Pattern Division Multiple Access (PDMA) and Sparse Code Multiple Access (SCMA) as shown in Fig. 3.1-3. Multiple access solutions will be likely be used with other 5G enabling technologies like the new waveforms described above as well as massive MIMO systems.

Non-orthogonal superposition technologies require complex receiver algorithm to canceling mutual interference to achieve optimal performance. The successive interference cancelation (SIC) based detector decodes symbols iteratively by subtracting the detected symbols of strong users first to facilitate detection of weak users. The decoded data of the early detected symbol is re-encoded and by using accurate channel knowledge, can be reconstructed to closely resemble the rea transmitted signal. In addition to its simplicity and amenability to implementation, SIC is also well-justified from a theoretical point of view. With accurate channel estimation and a large spreading factor, simple successive interference cancelation implementation with optimal coding was shown to approach the Shannon capacity for multiusers in the additive white Gaussian noise (AWGN) channel. SIC with single user decoding also achieves the Shannon capacity region boundaries for both the broadcast channel and multiple access channel. Lots of researcher studies efficient NOMA schemes that utilize space, time and frequency physical resources judiciously at the transmitter and thus are amenable to low-complexity SIC-based detection at the receivers.

These various non- and quasi-orthogonal superposition technologies are being designed to accomplish some or all of the following: 1) Overloading (multiple users superimposed in the power, code, timing, and/or spatial domains) compared to traditional strict resource-block allocation increases overall throughput, capacity, and connectivity; 2) supporting “grant-less” access for massive connectivity, and ultra-low latency for V2V and industry control; 3) enable open-loop transmission and low feedback overhead to be more robust against CSI error, and interference. These techniques are also well compatible with new waveforms, MIMO, and even application technologies – D2D/M2M/V2V.
From a test and measurement perspective, RF performance, link-level performance verification, and system-level performance will be covered. Advanced transceiver architectures will be introduced to address the new air-interface as well as the increased interference in the resulting hyper-dense networks. High level system analysis including scenarios selection, test metric presents new challenge for test equipment and instrumentation.

Test and measurement should consider following aspects:

- **RF measurements:** New definitions of EVM and radiated power measurements should be carefully investigated when multiple UEs are enabled in same time/frequency resource with non-orthogonal modes as shown in Fig 3.1-4.
- **Simulation assumptions to cover different test purpose:** How to define the test case verify access performance, data demodulation performance with well-designed simulation assumptions, for example, channel model, power difference between UEs, MIMO transmission mode, UE count.
- **System performance test:** defining typical deployment scenarios to verify the maximum UE loading, assess performance in live network with randomly selected modes, performance gain with long CSI report durations in high-speed mobility, performance gain in maximum UE loading configurations with random UE placement, coexistence with adjacent system, etc.

### 3.3 Measurements for full duplex and flexible duplex

Cellular systems have been deployed exclusively in licensed spectrum. 5G may introduce an advanced technology related to how to more effectively use limited frequency resources called full duplex, and flexible duplex.

#### 3.3.1 Flexible duplex

As wireless communications develops and consumes more spectrum, it has driven the growth of the use of unpaired spectrum when large amounts of contiguous spectrum are needed. Traditional TDD systems with static or semi-static uplink/downlink configurations have been used to exploit unpaired spectrum for mobile communication. However, flexible duplex, in which spectrum resources are dynamically assigned to downlink and uplink, enables transmission up to full bandwidth transmission capability in either direction and this solution can be suitable for managing dynamic traffic conditions.

Considering the huge mutual interference between uplink and downlink from different cells, more coordination is need for macro deployment scenarios. Flexible duplex is particularly suitable for small-cell deployments and isolated channel scenarios without too much signaling exchange. However, a highly flexible asymmetrical configuration will
present many issues requiring collaboration within the network system. Test and measurement challenges include verifying system coexistence in mixed uplink and downlink working modes, verifying the system’s mutual interference in system collaboration modes with small cells and Macro cells in on/off mode, Further-enhanced Inter-Cell Interference Cancellation (FeICIC) mode, and so on. These features should be carefully verified prior to large scale network deployment.

