The use of spectrum at millimetre wavelengths for cellular networks

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Abstract - This paper summarises the benefits and limitations of using spectrum at mm wavelengths for radio access in cellular networks. It discusses the engineering viability of using mm wavelengths for cellular use but focuses on the assignment of spectrum in this band from a regulation and policy use point of view. In particular, the analysis considers whether mm wavelength spectrum should be used as licensed or unlicensed bands, or a combination of both, when used for cellular networks.

This paper shows that mm wavelengths for cellular use is best used where coverage is not expected to be continuous or ubiquitous, and used in areas where capacity demands cannot be met by using the UHF band. In addition this paper shows that there are benefits of assigning part of the mm wavelength band as unlicensed spectrum for private individuals or small networks, and part of the adjacent mm wavelength band as licensed spectrum for cellular operators.

I. Introduction

Spectrum is a very valuable resource in cellular networks where the amount of spectrum and the frequency of use determine both the coverage and capacity achievable. Traditionally cellular networks use spectrum in the UHF band, which allows good radio propagation and meets most of the current demand for capacity. However the demand for capacity is increasing significantly, driven in part by the popularity of smart phones but also by the increase in wireless video content [1, 2] and the likely increase in machine to machine traffic. To meet the future demand for capacity a change in how spectrum is utilised needs to be considered. One possible solution is the use of millimetre (mm) wavelengths for cellular networks.

Millimetre wavelengths are defined as electromagnetic spectrum with wavelengths from 1 to 10 mm or 30 to 300 GHz – this is also known as the EHF or extremely high frequency band. Current cellular networks use frequencies in the UHF, or ultra high frequency band (300 MHz to 3 GHz). The UHF band has been used by first generation AMPS and DAMPS networks, second generation GSM and CDMA networks, third generation UMTS and even fourth generation LTE networks.

The main benefit of using mm wavelengths is the large bandwidths available for cellular network use. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths exceed 500 MHz [3]. The Shannon Hartley theorem [4] shows that the greater the bandwidth available then the greater the maximum capacity achievable i.e.

\[ C = B \log_2 (1 + S/N) \]  

Where C is the channel capacity, B is the bandwidth of the channel and S/N is the signal-to-noise ratio (SNR). Sometimes the SNR is expressed as the carrier to interference ratio. For the same signal to
noise ratio an increase from channel bandwidth from 20 MHz to 500 MHz would allow at least a 25 times increase in the corresponding capacity.

The second main benefit of mm wavelengths is the fact that advanced beam forming techniques are possible with the use of these smaller wavelengths [5]. In particular the fact that a large number of antennas are achievable in a small space allows directional beam forming and greater use of MIMO to enhance spectral efficiency. MIMO (multiple input and multiple output) allows multiple transmit and receive antennas to increase capacity by allowing multipath propagation, and adaptive beam forming allows the signal strength to be increased by adaptive spatial signal processing in a specific direction, for example between a base station and a mobile device.

However the use of mm wavelengths also has a downside. At these wavelengths there is very high attenuation (or blockage) of propagation through certain materials like concrete walls and foliage. At 28 GHz walls can cause 40-80 dB of attenuation, foliage up to 23 dB and the human body itself causes 20 to 35 dB of attenuation [6]. All these losses are dependent of the depth and construction of these materials. There is also higher air attenuation at these frequencies and higher outages due to rain. The high concrete, air and other material attenuation means that the coverage range of base stations would be much lower than the coverage range of base stations used in today’s macro cell sites [7], and many more sites may be required when compared to the standard cell sites used today to give ubiquitous coverage.

The addition of more base stations implies higher cellular rollout costs. Additional base stations require more backhaul (fibre), site power, site acquisition and design and planning and maintenance costs. Another challenge is that mm wavelength transceivers currently have high power consumption and high component cost [8], this affects both mobiles and base stations. This means that not only will more base stations be required, but each base station and the associated mobiles are likely to cost more.

Of particular relevance to cellular networks are frequencies located in the minima and maxima shown in figure 1, which is a plot of air attenuation at sea level in dB/km versus frequency (GHz). The frequencies used by cellular networks in the UHF band (0.3 to 3 GHz) have very low air attenuation. The minima at approximately 28 GHz, for example, are the frequencies where air attenuation is relatively low but the bandwidth of available spectra is relatively high. Conversely, for the maxima, for example 60 GHz, the air attenuation is high, caused by the resonance of oxygen molecules at this frequency. This means propagation is particularly poor at this frequency even though available spectrum is high.
Despite the challenges described above, research suggests that designing cellular networks using mm wavelengths is viable. Work reported in [7] on radio propagation path loss models showed a simulated effective cell radius of 220 m at 28 GHz, which agrees with measured data from [11]. The later paper concluded that since (mm wavelength) signals cannot readily propagate through outdoor building materials then indoor networks will be isolated from outdoor networks. They suggested that access points (base stations) may need to be installed for handoffs at entrances to commercial and residential buildings (to provide continuous coverage).

