5G Mobile Wireless Technology

The new 5G mobile communications system will enable many new mobile capabilities to be realised - offering high speed, enormous capacity, IoT capability, low latency and much more it provides the bearer for many new applications.

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The 5G mobile cellular communications system provides a far higher level of performance than the previous generations of mobile communications systems.

The new 5G technology is not just the next version of mobile communications, evolving from 1G to 2G, 3G, 4G and now 5G.

Instead 5G technology is very different. Previous systems had evolved driven more by what could be done with the latest technology. The new 5G technology has been driven by specific uses ad applications.

5G has been driven by the need to provide ubiquitous connectivity for applications as diverse as automotive communications, remote control with haptic style feedback, huge video downloads, as well as the very low data rate applications like remote sensors and what is being termed the IoT, Internet of Things.

5G standardisation

The current status of the 5G technology for cellular systems is very much in the early development stages. Very many companies are looking into the technologies that could be used to become part of the system. In addition to this a number of universities have set up 5G research units focussed on developing the technologies for 5G

In addition to this the standards bodies, particularly 3GPP are aware of the development but are not actively planning the 5G systems yet.

Many of the technologies to be used for 5G will start to appear in the systems used for 4G and then as the new 5G cellular system starts to formulate in a more concrete manner, they will be incorporated into the new 5G cellular system.

The major issue with 5G technology is that there is such an enormously wide variation in the requirements: superfast downloads to small data requirements for IoT than any one system will not be able to meet these needs. Accordingly a layer approach is likely to be adopted. As one commentator stated: 5G is not just a mobile technology. It is ubiquitous access to high & low data rate services.

5G cellular systems overview

As the different generations of cellular telecommunications have evolved, each one has brought its own improvements. The same will be true of 5G technology.

- ***First generation, 1G:*** These phones were analogue and were the first mobile or cellular phones to be used. Although revolutionary in their time they offered very low levels of spectrum efficiency and security.
- ***Second generation, 2G:*** These were based around digital technology and offered much better spectrum efficiency, security and new features such as text messages and low data rate communications.
- ***Third generation, 3G:*** The aim of this technology was to provide high speed data. The original technology was enhanced to allow data up to 14 Mbps and more.
- ***Fourth generation, 4G:*** This was an all-IP based technology capable of providing data rates up to 1 Gbps.

Any new 5th generation, 5G cellular technology needs to provide significant gains over previous systems to provide an adequate business case for mobile operators to invest in any new system.

Facilities that might be seen with 5G technology include far better levels of connectivity and coverage. The term World Wide Wireless Web, or WWWW is being coined for this.

For 5G technology to be able to achieve this, new methods of connecting will be required as one of the main drawbacks with previous generations is lack of coverage, dropped calls and low performance at cell edges. 5G technology will need to address this.

5G requirements

As work moves forwards in the standards bodies the over-riding specifications for the mobile communications system have been defined by the ITU as part of IMT2020.

The currently agreed standards for 5G are summarised below:

SUGGESTED 5G WIRELESS PERFORMANCE

PARAMETER	SUGGESTED PERFORMANCE
Peak data rate	At least 20Gbps downlink and 10Gbps uplink per mobile base station. This represents a 20 fold increase on the downlink over LTE.
5G connection density	At least 1 million connected devices per square kilometre (to enable IoT support).
5G mobility	0km/h to "500km/h high speed vehicular" access.
5G energy efficiency	The 5G spec calls for radio interfaces that are energy efficient when under load, but also drop into a low energy mode quickly when not in use.
5G spectral efficiency	30bits/Hz downlink and 15 bits/Hz uplink. This assumes 8x4 MIMO (8 spatial layers down, 4 spatial layers up).
5G real-world data rate	The spec "only" calls for a per-user download speed of 100Mbps and upload speed of 50Mbps.
5G latency	Under ideal circumstances, 5G networks should offer users a maximum latency of just 4ms (compared to 20ms for LTE).

5G communications system

The 5G mobile cellular communications system will be a major shift in the way mobile communications networks operate. To achieve this a totally new radio access network and a new core network are required to provide the performance required.

- ***5G New Radio, 5G NR:*** 5G new radio is the new name for the 5G radio access network. It consists of the different elements needed for the new radio access network. Using a far more flexible technology the system is able to respond to the different and changing needs of mobile users whether they be a small IoT node, or a high data user, stationary or mobile.
- ***5G NextGen Core Network:*** Although initial deployments of 5G will utilise the core network of LTE or possibly even 3G networks, the ultimate aim is to have a new network that is able to handle the much higher data volumes whilst also being able to provide a much lower level of latency.

