INSTITUTE FOR COMMUNICATION SYSTEMS

5G INNOVATION CENTRE

5G Whitepaper:
Meeting the Challenge of “Universal” Coverage, Reach and Reliability in the Coming 5G Era

Meeting the challenge of "Universal" coverage, reach and reliability in the coming 5G era

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(Note: The author's views are in a personal capacity and are not intended to reflect the views of their organisations)

1. Introduction

Everyone can foresee a gigantic capacity challenge for wireless networks over the coming decades. The research community is responding well by developing 5G technology in higher bands (eg mmWave) that will unlock huge data rates up to 10 Gb/s or more but its practical application will be limited to dense urban areas. This inevitably leads to *a new coverage challenge* being pulled behind this capacity challenge i.e, the coverage of higher speeds and capacity. Nowhere will this challenge be greater than in rural areas where it will be an economic struggle to *significantly* lift the capacity above the current 4G coverage prediction of 2 Mb/s. Yet in spite of such a glaring need there is scant attention being paid by the 5G research community to improving universal mobile coverage. This White Paper reviews a range of possible ways to improve rural coverage without regard to whether this needs new technology or just a more radical way of applying existing technology. This is in the spirit of the 5GIC's vision of 5G being both a new technology and at the same time being the envelope within which all the technologies (new and existing) work together to deliver "always sufficient" resources to match users' demands.

2. Context and Business Case

One of the early tasks for 5G planners has been to rationalise very diverse applications that make very different demands on a supporting infrastructure. The approach has been to group applications in a way that rationalises the number of different radio access technologies in order to serve the widest possible 5G market with the minimum number of new radio access technology (RAT) and/or spectrum band interfaces. A triangle of opportunities has emerged from these early efforts as illustrated in figure 1.

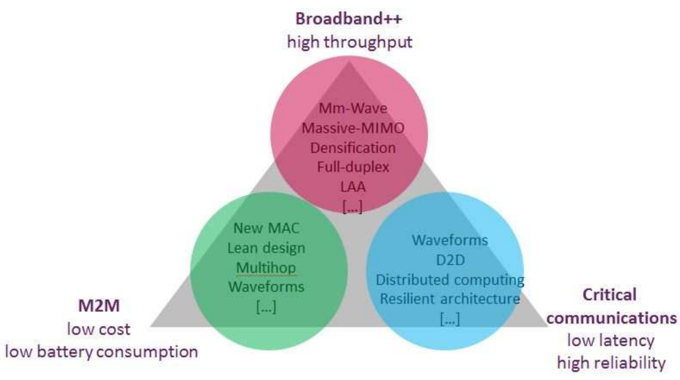

Figure 1 – Rationalising the use case opportunities in 5G communications

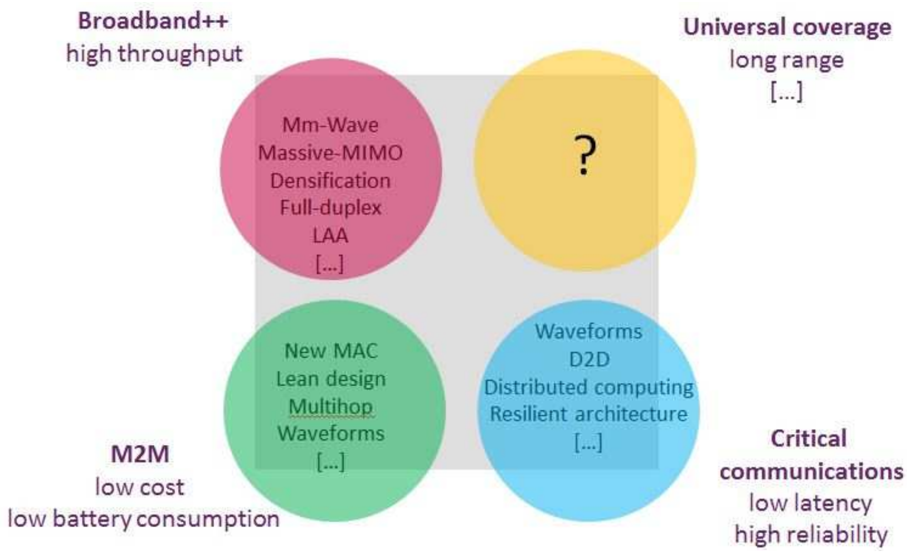

Figure 2 – Focussing on the universal service use case in future communication networks

