4G AND BEYOND IN AUSTRALIA

TECHNOLOGIES AND OPPORTUNITIES IN THE NBN ERA

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Fourth-generation cellular mobile wireless broadband systems are currently being trialled and deployed in Australia and around the world. This next generation is driven by increasing customer demand for ubiquitous access and higher data rates, the opportunity for increased revenues and lower costs for network operators, and the pursuit of more efficient, harmonised and profitable spectrum by regulators. Focusing on the 3GPP evolution path, we present an overview of technologies for 4G and beyond, and consider the opportunities in Australia in terms of spectrum, future wireless networks, and the National Broadband Network.

INTRODUCTION

Cellular wireless communications have evolved on an approximate ten-year generational cycle. In Australia second generation GSM was deployed in 1993, followed by UMTS (3GPP release 99) in 2003, and LTE (3GPP release 8) in 2011. Networks around the world and in Australia are currently entering the deployment phase of fourth generation (4G). If this trend continues, we can expect the next generation beyond 4G to emerge around 2020.

The ITU-R has established requirements for 4G under the banner of IMT-Advanced. While existing LTE deployments (3GPP release 8) do not meet these requirements, in October 2010, LTE-Advanced and WirelessMAN-Advanced were officially accorded IMT-Advanced status as 'true' 4G technologies (ITU-R 2010). In December 2010, the ITU-R allowed that the term 4G 'may also be applied to … LTE and WiMax, and to other evolved 3G technologies providing a substantial level of improvement in performance and capabilities with respect to the initial third generation systems…' (ITU-R 2010a).

While voice remains a key application, customers are increasingly demanding data-oriented services (Nokia Siemens Networks 2009), and are becoming agnostic to access and device technologies. Customers simply care about application performance and reliable, seamless access without regard to the technical details. Motivated by convenience, users wish to roam across heterogeneous technologies and providers locally or internationally (unless pricing distorts behaviour). While the delivery cost and price per bit is decreasing, increasing demand results in the end-user cost remaining approximately the same or even increasing.

Rapid sustained growth of customer base and usage, together with the global evolution of mobile broadband technologies provides an attractive business environment. The continuing advance of mobile broadband technology offers new services and applications, as well as opportunity for new players in the marketplace. Unsurprisingly the key driver for service providers and network operators is profit. They are moving to 4G and beyond with the clear goals of increasing capacity, increasing revenues and decreasing costs, alongside remaining competitive in terms of their offerings. There is a trend away from custom network cores and intelligence at the edge, towards a generic core with heterogeneous access and centralised service level intelligence.

4G and beyond wireless communications bring challenges to consolidated use of electromagnetic spectrum, as well as design of spectral-, cost- and energy-efficient high-speed systems with downward compatibility and upgrade capability. Meanwhile, there are tremendous opportunities, such as seamless access to all IP-based services anywhere, anytime.

In the Australian context, cellular operators are trialling and deploying 4G systems. The NBN will use TD-LTE (time division duplex), to support fixed wireless access broadband in areas beyond fibre-to-the-premises (FTTP) coverage. Looking forward, the NBN could provide a backhaul platform for beyond 4G, supporting future heterogeneous *cloud* and *distributed* network architectures.

KEY FEATURES OF 4G AND BEYOND

- **High data rate.** Proliferation of smart phones, tablets and mobile broadband equipped portable computers is causing mobile data usage to grow exponentially. It is predicted that mobile wireless data traffic will increase 50-fold by 2015 and perhaps 500-fold by 2020, corresponding to about 57 Gbytes per month per average subscriber (Liu et al 2011; Alcatel-Lucent 2011). Peak data rates have already evolved from kbps (2G), to Mbps (3G). Emerging 4G systems aim to offer 100Mbps up to 1 Gbps.
- **High spectrum flexibility.** Most previous and current commercial systems operate in crowded spectrum between 300 MHz and 3 GHz. Spectrum licenses are expensive for the network operator. Potential new spectrum in this range is limited to a few to-be-released bands occupied by older services such as the much-discussed 700 MHz analog television band. High spectrum flexibility is required to let 4G operate in different paired or unpaired configurations, including higher frequency bands, with flexible bandwidths, compatible with and superseding earlier generation systems.
- **High Capacity.** Customers demand seamless high-speed connection even in areas with dense subscriber populations. On the other hand, operators need the highest total data rate per Hertz of licensed spectrum from each base station to save cost (Dahlman et al 2011). IMT-Advanced peak spectral efficiency requirements are 15 bps/Hz (downlink) and 6.75 bps/Hz (uplink) (Wijting et al. 2009). Higher capacity delivers higher Quality-of-Service (QoS) and lower provider costs.
- **High energy- and cost- efficiency.** Base stations consume more energy to support wider coverage, higher data rates and more users per cell. Building more base stations could reduce the power consumption of each base station, but increases site and service costs. Higher energy consumption is undesirable from an environmental standpoint (Tombaz et al 2011; Alcatel-Lucent 2011; China Mobile Research Institute 2010). For customers, higher energy- and cost- efficiency means longer battery life, cheaper devices and lower environmental impact. 4G and beyond needs an innovative network architecture and smart end-user devices to achieve high energy- and cost-efficiency.
- **Low delay.** Interactive applications such as telepresence, real-time gaming, IP telephony, and social networking, as well as emerging machine-to-machine applications, have requirements for very low delay. The IMT-Advanced requirements are 100 ms for the control plane and 10 ms for the user plane (Parkvall et al 2011).