5G technologies

There are many new 5G technologies and techniques that are being discussed and being developed for inclusion in the 5G standards.

These new technologies and techniques will enable 5G to provide a more flexible and dynamic service.

The technologies being developed for 5G include:

- ***Millimetre-Wave communications:*** Using frequencies much higher in the frequency spectrum opens up more spectrum and also provides the possibility of having much wide channel bandwidth - possibly 1 - 2 GHz. However this poses new challenges for handset development where maximum frequencies of around 2 GHz and bandwidths of 10 - 20 MHz are currently in use. For 5G, frequencies of above 50GHz are being considered and this will present some real challenges in terms of the circuit design, the technology, and also the way the system is used as these frequencies do not travel as far and are absorbed almost completely by obstacles. Different countries are allocating different spectrum for 5G.
- ***Waveforms :*** One key area of interest is that of the new waveforms that may be seen. OFDM has been used very successfully in 4G LTE as well as a number of other high data rate systems, but it does have some limitations in some circumstances. Other waveform formats that are being discussed include: GFDM, Generalised Frequency Division Multiplexing, as well as FBMC, Filter Bank Multi-Carrier, UFMC, Universal Filtered MultiCarrier. There is no perfect waveform, and it is

possible that OFDM in the form of OFDMA is used as this provides excellent overall performance without being too heavy on the level of processing required.

- ***Multiple Access:*** Again a variety of new access schemes are being investigated for 5G technology. Techniques including OFDMA, SCMA, NOMA, PDMA, MUSA and IDMA have all been mentioned. As mentioned above it appears that the most likely format could be OFDMA
- ***Massive MIMO with beamsteering:*** Although MIMO is being used in many applications from LTE to Wi-Fi, etc, the numbers of antennas is fairly limited. Using microwave frequencies opens up the possibility of using many tens of antennas on a single equipment becomes a real possibility because of the antenna sizes and spacings in terms of a wavelength. This would enable beams to be steered to provide enhanced performance.
- ***Dense networks:*** Reducing the size of cells provides a much more overall effective use of the available spectrum. Techniques to ensure that small cells in the macro-network and deployed as femtocells can operate satisfactorily are required. There is a significant challenge in adding huge numbers of additional cells to a network, and techniques are being developed to enable this.

These are a few of the main techniques being developed and discuss for use within 5G.

5G timeline & dates

5G is developoing rapidly and it needs to meet some demanding timelines. Some trial deployments have occurred and some of the first real deploymets are anticipayed in 2020.

Many countries are rushing to deply 5G as effective communications enable economimc growth and are seen as an essential element of modern day life and industry.

5G NR New Radio

5G NR or 5G New Radio is the new radio air interface being developed for 5G mobile communications.

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With the demanding requirements being placed upon the new 5G mobile communications standard, a totally new radio interface and radio access network has been developed. Called 5G New Radio or 5G NR, the new radio interface provides for the growing needs for mobile connectivity.

The development of the 5G NR or 5G New Radio is key to enabling the 5G mobile communications system to work and it provides a number of significant advantages when compared to 4G.

5G NR has been developed from scratch taking the requirements and looking at the best technologies and techniques that will be available when 5G starts to be deployed.

5G NR utilises modulation, waveforms and access technologies that will enable the system to meet the needs of high data rate services, those needing low latency and those needing small data rates and long battery lifetimes amongst others.

The first iteration of 5G NR appeared in 3GPP Release 15. The draft specifications for Release 15 were approved in December 2017 and are expected to be finalized in mid-2019. Release 15 forms phase one of a 5G mobile communication standard. Release 16 will provide specifications for the second phase and this is expected to be finalized in December 2019.

5G radio access network gNB

5G New Radio, 5G NR Basics

The 5G New Radio has been developed to provide a significant enhancements in areas like flexibility, scalability and efficiency, both in terms of power usage and spectrum.

The 5G New Radio is able to provide communications for very high band with transmissions like streaming video as well as low latency communications for remote control vehicle communications as well as low data rate low bandwidth communications for machine type communications.

There are several cornerstones to the new radio used for 5G:

- ***New radio spectrum:*** Mobile communications usage is rapidly increasing, and the introduction of 5G will accelerate this trend with many more applications being accommodated by the technology. Whilst improvements in spectrum efficiency will be made these will not be able to accommodate the huge increases in usage, so more spectrum is needed.