To address the "universal coverage" gap in the 5G efforts we need to separately identify a market for a universal 5G service as illustrated in figure 2. We can then build up other complementary attributes to strengthen the commercial viability of this market. Users will want to hear an attractive headline data speed number. For example the Next Generation Mobile Networks Alliance (NGMN) proposed in its White Paper 50 Mb/s everywhere with the caveat of 95% of locations and 95% of the time. But a universal service is likely to demand better than 95% of locations [1]. There are also important applications that would not be viable if the connectivity was failing for up to 5% of the time. It is helpful to separate out two approaches to setting data speed objectives. First there is a political and marketing job to be done that finds an attractive way to present what is economically achievable. For example, the same capacity can be presented as various headline speeds from 5 Mb/s to 50 Mb/s with various associated probabilities and percentage of locations. For example Germany [2] is placing a coverage obligation on its release of 700 MHz spectrum that requires 10 Mbit/s to 98% of households and over 95% of each federal state and over 99% in city-states. However the second nobler, if less transparent, task is to give users the impression of infinite capacity by delivering an "always sufficient" response to instantaneous demand. It requires careful resource and experience management that is demand attentive. The user traffic is always varying and the challenge is to manage the peaks. This frees us from being slaves to the bits/s over all locations and times but implies a smarter network.

Separation of the control plane from the user plane allows greater flexibility in managing the peaks in user traffic. This leads to the possibility of a highly reliable control plane that reaches everywhere and can be used for short-term session control, resource allocations / co-ordination. It would be the control plane of last resort (or "the Home Page" of multiple spectrum bands). Its spectrum requirements would need to be kept modest, particularly when the intensity of connections increases, since we would ideally want it to operate under 1 GHz such as at 700 MHz.

In rural areas the control plane is likely to be very lightly loaded. This offers some headroom to serve very high priority low data rate applications and/or the needs of the emergency services and other vital services to improve the business case. On the other hand this starts to move away from the separation of control plane and user plane, which may be an undue complication for standardisation.

From a consumer perspective a priority need for better rural coverage has been for a voice 999 service [3]. If the modernisation of the 999 service allows a standardised "data" 999 call that in itself could extend the coverage as a lower speed data connection can be made to reach further than a voice connection. A data 999 service can of course also contribute significantly to the efficiency of delivering life-saving help. One of the features of 5G will be more awareness of context allowing smart prioritisation.

What now follows is a systematic look at the factors that could contribute to the objective of a leap forward in reach, reliability and rural coverage for the 5G era. The technical means by which this could be achieved considers all possible aspects of the end to end implementation of the wireless connection being that of base station deployment, cell size, backhaul links, spectrum, waveforms and the mobile terminal. Following this the reliability, economic considerations and business models will be addressed briefly.

3. Base Station Deployments and Topologies

3.1 Mast height at tree level as a limiting factor on reach and reliability

New ways for local planning authorities to work with mobile network operators offers huge future opportunities for local communities to benefit from a leap forward in rural coverage. In the past the priority for planning authorities has been to reduce mobile mast heights so that masts are visually screened by buildings and/or trees - with trees being the highest and more likely obstruction. However this also screens the RF signals and has defeated the objective of reliable coverage as illustrated in figure 3. The curves plotted in the diagram show how increasing the tree height above the line of sight from the base station and further into what is known as the "Fresnel zone" of the propagation channel will cause substantial diffraction or shadowing loss. To avoid this shadowing loss and be outside of the Fresnel zone, it is necessary for the tree height to be at least 3m less than the base station height.