THE PATH TO 4G

First-generation cellular systems of the 1980s were analog voice systems, and were replaced by second-generation digital systems such as GSM and IS-95 CDMA in the 1990s. These narrowband 2G systems provided initial peak data rates of 9.6 kbps (Dahlman 2008). In the late 1990s, General Packet Radio Services (GPRS) introduced packet data over '2.5G' cellular systems. As a pre-3G technology, enhanced data rates for GSM evolution (EDGE) was introduced in 2003 increasing data rates to 400 kbps.

The International Mobile Telecommunications-2000 project (IMT-2000) was developed by the ITU (ITU-R 1997) to fix formal requirements for 3G mobile telecommunications, whose peak data rates are required to be at least 200 kbps (Dahlman 2008). Evolutions of 3G provide mobile broadband access of several Mbps, including 3GPP's WCDMA, its upgrade high speed packet access (HSPA)/HSPA+, and 3GPP2's CDMA2000 system. All 3G systems are based on code division multiple access (CDMA), a spread-spectrum technology (Ekstrom et al. 2006); (Astély et al. 2009).

Since 2008, in order to meet traffic growth forecasts and other issues such as spectrum efficiency and internet convergence, 4G systems have been the focus of ITU-R Working Party 5D (WP5D). IMT-Advanced (ITU-R 2008) defines 4G requirements and system capabilities beyond IMT-2000 (3G). Candidate radio technologies have abandoned CDMA in favour of Orthogonal Frequency Division Multiple Access (OFDMA), moving to signalling schemes allowing for frequency-domain equalisation, as well as introducing multiple antennas, dynamic channel allocation and channel-dependent scheduling.

All 4G services are IP based, and offer peak data rates of 1 Gbps for low mobility users and 100 Mbps for high mobility (3GPP 2011a). In late 2010, the ITU-R confirmed LTE–Advanced, 3GPP LTE release 10 (Ghosh et al. 2010); (3GPP 2011b); (3GPP 2011c) and WirelessMAN-Advanced, IEEE 802.16m (Ahmadi 2009) as 4G technologies. In this paper we will focus on the 3GPP family of standards.

Figure 1 gives an overview of the development of 4G within the 3GPP family. The first release of LTE, 3GPP release 8 was finalised in 2008 (Astély et al. 2009), and first deployed in 2009, supporting 300 Mbps downlink and 75 Mbps uplink peak data rates. Release 9, finalised in December 2009, has additions such as LTE home NodeB, location services, Multimedia Broadcast Multicast Services (MBMS), and multi-standard base stations (Dahlman 2008). Release 10, which is LTE-Advanced was finalised in March 2011. It further extends the performance and capabilities of 3GPP LTE Release 8/9, in particular through the use of improved multiple antenna techniques and carrier aggregation (3GPP 2011c; 3GPP 2011b). In Australia, the evolution from 3G to 4G is currently dominated by LTE and LTE-A trials and deployments as shown in Table 1.

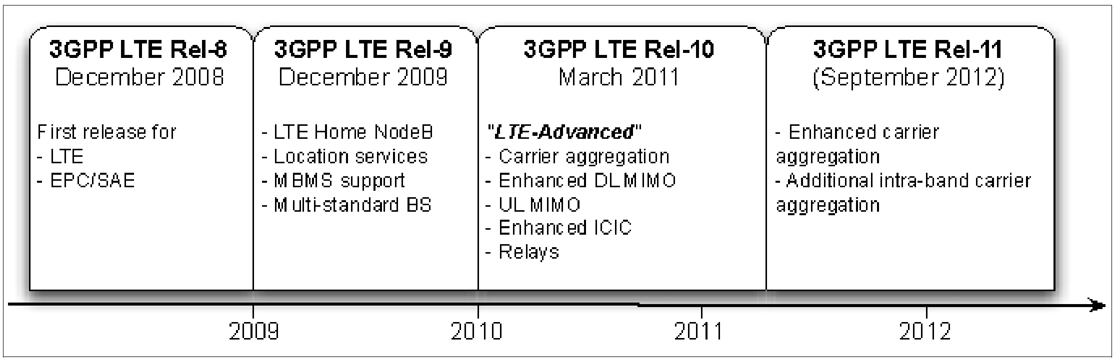

Figure 1 - Releases of 3GPP specifications for LTE/LTE-A.

Service Provider	Class	Carrier Frequency	Technology	Downlink	Uplink
Telstra	3G	2100 MHz	UMTS/ WCDMA / HSPA	Max: 384 kbps Typical: 200 kbps	Max: 384 kbps Typical: less than 200 kbps
	3G/ NextG	850 MHz	UMTS/ WCDMA / HSPA/ HSPA+	Max: 42 Mbps Typical: 20 Mbps	Max: 5.76 Mbps (HSUPA) Typical: 3 Mbps
	4G	1800 MHz	LTE Rel-7 & 8/OFDM/ SC-FDMA	Max: 100 Mbps	Max: 50 Mbps
Optus	3G	2100 MHz (Metro)/ 900 MHz (Regional)	UMTS/ WCDMA / HSPA	Max: 7.2 Mbps Typical: 512kbps–3Mbps	Max: 384 kbps Typical: 100 kbps – 250 kbps
	4G	1800 MHz (Trials) 700 MHz (Plan)	Note: 4G LTE (FD-LTE) services scheduled from April 2012 in Newcastle, Port Stephens, Hunter Valley and Lake Macquarie areas. Phased capital city rollout is expected from mid-2012. Optus has a scientific trial licence for testing in the 700MHz band in Bendigo, Victoria from October 2011, in partnership with Huawei.		
VHA	3G	2100MHz (Metro)/ 900 MHz (Regional)/ 850 MHz (Metro)	UMTS/ WCDMA/ HSPA	Max: 7.2 Mbps	Max: 384 kbps
	4G	1800 MHz (Trials)	LTE	Note: VHA/Huawei trails of LTE in Newcastle in Q4 2010,74.3Mbps downlink.	
Vivid Wireless	4G	2.3 GHz	WiMAX	Typical: 3.1 Mbps – 6.3 Mbps	N/A
NBN	4G	2.3 GHz	TD-LTE	Note: Wholesale only product Wholesaler guarantee minimal 500kbps to end user, up to 12 Mbps downlink, complete by 2015 Tri-sector base station connected to hub via 180 Mbps link Hub connected to fibre access using 900 Mbps Each base station serves 12 Mbps to 15 houses Supposed range up to 100 km from base station for 12 Mbps.	

