SMALL CELLS AND HETEROGENEOUS NETWORKS

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Meeting capacity and performance

Cellular mobile networks have evolved from offering a basic mobile telephony service to supporting high speed mobile broadband multi-media communications. But, can they continue to advance in order to cope with the ever increasing demands being placed on network capacity?

The mobile network is underpinned by wide area cellular radio coverage provided by macro-cell base station sites, typically deployed on building roof-tops, towers, columns and poles. Examples of macro-cell sites can be seen in Figure 1 overleaf.

Macro-cell sites typically consist of a number of cell sectors; individual radio transceivers which, via directional antennas, focus radio frequency energy in a specific direction. A typical site would consist of three cell sectors, each of 120 degrees to provide a complete 360 degrees of radio coverage.

Over the last decade mobile data traffic has grown at a phenomenal rate, driven by smartphone adoption, tablet computers and an ever-more diverse range of connected devices. The move to richer video-based content, along with the evolution from standard to high definition and ultra-high definition video, is placing ever greater demands on cellular network data capacity.

Mobile network operators have several techniques available to them for increasing system capacity, including improved spectral efficiency, more spectrum and more cell sites, as illustrated in Figure 2 overleaf.

Improved spectral efficiency

Spectral efficiency – measured in bits per second per Hertz (bit/s/Hz) - describes how much capacity (typically in Mbps) can be achieved from a given amount of spectrum (in MHz) and whilst modern cellular radio systems are getting as close as practically possible to theoretical limits, there is still scope for refarming spectrum from legacy systems to 4G Long Term Evolution (LTE) systems. Refarming refers to repurposing spectrum from one technology to another, for example from analogue Total Access Communication System to Global System for Mobile Communication (GSM) as witnessed in the 1990s. However nowadays maximum gains in spectral efficiency can be realised by refarming spectrum from GSM to LTE. For example; EE refarmed some of its 1800MHz spectrum from GSM to LTE to enable it to launch the UK's first 4G network in 2012, resulting in a net increase in the overall spectral efficiency of its spectrum holdings. Over the next decade it is likely that all mobile network operators will refarm ever more spectrum from GSM and Universal Mobile Telecommunications System (UMTS) to LTE. It is also possible to improve spectral efficiency by employing more complex antenna systems which focus the transmitted energy more precisely between the base station and mobile device.

More spectrum

Radio frequency spectrum is essential for the operation of mobile networks and the more of it an operator can acquire, the greater the system capacity they can offer from a given number of cell sites. However, it is not quite so simple; some spectrum is better suited to wide area coverage whilst some spectrum is ideal for capacity enhancements in high traffic areas. Low frequency band spectrum in the 800MHz and 900MHz bands tend to be well suited to wide area coverage whilst minimising the number of sites needed; mid-band spectrum in the 1800MHz and 2100MHz bands is reasonable for coverage and also useful for capacity while high band spectrum in the 2600MHz band (and higher bands in the future) is ideally suited to providing high capacity density in areas of significant demand.

More cells

The benefit of more cell sites is the opportunity for greater spatial reuse of spectrum assets. Modern cellular mobile systems typically implement a frequency reuse plan of 1, meaning that the same spectrum is deployed on each cell sector of every site. More cells could be realised through the increased sectorisation of macro-cell sites, typically splitting busy cells so they cover less area. For example, a 120 degrees coverage cell could be split into two cell sectors covering 60 degrees each, therefore increasing the number of cell sectors from three to four on a given site, If the other two cell sectors are upgraded through cell splitting in a similar manner, then a three cell sector site would become a six cell sector site. With the added interference due to the frequency reuse of 1, the net capacity gain of moving from a three cell sector to six will not be 100% but rather somewhere in the region of 70%.

