IMPLEMENTATION AND CONTROL OF WIRELESS DATA COLLECTION ON CONSTRUCTION SITES

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SUMMARY*: A mobile site level data collection system has been implemented for piling works utilising the IEEE 802.11b wireless protocol. The system, used by dedicated 'pile managers' and the workforce, allows for real-time data collection and storage into a site-based server, via a mobile wireless local area network (WLAN). The use of a WLAN allows for easy access and manipulation of timely construction data to assist in the management of the project, enhancing information flow throughout the site, reducing remedial costs and improving contract performance. This paper discusses the implementation of the WLAN on two construction sites, difficulties encountered, benefits and recommendations for further work, together with user perspectives. A cost-benefit analysis also suggests a substantial saving on remedial works can be made with the introduction of site-based data capture.*

KEYWORDS*: wireless network, mobile, communications, construction site.*

1. INTRODUCTION

The implementation of mobile user data capture on the construction site requires the consideration of three elements:

- hardware;
- software; and
- communications.

Hardware selection was recognised early by many previous researchers as an important factor in the success of implementing mobile data capture in construction. Citing factors such as screen size, outdoor readability, battery power, physical unit size and robustness as important considerations in the selection of appropriate hardware for the construction site (McCullough, 1997; Elzarka & Bell, 1997; Alexander et al, 1997) Such factors are now only currently being addressed by hardware manufacturers now keen to expand their market to include the previously neglected construction sector. However, the number of suitable mobile devices remains small. Without suitable hardware that can function reliably in the construction environment, any attempt to implement a data capture system will surely fail.

The use of appropriate software for the task of recording and accessing data is also an important factor. Although standardised packages exist for the mobile site workforce (Phair, 2000; Navarette, 1999) these are often targeted towards pre-determined inspection and reporting tasks. However, unlike manufacturing the construction site is more of a reactive environment, where unplanned changes to work regularly occur, this is no truer than in the piling industry.

Traditionally, it has been these two factors, which have formed the backbone of the success or failure of any IT solution. However, the early involvement of users in hardware selection and software development is advocated as being an important factor to successful system implementation (Ives and Olsen, 1984; Tait and Vessey, 1988). Furthermore the move towards mobile data capture requires that the third factor of communication also be considered.

1.1 Mobile Communications

Early development of mobile devices restricted the user to a limited selection of available communication technologies. The simplest form being the connection of two or more computers using hardwired means such as a docking station, serial or USB port. This was later enhanced by the introduction of infrared technology. Further developments have led to the amalgamation of mobile computing devices and mobile telecommunications protocols, with PDA’s now available with integrated mobile connectivity or via a separate mobile phone, through either a wired or wireless connection such as Bluetooth. This provides the mobile user with the ability to upload and download data from anywhere that a mobile signal is provided. The currently available technologies for mobile data transfer are Circuit Switched Data (CSD), High Speed Circuit Switched Data (HSCSD), General Packet Radio Systems (GPRS) and Third Generation (3G).

CSD is the original protocol used for data transmission over Global System for Mobile Communication (GSM) mobile communications networks. Maximum transfer rates vary between 9.6kbps and 14.4kbps depending on the mobile phone handset and the service provider in use. HSCSD is essentially a high-speed implementation of GSM, with some service providers offering a theoretical transfer rate of up to 57.6kbps. This speed makes it comparable to many fixed-line telecommunications networks and allows users to access the Internet and other data services via a GSM network. HSCSD is being rolled out across many GSM networks as a stopgap before broadband mobile services becomes more readily available. Just as with audio transmission on landline phones, both CSD and HSCSD charges are based on the time spent using the dial-up connection.

GPRS is a packet switched "always on" technology supporting Internet Protocols (IP) and is typically 2 to 3 times faster than CSD with a theoretical maximum speed of up to 114kbps. Because GPRS uses the same protocols as the Internet, the networks can be seen as subsets of the Internet, with the GPRS devices as hosts, potentially with their own IP addresses. In practice, connection speeds can be significantly lower than the theoretical maximum, depending upon the amount of traffic on the network and the type of handset being used, meaning that you could get higher GPRS rates in the evening and at night. However, GPRS services should be cheaper than circuit-switched connections, with the network only being used when data is being transmitted.