Table 1 - 3G/4G networks in Australia.
Source: websites of Telstra, Optus, VHA, Vividwireless and NBN Co, 2011.

SPECTRUM

For regulators, the advance of mobile broadband technologies is not just about providing spectrum to deliver public benefit, as articulated through their governments. 4G technologies and beyond offer the opportunity for re-organising spectrum allocations to align with allocations elsewhere in what is a global telecommunications environment, to use spectrum more efficiently, and to consolidate allocations and release spectrum for new uses.

SPECTRUM FOR LTE-A (WORLDWIDE)

A 'core band' of spectrum at 2 GHz was initially identified for 3G systems in 1992. Additional spectrum at 800/900 MHz, 1800/1900 MHz and 2.6 GHz was identified for IMT-2000 in 2000. In 2007, IMT-2000 identified spectrum at 450 MHz, the 700 MHz 'digital dividend' and an additional 300 MHz at 2.3 GHz and 3.6 GHz band for 3G/4G systems (Dahlman 2008; Dahlman et al. 2011). Apart from the 'core band', the applicability and availability of these new bands varies on a regional and national basis.

SPECTRUM FOR LTE-A (AUSTRALIA)

The Australian Communications and Media Authority (ACMA) has allocated a number of frequency bands for IMT services and applications, many of which are based on ITU-R definitions. Table 2 sets out the frequency bands that are available for IMT services in Australia (ACMA 2011c). Table 1 lists bands in use for current 3G services in Australia.

Band	Spectrum	Type	Existing usage
825–845 and 870–890 MHz	2 x 20 MHz	Spectrum licence	Mobile telephony (3G- WCDMA/HSPA)
890–915 and 935–960 MHz	2 x 25 MHz	Apparatus	Mobile telephony (2G - GSM900 and 3G - WCDMA/HSPA)
1710–1785 and 1805–1880 MHz	2 x 75 MHz	Spectrum licence	Mobile telephony (GSM1800). Licensed for Australia-wide use (restricted to the lower 2x15 MHz in regional areas)
1900–1920 MHz	20 MHz 20 MHz	Spectrum licence Apparatus	3G services - Licensed in capital cities only Broadband. Licensed in regional and remote areas only
1920–1980 and 2110–2170 MHz	2 x 60 MHz 2 x 40 MHz/ 2 x 60 MHz	Spectrum licence Apparatus	3G mobile telephony and broadband. Licensed in capital cities and regional areas (restricted to the upper 20 MHz) 3G mobile telephony and broadband. Licensed in regional (2 x 40 MHz) and remote areas (2 x 60 MHz)
2302–2400 MHz	98 MHz	Spectrum licence	Broadband. Licensed in capital cities and regional areas.
2500–2690 MHz	2 x 70 MHz 50 MHz	Spectrum licence Spectrum licence	Band currently under review to allow for new services such as mobile telephony and wireless broadband in 2 x 70 MHz. Technology flexible framework underpinning ENG operation in 50 MHz.
3425–3442.5 and 3475–3492.5 MHz	2 x 17.5 MHz	Spectrum licence	Fixed wireless access, broadband. Licensed in capital cities and major regional centres.
3442.5–3475 and 3542.5–3575 MHz	2 x 33.5 MHz	Spectrum licence	Broadband. Licensed in capital cities and regional areas.
3575–3700 MHz	Up to 30 MHz	Apparatus	Fixed wireless access, broadband to coordinate with fixed links and Earth stations. Licensed in regional and remote areas.

Table 2 - Spectrum bands released for IMT services in Australia.
Source: 'Towards 2020 – Future spectrum requirements for mobile broadband', ACMA, May 2011.

Based on the total 800 MHz bandwidth of existing mobile spectrum, as shown in Table 2, the ACMA estimates that up to a further 150 MHz and 300 MHz of spectrum will be required by 2015 and 2020, respectively (ACMA 2011c). The ACMA have identified 700 MHz, 900 MHz, 2.5 GHz and 3.6 GHz as bands that could be made available for future LTE/LTE-A usage (ACMA 2011a; ACMA 2011c).

a) The 700 MHz Band

As a result of the analog television switch-off, the ACMA proposes to release the 700 MHz 'digital dividend' band to wireless communications. Two 45 MHz blocks of spectrum, 703–748 MHz and 758–803 MHz, will be reallocated nationally, from 2 November 2011 to 31 December 2014 (ACMA 2011d; ACMA 2011a). Optus in partnership with Huawei is trailing LTE in the 700 MHz band, as described in Table 1.

b) The 900 MHz Band

The ACMA is examining options to replan the 805-960 MHz band (currently planned for GSM) to improve its utility and potentially make additional spectrum available in the medium term for mobile broadband services (ACMA 2011b; ACMA 2011c).

c) The 2.5 GHz Band

Towards international harmonisation (ACMA 2011c), the ACMA is planning the 2.5 GHz band to permit 2 x 70 MHz segments in the frequency ranges 2500–2570 MHz and 2620–2690 MHz to be used for emerging wireless broadband access services, at least in major metropolitan areas (ACMA 2011d).

