NGARA BROADBAND ACCESS SYSTEM FOR RURAL AND REGIONAL AREAS

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Multi-user multiple-input multiple-output (MU-MIMO) systems have been proposed as a solution for increasing bandwidth efficiency in wireless networks. In this paper we describe a new approach to MU-MIMO for rural and regional areas that we have developed and implemented. The proposed system has achieved six-user MU-MIMO with 12 Mb/s per user data rate in each direction (uplink and downlink, ie. symmetric) over a single 7 MHz channel in an actual rural environment for the first time in the world. The system is in fact capable of providing 50 Mb/s symmetric broadband access for up to 12 simultaneous users over a 28 MHz channel from a single access point. The key aspects of the new system are a synchronisation technology, an access point multi antenna design, an accurate channel estimation and feedback algorithm, and a low computational complexity implementation of crucial signal processing components.

INTRODUCTION

Access to the Internet is becoming increasingly important across the full spectrum of daily life. As such, it is ever more important to work towards enabling the ultimate goal of universal coverage, to ensure no segments of society are left behind. The challenge though is not just to provide coverage, but to provide it universally at the highest possible data rates. High density geographic areas have a natural advantage in terms of the practical aspects of reaching households with fibre rollout and individuals with mobile services. They also have the economic advantages of economies of scale. Rural and regional areas are much more challenging.

In many respects it is rural and regional areas that need high data rate broadband the most. The barriers of isolation and the sheer distances from population centres are two of the things that broadband communications is ideally suited to addressing. Many critical broadband services, especially the anticipated future services, such as telehealth, remote-education, e-Commerce and e-Government services, will have their most profound impact in the rural and regional areas. Many of them require (or will require) high definition real-time two-way video; and this dictates that the broadband infrastructure must support access speeds of up to 50 Mbps – as high as the speeds available over optical fibre in high density cities.

Providing inexpensive high data rate Internet access to the home in rural and remote areas presents many challenges. User terminals are scattered over large geographic areas (e.g. tens of residences per 100 km^2), and the cost of deploying a wired network is considered to be prohibitive. Satellite technology has been known to be effective in establishing wireless data links in remote areas; however it is also known to have limited data capacity and may not be suitable for servicing a larger population. In this paper we consider terrestrial wireless access.

Two of the main challenges in any network design are coverage and capacity. In wireless networks there is the additional challenge of needing to use the limited spectrum most efficiency. In the rural and regional deployment case, these considerations come together and present a problem that is not directly addressed by current wireless systems that either tend to be focused on high density deployments or long range point to point links.

Some efforts have been made to specifically address the particular challenges presented by rural and regional wireless deployment. These include wireless local loop (Momtahan 2001; Nedevschi 2007), wireless local area network (Zhang 2004; Raman 2007; Paul 2007), wireless metropolitan area network (Hincapie 2007; Giuliano 2008), and more recently wireless regional area network (Liang 2008). However, the bandwidth efficiency achieved by those technologies is typically limited to less than 5 bits/s/Hz. This means that it is necessary to either have an extremely wide band spectrum allocation or a very large number of base stations, in order to provide data rates comparable to those available in heavily populated city areas. Neither of these options is practical. Clearly, new highly spectrally efficient wide coverage technologies are needed.

Multi-user multiple-input multiple-output (MU-MIMO) systems have been proposed as a solution for increasing bandwidth efficiency in wireless networks (Spencer 2004; Peel 2005; Hochwald 2005). MU-MIMO typically consists of multiple user terminals, each equipped with a single antenna, and a central access point or base station, equipped with multiple antennas. MU-MIMO performs space division multiple access (SDMA) that allows the use of the same frequency at the same time by multiple user terminals. Conceptually it can be viewed as parallel beamforming, where separate beams are formed to each user (at the same time), as opposed to traditional beamforming that only forms a single beam at any given time. The bandwidth efficiency improves by the factor corresponding to the number of SDMA user terminals.

While the concept of MU-MIMO has been incorporated in the latest and near future mobile wireless standards, such as Long Term Evolution (LTE) and Long Term Evolution Advanced (LTE-A) (Ghosh 2010), very few actual implementations have so far been reported in the literature. Only up to two-user MU-MIMO SDMA has been previously demonstrated in a realistic environment (Nortel 2007).