Test and measurement solution should handle:

- RF measurement: Verification of the TDD time switch mask
- Link-level measurement: Verification of the network interference-awareness capability to ensure the accuracy TDD switch control
- System-level measurement: Detection of the mutual interference sources and of the dynamic scheduling mechanism.

3.3.2 Full duplex

Full-duplex communication with simultaneous transmission and reception on the same carrier at the same time can also be applied if appropriate interference-cancellation techniques are implemented.

This is achieved with a combination of antenna isolation methods, RF/IF signal cancellation, and baseband compensation algorithms. For testing we need to provide a very high isolation test environment to verify each stage suppression performance if possible. The core technologies required for full duplex is expected to provide excellent interference-canceling performance of greater than 115dB. Test capabilities have to meet the tradeoff of having high-performance usable in multiple frequency bands while meeting the cost and complexity constraints of specific full-duplex implementations. Furthermore, complexity can rapidly increase with the use of multiple-antenna systems. In the case of using full duplex in live radio access network (RAN), we also need to consider the multiple-path interface from intra-eNB. Additional complexity comes from interference from inter-eNBs since this interference signal is unknown for the canceling system. This drives complexity in the system-level verification and should be carefully studied prior to network deployment. The fast fading channel and huge data exchange between antennas (interference canceling needs the transmitted signal from all antennas) make implementation much complicated as shown in the Fig 3.3-1.

![Interference Analysis of Full Duplex](image)

Fig 3.3-1: interference analysis of full duplex
Some more detailed examples of test and measurement consideration is following:

- **RF measurement:** RF receiver architecture has great evolution to handle very high dynamic range, including introduction balun or analog multiple tap line to canceling interference. The system and overall test methodologies and test case should cover all possible worse cases and typical cases. For RF receiver performance, receiver sensitivity for noise figure should be carefully verified to guarantee coverage. Also how to redefine receiver performance is also to be studied.

- **Link-level performance:** reasonable simulation assumptions including power different between receiver and transmission power, channel condition, MIMO transmission mode should be carefully studied. Most important, spectral efficiency verification is key test items for full duplex.

- **System-level performance analysis and verification:** considering current the state of the art for SIC architectures canceling gain is limited for cellular systems. Achievable rates under limited dynamic range and fast fading/multiple path channels with imperfect channel estimation, fast changing pre-coding and dynamic stream allocation in MIMO mode, multiple MIMO transmission schemes, transmission strategies for multi-user situations, and average rate gain under multi-cell scenarios have all been investigated. However, current studies mostly focus on theoretical analysis and experiments based on very simple models. The analyses for complicated scenarios, such as massive MIMO and large scale multi-cell multi-user field verification, ultra-density small cell deployment, are still lacking.

Selecting the most viable deployment scenarios and system-parameter configurations would be a long investigation.

4. The System and network infrastructure test and Measurement

4.1 Service and System Level Centric Testing

A future 5G eco system will include big cells, small cells, and overlay cells, cells with no edge, microwave and optical back haul. This leads to a complex mix of wireless technologies supporting intelligent off-loading and on-loading. To manage this very complex, seamlessly integrated eco system, federated domains of management and control at the RAN and Core Network level will evolve exploiting key enabler technologies like Software Defined Networking (SDN) and Network Function Virtualisation (NFV) which jointly support the deployment of dynamic intelligence as when required.

This leads to concepts like architecture on demand built on top of the separation of control and data planes. Evidently, these notions are already being articulated in RAN concepts like Edge-RAN (ERAN) and Cloud-RAN (C-RAN). ERAN is about placing the intelligence as close to the access point as possible to finely manage and control the radio environment. While C-RAN is about bringing everything together in the cloud on super computer base stations serving a specific geographic area through thousands of remote radio heads.

This evolution of multi-faceted RAN architectures leading towards highly intelligent self-organising and autonomous eco systems significantly increasing network capacity; efficiencies at all operational levels; functions and service ranges
to satisfy diverse qualities of experience in novel new applications; require a new generation of network infrastructure test and measurement technologies.