KEY TECHNOLOGIES FOR 4G

A wide array of technologies (software, devices, terminals, interfaces) will underpin the evolution to 4G and beyond. Here we focus on technologies specific to the radio air-interface.

CARRIER AGGREGATION

In order to meet the higher data rate requirements defined in IMT-Advanced, higher spectrum efficiency and wider transmission bandwidths are necessary than specifications in 3GPP LTE Release 8 & 9. Due to limited spectrum availability, it is difficult to reach the 100 MHz bandwidths specified in LTE-A (3GPP LTE Release 10) with improved spectrum efficiency alone. One of the most distinct features of LTE-A, carrier aggregation (CA), is the preferred solution (3GPP 2011b). Multiple component carriers (CC) are aggregated to form an equivalent larger transmission bandwidth for user equipment (UE), as illustrated Fig. 2. Up to five component carriers may be aggregated, possibly with different bandwidths up to 20 MHz (Holma and Toskala 2009; Dahlman 2008), providing a maximum bandwidth of 100 MHz (Guangxiang Yuan et al. 2010). With respect to the frequency location of the different CCs, as shown in Fig. 2, three different types can be identified:

A) Contiguous aggregation of CCs in a single spectrum band.

B) Non-contiguous aggregation of CCs in a single spectrum band.

C) Non-contiguous aggregation of CCs over multiple spectrum bands.

In addition to exploitation of fragmented spectrum and expansion each user’s overall bandwidth, carrier aggregation provides frequency domain interference management schemes for heterogeneous networks (Garcia et al 2009).

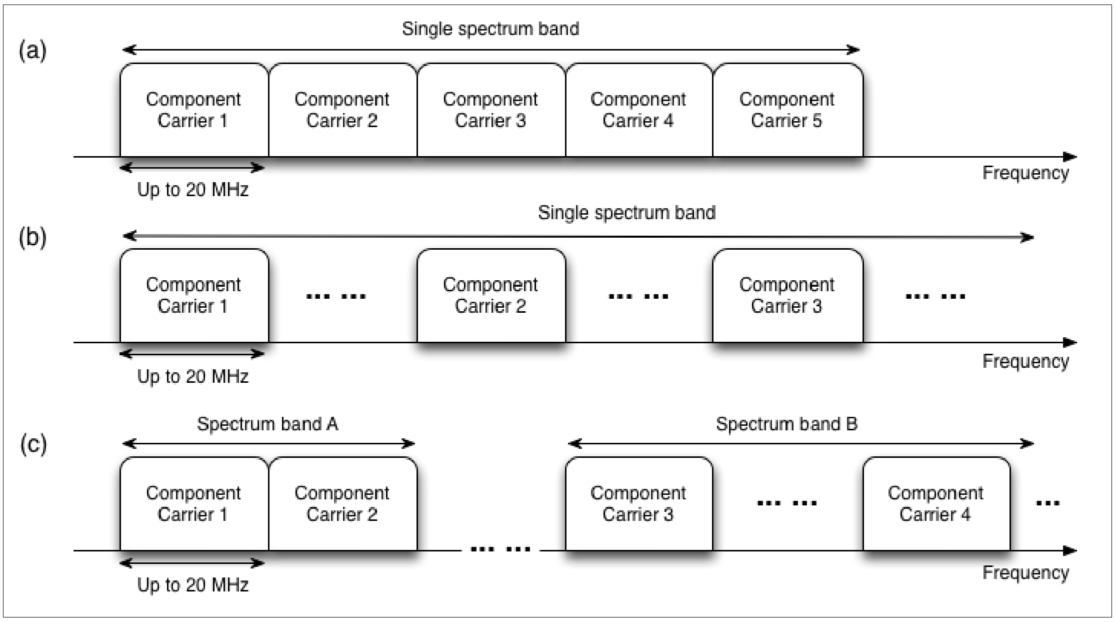

Figure 2 - Carrier aggregation types: (a) intraband contiguous; (b) intraband non-contiguous; (c) interband non-contiguous.

ENHANCED MULTIPLE ACCESS SCHEMES

a) Downlink: OFDMA with Component Carrier (CC)

Orthogonal Frequency Division Multiplexing (OFDM) (Holma and Toskala 2009) is a multicarrier modulation technique with high spectral efficiency and low complexity frequency-domain equalisation. OFDM transforms the frequency-selective mobile channel (which would otherwise require complex equalisation) into parallel flat fading channels requiring only single tap equalisers in the user equipment. OFDM can be efficiently implemented using the fast Fourier transform (FFT). OFDMA is a multiple access strategy based on OFDM, illustrated in Fig. 3, which has been chosen for the multiple access in downlink of LTE (Ekstrom et al. 2006; Dahlman 2008; Dahlman et al 2011). OFDMA also allows the possibility of efficient mapping of data onto advantageous subcarrier blocks, based on channel quality measures for the target user equipment. One of the challenges of OFDM is the large ratio of peak-to-average power, necessitating power amplifiers with high dynamic range. There are a number of signal pre-processing methods available to reduce this problem.