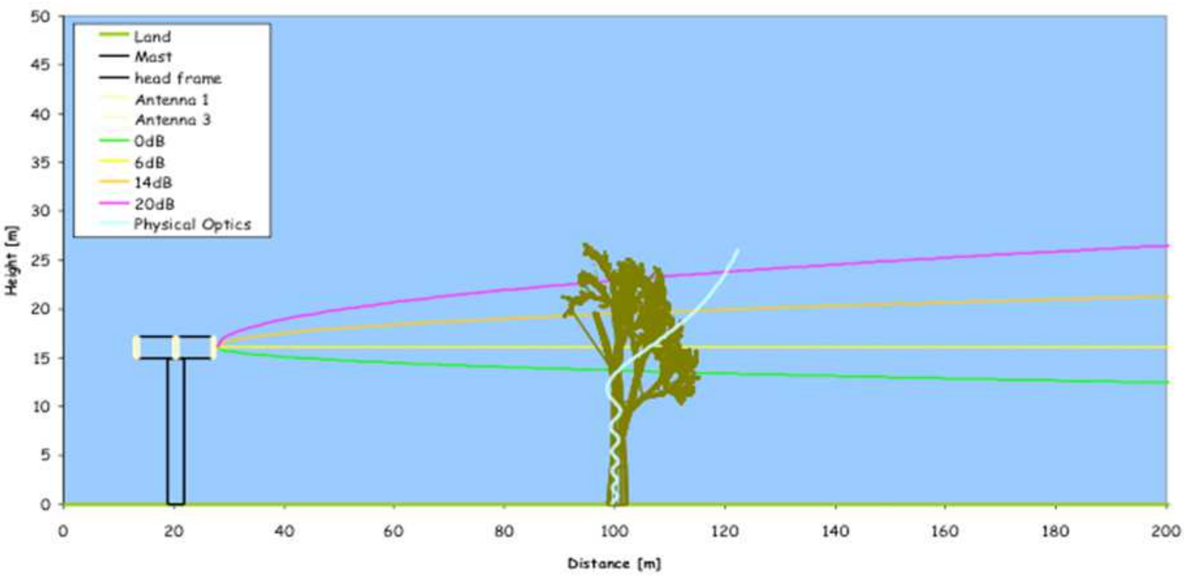

Figure 3 – Screening the visual impact of masts with trees also screens the RF signal. Source Telefonica UK

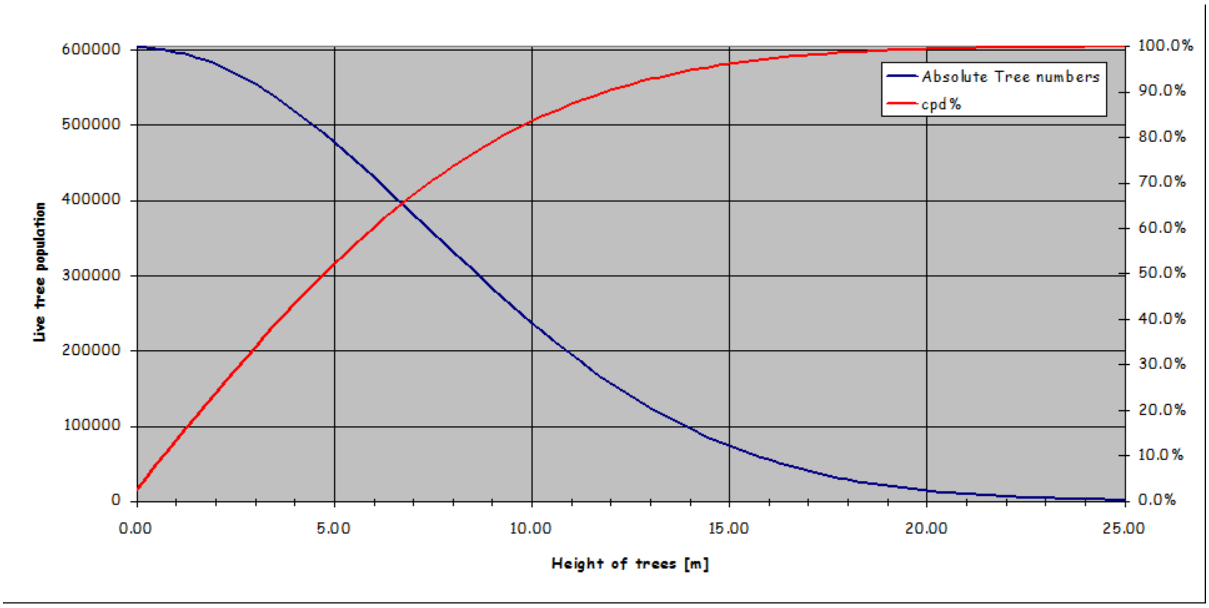

Figure 4 – Cumulative Distribution of tree heights against absolute numbers. Source Telefonica processing data from [4]