The nature of network infrastructure is such that it is made up of many components in an attempt to function as an intelligent, coordinated and cooperating complex system. Testing the individual components alone no longer gives us insight into how the complex system will behave under extreme conditions or in the real physical world when deployed and experiencing diverse service demands. Equally, this paradigm shift in testing strategy is evident in the R&D lab where functional tests are required as these complex systems of components are developed and coupled together towards a holistic system under test.

It is evident that a new approach is required for testing complex systems and that the obvious abstraction is system level or service level centric testing. Under this new strategy a testing paradigm in the near future will need to encompass more intelligent system/service level key Performance Indicators (KPIs). New correlation strategies and analytical engines that exploit these advance KPIs in reasoning about the complex system under test spanning link, protocol, resource management and service characteristics. Equally, in the lab and potentially during the deployment phase we will see a need for the reproduction or creation of live network scenarios to assist with debugging, root cause analysis, performance optimisation and test driven design and specification. Closed-loop test and validation will also need to be applied at a system/service level with innovative techniques to help eliminate risk and enable evolution of efficient and innovative systems.

With the addition of SDN and NFV concepts and the clean separation of control and data how these complex systems dynamically change over time during service provisioning also impacts test and measurement. Strategies for test and measurement that encompass control, data and test plan need to be derived together with methodologies for orchestration and deployment. To simplify, the test strategy may need to be orchestrated with data and control and may share and run on the same infrastructure used for provisioning.

### 4.2 New Metrics for Networks and Users

Before we address the need for new metrics as applied to networks and users driven by new service models and applications including M2M, V2V, D2D, augmented reality and interactive gaming, we need to come to a common understanding of Quality of Service (QoS) and Quality of Experience (QoE). Both these terms are used loosely and sometimes interchangeably.

When we monitor single components of an infrastructure such as a server, router or even network traffic (e.g. IP packets), the measurements made tend to be device or transport oriented. For example we derive metrics for packet loss, jitter, one-way delay, response time, etc. These metrics are QoS metrics and are well suited to help us troubleshoot and analyse root-cause of failure. However, they are also limited to give us a network-centric view of the world. We observe the performance of the constituent parts that make up a service but not the sum of its parts. More importantly, considering the nature of the future 5G eco system as described above, the sum of the parts may be continuously adapting and changing with respect to network conditions. So how do we relate this to user experience?

This is where QoE comes into play and a raft of measurement techniques and approaches have been derived for traditional IP networks that connect to services just like real users would. The metrics are now user-centric and can be attributed to things like time to download a web page, time to access and interactive service, the measure of video and audio quality (MOS), etc. They provide factual information of the behaviour of the sum of the parts and the usability of a service over time.
In an evolved 5G eco system one needs to consider both network-centric and user-centric measurements but with the added dimension of context-awareness. Application flows that make up a service may be continuously adapting and even cross multi-RAT boundaries with very diverse network properties and characteristics over time.

With respect to measurement approaches traditional monitoring paradigms involving passive and active measurement science are required. Passive approaches rely on the observation of real user traffic and correlation of events across multiple measurement points. While active techniques imply the injection and analysis of synthetic traffic. Both paradigms have been heavily utilized in generic Internet monitoring and in the deployment of tradition operational support systems for cellular networks. The step change here is that the control and data plane will be separated and hence any monitoring system will need to accommodate this in the deployed monitoring strategy and methodology. Passive systems may need to make measurements across multiple points and correlate across data and control planes. While active systems may need to introduce bot synthetic traffic and control data to monitor a set of metrics.

What are the new network-centric and user-centric measures? Some key performance metrics are already making the 5G literature such as latency, reliability, availability, throughput in both directions, and with respect to QoE most literature points to the challenges in meeting augmented reality and tactile internet constraints. Either way clear KPIs are needed that reflect these new performance metrics whether it be for network-centric or user-centric applications. These KPIs may introduce metrics pertinent to RF characteristics and equally the derivation of the KPIs may require the co-ordination of synthetic waveforms with real-time control across multiple antenna elements or across diverse radio technologies. This poses some very interesting and significant challenges to future monitoring systems.