In order to support carrier aggregation in LTE-A, the downlink of LTE-A employs OFDMA with a component carrier based structure. Each transport OFDMA block is mapped to one CC and multiple CCs are transmitted in parallel (Dahlman etal 2011).

b) Uplink: DFT-Spreaded OFDM (DFT-S-OFDM)

User equipment requires energy efficient transmission to the base station to both maximise coverage and battery life. In part due to the significant increase in the cost of the mobile terminal to include a power amplifier with large dynamic range, OFDMA was not adopted for the LTE uplink (3GPP 2011b). One method to reduce the large power peaks of an OFDMA signal is precoding. Single Carrier Frequency Division Multiple Access (SC-FDMA), also known as DFT-S-OFDM, applies discrete Fourier transform processing before OFDMA and is used for the LTE uplink (Hyung G Myung et al 2006; Erik Dahlman, Stefan Parkvall, and Sköld 2011). Fig. 3 shows a block diagram of a SC-FDMA baseband system and the difference from OFDMA.

In 3GPP LTE Release 8 & 9 standards, only DFT-S-OFDM is employed for uplink. The enhanced uplink is applied to LTE-A (Release 10), in order to support carrier aggregation. DFT-S-OFDM is used for contiguous component carriers, while an additional clustered DFT-S-OFDM allows non-contiguous component carriers to form a wider bandwidth to single user equipment (Technologies 2011). The only difference between DFT-S-OFDM and clustered DFT-S-OFDM is the different subchannel assignment/collection blocks, as shown in Fig. 3.

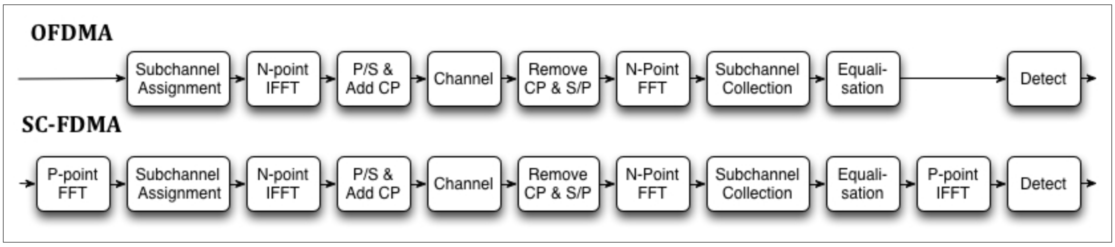

Figure 3 - Baseband system structure of OFDMA and SC-FDMA systems.

c) Advanced Multi-Antenna Transmission

Use of multiple antennas at the transmitter, receiver, or both in combination with advanced signal processing can significantly improve spectral efficiency, data rates, and signal coverage. Many multi-antenna transmission techniques are involved in LTE Release 8 & 9, including space-frequency block coding (SFBC), frequency shift time diversity (FSTD), spatial multiplexing with up to four layers (Dahlman 2008), codebook-based beamforming, and multi-user (MU) multi-input multi-output (MIMO) (Parkvall et al 2011).

The performance of downlink and uplink transmission in LTE Release 10 (LTE-A) is enhanced by the following multi-antenna features (Ghosh et al. 2010), as shown in Fig. 4:

- *Enhanced single-cell downlink MU-MIMO:* Two layers of orthogonal UE-specific reference signals enables two data streams to be multiplexed to a single UE or to two different UEs in spatial diversity fashion.
- *Extension to eight-layer downlink spatial multiplexing:* Aims to improve the downlink peak throughput of LTE-A employing eight or more transmit antennas.
- *Downlink Coordinated Multi-Point (CoMP) transmission:* CoMP enables corporation among eNBs that may or may not be collocated, including coordinated multi-point transmission in downlink and coordinated multi-point reception in uplink, in order to increase the throughput of cell-edge users (Osseiran et al. 2009).
- *Extension to four-layer uplink spatial multiplexing:* It is envisioned that LTE Release 10 compatible UE may support up to four transmit antennas, and the extension to four-layer spatial multiplexing is targeted to improve the uplink peak rate in such cases.

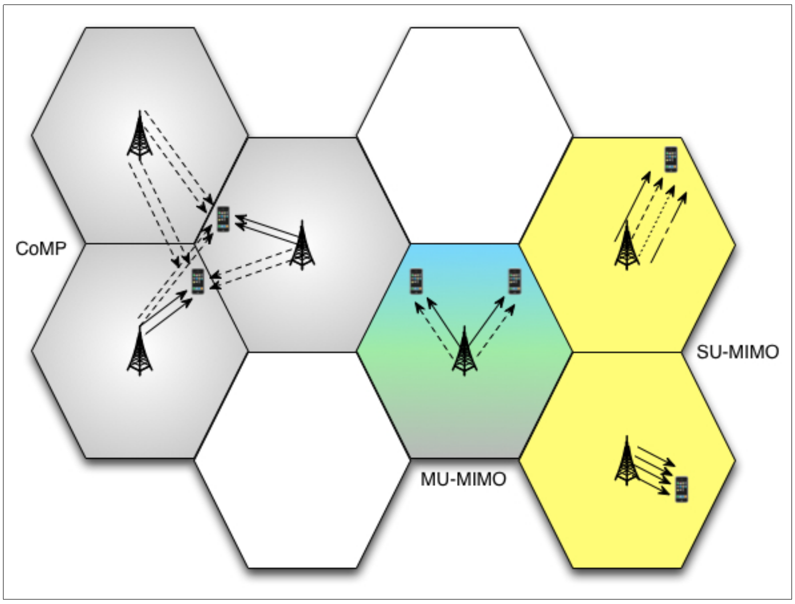

Figure 4 - LTE-A main MIMO modes.