The full national damage to mobile reach and reliability emerges from the data on UK tree heights plotted in figure 4. Data is plotted showing the absolute numbers of trees at heights from 0m to 25m, while the cumulative probability distribution (CPD) is also shown. The CPD shows that even with a mast 10 meters tall there is still has a 30% chance of being blocked by trees (accounting for the Fresnel zone), whereas at 15 metres there is only less than 10% chance of blockage. At 25 metres the probability drops to less than 1%, which is a significant improvement for a small increase in base station height.

Having adjacent trees and or building at comparable heights to the mast can reduce coverage by as much as 70% in that direction, which is not in the interests of the operator, the local planning authorities and more importantly the mobile phone user. This is the source of many of today's mobile coverage issues for consumers in many rural locations.

It is natural for a local communities to object to a new "unsightly" mast suddenly appearing on a familiar landscape and particularly when many of these masts were built in an era when owning a mobile phone was a comparative rarity and therefore the benefits of good mobile coverage was not evident to many local communities. In the coming years many masts will be facing end-of-design life renewal. This provides the opportunity point for a new 5G approach that finds a more optimal balance between landscape aesthetics versus better mobile coverage. The key to a new approach is for local planning authorities to co-own the resulting quality of mobile coverage for their communities and their visitors. The proposition is for local planning authorities in rural communities to re-assess the benefits of increasing the height of existing masts to 25m, of which around 50% are 15m or less. There is also a possibility to make the aesthetics of such new "5G ready" taller masts more pleasing in much the same way the electricity industry has pursued for a new generation of electricity pylons that have proved to be more pleasing to the eye. Perhaps a design competition could spur this creativity. A new 5G approach that increases mast heights in rural areas needs to be carried into the Public Planning Guideline number 8 (PPG8) and General Permitted Development Order (GPDO) to facilitate the rolling out of the most cost effective and ubiquitous universal coverage.

3.2 Dressing the masts in an optimal way

A taller mast improves coverage but the extent depends upon the choice of which frequency band and corresponding set of antennas is put at the top of the mast and which are attached further down the mast.

Generally signals in lower frequency bands travel further. Therefore putting the lower frequency band antennas at the top of the mast provides the very best coverage reach. However signals in the higher bands are far more severely hit by attenuation from obstructions. This makes putting the antennas for the highest bands at the top of the mast the better option for users closer to the mast that can enjoy more capacity. However, this is at the expense of users at the extremities getting no signal at all. Each location needs to be considered on its merits. In very sparsely populated areas where say the prime application is mountain rescue or serving automated agriculture then the lowest frequency band antennas at the top of a 25m mast would be the best option. Other circumstances of a different demographic would lead to a different optimal solution. Modern multi-port, multi-band antennas may help here for single operator partnership sites, e.g. Mobile Network Partnership Ltd. (MBNL) or Cornerstone Telecommunications Infrastructure Ltd. (CTIL). More of a challenge will be shared (MBNL and CTIL) sites where maybe the minimum set of antennas should be at 25 metres and therefore requiring 30 metres in total in this circumstance.

Particular demographics may allow for directive antennas providing useful antenna gain. Massive-multiple input multiple output (MIMO) may also be a possibility particularly to serve users when they are nomadic or static by providing beamforming gains particularly in receive mode in uplink. Channel estimation (usually the main show stopper for Massive-MIMO at large distances) could be obtained by using "spatial swiping". Electronic tilting and 3D-beamforming (currently under study in 3GPP) may be applicable in some circumstances.

3.3 Relay and small cell infill technology

Traditionally it has been assumed that rural coverage is challenging in business case terms due to the low population density available to fund cell site investment. However, this stems from a low mean population density. Closer inspection of population distributions show that the vast majority of the rural population lives in clusters – small towns, villages and hamlets – where the local population density can be at suburban levels.

To meet these needs cost effectively, cells which can deliver coverage and capacity to small areas at costs which scale down at least as quickly – and preferably faster – than their capacity and coverage compared with traditional solutions.