  Release 15 also outlines several groups of new spectrum specifically for NR deployments. These range in frequency from 2.5 GHz to 40 GHz. Two bands being targeted for more immediate deployment are in the regions of 3.3 GHz to 3.8 GHz and 4.4 GHz to 5.0 GHz.

  The 3.3 GHz to 3.8 GHz spectrum has already been released in countries like the USA< Europe and certain Asian countries and they could see deployment as early as 2018. Other higher frequency bands but below 40 GHz are also being reserved for 5G but this is only the beginning as there is talk of usage of frequencies up to 86 GHz.

  The advantage of the higher frequency bands is that they are much wider and they will be able to allow much higher signal bandwidths and hence support much higher data throughput rates. The disadvantage in some aspects is that they will have a much shorter range, but this is also an advantage because it will also allow much greater frequency re-use.
- ***Optimised OFDM:*** An early decision was taken to use a form of OFDM as the waveform for phase one of the 5G New Radio. It has been very successfully used with 4G, the more recent Wi-Fi standards and many other systems and came out as the optimum type of waveform for the variety of different applications for 5G. With the additional processing power available for 5G, various forms of optimisation can be applied.

Basic concept of OFDM, Orthogonal Frequency Division MultiplexingThe specific version of OFDM used in 5G NR downlink is cyclic prefix OFDM, CP-OFDM and it is the same waveform LTE has adopted for the downlink signal.
Read more about *. . . . 5G waveforms: CP-OFDM & DFT-SOFDM.*

- ***Beamforming:*** Beamforming is a technology that has become a reality in recent years and it offers to provide some significant advantages to 5G. Beamforming enables the beam from the base station to be directed towards the mobile. In this way the optimum signal can be transmitted to the mobile and received from it, whilst also cutting interference to other mobiles.

  Concept of antenna beamforming used with 5G NRThe move to higher frequencies allows for much smaller antennas and the possibility of programmable high directivity levels.

  On frequencies above 24 GHz where antennas are smaller, there is the possibility of having high performance beamsteering antennas that are able to accurately direct the power to the mobile in question, and also provide receiver gain in this direction.
- ***MIMO:*** MIMO, multiple input multiple output has been employed in many wireless systems from Wi-Fi to the current 4G cellular system and it provides some significant improvements. Within 5G, MIMO will be one of the mainstay technologies.

  5G will take full advantage of Multi-User- MIMO, MU-MIMO where it will provide multiple access capabilities to MIMO by utilising the distributed and uncorrelated spatial location of the various users.

  In implementing this the gNB (5G base station) sends a CSI-RS (Channel State Information Reference Signal) to the different user equipment's and then dependent upon the responses, the gNB computes the spatial information for each user. It uses this information to compute the required information for the pre-coding matrix (W-Matrix) where the data symbols are constructed into the signals for each of the elements of the gNB antenna array.

  The multiple data streams have their own weightings which includes phase offsets to each stream to enable the waveforms to interfere constructively at the receiver. This maximises the signal strength to the user whilst also minimising the signal and hence interference to other users.

  In this way the gNB is able to talk to multiple devices concurrently and independently by using spatial information. This means that 5G MU-MIMO enables the UEs to operate without need for knowledge of the channel or additional processing to obtain the data streams.

  MU-MIMO on the downlink significantly improves the capacity of the gNB antennas. It scales with the minimum of the number of gNB antennas and the sum of the number of user devices multiplied by the number of antennas per UE device. This means that using 5G MU-MIMO the system can achieve capacity gains using gNB antenna arrays and much simpler UE devices.
- ***Spectrum sharing techniques:*** Much of the radio spectrum, although allocated, is not used in an efficient manner. One of the techniques being proposed is for spectrum sharing.
- ***Unified design across frequencies:*** With the 5G New Radio utilising a wade variety of frequencies, possibly 3.4 to 3.6 GHz below 6GHz and then 24.25 to 27.5 GHz, 27.5 to 29.5 GHz, 37 GHz, 39 GHz and 57 to 71 GHz range as possibilities for the mmWave radio. It is important to have a common interface across these frequencies.
- ***Small cells:*** As network densification is required to provide the required data capability more use of small cells and small cell networks are being proposed. A small cell network is a group of low power transmitting base stations which uses millimetre waves to enhance the overall network

capacity. The 5G small cell network operates by coordinating a group of small cells to share the load and reduce the difficulties of physical obstructions which become more important at millimetre waves.