In this paper we describe a new approach to MU-MIMO for rural and regional areas that we have developed and implemented, that has achieved six-user MU-MIMO SDMA with 12 Mb/s per user data rate in each direction (uplink and downlink, ie. symmetric) over a single 7 MHz channel in an actual rural environment for the first time in the world. The system is in fact capable of providing 50 Mb/s symmetric broadband access for up to 12 simultaneous users over a 28 MHz channel from a single access point.

The key aspects of the new system are a synchronisation technology that has been developed using global positioning satellite (GPS) signals for timing references in the user terminals, an access point multi antenna design that limits electromagnetic coupling between elements, an accurate channel estimation and feedback algorithm, and a low computational complexity implementation of crucial signal processing components (Suzuki 2009).

We call the proposed system Ngara Wireless Broadband Access. Ngara is a word of the Aboriginal Darug people meaning to listen, hear and think. In the system, user terminals are each equipped with a directional antenna free of clutter, and equipped with a GPS receiver which we use as the basis for a multi-user synchronisation scheme. Unlike in mobile systems, the use of GPS is practical since the user terminal antenna is stationary, outdoors (so the GPS signal is always available), and can be connected to mains power (so battery life is not an issue). The central access point is equipped with a uniform circular array installed on a high tower.

Our proposed GPS based synchronisation enables user terminals to form a virtual antenna array. Hence, MU-MIMO signal processing with zero-forcing equalisation can be used to provide a highly spectrum efficient uplink. By utilising the reciprocity of the channel, the same zero-forcing matrix can be used to perform zero-forcing precoding on the downlink. We also note that the use of channel reciprocity is not essential to the proposed system. In the event where channel reciprocity does not hold (due to imperfection of radio hardware, for example), downlink channel estimates need to be fed back from user terminals to the access point via uplink.

This paper is organised as follows. The system architecture of the Ngara Wireless Broadband Access is described in Section 2. In Section 3, the key technical aspects of the system are reviewed. We have performed three public demonstrations using the Ngara Wireless Broadband Access technologies, which are described in Section 4. Comparison with standard LTE based system is discussed in Section 5, followed by conclusions in Section 6.

SYSTEM ARCHITECTURE

The architecture of our Ngara Broadband Access system is shown in Figure 1. The system consists of a central access point and multiple of user terminals.

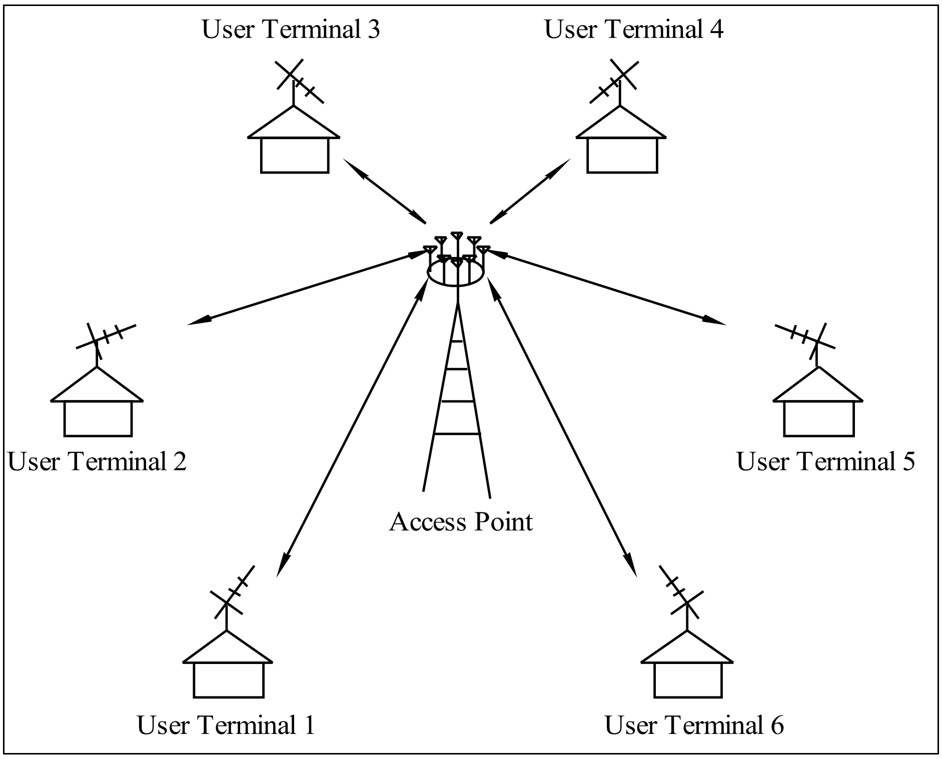

Figure 1 - An example configuration of proposed fixed wireless access system in rural areas.