Note that 28 GHz is strictly not in the EHF or mm wavelength band i.e. 1 to 10 mm or 30 to 300 GHz, but lies just outside this range. However 28 GHz is important due to the location of the minima as shown in Figure 1 at this frequency.

Regulators will play an important role in determining policy for the use of mm wavelengths. The FCC has already submitted a notice of inquiry in the matter of ‘use of spectrum bands above 24 GHz for mobile radio services’ [12]. Certainly the use of mm wavelengths in future generations of cellular networks seems likely given the large amounts of available spectrum. Whether this is for 5G or some later generation of cellular networks remains to be seen.
II. Millimetre wavelength propagation

Predicted LTE coverage areas using 28 GHz and 1800 MHz carriers are shown in Figures 2 and 3, respectively. These figures show the significant coverage achievable using the UHF band (Figure 3) versus the coverage achievable using mm wavelengths (Figure 2).

Figure 2. Simulated LTE coverage from a coastal cell site using mm wavelengths (28 GHz).

Figure 3. Actual LTE coverage from the same coastal site, using the UHF band (1800 MHz).
Both these coverage plots have the following legend.

<table>
<thead>
<tr>
<th>Legend</th>
<th>LTE: Coverage by Signal Level (DL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Signal Level (dBm) &gt; -70</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -75</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -80</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -85</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -90</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -95</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -100</td>
<td></td>
</tr>
<tr>
<td>Best Signal Level (dBm) &gt; -105</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Legend for LTE coverage plots shown in Figure 2 and 3.

The mm wavelength coverage prediction as shown in figure 2 has a maximum transmit power of 30 dBm, a single horn antenna per sector, with 17 dBi gain and a 3 dB beam width of 26.25 degrees. Figure 2 uses the 3GPP urban micro (UMi) path loss model [8] and [13] given by:

$$PL(d) [\text{dB}] = 22.7 + 36.7 \log_{10}(d) + 26 \log_{10}(fc)$$  \hspace{1cm} (2)

Where $PL$ is the path loss, $d$ is the distance from the base station and $fc$ is the carrier frequency (28 GHz) in this case. The path length of figure 2 matches that achieved in other published works [11].

The UHF coverage prediction as shown in figure 3 shows the actual LTE coverage from a LTE 1800 MHz cell site in Auckland, New Zealand. This coverage has been confirmed by drive test results. This shows a large coverage area typical of a sub-urban cell site (near water). The coverage prediction as shown in figure 3 has a maximum transmit power of 30 dBm, a single panel antenna per sector, with approximately 17 dBi gain and a 3 dB beam width of approximately 60 degrees.

A comparison of figure 2 and figure 3 shows that the coverage using UHF band in this example far exceeds the coverage using mm wavelengths. This is shown in the total coverage from each base station, in the coverage from each sector, and in the coverage achieved at high signal levels.

The greater coverage from each sector, in the UHF band example, is caused not only by the difference in propagation between mm wavelengths and the UHF band but is also due to the difference in beam widths of the antennas at these bands. The antennas currently available at higher frequencies generally have narrower beam widths. This could be partially overcome by having greater number of antennas at each base station i.e. increasing the number of sectors when using mm wavelengths with a corresponding increase in cost.

Figures 2 and 3 also show that there is a greater amount of coverage in the UHF band example at higher signal levels. For example a greater area covered where the signal level is -80 dBm or higher in the UHF band example. A high signal strength helps offset any losses caused by obstructions such as walls and foliage. A low signal strength (signal to noise ratio) can also negatively affect the capacity achieved, as shown earlier in this paper in the Shannon Hartley theorem (equation (1)).

Figures 2 and 3 confirms the greater number of base stations required if using spectrum at mm wavelengths for cellular networks when compared to the use of spectrum in the UHF band.
III. Millimetre wavelength – licensed spectrum

This section of this paper considers assigning mm wavelength bands for cellular use as licensed spectrum. This means regulators would assign spectrum under an auction system such as the combinatorial clock auction [14] or other allocation methods [15]. The licenses would be for a fixed amount of spectrum, covering a large geographic area, for a large timeframe. Licensed spectrum is desired by cellular operators as it allows the operators exclusive use to this spectrum with the ability to manage interference from third parties.