3G is an emerging broadband packet switched technology currently being targeted at picture and video streaming applications on mobile handsets. Data transmission speeds are dependent upon the environment the connection is being made with speeds of up to 2Mbps (Megabits per second) achievable in indoors and stationary environments. However, for high mobility such as required in construction, these rates can be reduced to as little as 144kbps.

Established technologies such as CSD, HSCSD and GPRS allow for the transfer of data to and from mobile devices on site to remote locations such as the head-office. However, this requires data to be stored locally on the device during work, potentially placing collected data at risk if the device is damaged or, in the case of mobile devices, loose battery power and hence state. Such limitations require the user to be in active control of the data and the state of the device, increasing the complexity of the data collection task. Whilst the advent of 3G may allow true mobile thin-client capabilities for site users, issues with respect to signal coverage, speed and costs still remain.

1.2 Wireless Communications

In order to relieve the burden of uploading, downloading and synchronisation required by other communications technologies, it is necessary to implement thin-client applications. This can be achieved through the use of currently available wireless networking technologies. Technologies such as IEEE 802.11b utilise radio waves for the transfer of data and allow connection speeds up to 11Mbps, which is far in excess of any other mobile communication technology. Whilst the indoor use of IEEE 802.11b has found popularity for replacing traditional wired LAN, the protocol is now being applied in open environments with emergence of outdoor public wireless local area networks (WLAN). Known as ‘Hot-spots’ these provide high speed internet access in densely populated areas such as airport lounges, railway stations and hotels to mobile corporate and private users, with analysts predicting as many as 90,000 throughout Europe by 2006 (Toland, 2002). Although still in their infancy, the possibility of providing location and context-aware services, which can be used to target advertising or services to roaming wireless users, has long been discussed (Schilit, et al 1994; Long, et al. 1996). However, due to the restricted range of IEEE 802.11b, there is a requirement to provide localised server technology to support such applications.

This technology has allowed, for the first time, users to operate functionally as a mobile thin-client without the restraints of slow dial-up connections. However, its application within the construction environment has been little exploited. This paper discusses the implementation and operation of WLAN operating on two construction sites in London, together with the use of thin-client devices for mobile data capture.

2. BACKGROUND

A three-tier system (SHERPA) has been developed to facilitate real-time data capture for construction site piling works (Ward, et al. 2003). This consists of:

- site based server-side database;
- IEEE 802.11b wireless local area network;
- wireless thin-client devices;

The system grew out of the need to provide real-time data capture to the site workforce for the recording of pile construction information, whilst taking consideration of the construction methods, practices and the reactive nature of the site. The difficulties and requirements were highlighted as being:

1. the need to reduce defective work caused by incomplete, ambiguous, duplicate, missing or incorrect information;
2. unsuitability of the site for bulky paper documentation;
3. lack of verification on the data collected;
4. errors in data translation between the site and office;
5. lack of data re-use throughout the company; and
6. the ability to meet the reactive nature of the construction process and sequence of work.

2.1 Server-side Database

A server-side database was developed to provide a single point of access to all data relating to the construction of the piles. The intention was that this would counter the problems caused by duplicate or incomplete paper-based information on site and also eliminate the need for users to carry bulky paper documentation. The database also allows for a single point of data entry with all users having access to all of the construction data captured by other personnel. This allows for the free use of information between users and working gangs removing the burden of collating revised construction information caused by unplanned sequence changes or plant breakdowns.