4.3 Energy consumption

Large scale mobile communication networks have become a non-negligible part of the world energy consumption. Power/energy consumption is an important factor for battery powered user devices or sensors affecting directly their operation time especially for low-end M2M device which is placed in remote suburb or basement. Base stations have generally higher transmission powers than user terminals and therefore their improved energy efficiency has global impact in the reduction of greenhouse gases emissions. Considering scenarios for the ultra-dense network and ubiquitous network, where the massive machine communication is a key application, energy consumption, energy-efficient green communications become extremely important and urgent topic. Moreover, the evaluation of Power/energy consumption is also fairly important to compare different technologies and protocol design.

- Energy consumption per bit/area unit: The Power/energy consumption /unit area is directly related to energy consumption. How to design practical measurement flow is under investigation.
- Carrier frequency range: The choice of carrier frequency affects the total required energy consumption. Depending on the distance between user terminal and base station, either a higher or lower carrier frequency may be better suited. It may be beneficial from energy consumption point of view to have only one BB processing unit running even though several carrier frequencies are used in a system.
- Shared baseband pool or RRU: according to business variance and fluctuation in different site and time. Centralizing baseband signal processing with flexible and scalable used bandwidth may reduce the amount of total energy needed.
- Intelligence radio resource management design: Traditional radio resource manager focus on maximum spectrum efficiency, rarely focus on the energy efficiency. In the future, we should balance between energy
efficiency and spectrum efficiency. Network should select suitable RAT to match UE geographical position and business mode.

- On/off for BSs: Due to non-uniform traffic distribution in different site and time, it’s a waste of energy to keep all BSs working all time. In 5G era, in ultra-dense and heterogeneous network, how to efficiently select sleeping BSs, wake up slept BSs, and design convergent algorithms are still open.

Dynamic cell size adjustment: terminals are moving in cell. Dynamically adjusting transmit power from eNB is efficient way to reduce energy consumption based on users’ location and QoS requirements without loss coverage. This method would generate unpredictable interference to its adjacent cells.

All these strategy will be considered for future 5G tests and measurement solution related to energy efficiency.

4.4 Performance Test in Typical Scenarios

4.4.1 Audio and Video test

The voice of traditional conversation call transmits through CS of Operator. It is reality that voice call can be transmitted by Internet after Internet call appeared. The voice quality of Internet call was promoted a new level after 4G VoLTE technology. For 5G, it will not only change the people habit of surfing internet, but also make subversive change for communication industry. The voice and video of 5G is different from traditional 2/3G call service, but it is evolved version from 4G IP end to end technology. The voice quality of 5G will beyond traditional call and replace some incomplete voice switch function of 4G.

For Operator, 5G means an evolved road for mobile super wideband voice and video. For a long run, this will take two sides value, one is that will promote frequency efficiency and reduce network cost, because 5G frequency use ratio outdistance traditional technology which is more than ten times of LTE; other is that promote customer experience, because new HD voice and video code technology are imported which promote communication quality and reduce call delay time, so 5G voice and video will be much better than traditional CS voice and 4G VoLTE.

It is more difficult to test voice or video quality due to a mass of new technology, frame structure and HD voice and video technology and 3D video application. Customers experience feeling depends on voice and video call quality performance, so voice and video quality measurement will be the key manner for assessment.

In order to test voice and video call quality, we should simulate 5G network and all kinds of scenario to test DUT call quality performance.
4.4.2 IOT test

Mobile internet and the Internet of Things (IOT) are the two main drivers in the future development of mobile communications. They will provide a broad prospect for the 5G. The IOT has extended the scope of mobile communications services from interpersonal communications to smart interconnections between things and things, and between people and things, allowing mobile communications technologies to penetrate into broader industries and fields. Looking forward to the year 2020 and beyond, applications such as mobile health, Internet of Vehicles (IOV), smart home, industrial control, and environmental monitoring will drive the explosive growth of IOT applications.