However, there is only so much capacity which can be gained from cell splitting on macro-cells and this assumes the macro-cell can be upgraded in this manner which is not always the case and may not be the most cost-effective or best technical solution. Over the years many network operators have deployed ever smaller cell sites for a number of reasons, including capacity uplift, these are often mounted on small poles, lampposts

Figure 1: Typical macro cell site types

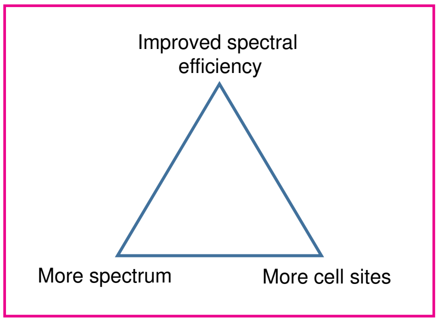

Figure 2: Network capacity levers

and buildings and are known as micro-cells. Examples of smaller micro-cell site types can be seen in Figure 3.

Micro-cells generally consist of macro-cell equipment with restricted power output to meet the requirements of their deployment scenario. The three sites in Figure 3 all have stand-alone base station equipment cabinets which are connected to external antennas via coaxial feeder cables, similar to a macro-cell design. These micro-cells are generally integrated with the macro-cell network and are typically deployed for coverage and/or capacity reasons. These sites are different to what is generally referred to as a small cell nowadays.

Small cells

Small cells are often considered to be anything non-macro although, as discussed above, it is not quite that simple. Bearing in mind micro-cells fall within the general category of macro networks, we are left with the need for a definition of small cells. Small cells are self-contained cellular radio base stations with integrated antenna systems. But even this definition takes us in two different directions, residential femto-cells and public access pico-cells. Residential femto-cells are small very low power base stations which are used for in-building coverage and generally connect to the mobile network via the subscriber's broadband line. Pico-cells on the other hand are deployed for public access in a range of locations to add capacity to an existing macro-cell network. They could be used also for coverage although it is reasonable to say that the primary use case is capacity in dense urban areas. The remainder of this article focusses on 4G LTE public access pico-cells and their use in heterogeneous networks consisting of a small cell layer and macro-cell layer.

Figure 4 (see foot of next page) illustrates the basic principle of a multi-layered heterogeneous network with a wide area macro-cell providing geographical coverage with an amount of data capacity while the underlying small cell layer provides additional capacity to meet the demand in high-traffic areas.

Small cell use cases

Given the definition we're using of a small cell as a public access pico-cell, we can identify a number of use cases including cell edge performance enhancement, in-building coverage, hot-spots and contiguous areas of

Figure 3: Smaller cell sites, often known as micro-cells

small cell coverage. The typical radio frequency output power of a pico-cell is between 1W and 5W.

Cell edge performance enhancement

One of the challenges of cellular network planning is that of cell edge performance. As a user moves away from a macro-cell, the signal-to-noise ratio gets worse and, as a result, the modulation scheme will step down and the coding depth will increase, both having the effect of reducing the user data rate. Macro-cell vendors invest significantly in radio resource schedulers and protocols to minimise this cell edge condition although it is a simple fact of co-channel cellular network operation. This issue is a challenge which LTE evolution and 5G research is seeking to address.

The diagram at the top of Figure 5 illustrates the standard macro-cell operation with a cell edge user being served by one macro-cell site whilst the other acts as a source of interference. Scheduling algorithms and inter-site coordination, typically via the LTE X2 interface [1], manage this interference at the expense of user data rate which can be significantly lower than that achievable by a user closer to the cell site.