2.2 Wireless Local Area Network

It is often the case that piling works are carried out in conjunction with both demolition and reconstruction of the site, with piling undertaken in predetermined work zones. It is for this reason that a system of Wireless Network Cells (WNC) has been developed (Ward, et al. 2003) to provide wireless coverage to the site. The WNC have been designed to be fully portable, rugged and re-configurable to meet these requirements. Each WNC provides coverage to a certain area of the site allowing roaming users to connect to the server-side database. WNC can be ‘daisy-chained’ to increase coverage distance or divert the wireless signal around obstructions. (Fig.1)

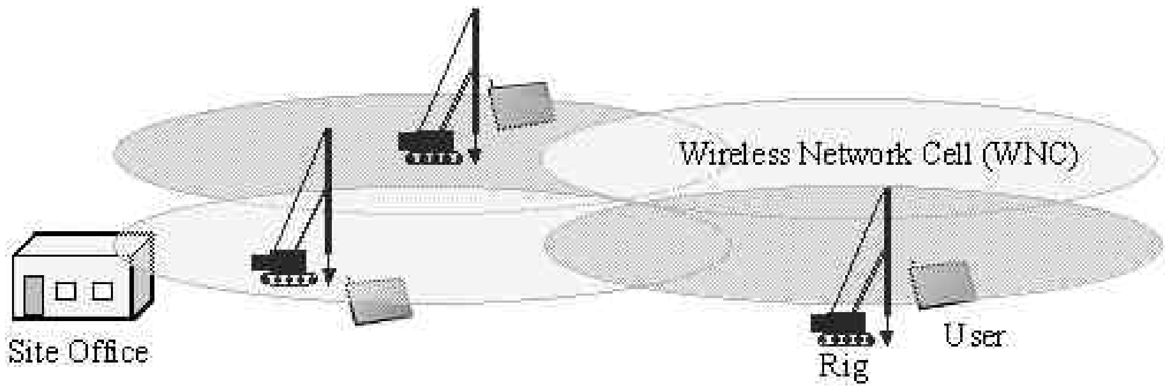

FIG. 1: Typical Wireless Network Cell Configuration

2.3 Thin-client Devices

Each user is equipped with a touch-screen Windows CE tablet computer (Fig.2), which provides thin-client capability This enables the user to gain access to the server-side database over the wireless network, effectively providing full desktop capability to the users. Each tablet is equipped with an IEEE 802.11b wireless card, which is fully inserted into the PCMCIA slot, leaving no exposed parts. A small retractable antenna (5cm) is provided on the tablet to improve signal performance.

FIG. 2: Touch-screen tablet computer being used on site.

2.4 The Sites

2.4.1 Kings Cross Underground Station Redevelopment

This was the first project on which the SHERPA system was deployed and is part of the development of the Kings Cross and St Pancras railway stations to facilitate the increased passenger numbers expected from the arrival of the Channel Tunnel Rail Link (CTRL) into St Pancras station. The piling works contract is valued at £10.5M and involves the construction of 575 piles with diameters ranging between 750mm and 2100mm, and depths ranging between 14m and 40m. The construction site is located to the rear of Kings Cross Station in an area of approximately 1500 square metres with the site office remotely located approximately 250m away in a site compound. (Fig. 3)

FIG.3: Kings Cross construction site showing location of site compound

2.4.2 Wembley National Stadium

The replacement of Wembley Stadium with a new 90,000 seat multi-functional sporting arena has created a single construction site of approximately two square kilometers. The value of the piling works contract is approximately £6M and requires the installation of approximately 4,500 piles ranging in diameter between 600mm and 1800mm with depths of between 20m and 40m. Due to the size of the site, the piling works contractor has been afforded an area of the site in which to locate their portable site offices and steel-fixing yard.