Historically licensed spectrum is sold for cellular use with a condition stating a high percentage of the population must be covered with this spectrum. For example, in the recent 700 MHz auction in New Zealand there was a requirement that operators achieve 75% national population coverage with this spectrum, including at least 50% population coverage within any given region, within five years [16].

The rollout of a licensed mm wavelength ubiquitous network would require a significant investment from cellular operators. Figure 2 shows the existing base station location of a cellular network in Auckland, New Zealand (a city of 1.4 million people). The sites located in the CBD are typically pico cells – with a distance between base stations ranging from 100-300 m. The sites in suburban locations are typically micro cells – with a distance between base stations ranging from 1-2 km. The sites located in rural areas are macro cells – with a distance between base stations typically 20 km+ (sometimes coverage is not continuous between rural sites in which case the distance between base stations is network specific). These distances match those in [17].

Figure 5. Existing base station locations for a single operator in Auckland, New Zealand. Data has been collected from public spectrum license information from Radio Spectrum Management [16]. Web version http://gis.geek.nz/infrastructure.html. The highest concentration of sites is in the city CBD, the other sites shown are in suburban areas.

If ubiquitous coverage is a requirement for a `licensed` mm wavelength cellular network then having base stations at least every few hundred metres to cover 75% of the population (i.e. the requirement in New Zealand for operators to use 700 MHz) would be a very significant, if not prohibitive, cost. This
means licensed band use of mm wavelengths for cellular use may not be able to follow standard regulatory conditions historically imposed on cellular rollouts. Therefore a heterogeneous network is a likely solution. This means a network where coverage to most of the population is via a UHF band providing voice and data but with a mm wavelength network providing localised high capacity data.

The most obvious place to use licensed mm wavelengths would be in the city CBD. This is where capacity demands are traditionally high and where the distance between existing cell sites of 200-300m, as shown in Figure 2, matches those required for a mm wavelength network [5]. As these are existing sites there will be existing backhaul (normally using optical fibre) and existing property lease and planning permission. However most of these existing cell sites are located external to property. This means in-building coverage would require separate indoor base stations (also called access points).

Table 1 lists the cellular networks in use in New Zealand today. This table shows that existing cellular services all use the UHF band and that the existing services form a heterogeneous network – with 3G providing voice and data but roaming onto 2G services as required. 4G networks offering high capacity data are already available in urban areas, with 4G rollouts to rural areas using 700 MHz being planned.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Cellular Network Examples</th>
<th>Frequency (NZ)</th>
<th>Areas used (NZ)</th>
<th>Density of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>2G</td>
<td>GSM</td>
<td>900 and 1800 MHz</td>
<td>Nationwide (approx. 94% of population)</td>
<td>Macro – 20 km +</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900 and 1800 MHz</td>
<td>Nationwide (approx. 94% of population)</td>
<td>Micro – 1-2 km</td>
</tr>
<tr>
<td>3G</td>
<td>UMTS</td>
<td>850 or 900 MHz, 2100 MHz</td>
<td>Nationwide (approx. 94% of population)</td>
<td>Pico ~ 300 m</td>
</tr>
<tr>
<td>4G</td>
<td>LTE</td>
<td>1800 MHz and 700 MHz</td>
<td>City coverage (currently), 75% national population within 5 years</td>
<td></td>
</tr>
<tr>
<td>5G or later generations</td>
<td>TBA</td>
<td>millimetre wavelengths e.g. 28000 MHz</td>
<td>Proposed to be used in CBD’s or areas with high capacity requirements.</td>
<td>200-300 m</td>
</tr>
</tbody>
</table>

Table 1. Cellular services in New Zealand

The areas used and density of cells shown in the table above shows that the addition of a mm wavelength network in the CBD and in some urban environments would only support the existing generations of cellular networks. This is because an LTE network would still be required to offer high speed data to suburban and some rural areas with Micro cells for example, likewise a UMTS network would still be required to offer voice and low speed data to other areas, for example rural locations with Macro cells. The GSM network may become obsolete in the next 2-5 years but this is still being used for voice roaming from UMTS when required and some M2M (machine to machine) communications. However it is not the addition of mm wavelengths that would make a GSM network, or any other generation of cellular network, obsolete.

IV. Millimetre Wavelengths – unlicensed spectrum

The second section of this paper considers assigning mm wavelength bands for cellular use as purely unlicensed spectrum. This would be similar to the ISM bands used for Wi-Fi today. ISM bands (also known as unlicensed or general licensed bands) are designated for industrial, scientific and medical
applications. As these are unlicensed, the services operating within these bands are subject to interference from other applications using the same frequency band.