d) Heterogeneous Networks

Traditional wireless cellular networks are homogeneous, deploying base stations in a carefully planned manner. User terminals connect to the cell with the strongest received downlink. Increased capacity and spectral efficiency can be achieved by bringing the base station closer to user terminals (Qualcomm 2011). As an advanced network topology used in LTE-A, heterogeneous networks provides a diverse set of low-power nodes to let user terminals connect to nodes with the lowest path loss. Distributed low-power nodes can be relays, home-eNBs, micro-eNBs, pico-eNBs, and distributed antenna systems (DASs). The signal-to-interference ratio experienced by the terminal at the outermost coverage area of the low-power node is, due to the difference in output power between the high-power macro and the low-power node, significantly lower than in a homogeneous macro network (Parkvall et al 2011) (Ghosh et al. 2010).

As shown in Figure 5, relaying is one of the heterogeneous network features being proposed for LTE-A. Relaying aims to enhance coverage, capacity and cell edge performance (Loa et al. 2010). Two types of relay nodes (RN) have been defined in LTE-A (Yang Yang et al. 2009):

- *Type 1 LTE relay nodes*: Transmitting their own synchronisation channels and cell identity, cells controlled by type 1 LTE relays are downward compatible with LTE Release 8.
- *Type 2 LTE relay nodes*: These relay nodes do not have their own cell identity and appear just like the main cell to the UE. UEs are controlled by the eNB and communicate with both relay nodes and the main eNB.

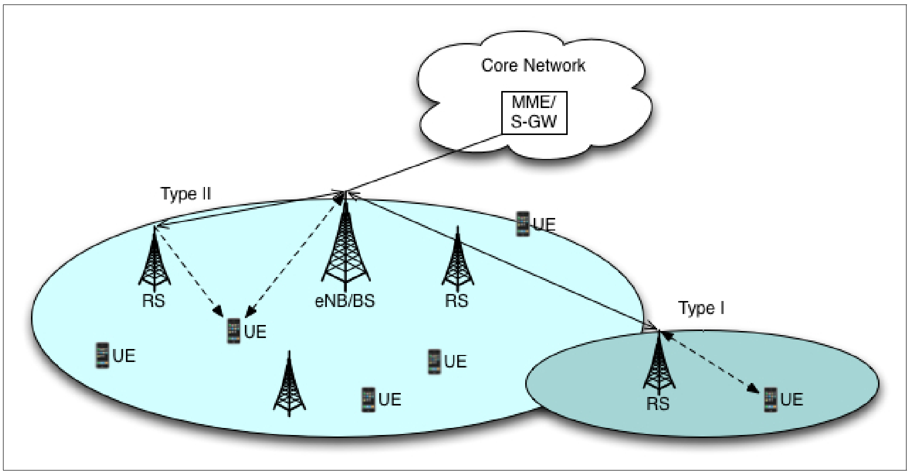

Figure 5 - LTE/LTE-A relaying architecture.

e) Software Defined Radio (SDR)

Earlier generations of mobile wireless systems, including many 3G deployments, used application specific integrated circuits (ASICs) in both infrastructure and handsets. This was motivated by power consumption; size and cost per unit, but entailed high non-recoverable engineering (NRE) costs, and difficult upgrade paths, particularly for air interface changes. In recent years, the cost, size and capability of reconfigurable and reprogrammable processing technologies such as field programmable gate arrays (FPGAs) and digital signal processors (DSPs) have become attractive for software-defined radio implementation.

These reconfigurable and reprogrammable devices, together with general-purpose processors (GPPs), have made software-defined radio (SDR) possible. In the SDR approach, large parts of the radio waveform are defined in software. The radio waveform can be changed during operation through software control and additional waveforms and modifications can be implemented with software updates, without modification of the SDR hardware platform (Ulversoy 2010).

SDR technology offers the possibility of adaptive and cognitive operation, multi-band and multi-mode (i.e. multi-protocol) operation, radio reconfiguration, remote upgrade and potential to accommodate new applications and services without hardware changes (Kaul 2007). Such flexibility is attractive for both infrastructure and smart phone handsets in mobile broadband networks where multi-protocol operation, common platform, backward compatibility, and equipment upgrade paths are all highly desirable.

Many smart phones are already software defined to a large extent, although this does not always extend to the radio air-interface. Several base stations for 4G are already SDR implementations of one form or another, including products from Huawei, Ericsson and Alcatel-Lucent that allow for a single radio access network (RAN) for various wireless standards (2G, 3G and 4G on the same platform).

TECHNOLOGIES FOR BEYOND 4G

Beyond 4G mobile wireless communication systems will be concerned with increasing capacity, as well as spectral-, cost- and energy-efficiency. Potential solutions include dense small cells and a move towards innovative radio access network architectures.

The future mobile network will be heterogeneous with diverse low-power base stations, supporting macro- pico- and femto-cells, relays, and advanced distributed antenna systems, all in the same spectrum. We expect a continued migration from intelligence at the edges towards intelligence 'in the cloud'. Such a network needs a high capacity backhaul transmission and enhanced radio access network (RAN) topology. Possibilities include centralised and distributed architectures. The objective of all of these approaches is to move towards thinking of the RAN as a massive distributed multi-antenna array dynamically adopting a variety of transmission strategies (from connection to a single cell through to spatial diversity/re-use and relaying through to distributed multi-cell MIMO). These architectures aim to reduce network and operation costs, optimise resource allocation, improve power efficiency, facilitate collaborative radio technology, and support multi-standard operations.