By utilising these techniques and many others, the 5G New radio, 5G NR will be able to significantly improve the performance, flexibility, scalability and efficiency of current mobile networks. In this way 5G will be able to ensure the optimum use of the available spectrum, whether it is licensed, shared or unlicensed, and achieve this across a wide variety of spectrum bands.

5G NextGen Core Network

The 5G NG NextGen core network will play a crucial role in enabling the overall performance of the 5G mobile communications system to meet its performance goals.

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The 5G NextGen, NG core network will play a key role in enabling the performance of the 5G mobile communications system.

Defining the next-generation architecture is the responsibility of the 3GPP's System Architecture (SA) Technical Specification Group on Service and System Aspects.

The study phase, completed last year in 2016, outlines what this new core network, known as NG Core, or NextGen core network, will look like.

5G NextGen NG core network basics

The requirements for the network for 5G will be particularly diverse. In one instance, very high bandwidth communications are needed, and in other applications there is a need for exceedingly low latency, and then there are also requirements for low data rate communications for machine to machine and IoT applications.

In amongst this there will be normal voice communications, Internet surfing and all the other applications that we have used and become accustomed to using.

As a result the 5G NextGen network will need to accommodate a huge diversity in types of traffic and it will need to be able to accommodate each one with great efficiency and effectiveness. Often it is thought that type suits all approach does not give the optimum performance in any application, but this is what is needed for the 5G network.

To achieve the requirements for the 5G network a number of techniques are being employed. These will make the 5G network considerably more scalable, flexible and efficient.

- ***Software defined networking, SDN:*** Using software defined networks, it is possible to run the network using software rather than hardware. This provides significant improvements in terms of flexibility and efficiency
- ***Network functions virtualisation, NFV :*** When using software defined networks it is possible to run the different network function purely using software. This means that generic hardware can be reconfigured to provide the different functions and it can be deployed as required on the network.
- ***Network slicing:*** As 5G will require very different types of network for the different applications, a scheme known as network slicing has been devices. Using SDN and NFV it will be possible to configure the type of network that an individual user will require for his application. In this way the same hardware using different software can provide a low latency level for one user, whilst providing voice communications for another using different software and other users may want other types of network performance and each one can have a slice of the network with the performance needed.

The performance required for the 5G NextGen network has been defined by the NGMN (Next Generation Mobile Network Alliance). The Next Generation Mobile Networks Alliance is a mobile telecommunications association of mobile operators, vendors, manufacturers and research institutes and by using the experience of all parties, it is able to develop the strategies for the next generation mobile networks, like that for 5G.

As such the 5G NG, NextGen core network will be able to utilise far greater levels of flexibility to enable it to serve the increased and diverse requirements placed upon it by the radio access network and the increased number of connections and traffic.

5G Waveform: CP-OFDM & DFT-SOFDM

The waveform that has been adopted for the 5G New Radio is based on OFDM but with updates to that used with LTE

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The standard for the 5G New Radio phase one has been released and within this the waveform to be used has been defined.

A number of candidate waveforms were investigated for 5G, and after much discussion it was decided that a waveform based n OFDM would provide the optimum results.

Accordingly cyclic prefix OFDM, or CP-OFDM was chosen as the main candidate with DFT-SOFDM, discrete Fourier transform spread orthogonal frequency division multiplexing being used in some areas.

5G waveform background

Orthogonal frequency division multiplexing has been an excellent waveform choice for 4G. It provides excellent spectrum efficiency, it can be processed and handled with the processing levels achievable in current mobile handsets, and it operates well with high data rate stream occupying wide bandwidths. It operates well in situations where there is selective fading.

However with the advances in processing capabilities that will be available by 2020 when 5G is expected to have its first launches means that other waveforms can be considered.

There are several advantages to the use of new waveforms for 5G. OFDM requires the use of a cyclic prefix and this occupies space within the data streams. There are also other advantages that can be introduced by using one of a variety of new waveforms for 5G.

One of the key requirements is the availability of processing power. Although Moore's Law in its basic form is running to the limits of device feature sizes and further advances in miniaturisation are unlikely for a while, other techniques are being developed that mean the spirit of Moore's Law is able to continue and processing capability will increase. As such new 5G waveforms that require additional processing power, but are able to provide additional advantages are still viable.

5G waveform requirements

The potential applications for 5G including high speed video downloads, gaming, car-to-car / car-to-infrastructure communications, general cellular communications, IoT / M2M communications and the like, all place requirements on the form of 5G waveform scheme that can provide the required performance.