A user terminal contains the following:

- a GPS receiver that provides accurate timing and frequency references,
- a digital signal processing module that generates and decodes radio packets in real-time,
- a radio up-converter and down-converter module,
- a radio power amplifier module, and
- an antenna switch module,

The central access point consists of the following:

- a 12 element uniform circular array with half-wavelength element spacing,
- a 12 channel high performance 7 pole bandpass filter,
- a 12 channel radio power amplifier and antenna switch unit,
- a 12 channel radio up-converter and down-converter unit,
- a 12 channel high performance digital signal processing unit , and

- a GPS receiver that provides accurate timing and frequency references.

A wireless data link using conventional orthogonal frequency division multiplexing (OFDM) is established between the central access point and each of the user terminals at the same time using the same radio frequency, improving the spectrum efficiency of the system, ideally, by the minimum of the number of access point antennas and the number of simultaneously active user terminals. This is achieved by employing MU-MIMO signalling. The uplink MU-MIMO-OFDM transmission can be realised by the access point receiver having an accurate knowledge of the uplink channel. Downlink MU-MIMO-OFDM transmission can be realised by the access point having an accurate knowledge of the downlink channel.

Figure 2 shows a basic block diagram of the downlink of the MU-MIMO system for a single OFDM channel. It shows that the coded digital data (DD) to be sent to each user terminal (UT) is first mapped (MAP) onto a modulation constellation point, and then the vector of points is linearly pre-filtered using a zero forcing prefilter (ZFP). This generates a vector of modulation points with elements that correspond to the different transmit antennas (Tx) at the access point (AP) that are converted to radio frequency (RF) signals at the carrier frequency. The ZFP essentially pre-cancels the MIMO channel and ensures that the data for each UT will be received at the UT without interference from the other data streams. The block diagram for the uplink is essentially the same diagram but with the arrow directions reversed, and the ZFP function replaced by a zero forcing detector (ZFD), the MAP function replaced by a de-MAP function, and the transmit RF blocks replaced with receive RF blocks. In other words the stream separation process (ie. ZFP and ZFD) is done at the AP for both the uplink and downlink in MU-MIMO systems.

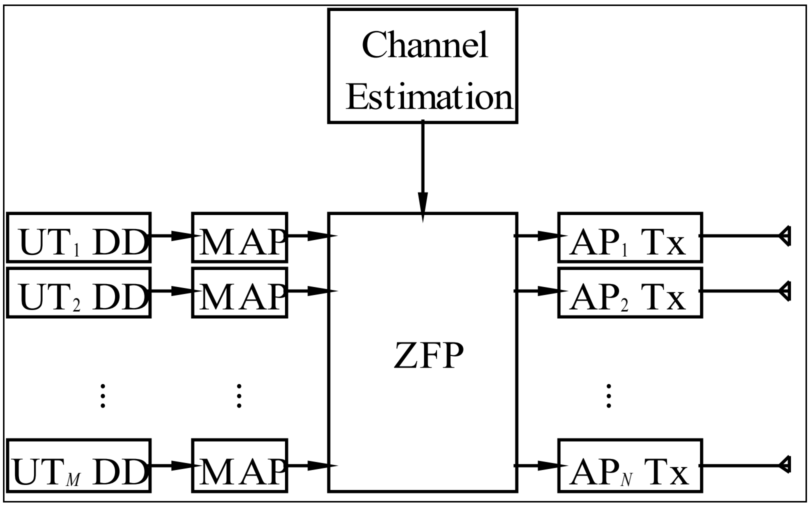

Figure 2 - Downlink signal processing at access point for a single OFDM channel.