For smaller-scale networks, a centralised cloud RAN can distribute the radio frequency (RF) processing at remote radio units (RRUs), and centrally process the baseband and radio resource management (RRM) at the network controller. By combining cloud computing technologies and MIMO signal processing, centralised cloud RAN can achieve the significantly improved energy efficiency and capacity, adaptability to non-uniform traffic, cost-saving on Capital expenditure (CAPEX) & Operational expenditures (OPEX) and smart internet traffic offload (Liu et al 2011) (China Mobile Research Institute 2010).

Fig. 6 illustrates one possible implementation of the centralised RAN concept: Centralised processing, Cooperative radio, and Cloud infrastructure Radio Access Network (C-RAN) proposed by China Mobile Research Institute (China Mobile Research Institute 2010). Based on SDR multiprotocol platform, C-RAN architecture involves many small RRUs and centralised processing units (CPUs). It uses virtualised baseband processing by combining all radio and computing resource scheduling.

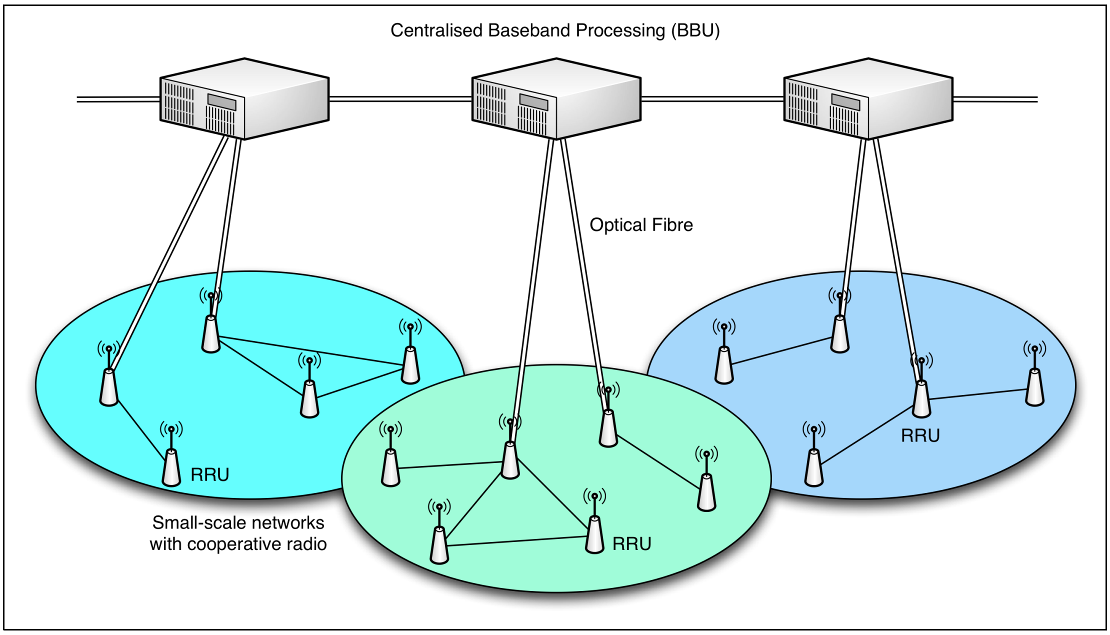

Figure 6 - C-RAN architecture.

For large-scale networks or when backhaul transmission is expensive, distributing some computation and processing at the cell access points may be preferred. In this case the RAN consists of dense small cells with compact micro/pico base stations, which take care of the baseband processing and maybe part of the RRM control. This distributed architecture is more scalable because of the reduced computational and signalling loading in the network controller, however the robustness and effectiveness of the control algorithms will be challenging.

One example of a distributed RAN is lightRadio, proposed by Alcatel- Lucent (Alcatel-Lucent 2011), illustrated in Fig. 7. Antennas and base stations are broken out into small, smart components that are distributed throughout the network. There are three different baseband processing configurations: baseband processing in the radio head (all-in-one), processing at the base of the tower (conventional baseband units) and centralised, pooled baseband processing ('in the cloud') (Alcatel-Lucent 2011).

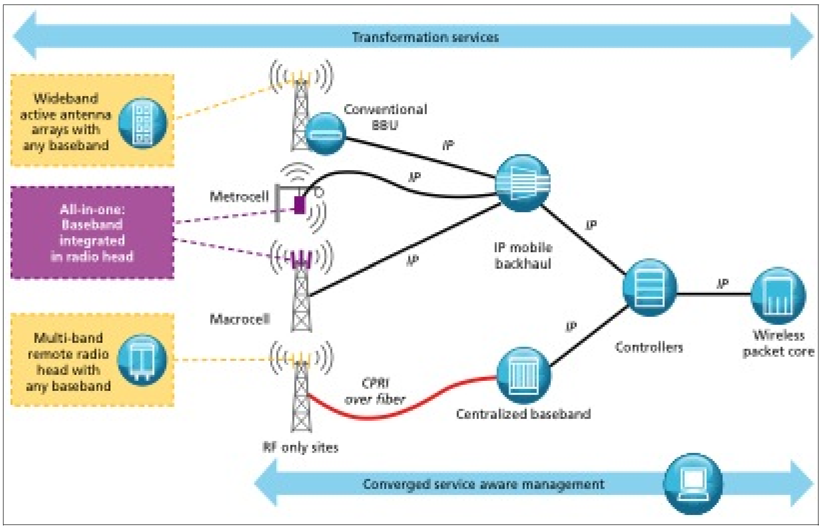

Figure 7 - lightRadio architecture.
Source: Alcatel-Lucent, 'lightRadio Portfolio: Technical Overview', White Paper, June 2011.