Such solutions are starting to emerge, building on small cells developments originally intended for dense city areas. Repurposing such 'metrocell' technology for rural applications – which could be known as 'meadowcells' illustrated in figure 6 allow total operational costs to be reduced to as low as one tenth of a traditional macrocell or even lower. Solutions based on relay and even airborne technologies such as those illustrated in figure 5 are already available and more radical ideas also merit exploration in more detail including "personal base stations" for cars, device-to-device relays, unmanned aerial vehicles and low earth orbiting satellite constellations.

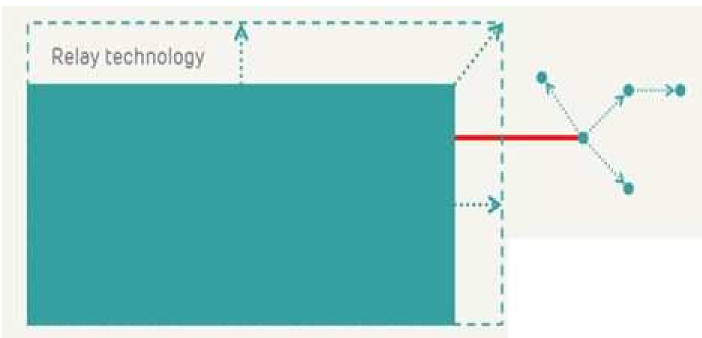

Figure 5 – Fibre infrastructure build – microwave radio extension

Figure 6 – Illustrative use of "meadow" cells. Source: Real Wireless Ltd.

Community Cells or "Meadowcells" can be applied to rural areas can be adapted from their urban counterpart for the following reasons:

- Metrocells have high capacity city slicker outdoor small cells
- Almost the same hardware can fit coverage needs to served compact settlements

A global analysis shows huge potential benefits in terms of increased population coverage for a given expenditure [5]. Some 650 million additional people could potentially benefit from mobile via small cells worldwide. The number of people benefiting increases sharply as the price of small cells falls. The study shows that a 9% increase in coverage equates to $1 trillion increase in GDP worldwide.

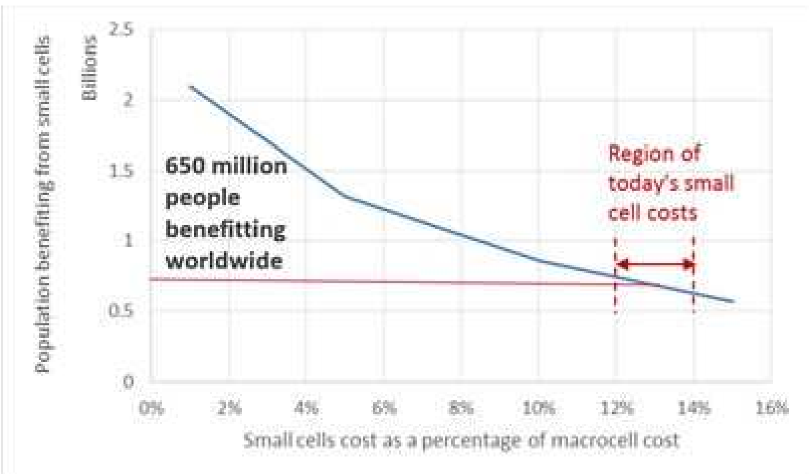

Figure 7 – Population benefiting from small cell globally for different small cell cost levels. Source Real Wireless Ltd. Note: costs in figure 7 are for small cells as opposed to Femto cells.

4. Spectrum Opportunities

New spectrum is often useful in providing an opportunity to do something radical. The UK is fortunate in having spectrum at 700 MHz being released on a convenient time-scale for a 5G rural initiative. A 700 MHz universal control plane is a possibility that merits study. White space is another potential opportunity below 1 GHz that might find application in rural solutions if the relevant bands find their way into the global smartphone supply chain. There is a growing body of mobile operator opinion to re-farm their 3G spectrum at 2.1 GHz that could be used for smaller macro-cells to in-fill capacity. All these spectrum opportunities are a useful incentive in the search for solutions to the rural coverage challenge. There is an inevitable trade-off between coverage and capacity in the selection of the channel widths. A 5 MHz wide channel with a longer frame structure may be a good point of departure for optimisation.