Some of the key requirements that need to be supported by the modulation scheme and overall waveform include:

- Capable of handling high data rate wide bandwidth signals
- Able to provide low latency transmissions for long and short data bursts, i.e. very short Transmission Tine Intervals, TTIs, are needed.
- Capable of fast switching between uplink and downlink for TDD systems that are likely to be used.
- Enable the possibility of energy efficient communications by minimising the on-times for low data rate devices.

These are a few of the requirements that are needed for 5G waveforms to support the facilities that are needed.

Cyclic Prefix OFDM: CP-OFDM

The specific version of OFDM used in 5G NR downlink is cyclic prefix OFDM, CP-OFDM and it is the same waveform LTE has adopted for the downlink signal.

Basic concept of OFDM, Orthogonal Frequency Division Multiplexing

The 5G NR uplink has used a different format to 4G LTE. CP-OFDM- and DFT-S-OFDM-based waveforms are used in the uplink. Additionally, 5G NR provides for the use of flexible subcarrier spacing. LTE subcarriers normally had a 15 kHz spacing, but 5G NR allows the subcarriers to be spaced at 15 kHz x 2s with a maximum spacing of 240 kHz. The integral s carrier spacing rather than fractional carrier spacing is required to preserve the orthogonality of the carriers.

The flexible carrier spacing is used to properly support the diverse spectrum bands/types and deployment models that 5G NR will need to accommodate. For example, 5G NR must be able to operate in mmWave bands that have wider channel widths of up to 400 MHz. 3GPP 5G NR Rel-15 specification details the scalable OFDM numerology with 2s scaling of subcarrier spacing that can scale with the channel width, so the FFT size scales so that processing complexity does not increase unnecessarily for wider bandwidths. The flexible carrier spacing also gives additional resilience to the effects of phase noise within the system.

The use of OFDM waveforms offers a lower implementation complexity compared to that which would be needed if some of the other waveforms considered for 5G had been implemented. In addition to this, OFDM is well understood as it has been used for 4G and many other wireless systems.

5G Modulation Schemes

- the modulation scheme or schemes adopted for 5G will play a major role in determining the performance and complexity of the handsets and other nodes used.

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The modulation schemes used for 5G will have a major impact on performance.

Whilst there are requirements to ensure that the data rates needed can be carried and the 5G modulation schemes performance issues including peak to average power ratio, spectral efficiency, and performance in the presence of interference and noise need to be included in any decisions made.

Peak to average power ratio, PAPR

The peak to average power ratio is one aspect of performance that needs to be considered for any 5G modulation scheme.

The peak to average ratio has a major impact on the efficiency of the power amplifiers. For 2G GSM, the signal level was constant and as a result it was possible to run the final RF amplifier in compression to obtain a high level of efficiency and maximise the battery life.

With the advent of 3G, then its HSPA enhancements and then 4G, the modulation schemes and waveforms have meant that the signals have become progressively more 'peaky' with higher levels of peak to average power ratio. This has meant that the final RF amplifiers cannot be run in compression and as the PAPR has increased, so the efficiency of the RF amplifiers has fallen and this is one factor that has shortened battery life.

The opportunity now arises to utilise 5G modulation schemes that can reduce the PAPR and thereby improve efficiency.

Spectral efficiency

One of the key issues with any form of 5G modulation scheme is the spectral efficiency. With spectrum being at a premium, especially in frequencies below 3 GHz, it is essential that any modulation scheme adopted for 5G is able to provide a high level of spectral efficiency.

There is often a balance between higher orders of modulation like 64 QAM as opposed to 16 QAM for example and noise performance. Thus higher order modulation schemes tend to be only sued when there is a good signal to noise ratio.

Accordingly any 5G modulation scheme will need to accommodate high levels of performance under a variety of conditions.

5G modulation schemes

3G and 4G have used modulation schemes including PSK and QAM. These schemes provide excellent spectral efficiency and have enabled the very high data rates to be carried but fall short in terms of their peak to average power ratio.

To overcome the PAPR issue, one option being considered for a 5G modulation scheme is APSK or amplitude Phase Shift Keying.

However in view of the fact that amplitude components of a signal are more subject to noise, which is substantially amplitude based, it is likely that any overall 5G modulation scheme will be adaptive, enabling the system to switch to the most optimum for of modulation for the given situation.

5G Multiple Access Schemes

- *preliminary details and information about the multiple access schemes and technology being developed for 5th generation or 5G mobile wireless or cellular telecommunications systems.*

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One key element of any cellular communications system is the multiple access technology that is used.