WIRELESS BROADBAND IN THE ERA OF NBN

The National Broadband Network (NBN) is a nationwide next-generation high-speed broadband network supported by the Australian government (NBN Co 2011). The NBN is providing initial peak download speeds of 100 Mbps, with the capacity for further upgrades in the future, to 93% of Australian premises by fibre-to-the-premises (FTTP) and 12 Mbps to the remaining 7%, in which 4% will be serviced by fixed wireless and the other 3% by satellite, as shown in Fig. 8.

The fixed-wireless broadband network of the NBN operates in a 2.3GHz band and uses LTE in time division duplex mode (allowing operation in unpaired spectrum). NBN Co. may also be interested in the upcoming 700 MHz 'digital dividend' (Alcatel-Lucent 2009). The NBN fixed wireless will serve rural Australia with download speeds of up to 12 Mbps and upload speeds reaching 1Mbps to mass-market customers and 4 Mbps for business customers. Unlike mobile broadband, the NBN fixed wireless solution has no inter-cell handoff and offers consistent and stable services to a known number of users in the coverage area.

In a thought-provoking paper in a previous edition of this journal, Tucker (Tucker 2010) lucidly argued against National broadband access via wireless alone, citing a requirement for a large, ugly radio tower outside of each and every residence. Somewhat ironically, the impending availability of near-ubiquitous, plentiful residential backhaul creates an interesting opportunity, where the heterogeneous beyond 4G RAN architectures described above could become one of the 'killer apps' of the fibre-centric NBN. This could be facilitated by small, low cost, commodity mobile broadband access points indeed located at every residence.

Whereas limited backhaul speeds and pricing structures have previously limited the exploitation of commodity wireless 'hot-spots', vastly increased data rates and wholesale backhaul provides new opportunities and business models. With the NBN operating in a technology neutral wholesale model, innovative service providers (or virtual mobile network operators) could potentially deliver pico and/or femto cells at the premises providing user access and extending the reach of centralised/distributed heterogeneous operator RANs, as illustrated in Fig. 8.

An FTTP network could eventually complement existing mobile core networks to facilitate 'mobile-over-fibre' and 'fixed/mobile convergence', which are promising and viable solutions for beyond 4G.

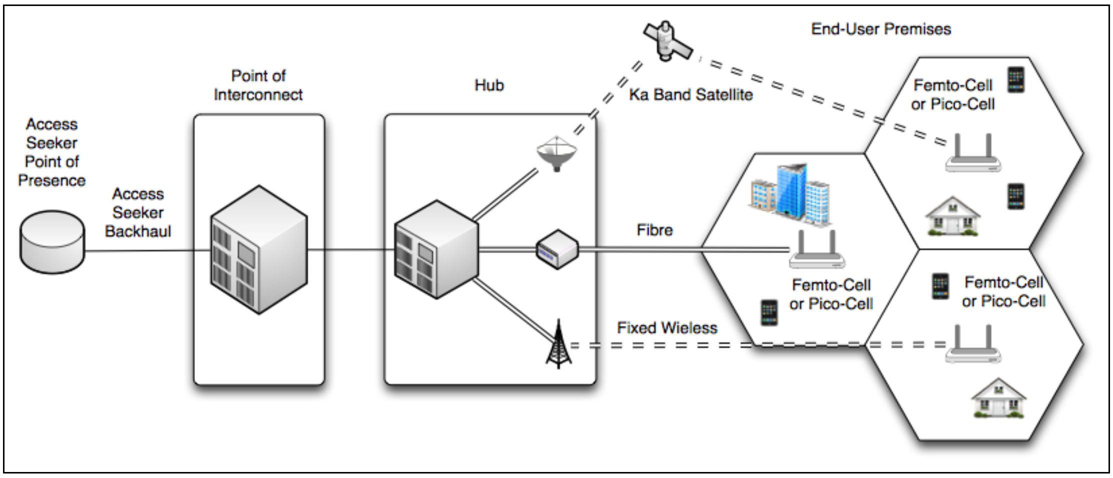

Figure 8 - NBN architecture and small cells backhauled by the NBN.

CONCLUSIONS

Australian network operators and regulators are facing the challenges and opportunities raised by a shift to data-centric 4G mobile wireless broadband concurrent with deployment of the National Broadband Network. Australia has a history of leadership and innovation in mobile broadband deployment and uptake. Looking forward can Australia lead the world beyond 4G? In this paper we gave and overview of drivers, history and technologies for 4G and beyond. We propose the use of near-ubiquitous fibre infrastructure as a platform to support future beyond 4G wireless broadband services, facilitating the concepts of mobile-over-fibre and fixed/mobile convergence, towards future *green, efficient* and *fast* mobile wireless communications in Australia.

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Cite this article as: Luo, Lin; Davis, Linda; Grant, Alex. 2012. '4G and beyond in Australia: Technologies and opportunities in the NBN era'. *Telecommunications Journal of Australia* 62 (1): 15.1-15.15. Available from: http://tja.org.au.