3. IMPLEMENTATION AND TESTING

3.1 Initial Configuration

Initial configuration comprised a wireless bridge located in the site office and two WNC all equipped with 360-degree omni-directional antennae. The server and tablet computers were equipped with Cisco Aironet 350 WLAN cards, although any 802.11b compatible WLAN card would have been suitable. Two WNC were initially located on the site hoarding and foreman's hut (Fig.4)

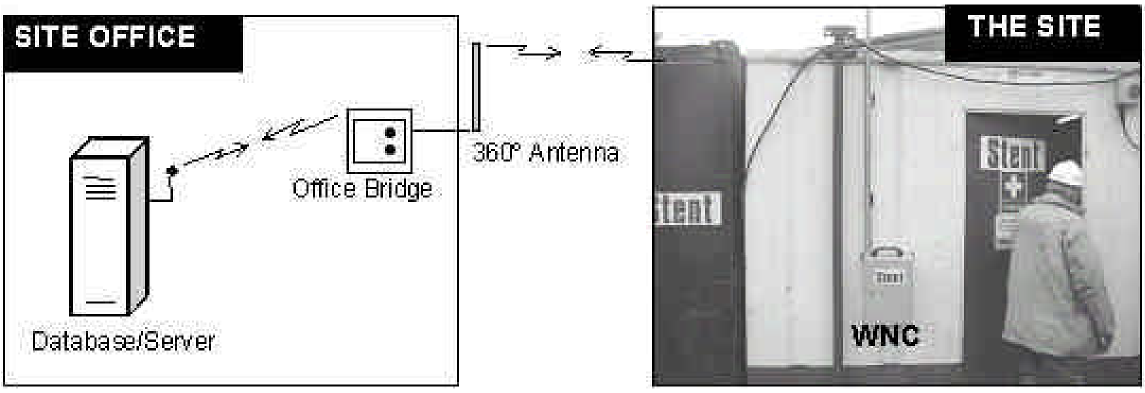

FIG. 4: Initial Configuration at Kings Cross with wireless connections at site office and between site

Initial tests showed that connection from site to the server was slow. This was caused by the final wireless link between the server and bridge located in the site office, creating a 'bottle-neck' to the server. This original configuration was chosen to allow for a fully flexible system, which included for moving and relocating the server as necessary. Due to the period of the contract and the static nature of the site offices, this functionality was not required and the wireless connection was replaced with a standard Tbase10 network connection between the site office bridge and the server, which considerably improved the connectivity speed.

3.2 Site Configuration

Site offices on both sites were not moved throughout the duration of the contracts, which made it possible to maintain a fixed office bridge and server location on both sites. However, the progression of work on both sites dictated the areas in which piling could be carried out and hence how the WLAN would be configured. Piling work at both sites was carried out during both demolition and superstructure works. This meant that the dates and sequence that particular areas would be handed over to the piling works was flexible, dependent upon the completion of the demolition work. Also, on completion of piling works an area would be handed over for superstructure work with the possible creation of barriers to the signal propagation. These factors were not considered to be a difficulty to the WLAN as it had been designed specifically with this in mind.

3.3 Signal Propagation

Omni-directional antennas equipped with a 360-degree azimuth were initially used to propagate the wireless signal from the site office and for each WNC around the site. These antennas were selected in the original design and off-site testing of the system to allow for full flexibility in the location of the WNC and the site office.

Although located at the periphery of the site, the use of omni-directional antennas on the WNC allowed them to be easily relocated without the need for antenna re-alignment, as would be required by patch or directional antennas which provide a restricted azimuth (typically between 12 and 75 degrees). Utilising such antennas at the edge of the site inevitably causes unused signal to propagate into public or other private space. However, this was accepted as a consequence of having easier management and greater flexibility in the system.

The main difficulty for signal propagation arose from the large area of the Wembley site and the commencement of superstructure works such as shear cores. Although the signal can propagate through up to four concrete walls (dependent upon thickness), each wall reduces the strength of the signal and hence the distance that it can travel beyond each wall. The location of the shear cores and size of site meant that locating a WNC on the site boundary would not be sufficient to provide a signal in the centre of the site. Signal propagation was also hindered at both sites by the creation of hardcore spoil heaps, up to 10m high, which proved to be impenetrable to the WLAN signal. The spoil heaps were created by the demolition and earthworks contractor and as such their positioning was out of control of the company. Varying working levels at Wembley also exacerbated the problems caused by spoil heaps and superstructure construction (Fig 5).