5. Possibility of better waveforms

LTE has a highly spectrally efficient waveform. The down-sides of LTE are the high signalling overheads and poor cell edge performance of a fully loaded network. The collapse of data capacity at the cell edge for fully loaded 4G cells represent a new class of coverage issue as very large cells (of the sort expected at 700 MHz in semi-rural/semi-urban areas) will lead to the cell edge areas that are also very large. In dense urban areas the cell edge capacity chasms can be filled with small cells using spectrum in the 2-4 GHz range. That may not be an economic general solution in semi-rural or perhaps even many semi-urban areas. It is one of the new "coverage of capacity" challenges.

The up-path cell edge issue can be helped by coordinated multipoint (CoMP), co-ordinated scheduling/beamforming and joint decoding but applying this has significant impact on the backhaul along with time synchronisation requirements. Applying similar techniques to the down-path typically places even heavier demands on the network in terms of latency and synchronisation and there may be more efficient solutions.

In the white papers from leading vendors are two proposals for a new waveform for wide area cells: Samsung propose Frequency Shift Keying and Quadrature Amplitude Modulation (FQAM) that they claim can deliver a 3-fold improvement in cell edge performance due to non-Gaussian inter-cell interference. Whilst the cell spectral efficiency might be lower than current orthogonal frequency division multiplexing (OFDM) used in 4G, the area spectral efficiency could win out for fully loaded cells. The 5G IC has also been studying both FQAM and also a novel scheme that can deliver an improvement in cell edge throughput by a factor of 14. Alcatel-Lucent propose in their white paper universally filtered orthogonal frequency division multiplexing (UF)-OFDM that provides flexible guard space between symbols and is suited to a wide range of data-rates with good peak to mean and spectral leakage characteristics. Note that it is important that the air interface be able to efficiently handle a wide range of traffic types including short messages.

Work remains to be done exploring what a new waveform might contribute to extending reach and reliability.

6. The Backhaul challenges

Backhaul is a key challenge with possibilities including taking fibre deep into rural areas to macro-cells with microwave extensions and community cells. Massive multiple input multiple output (MIMO) technology could be applied to backhaul links such that they would provide a beamforming gain to extend the range of the receive end, while the transmitter will still radiate the same level of electromagnetic power density within legally required radiation limits. Satellites and high altitude platforms could make a useful contribution to extending the reach of backhaul to far-flung remote locations. As an illustrative possibility Leo satellites could provide a sparse cell network coverage overlaying the dense cells and rural areas. It would provide a low latency C plane backhaul for all the terrestrial cells out of convenient (or low cost) reach of fixed network and the U plane for those users falling outside of the dense cells perhaps via community cells referred to earlier.

They could also pick up the low rate IoT traffic freeing small cells for what they are basically designed for, which is high rate data.

Use of traditional mobile spectrum should also be considered for ‘in-band’ backhaul as it’s unlikely that all of this spectrum will be required for capacity in rural locations and its low band and non-line of sight capability is likely to be useful in certain scenarios. An analysis of various unlicensed international scientific and medical (ISM) bands may offer opportunities as well, particularly in the 5GHz band though this may require new licencing rules to enable a higher effective isotropic radiated power (EIRP).

7. Performance of the Mobile Device (eg smartphone)

Effective coverage is being adversely affected by a rapid increase in the number of mobile spectrum bands being released, which requires ever more antennas to be packed into a tiny space of a smartphone to support several radio access technologies with several transceivers. It has become a runaway world for mobile device designers. The situation is exacerbated by the unavailability of high performance tuneable transceivers and antennas, which could be used on a single mobile terminal. The occupation of up to ten antennas on a single mobile terminal, where the antennas below 1GHz are small compared to a wavelength (otherwise known as having a small form factor) leads to an ever declining efficiency off-setting some of the coverage advantage of using spectrum under 1 GHz.

The degree of freedom for the smartphone designer is severely constrained by the user’s preference for the form factors that can be seen across the products on the market today, a large flat or curved screen with a small boundary frame, and an ever decreasing thickness. The efforts of the leading smartphone designers are nothing short of heroic in the face of these challenges. That said, from the network viewpoint, this decline in RF performance directly impacts the ability of the base station to reach the mobile resulting in a poorer “effective” coverage leading to rising consumer complaints and ever rising political pressure for greater investment in a “non-economic” solution. Figure 9 obtained from [6] illustrates the perspective of many network operators who, it has to be added, do not have the direct responsibility for solving the huge smartphones design challenges.