According to the experience from 2G to 4G, there were many kinds of standardized tests according to such as GCF/PTCRB. In addition, many leading network operators paid more and more efforts to define their own specified tests for mobile devices due to increasing complexity of technology. In the future, there will be 100 billion devices with different types in 5G network. To ensure all these devices can work fine in the entire network, network operators shall define many aspects of Inter-operability tests and apply different tests to different types of devices, such as protocol test, performance test, remote control and monitoring and so on.

4.4.3 LBS test

In 5G era, UE will be everywhere; it’s will be the basic feature to know the UE’s position, not only to operator and also to user. Location service will be the obligatory option for 5G UE, and there will different location technology for different scenario. It will become important to test UE’s location function and location performance (precision and delay) in different scenario: Beamforming, Micro base station and D2D.

4.2.4 OTT test

Compared to 4G network, 5G network will support larger mobility as well as higher transmission rate, higher user experience rate, energy efficiency, spectrum efficiency and so forth. All of these will boost a variety of multimedia services, especially for Over-The-Top (OTT) services. OTT refers to services that are used on top of network access services, the network operator usually has no control over the behavior of the app. So far, OTT services have already gained great popularity and contributed to large traffic consumption, which propose a challenge for operators.

Analysis and test of app’s behavior is essential for mobile device manufactures as well as network operators in order to optimize device and network behavior. For example, improper OTT application behavior will create signaling overload and this “always on line” behavior will also increase the battery consumption on UE side.

OTT testing scenario includes field network testing, trial-network testing, and lab instrument testing and virtual PC AP testing. OTT testing is becoming more and more important with the deployment of 4G network and incoming 5G technology. High throughput, low latency, M2M give the 5G technology a various of possibility of application and also give us a lot of challenge for OTT testing.
5: The instrument requirement of 5G test and measurement

5.1 Test challenges of 5G

The 5G vision "Information a finger away, everything in touch" brings the ultimately excellent experience to user, while, it also requires significant innovation and improvement for the network infrastructure and air interface technology. In order to achieve the very high speed data rate of the user experience, 5G signal bandwidth and baseband signal processing speed will be greatly increased, ultra-wideband signal waveform quality, power, spectrum analysis as well as very high-speed real-time processing of data streams analysis, put the 5G test forward a higher level requirements.

For software define air interface, to increase the number of user connections as well as to improve the transmission efficiency, the 5G adopts large-scale MIMO and new multiple access technique. Performance calibration among the transmission channels and specific indicators analysis of algorithms will be big problems. As bandwidth increases and large-scale use of MIMO, the 5G transmission carrier frequency will expand to a higher band, signal receiving and transmission characteristics of the millimeter waveband of testing brought new demands. In response to a variety of future scenarios and compatibility with existing technology systems, 5G system will co-exist with the superposition of multiple networks, complex scenes heterogeneous networks, coverage and multi-dimensional channel systems under simulated test will bring new challenges. The 5G communications test challenges exist as shown below.

Existing challenges of 5G communications test:
- Ultra wideband - waveform quality, power, spectrum
- Very High-speed - data transmission, storage, analysis
- Multi-channel - Large-scale MIMO, consistency calibration
- Full Spectrum - millimeter waveband transceiver
- New Multiple Access - algorithm-specific Performance Analysis
- Heterogeneous Network
- Multilayer cover
- 3D channel

Fig 5.1-1 Test Challenges of 5G

For 5G network infrastructure, it will cloud radio access networks (Cloud RAN) with using Software Defined network (SDN) and in core network (Cloud CN) with using Software Defined Network (SDN) infrastructure. Full virtualization of NFV network functions implemented in 5G infrastructures will be adopted in the near future. This virtualization of NFV network functions should cover the control and management of QoS, the service policy and prioritization of traffic. This virtualization of the network and its functions will require a corresponding virtualization of the testing methods and tools to be used.
Complicated network collaboration across different layer and heterogeneous network will bring significant challenge for test. A revolutions test and measurement methodology will be introduced in future network online test and measurement and online issue detection except traditional field test, drive test, UE emulator behavior. intelligent test cases and overall live network scenarios is very important for evaluating future KPIs; there will be many new situation with impacts to network performances to model (e.g. end user behaviour); complicated network infrastructure requires system usability interface to manage the complexity of both system under test and test system.