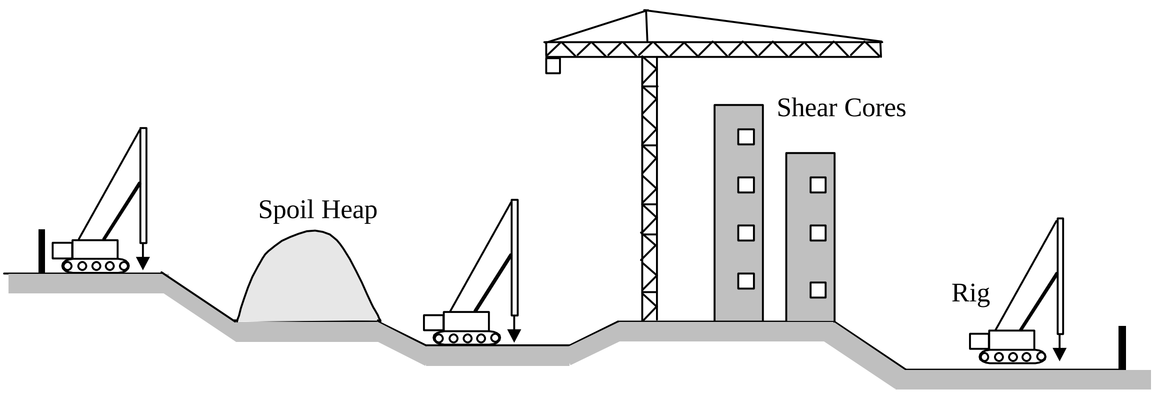

FIG. 5: Typical site cross-section showing platform levels and obstructions

The layout of the site and remote nature of the site offices at Kings Cross required that the wireless signal between site office and site be passed over public and other private space. Even on sites where the site office is located on the site, the nature of wireless networks dictate that some signal leakage will propagate from the site. In such circumstances it is necessary to understand the increased security risk posed to the system, through potential hacking.

3.4 WLAN Security

In order to indicate its presence to clients within its listening area, each WNC broadcasts (approximately every ten seconds) a Service Set Identifier (SSID), identifying the name of the WLAN. This enables wirelessly equipped computers within range of the access point to receive the SSID and establish a connection with the network. The 802.11b standard also includes an encryption method, wired equivalent privacy (WEP), which is based on the RC4 algorithm. Unfortunately, WEP has been cracked for over two years, resulting in a surge of publicity regarding security of WLAN's (Knight, 2002; WiFi, 2003). The cracking of WEP also spawned a movement known as 'war driving'. War driving involves driving in a car with a Global Positioning System (GPS) and wireless equipped computer or handheld device, actively seeking locations of WLAN's, both private and corporate. This practice has spawned 'war-chalkers' who chalk buildings or pavements with back-to back C's or open circles where wireless networks have been found. The locations of discovered WLAN's and corresponding SSID's are then publicised on the Internet.

Although, WEP has been cracked, there still exist a number of solutions that can be used to further secure WLAN's such as:

- Turning off the broadcast of SSID's
- Not using default settings on the WLAN equipment.
- Installing proprietary security measures such as EAP, RADIUS and firewalls.

All SHERPA wireless networks have a unique SSID, the broadcast of which is turned off. Site-office wired networks are used primarily on larger long-term contracts and often include links direct to the head-office. In such cases, it is envisaged that firewalls would be implemented between the SHERPA server and the corporate network.

3.5 WNC Power

Each WNC was initially powered by a 26Ah sealed lead acid battery, which was designed to allow the WNC to operate for a whole week between battery swaps, thereby reducing the burden on management. However, the weight and size of the batteries (approximately 7kg) was restrictive and unwieldy, especially when being carried between the site office and WNC. A decision was made to replace the battery with a smaller 12Ah battery, which would provide enough power for two day's operation. This however, would increase the burden on the site staff to replace the batteries and maintain power to the WNC.