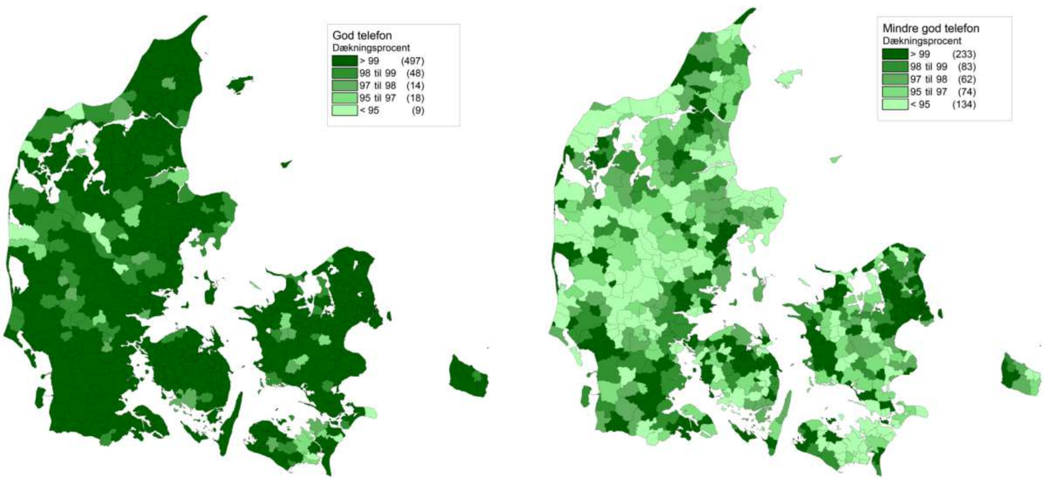

Figure 9 – Study by Denmark shows poor mobile phone performance hits national coverage hard. Source: Danish Business Authority [6]. Reproduced by kind permission.

From whichever perspective an important place to look for improvements in “effective” coverage is inside the future smartphone. Improved compact and low cost receiver amplifiers coupled together with improved efficiency in antennas above their minimum requirements for mobile standards, which many devices may already exceed to some extent, could enable the signal to noise ratio to be increased *as high as 40 times*. This will undoubtedly have impact on the ability to extend coverage to mobile devices in rural areas. Figure 8 illustrates how the components of the radio can be maximised, with the inclusion of using spectrum below 1GHz and the frame structure accommodated by choosing a waveform suited to low bandwidths. This will enable a low bandwidth RF front end with a high quality or Q-factor (maximised gain with low bandwidth) and also for receiving purposes it would require a low noise figure to avoid degradation in received signal to noise ratio. Finally an antenna with improved efficiency could be achieved by being external to the device.

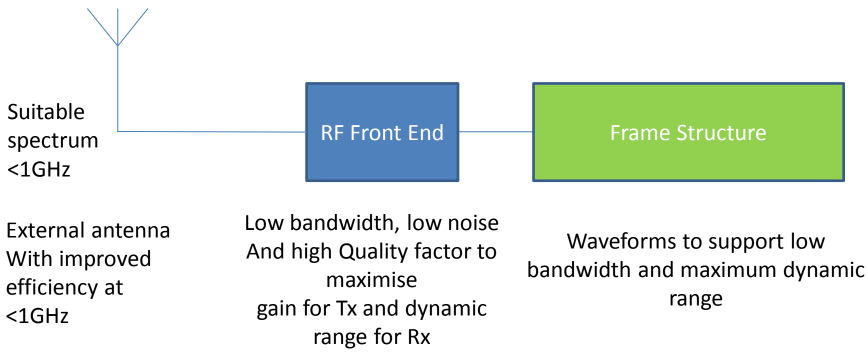

Figure 8 – Taking a deep look inside the smartphone for potential performance gains

Ideas for better RF performing smartphones include:

- <u>All devices</u> to have a standardised aerial socket <u>accessible to the consumer</u> so that those in problematic coverage areas could snap-on an external antenna to a standard smartphone. Standardised test methods should be made available to ensure these devices improve performance and do not emit unwanted RF signals.
- A localised repeater carried by the user or attached to the device with a high efficiency transceiver when necessary.
- Better RF front end sensitivity through development of low cost compact low noise amplifiers, while maintaining the high linearity demanded by the busy radio spectrum.
- Reserving at least one spectrum band under 1 GHz that is supported at device level with a carefully optimised high Q (or quality factor) front end providing not only a low noise figure but also a high antenna plus amplifier gain to maximise signal to noise ratio. This would need to by-pass the loss from sub-optimal multi-purpose wideband radios with a low Q which embraces all mobile bands.
- Some limited steerable directive antenna innovation at the device, which would additionally improve the signal to noise ratio.

The EU Radio Equipment Directive (RED) [7] is also changing the landscape by using over the air testing in addition to the conventional antenna port testing used today. While this is a great step forward in European mandated testing, it does present a major challenge to the proposal for the use of an external antenna. Any external antenna would have to have been tested with the specific phone for it to meet the directive. This is not necessarily a bad thing as the consumer interest is not served by poor designs that make things worse (detuning the front end or radiating intermodulation interference).

Smarter use of spectrum could improve the effective capacity in rural areas. For example if there was a choice of 700 and 1800MHz spectrum from a base-station site and all other things being equal, the mobile users that are far from the site could use the 700MHz spectrum and those that are nearer could use the 1800MHz spectrum. This capability exists today in long term evolution advanced carrier aggregation (LTE-A CA) optimisation and needs to be pushed further as a self-organising network (SON) optimisation across all bands.

8. Better reliability beyond just better coverage

Increasing reliance on mobile communications connectivity drives the need for ever more reliable networks and even ultra-reliable networks. This introduces a third class of new coverage challenge – the coverage of very dependable signals. Coverage also needs to be provided in such a way that the impact of technical network failures is minimised, there are a number of techniques available, many at a cost, to increase overall network availability. Consideration should be given within the field of SON to enabling ultra-reliable networks, opportunities include; use of spectrum and antenna tilts/beam-forming from adjacent sites to provide a level of coverage to compensate for a failed site, backhaul meshing should be possible through the use of traditional and cellular in-band techniques in parallel. Additionally, equipment redundancy and battery back-up will enhance overall service availability.

9. Innovative business models to bring down coverage costs in rural areas

There may be lessons to be learned from innovative approaches in India and Africa in taking cost out of infrastructure in areas of intrinsically low revenue such as rural areas. Some of these approaches, such as infrastructure sharing and outsourcing, are already being used by some UK mobile operators. The use of public networks by the emergency services and for connecting smart meters shows another route to improving the economics of better public coverage if any extra coverage put in for these specialist uses also becomes available for public use (even on a lower priority basis). Partnerships with local authorities or community groups could reduce the costs for operators to deploy while enhancing the digital credentials of a given location and therefore attracting greater inwards investment. This is only a superficial flagging of possibilities at this stage to stress that it requires more than just technical innovations to maximise the rural coverage.

10. Conclusions

The purpose of the White Paper has been to raise the profile in the global debate of the potential 5G contribution to improving universal (rural) reach and reliability. The White Paper has identified three future coverage challenges:

1. The tradition coverage issue of a getting a basic signal everywhere.
2. The "coverage of capacity" arising from the way new capacity solutions are highly uneven geographically.
3. The coverage of dependable connectivity – a combination of both a reliable signal and enough capacity.

It identifies possibilities rather than providing ready answers to these multiple coverage challenges. Some of the possibilities mentioned do not have to wait for 5G. However where they involve mutual action to be taken by different parties then attaching them to the 5G initiative can catalyse these different parties to work together. Finally, this contribution is no more than a first pass on an issue that requires a lot more work and attention including some worthwhile avenues for new research. There is always likely to be a huge gap between the best capacity/speeds in dense urban areas and what is economic to deploy across rural areas. Ambitions have to be scaled accordingly, but there remains significant scope for a significant leap in the capacity and reach of a universal mobile service for the 5G era. Further whilst capacity may always be more constrained this still leaves open the avenue of making what is provided ultra-reliable.

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