In this scenario a private individual would deploy their own mm wavelength base station or access point locally, thus meeting the installation costs themselves. The individual would pay for power and installation costs and provide backhaul via ADSL or fibre. Cellular operators could then off-load traffic to this network using unlicensed spectrum in the mm wavelength band (similar to how Wi-Fi is used today) keeping the UHF bands for spectrum licenses using mainly voice traffic, and data traffic where no mm wavelength network coverage is available.

As the public already use Wi-Fi hotspots on cellular phones they are more likely to be comfortable using a similar arrangement but with a mm wavelength network. This means that continuous coverage would not be expected, as compared to the expectation of continuous coverage if this service was offered as a 5G service by a cellular operator. This means a mm wavelength network could be used to provide coverage to cell phones only in certain areas of a city. Examples would be airports, business requiring high data services, in-door only hotspots, stadiums and some residential houses.

Millimetre wavelength ISM bands already exist in New Zealand and other countries that maybe suitable for cellular or wireless LAN networks. In addition to the 2.4 and 5.8 GHz networks already used for Wireless LAN there are ISM bands designated from 24 to 24.25 GHz and from 61 to 61.5 GHz and higher frequencies. These are shown in Figure 6. Despite the fact that ISM bands at 2.4 GHz and 5.8 GHz are used for Wireless LAN, higher frequency bands may require spectrum regulator (local radio spectrum management) permission to use this for telecommunications.

![Figure 6](image_url)

Figure 6. Unlicensed ISM bands designated in New Zealand. This shows the centre frequency in MHz of the ISM band and the amount of spectrum (bandwidth) currently available at that frequency.
Of particular interest is the 250 MHz of unlicensed spectrum available at 24 GHz, this is close to the local minima of air attenuation shown in Figure 1, but also close to existing licensed spectrum designated for LMDS (Local Multipoint Distribution Service) in New Zealand. LMDS is designated for point to multipoint services that are similar to the cellular services offered today.

V. Millimetre wavelengths – combined licensed and unlicensed spectrum

This section considers the allocation of both licensed and unlicensed spectrum in adjacent mm wavelength bands for cellular use. Part of the same band could be assigned for licensed use and part assigned for unlicensed use, with a guard band and rules defining transmitter conditions to reduce the chance of interference. In this scenario a single mobile device could cover the same band consisting of both licensed and unlicensed spectrum.

This would allow a licensed approach – allowing operators to manage interference with large amounts of spectrum available to provide capacity. Plus the option for a private individual (or smaller network operators) to have self-owned networks using the unlicensed part of this band. This scenario would effectively still be a heterogeneous network, keeping a UHF network for ubiquitous coverage, and a licensed mm wavelength to provide coverage in areas with high data demands, and an unlicensed mm wavelength network installed by third parties.

The benefits to operators using this approach would be the same as described earlier in this paper. Operators would have a licensed band to provide additional capacity as required. But would also allow operators to offload to local unlicensed base stations (if available), when required by traffic demands.

The benefits to the public of having the unlicensed band would also be the same as described early in this paper. However because there is a licensed band adjacent to the unlicensed part of this band, potentially used by operators and the public then there will be some advantages due to the economies of scale in the availability of equipment from vendors. This means that vendors are more likely to offer handsets and base stations in a particular band if this band is used by many operators and the public – i.e. supply will match this high demand.

Figure 7 shows the radio spectrum assignment around 28 GHz in New Zealand which follows a similar assignment strategy as many other countries (based on the ITU (International Telecommunication Union) designation). This shows the existing ISM band (general license / unlicensed) designation and that assigned for LMDS. There are no New Zealand nationwide nor city-wide networks using this unlicensed spectrum (to date). In New Zealand the management rights to the LMDS spectrum are already owned by a cellular operator. This has not been used to date – i.e. there are no current nationwide or city-wide networks using this licensed spectrum.

![Figure 7. Radio Spectrum Usage in New Zealand – existing designation around 28 GHz. Data sourced from Radio Spectrum Management [18]. DMR (Digital Microwave Radio), ISM (Industrial, Scientific and Medical band), LMDS (Local Multipoint Distribution Service).](image-url)
Figure 8. Possible adjustment of designations to increase ISM band allocation for unlicensed Wireless LAN use. The mm wavelength allocation here could be divided into an upper and lower band for frequency division duplex use.