The system protocol is designed so that it takes advantage of the nature of the fixed installation. The radio propagation channels in rural area for fixed antenna installation are stationary for longer period compared to the radio propagation channels in metropolitan areas for mobile cellular environment. In addition, antennas are typically installed at a higher height away from local clutter contributing further to the stationarily of the channel. Accurate estimation of the channel can be achieved by utilising signal processing gain. Availability of the accurate timing and frequency references provided by the GPS receiver further enhances the accuracy of the channel estimation, which is typically not available for mobile systems. These are key aspects that differentiate the system from standard cellular systems designed for mobile applications, which are typically deployed in metropolitan areas.

More technical details can be found in Suzuki 2009; Suzuki 2011; CSIRO 2011; Hellicar 2011 and Suzuki 2012.

KEY TECHNICAL ASPECTS

PROPOSED GPS ASSISTED TIMING

We have developed a new synchronisation and packet delay algorithm that greatly increases the spectral efficiency of the overall signal, and also reduces considerably the implementation computational complexity. In order to provide accurate time and frequency reference information, we propose that each user terminal be equipped with a GPS receiver. Commercial off-the-shelf GPS receivers with the required degree of accuracy have recently become available at relatively low cost. The new accurate time and frequency reference synchronisation scheme among user terminals allows the direct use of a simple low complexity MIMO detection scheme, such as zero-forcing, to decode spatially multiplexed signals from user terminals at the access point.

GPS receivers have been used previously to synchronise base stations in cellular systems, but never for symbol level timing adjustment in a MU-MIMO system where the accuracy requirements are much higher. The use of GPS for accurate time and frequency synchronisation among user terminals is impractical for conventional mobile services, since a mobile user terminal may lose the GPS signal by, for example, changing its location from outdoor to indoor. Since the antennas in our Ngara system are fixed and always outdoors, GPS is an ideal solution. In addition to synchronisation, the use of user terminal GPS also enables accurate location information from each user terminal to be sent to the access point, which can then be used to assist in grouping users into neighbouring frequency bands to avoid ill-conditioned channels, as discussed in the following section.

The key idea of the new synchronisation algorithm is to delay the transmission of symbols between the user terminals on the uplink so that all symbols arrive at the access point at the same time. In urban cellular systems with small cells it is not necessary to delay symbols, but for larger cell sizes in rural and regional deployments it is a crucial concept. By using GPS signals for reference we are able to ensure extremely tight timing accuracy from the global clock; something that is not possible with other clock distribution techniques in wireless networks over long distances. We are able to align the symbols with an accuracy of 15 ns, which is more than enough for rural and regional deployments.

PROPOSED GPS ASSISTED FREQUENCY REFERENCE

We also use the GPS receivers at each user terminal to provide an accurate carrier frequency reference. However there is still the problem of drift in the GPS reference due to either atmospheric changes affecting the radio propagation of the GPS signal or hardware imperfection. We have developed a new channel estimation algorithm that takes into account the GPS reference drift. It overcomes a drift of up to 100 Hz, which has been shown to be sufficient to overcome practical drifts of commercial GPS receivers (Suzuki 2011).

PROPOSED USER GROUPING

If any two neighbouring user terminals are located close in angle, the channel becomes ill-conditioned and the system performance degrades. In practice, user terminals are typically not distributed regularly in rural areas, and this condition will often arise. We have developed a simple user terminal grouping method to improve the performance in this case by assigning the user terminals with small angular separation into different frequency channels, or different time slots. The access point can estimate the angle by utilising the location information of user terminals provided by the GPS receiver equipped at each user terminal – another benefit of having a GPS receiver in the user terminal.

PUBLIC DEMONSTRATIONS

Three public demonstrations were performed using the proposed Ngara Access system during 2010/2011 as follows:

- Six user simultaneous uplink inside a laboratory in Marsfield, November 2010.
- Six user simultaneous uplink plus one user downlink in Smithton, Tasmania, December 2010.
- Six user simultaneous uplink and downlink, Marsfield, March 2011.

Figure 3 shows the photograph of the user terminal unit. Basically, the user terminal unit converts radio packets to Ethernet packets, and vice versa, to provide a personal computer connected to the user terminal an Internet access.

Figure 4 shows the photograph of the access point units.

Figure 3 - Photograph of user terminal unit.

Figure 4 - Photograph of access point units.