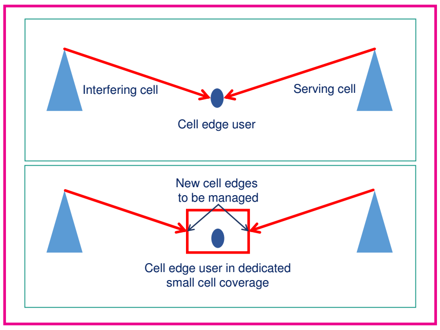

Figure 5: Macro-cell edge user without small cell and in enhanced small cell coverage

The diagram at the bottom of Figure 5 illustrates the concept of using a small cell to enhance cell edge performance. In this scenario the user connects to the small cell as the dominant serving cell. The radio conditions will be significantly improved and therefore the user will experience a higher data rate in both downlink and uplink. The small cell may be using dedicated spectrum, which is the ideal situation although, in many practical implementations in LTE networks, the small cells will be using spectrum that is also deployed in the macro-cell. This co-channel operation results in new challenges; the existence of a small cell results in new cell edges between the small cell and macro-cells. However, as the macro-cells transmit significantly higher power than the small cell, there needs to be a new mechanism to protect the small cell and enable efficient operation. This new mechanism is known as Enhanced Inter-Cell Interference Coordination (eICIC) and aims to enhance the small cell performance by minimising the power in certain resource blocks from the macro-cell. eICIC is not just a cell edge function, it can be used on co-channel small cells anywhere within the macro-cells network coverage.

In-building coverage

A dedicated small cell-based solution could be used to provide coverage and data capacity in buildings such as offices and shopping centres. There are several competing techniques which can address in-building coverage requirements and, to date, public access pico-cells have yet to be deployed extensively in this use case.

Hot spots

Hot spots are localised areas of significant data demand; places where people gather, quite often in city and town centres where there is already a high level of data demand. Small cells could be deployed on buildings or lampposts to address the specific demand and therefore free-up macro-cell capacity for the remainder of the wide area coverage.

Contiguous coverage

Small cell contiguous coverage is deployed to an area of significant data demand. This could be an area within a city or town, an example being the busy London shopping area on Oxford Street where small cells could be deployed to support the high data demand from people in the local shops, on the street and in the surrounding cafes and bars. Areas of contiguous coverage are the foundation of truly heterogeneous networks

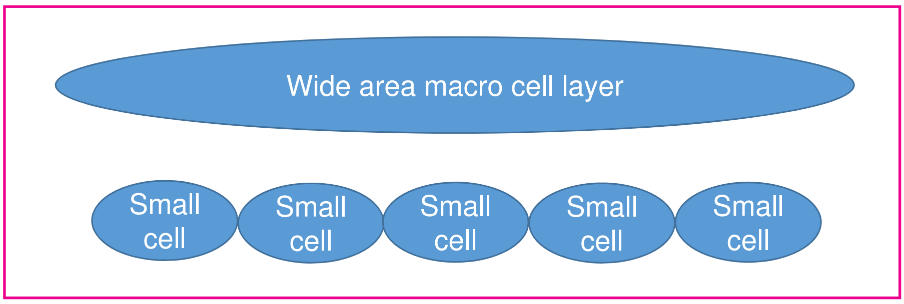

Figure 4: Basic principle of multi-layered cellular heterogeneous network

Figure 6: Small cell deployment on a lamppost

and is the principle on which 5G ultra-dense networks is being developed [2]. It is important to manage mobility in and out of the small cell layer to minimise signalling and optimise overall user experience. Going back to our use case of Oxford Street, whilst it is advantageous to off-load users to the small cell layer, it would be troublesome to have vehicles travelling at speed handing in and then over between many small cells as they drive the length of Oxford Street. In this case it is important to set the correct parameters to optimise the heterogeneous network operation. Hysteresis could be set such that a user needs to dwell on the small cell layer for a given period of time before handing down from the macro-cell; pedestrians would be handed down whilst users in vehicles would stay on the macro-cell network layer.

Small cell equipment

Small cell equipment is designed to be mounted on existing infrastructure such as lampposts, the side of buildings or bus shelters, thereby minimising the cost of deployment and visual impact of the radio infrastructure. Modules contain the radio base station and integrated antennas system although, in the majority of cases, will require additional equipment to provide the backhaul transmission connection towards the mobile operators core network.