5G brings verification methodology requires to solve complexity system evaluation and verification issues capability.

- New simulation methodology: New performance metrics would be introduced such as connection density, mobility, traffic density, latency, power and cost efficiency, and QoE etc. Sophisticated link to system model should be reconsidered.
- Measurement challenges: the solutions of high frequency, wide bandwidth and massive and scalable antenna ports will be rethought

### 5.1 The requirement of test and measurement instrument

Test and measurement covers the entire life cycle, from early 5G research phase to late network operating and maintenance, during these phase, many evolving test methodology and instruments capability of:

- Early Research phase: prototype verification includes signal generator and analyzer, very high-speed baseband signal generator and signal acquisition device. Simulation platform including link-level simulation, component-level simulation and system-level simulation et al. channel sounding test solution for high frequency is also been address in this phase.
- R&D phase: the test instruments such as RF conformance tester, protocol conformance tester, radio resource manage (RRM) conformance tester, and radiated spurious emissions (RSE) tester should be used to verify the performance of RF transceiver, signaling interworking, RRM behavior and electromagnetic compatibility. Furthermore, system-level, configurable, scalable and testability test solutions will be introduced for complicated RF system test especial for massive MIMO system. Application-level test and verification includes internet-of-thing, on-line video and audio test.
- Manufacturing phase: In the large-scale commercial stage, a low cost, versatility, high test speed, high degree of automation, simple operation production class testing instruments to meet the assembly line requirements, including terminal integrated tester, base station integrated tester.
- Operation & maintenance phase: the network’s stability, reliability, and user experience will be tested or detected by driver test instrument, air detector, and application level test system.

### 6. Suggestions and Future Work

Based on the test and measurement requirements for 5G in the previous sections, here are the recommendations for test and measurement vendors to support the 5G development:

1. Actively participate in the channel sounding and modeling work in the new frequency band in mmWave (for example, 14GHz, 28GHz, 60GHz or higher) with key academic research entities and industry players. Be able
to model and evaluate the channel characteristics in the interested frequency bands, and recommend the appropriate frequency plan for 5G in China at ITU WRC-19 and to other international organizations.

2. Network Operators, Network System Suppliers, and Terminal Chip Suppliers will involve Test & Measurement Vendors and plan the future 5G test demands or requirement. For each specific technology like new waveform, full duplex, massive MIMO, etc., work with key vendors to build up test and measurement solutions and support the technology evolution. Especially with focus on the technology which could be integrated as the LTE/LTE-A 4G evolution (like 3D-MIMO, NOMA), the test and measurement solutions would help the standardization process of 3GPP new revisions and deployment with operators prior to the whole new 5G changes coming later.

3. Massive MIMO OTA test is demanding, for feature verification purpose and future qualification test purpose, a compromised Massive MIMO OTA Test KPI and the specification should be planned by MNO, Network System Suppliers, and Test Vendors. On the same specification base, different MIMO solution can be evaluated or benchmarked.

4. For government and operator, build the key milestones and timelines for test and measurement solutions with the new trial 5G network:
   a. Identify the key components of 5G trial network
   b. Define the key milestones backwards from the timing required for 5G trial network
   c. List the test and measurement capability required to support the 5G trial network
      i. Freq planning
      ii. Base station/UE test
      iii. Interoperability test
      iv. Network test
      v. System performance test

Future work is listed below for further study:
- Flexible spectrum usage – how do we be able to test it?
  o Licensed band + unlicensed band
  o Cognitive radio with broadcast TV band
- New network architecture
  o Multi-RAT interoperability test
  o UDN
  o SDN/NFV
References


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