MARSFIELD LABORATORY DEMONSTRATION

A public demonstration of the proposed system was conducted in CSIRO's Radio Physics Laboratory in Marsfield in November 2010. In this demonstration, a six user simultaneous uplink was demonstrated. Prior to this demonstration, the authors know of only one public demonstration that demonstrated MU-MIMO uplink. Nortel reported in 2007, noting that "Nortel is the only vendor in the world that offers a Multi-user MIMO LTE demonstration." (Nortel 2007) With Nortel's demonstration, each user equipment had a single transmitting antenna and was capable of delivering 10 Mb/s throughput using 5 MHz bandwidth, with two receiving antennas at the access point. The spectral efficiency achieved was 4 bits/s/Hz. As a comparison, CSIRO achieved in this demonstration 20 bits/s/Hz. This was the world first achievement to publicly demonstrate six user MU-MIMO uplink with 20 bits/s/Hz spectral efficiency.

Figure 5 shows the photograph of the demonstration setup. The access point was equipped with a twelve element uniform circular antenna array with a folded dipole antenna as an element. Each user terminal was equipped with the same folded dipole antenna. Both the access point and the six user terminals were located in one room. In order to limit the radiation power from the radio transmitter, 30 dB attenuator (1/1,000th power) was attached to each of the transmitter. By utilising the 12 Mb/s data link, each user terminal streamed digital video to the access point. The access point was connected to an Ethernet switch which separated the six video streaming into six personal computers that displayed the video content. The system demonstrated flawless video streaming over the wireless links.

Figure 5 - Six simultaneous user uplink demonstration in Marsfield, November 2010.

SMITHTON FIELD DEMONSTRATION

A field demonstration of the Ngara Access system was performed in Smithton, Tasmania, in December 2010. In this demonstration, a six user MU-MIMO uplink plus one user downlink was demonstrated. The radio frequency of operation was at 641.5 MHz, which is commonly used by television broadcasting services for UHF channel 44. Scientific frequency licence was acquired from the Australian Communications and Media Authority prior to the demonstration.

Figure 6 shows the geographical location of the access point and user terminals. Six user terminal sites, UT1 to UT6, except UT2, were chosen near existing residential houses, representing a practical deployment of fixed wireless broadband services in rural areas. The location of UT2 was chosen to be close to that of the access point in order to verify the robustness of the proposed system from near-far effects. The distances between the access point and user terminals range from 10 m to 8.5 km. Terrain profile analysis between the access point and each of the user terminal sites was conducted by using the digital elevation data (3 second resolution) obtained by the Shuttle Radar Topography Mission. The analysis showed that none of the selected sites have substantial obstruction of the first Fresnel zone by the terrain.

Figure 6 - Geographical locations of the user terminals (UT) and access point (Will HIll Tower).

The access point was equipped with a 12-element antenna array, with a vertically polarised folded dipole antenna as an element. The 12 antennas formed a uniform circular array in horizontal space with a radius of 40 cm (approximately one wavelength), but were displaced in vertical space in three levels, with a level separation of 40 cm, in order to remove antenna mutual coupling effects. Figure 7 shows the photograph of the access point 12-element antenna array installed on the Broadcast Australia's Willis Hill tower. Notice the very small profile of the antenna array of the proposed system, compared to existing broadcasting and microwave antennas. The height of the antenna array was 71 m from the local ground.

Figure 7 - Access point 12 element antenna array installed on Broadcast Australia's Willis Hill tower.

The user terminal was equipped with a directional Yagi antenna with a nominal gain of 11.5 dBd. Figure 8 shows an example of antenna installation for the user terminal. Typically, the directional user Yagi antenna was installed at the height of 9 m from the local ground. (The photo shows the antenna height at 6 m from the local ground.) The main lobe of the user terminal antenna was pointed towards the access point site at each of the user terminal site.

Figure 8 - An example of user terminal antenna installation.

The physical layer (PHY) protocol was based on OFDM with parameters as given in the Table 1. Maximum PHY data rate is 23.625 Mbps (1680 × 6 bit × 3/4 / 320 µs) per UT. With total of six UTs, the maximum system PHY data rate is 141.75 Mbps. The demonstration used TDD with 50% uplink time and 50% downlink time, and thus nominal max PHY data rate for the uplink or downlink is 11.8125 Mbps each. Approximately 9 Mbps Ethernet packet throughput per UT was been measured for both uplink and downlink.