As a result the 5G multiple access schemes are being carefully considered and researched to ensure that the optimum technique or techniques are adopted.

There are several candidate 5G multiple access schemes that are in the running. Each has its own advantages and disadvantages and as a result, no single technique is likely to meet all the requirements.

5G multiple access schemes

There are several candidate systems that are being considered as the 5G multiple access scheme. They include a variety of different ideas.

- ***Orthogonal frequency division multiple access, OFDMA:*** OFDMA has been widely used and very successful for 4G and could be used as a 5G multiple access scheme. However it does require the use of OFDM and requiring orthogonality between carriers and the use of a cyclic prefix has some drawbacks. As a result other multiple access schemes are being investigated.
- ***Sparse Code Multiple Access, SCMA:*** SCMA is another idea being considered as a 5G multiple access scheme and it is effectively a combination of OFDMA and CDMA. Normally with OFDMA a carrier or carriers is allocated to a given user. However if each carrier has a spreading code added to it, then it would be able to transmit data to or from multiple users. This technique has been developed to use what are termed sparse code and in this way significant numbers of users can be added while maintaining the spectral efficiency levels.
- ***Non-orthogonal multiple access, NOMA:*** NOMA is one of the techniques being considered as a 5G multiple access scheme. NOMA superposes multiple users in the power domain, using cancellation techniques to remove the more powerful signal. NOMA could use orthogonal frequency division multiple access, OFDMA or the discrete Fourier transform, DFT-spread OFDM. .

There are several multiple access schemes that could be used with 5G. The one or ones used will be chosen as a result of the standardisation process which is currently onging.

5G Millimetre Wave

- *preliminary details and information the millimetre wave technologies being developed for 5G mobile communications*

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One of the options that is most likely to be incorporated into the 5G technologies that are being developed for the 5G cellular telecommunications systems is a millimetre wave capability.

With spectrum being in short supply below 4GHz, frequencies extending up to 60GHz are being considered.

5G millimetre wave basics

One of the interfaces being considered for 5G mobile communications uses millimetre wave frequencies.

It is estimated that bandwidths of several GHz may be required by operators to provide some of the extremely high data rates being forecast.

Currently frequency below 4GHz are being used by cellular communications systems, and by the very nature, these frequencies could only offer a maximum bandwidth of 4 GHz, even if they were all clear for use which is obviously not possible.

By having a 5G millimetre wave interface, much wider bandwidths are possible, and there are several candidate millimeter bands that are being considered for allocation to this type of service.

5G millimeter wave propagation

The propagation characteristics of millimetre wave bands are very different to those below 4GHz. Typically distances that can be achieved are very much less and the signals do not pass through walls and other objects in buildings.

Typically millimetre wave communication is likely to be used for outdoor coverage for dense networks - typically densely used streets and the like. Here, ranges of up to 200 or 300 metres are possible.

One of the issues of using millimetre wave signals is that they can also be affected by natural changes such as rain. This can cause a considerable reduction in signal levels for the duration of the precipitation. This may result in reduced coverage for some periods.

Often these 5G millimetre wave small cells may use beamforming techniques to target the required user equipment and also reduce the possibility of reflections, etc.

Millimetre wave coverage

Simulations have shown that when millimetre wave small cells are set up they provide a good level of coverage. Naturally, typically being lower down than macro cells, the coverage will not be as good, but when considering the level of data they can carry, they provide an excellent way forwards for meeting the needs of 5G systems.

A further issue to be considered when looking at 5G millimetre wave solutions is that they will incur a much greater number of handovers than a normal macro cell. The additional signalling and control needs to be accommodated within the system. Also backhaul issues need to be considered as well.

Connectivity in both wired and wireless forms is part of everyday life. From wired and fibre broadband to mobile communications - 2G, 3G, 4G and 5G, Wi-Fi, Bluetooth and many other wireless technologies through to standards like Ethernet, USB and many others. These all form part of today's connected world.

Mobile phones / cellular telecommunications

- Cellular / mobile communication basics
- What is 3GPP?
- 2G GSM
  - 2G GPRS
  - 2G GSM EDGE
- IS95 / cdmaOne

  - 3G UMTS
    - 3G HSPA
  - 4G LTE
    - LTE Advanced
  - 5G technology

Wireless Connectivity

- WiFi - IEEE 802.11
- Bluetooth
- RFID: radio frequency identification
- NFC: near field communication
- IEEE 802.15.4
- WiMAX

  - DECT
  - SIGFOX
  - LoRa
  - Zigbee
  - Z-Wave