Figure 6 is an example of a small cell deployed in a UK trial. This pico-cell is manufactured by Airspan[1] and supports a 20MHz LTE radio channel with 2 x 2 Multiple Input, Multiple Output (MIMO) and 1W of output power per transmit path. Small cells are available from a wide range of vendors, including Ericsson[2], Huawei[3] and Nokia[4]. Depending upon the duplex mode of operation or features implemented in support of the heterogeneous network, the small cell will require frequency synchronisation and probably phase synchronisation as well. Phase synchronisation is a requirement if the small cell is Time Division Duplex-based or if eICIC is implemented in support of co-channel operation [3].

Small cell backhaul

Small cell backhaul is a specialist field in its own right. Every public access pico-cell requires connectivity back to the mobile operators core network. There are a number of technologies which could be used for small cell backhaul from copper based solutions such as G.Fast, to fibre solutions such as dedicated point-to-point fibre and Passive Optical Network technologies along with a wide range of wireless small cell backhaul solutions.

Prior to selecting a backhaul technology, it is important to understand the capacity, performance and availability requirements of the small cell network. Small cells deployed for capacity in high-traffic areas will likely contain multiple radio frequency carriers and/or multiple radio access technologies, an example being LTE with WiFi. The minimum LTE MIMO mode is 2x2 although a larger number of antennas could be deployed. In addition, recent developments in standards have specified the use of 256 Quadrature Amplitude Modulation for LTE. This is likely to further increase the overall throughput of the small cell and therefore drive higher backhaul capacity requirements.

To ensure the user experience is consistent, the backhaul performance in terms of packet error loss rate, latency and packet delay variation must be as good as, if not better than, the wide area macro-cell network while availability must be very high to ensure user satisfaction and avoid congestion on the macro-cell layer.

Another consideration is the backhaul topology, given the deployment of small cells at street level. These considerations will vary between operators although the final solution will likely be a mix between fibre-based solutions and wireless links - possibly some advanced copper based solutions too. Reviewing these solutions in turn:

Copper

Advanced Digital Subscriber Line (DSL) technologies such as Vectored VDSL2 may be suitable for low capacity small cells although G.Fast is the most suitable solution given its high capacity and low latency. Coaxial-based solutions could also be used, the most common being cable TV-based DOCSIS3.0 and 3.1.

Fibre

Point-to-point fibre is ideal although the practicalities of managing such a high fibre count along with the cost of using so many fibres for relatively low capacity connections will be significant. Given the small cell deployments in dense urban areas, the practicalities of construction will also be difficult and costly. An alternative to point-to-point fibre is a solution based on passive optical networks, either Ethernet or Wavelength Division Multiplex-based.

Line-of-sight wireless solutions

Wireless small cell backhaul spans a range of solutions which vary from point-to-point, point-to-multi-point and multi-point-to-multi-point (mesh)-based radio systems [4]. Frequency bands vary from those used today for traditional higher-frequency microwave radio systems; anything from 28GHz upwards is considered appropriate whilst even higher frequencies in the millimetre wave bands are possible given the relatively short range links which are typical of this deployment scenario.

Point-to-multi-point and multi-point-to-multi-point systems in the 28GHz, 32GHz and 40GHz bands are being deployed to

[1] Airspan - see: http://www.airspan .com/solutions/small-cells/
[2] Ericsson - see: http://www.ericsson .com/ourportfolio/products/small-cells
[3] Huawei - see: http://www1.huawei .com/en/products/radio-access/small-cell/index.htm
[4] Nokia - see: http://networks.nokia .com/portfolio/products/small-cells

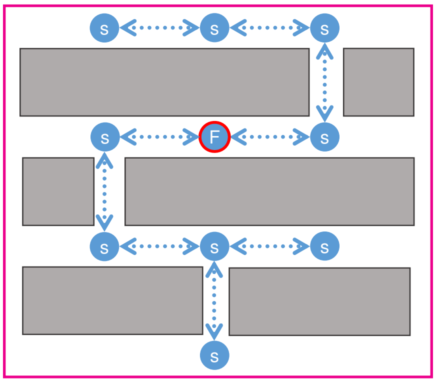

Figure 7: Fibre and wireless small cell backhaul topology

support small cell backhaul. These solutions reduce the number of physical radio nodes required on a given structure to support multiple connections; an important practical consideration for small cell site design.