Carrier frequency	641.5 MHz
Operational bandwidth	7 MHz
Number of occupied sub-carriers	1705
Number of data sub-carriers	1680
Sub-carrier spacing	8 MHz / 2048 ≈ 3.9 kHz
OFDM symbol duration (without guard interval)	256 µs
Cyclic prefix	64 µs
OFDM symbol modulation	64QAM
FEC	convolutional
FEC rate	3/4

Table 1 - PHY parameters for Smithton Trial.

Figure 9 shows the channel frequency responses for the channels between each of the 6 users and each of the 12 antennas at the access point. It also shows the reconstructed constellations after the detector. The effective SNR (after equalisation) is typically from 25 dB to 30 dB. Virtually error free video streaming was demonstrated.

More details of the demonstration are given in a technical report (CSIRO 2011).

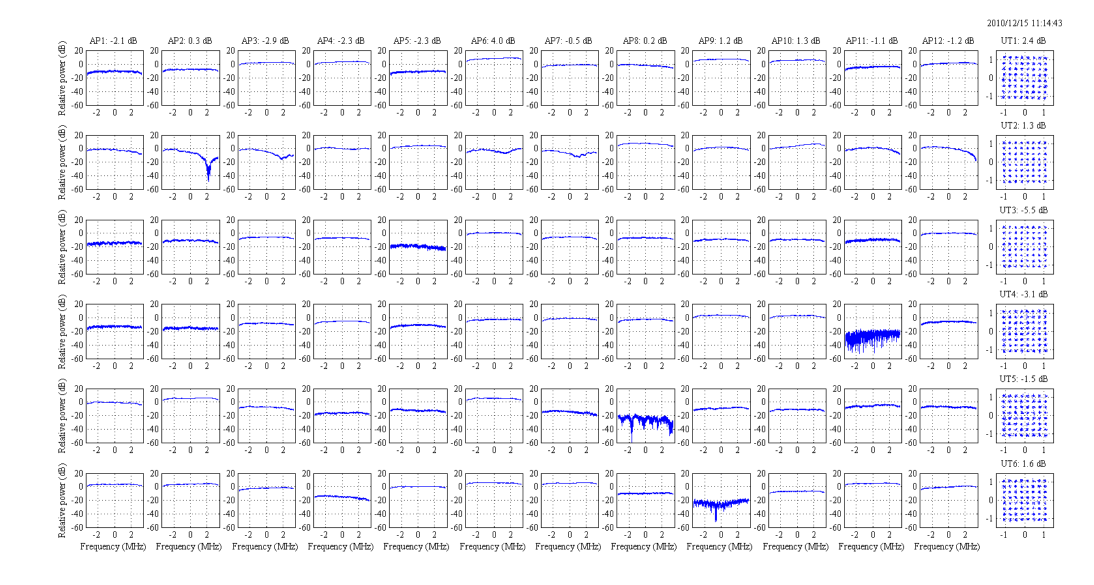

Figure 9 - Uplink MIMO-OFDM channel frequency responses and reconstructed 64QAM symbols for the system with 6 users and 12 AP antennas.

MARSFIELD FIELD DEMONSTRATION

A field demonstration of the complete uplink and downlink of the Ngara Access system was performed within the property of the CSIRO's Radio Physics Laboratory in Marsfield in March 2011. In this demonstration, simultaneous uplink and downlink was demonstrated to six user terminals arranged as shown in Figure 10. Prior to this demonstration, Nippon Telegraph and Telephone Corporation (NTT) reported successful six user MU-MIMO-OFDM downlink in May 2010 (NTT 2010). A real-time wireless transmission with up to six terminals at a total maximum data rate of 1.62 Gbit/s was reported to be achieved. However, according to their published figure, "six terminals" are contained in one case, indicating that the "six terminals" share the same frequency and timing references, and thus the problem of each terminal having different frequency and timing references has not been addressed by their demonstration. CSIRO solves this problem by utilising a GPS receiver at each user terminal.