Figure 8 is a recommended alteration to the spectrum allocated around 28 GHz in New Zealand. The ISM band is increased from a bandwidth of 250 MHz to a bandwidth of 1.392 GHz (compare this to the 100 MHz (0.1 GHz) currently available for Wireless LANs at 2.4 GHz). The LMDS band is reduced to the upper part of the band (25.557-28.35 GHz), still providing a 2.793 GHz bandwidth for licensed spectrum (compare this to 2 x 45 MHz currently (0.045 GHz) in use at 700 MHz for LTE). This increase in the amount of spectrum available allows a corresponding increase in capacity.

By having an unlicensed band adjacent to a licensed band for cellular networks also offers a unique opportunity, in the use of LTE-U (unlicensed) with LTE (or the 5G equivalent) and carrier aggregation. Carrier aggregation in LTE allows discontinuous channels to be used to provide greater capacity. These can be intra-band carrier aggregation with continuous or non-continuous component carriers or inter-band carrier aggregation such as in the example above where part of the licensed bands and part of the unlicensed band could be aggregated to carry traffic. This would require a UE (user equipment) to have a transceiver capable of using a large bandwidth (in this example 24 to 28.4 GHz). This may have an impact on cost and power consumption and the performance of the device. But would allow significant amount of bandwidth and associated cellular capacity.
VI. Conclusion

The main benefit of using mm wavelengths for cellular networks is the large bandwidth available which in turn allows a large increase in the capacity available in the radio access network. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths can exceed 500 MHz. The second main benefit of mm wavelengths is the fact that advanced beam forming techniques are possible with the use of these smaller wavelengths. In particular the fact that a large number of antennas are achievable in a small space allows directional beam forming and greater use of MIMO to enhance spectral efficiency.

However the high air attenuation and high attenuation through concrete and foliage means the path length of mm wavelength base stations would be much lower than the path length of base stations used in today’s macro cell sites. In addition, as signals cannot readily propagate through outdoor building materials, many more indoor base stations will be required. LTE (4G) coverage predictions were presented in this paper showing the coverage using 28 GHz and 1800 MHz using similar transmission parameters, except frequency. The resulting plots showed a base station path length of 200-300m when using mm wavelengths as compared to a base station path length of 2 km+ when using spectrum in the UHF band. This result showed that many more base stations would be required if using mm wavelengths to provide the same coverage as that achieved using spectrum in the UHF band.

This paper first considers assigning mm wavelength bands for cellular use as licensed spectrum. Using licensed bands, a heterogeneous network is likely with UHF bands providing ubiquitous coverage and mm wavelengths covering areas with a high capacity demand. This may be a CBD only coverage but may need to be city wide if mm wavelengths are offered as a 5G or a later generation service. A nationwide rollout with a high density of mm wavelength base stations would be cost prohibitive. Since a heterogeneous solution is likely the use of mm wavelengths for cellular use would initially have little effect on the current demand for UHF bands.

The second section of this paper considered assigning mm wavelength bands for cellular use as purely unlicensed spectrum. This would be similar to the ISM bands used for Wi-Fi today. In this scenario private users would setup a mm wavelength base station locally, thus meeting the costs themselves. Operators could then off-load traffic to this private network using unlicensed spectrum, keeping the lower frequency (UHF) licensed bands for voice traffic and for data traffic where no mm wavelength network coverage is available. This means an unlicensed mm wavelength base station could be used at city hotspots with high demands for capacity.

The fact that operators in New Zealand already have a management right to use the LMDS bands for point to multipoint services around 25-28 GHz and the fact that there is an existing ISM band (unlicensed band) at 24 GHz, both unused for cellular networks, is indicative that cellular operators still perceive the UHF band as the most important band at this stage.

The third section of this paper considers the allocation of both licensed and unlicensed spectrum in adjacent mm wavelength bands for cellular use. This scenario would effectively be a multi-band network, keeping a UHF network for ubiquitous coverage, and a licensed mm wavelength to provide additional coverage in areas with high data demands, and an unlicensed mm wavelength network installed by third parties. A possible spectrum allocation around 24-28 GHz was presented using ISM band spectrum at 24 GHz and adjacent spectrum at 27 GHz assigned for a LMDS service. This allocation of spectrum has the benefits of both the two scenarios described above, allowing both LTE and LTE-U traffic for example. This also has the benefit of allowing carrier aggregation – allowing both licensed and unlicensed band to carrier traffic on the same device.
Given the fact that capacity demands are rising almost exponentially, it is highly likely that mm wavelengths will be used in some form to meet this demand. Whether this is for 5G or some later generation of cellular networks remains to be seen.
VII. References