V-band refers to the band centred around 60GHz which is unlicensed in the UK and most other countries. V-band systems tend to be point-to-point at the moment although the potential for mesh-based solutions is being explored. As well as benefitting from small antennas, V-band exhibits high atmospheric absorption which is actually beneficial in this scenario enabling greater frequency reuse and therefore higher link density. Beam-forming antennas are currently being developed for V-band radios which will reduce the on-site installation and commissioning time and avoid any issues with pole-sway (due to the narrow beam-width of current parabolic antennas in this band). E-band is another option for small cell backhaul although today these radios and antennas are a little too large to be practical. Smaller radios with evolved antennas should be on the market in a few years and will drive a re-evaluation of E-band for small cell backhaul.

Non or near line-of-sight wireless solutions

Wireless backhaul opportunities exist in sub-6GHz spectrum which is often used as radio access spectrum for cellular or WiFi. These lower frequency bands offer the advantage of not requiring a clear line-of-sight to maintain a working link although there is a price to be paid for this flexibility in terms of lower capacity and higher latency.

Figure 7 is an example of a small cell backhaul network topology following the street grid as the radios are installed below building height. In this scenario it is easy to understand how the required backhaul data rates increase as the traffic flows from the small cells to the fibre point-of-presence (the red circle identified with F). It is likely that operators will use parameters within the heterogeneous network to push traffic from the macro to the small cell layer whenever possible and therefore the backhaul will have to manage a high load on many adjacent cells simultaneously, limiting the benefits from statistical multiplexing within the backhaul traffic flow to the fibre point-of-presence.

Network security

As with all aspects of modern telecommunications network engineering, it is essential to consider the security aspects of small cell deployments. Given that small cells will be deployed on lampposts, walls of external buildings, in shopping centres, etc., the amount of physical security will be less than larger base stations which are accommodated in secure enclosures, many of which are surrounded by high fences. Physical and logical security will be necessary with precautions ranging from locking down unused Ethernet ports to implementing authentication to prevent man-in-the-middle attacks. In addition the user and control plane traffic will be encrypted through the use of IP Security.

AUTHOR'S CONCLUSIONS

4G LTE mobile networks will evolve to meet future capacity and performance requirements through the use of small cells and heterogeneous networks. Heterogeneous networks could include multiple layers and/or multiple radio access technologies, including WiFi. The principles explored here will form the basis of 5G ultra-dense networks which will likely be operational from 2020 onwards.

ABOUT THE AUTHOR

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Andy is BT's Principal Network Architect with responsibilities for radio access network architecture evolution and mobile backhaul strategy and architecture. Andy has over 30 years of experience within the telecommunications industry, mainly in radio access, transmission and transport network strategy, architecture and design. Andy has worked for Mercury Communications Ltd, Orange, France Telecom Group, H3G and EE. He is a Chartered Engineer, a Fellow of the ITP and a Fellow of both the Institution of Engineering and Technology and British Computer Society. He is a research mentor and industrial partner of the 5GIC at the University of Surrey, and a Visiting Professor at the University of Salford.

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ABBREVIATIONS

DSL	Digital Subscriber Line
eICIC	Enhanced Inter-Cell Interference Coordination
GSM	Global System for Mobile Communication
LTE	Long Term Evolution
MIMO	Multiple Input, Multiple Output
Mbps	Megabits per second

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