Figure 11 shows the access point antenna array and outdoor enclosure installed on the rooftop of CSIRO Radio Physics Laboratory building in Marsfield. The design of the access point antenna array was the same as that for Smithton Field Demonstration. It consisted of 12 folded dipole antennas uniformly distributed in a circular array in horizontal space, which are also displaced in vertical space.

Figure 12 shows the demonstration setup at one of the user terminals. The setup was decorated to emulate a farmer's lounge. The setup consists of a user terminal unit (right), a laptop personal computer for displaying downlink symbol constellation, a monitor, high quality video conferencing unit, and an IP phone.

By utilising the 12 Mb/s uplink and 12 Mb/s downlink for each user terminal, we have demonstrated a range of Internet applications including web browsing, video streaming, teleconferencing, multi-user video conference, and high quality point-to-point video conferencing. Video quality and the lack of latency were considered to be excellent by the audience of the demonstration.

The measured uplink error rate was too low to measure with any statistical accuracy over the timescale of the trial. On the downlink the wireless packet error rate for 1 Mb packets was in the order of 0.1% to 0.6%, which corresponds to an Ethernet frame error rate in the order of 1000 times lower (although it was not directly measured).

Figure 10 - Locations of the user terminals and the access point in Marsfield Field Demonstration.

Figure 11 - Access point antenna array (right) and outdoor enclosure (left) installed on the rooftop of CSIRO Radio Physics Laboratory building in Marsfield.

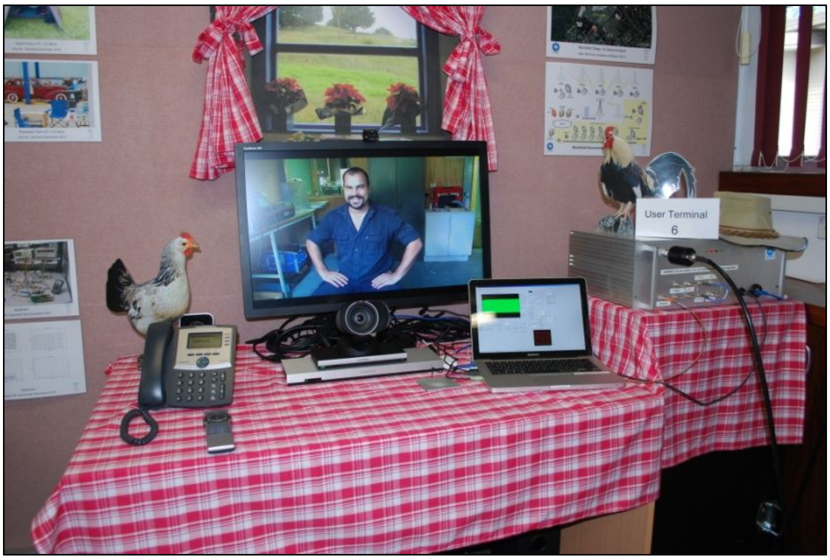

Figure 12 - Demonstration set-up at user terminal.

COMPARISON WITH AN LTE-BASED SYSTEM

In this section we compare our Ngara system with an alternate possible 4G LTE-based system design. For a fair comparison we assume the LTE-based system has a 3-sector access point cell with 4 transmit antennas per sector (12 access point antennas in total), and we allow the system to use fixed directional antennas at the user terminals. When the number of transmit antennas are the same as the number of users, we assume that ill-conditioned user location is perfectly removed by an appropriate user grouping or user selection for both systems. The LTE standard has MU-MIMO as a mode, but does not have the flexibility of our system, nor the non "standard" high performance aspects we have developed for the rural and remote regions – since LTE is primarily designed for mobile user terminals in metropolitan cells. It also issues along sector boundaries, which is especially troublesome for fixed wireless scenarios. From simulations we have found that for practical signal to noise ranges the achievable throughput of our demonstrated system is in the order of three times that of an LTE-based system.

CONCLUSIONS

In this paper, we have described the Ngara Broadband Access System developed by CSIRO ICT Centre. Symmetric 12 Mb/s uplink and downlink for six simultaneous users using only 7 MHz of frequency bandwidth have already been demonstrated. We are currently in progress with the development of a hardware demonstrator capable of symmetric 50 Mb/s uplink and downlink for twelve simultaneous users using 28 MHz frequency bandwidth which would achieve the spectral efficiency of 40 bits/s/Hz.

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