The use of a small solar panel to increase the operating time of the WNC through trickle charging the battery was found to be suitable only in direct sunlight when the full 350mA output could be achieved. This was reduced to a variable 100mA output in broken cloud and to 30mA in overcast or shadowy conditions proving impractical for use. Unfortunately the Kings Cross site is located directly to the north of four and five storey buildings which cast a shadow over the site throughout the day causing the output from the solar panel to be ineffective in increasing the life of the WNC.

The WNC was originally designed to be fully mobile and reconfigurable. This could only be achieved by providing a mobile power source to each unit. Users were provided with replacement batteries and recharging units and given guidance on the replacement of the batteries and the period in which they were to be replaced (every two days). However, during the first two months of operation the users often complained of a lack of signal and slow connection to the server. On investigation it was found that the WNC had lost power and the batteries had not been replaced. Although training was given, users did not fully understand the implications of failing to replace the batteries in the WNC. This is because they could still connect to the server via the office bridge when out on site, thereby bypassing any apparent need for the WNC. Although there was a lack of WNC maintenance, users were still able to connect directly to the server via the office bridge. However, because the users were operating at the boundary of the office signal they were losing speed and connectivity on a frequent basis.

4. IMPROVEMENTS

Following implementation and an initial testing period on both sites, the following improvements were made to the WLAN:

1. a rig mounted WNC was developed;
2. omni-directional antenna were replaced with a directional antenna; and
3. tower crane mounted WNC positions were investigated.

4.1.1 Rig-mounted WNC

To remove the burden of battery management on the WNC, a rig mounted WNC was developed. The intention was to design a WNC that could be fully reconfigurable but utilise the 175Ah battery located on the rig. All of the equipment from the original WNC was repackaged into a watertight and crush proof ABS case, with connections for an antenna and 12-volt power to the battery provided on the side of the case, (Fig.6). The emphasis on portability was maintained in the design of the rig-based WNC, with flat magnets placed on the underside of the unit to allow it to be relocated as necessary on the outside of the rig. The 360-degree antenna was placed on top of the driver's cab and antenna cable run down to the case. The power supply to the rig-based WNC was taken directly from the rig battery ensuring that the signal is available even when the rig is not in-use.

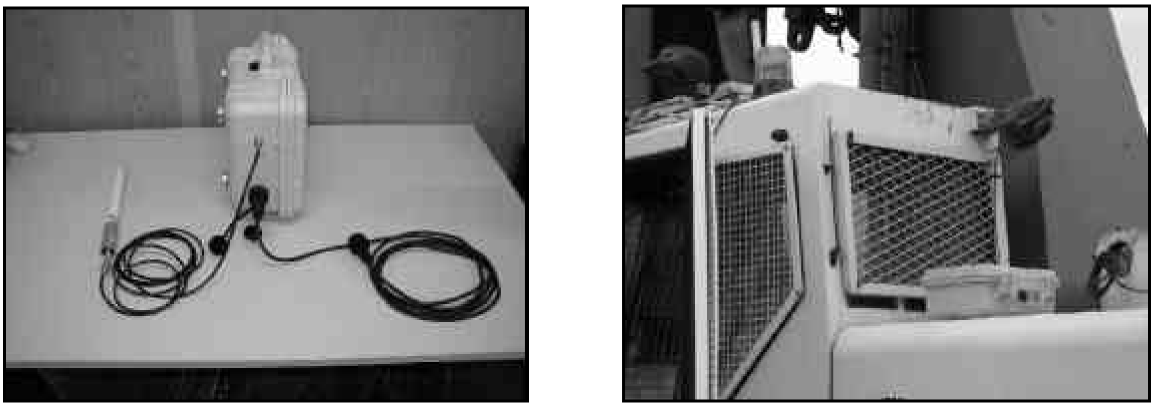

FIG.6: Rig mounted WNC design and Installation

4.1.2 Directional Antenna

The use of a directional antenna in the original design of the system was avoided due to its limited azimuth, which it was thought would compromise the flexibility of the system. However, due to the distances provided between the site offices and the working site and the permanent nature of the site offices it was decided to replace the office bridge antenna with a directional yagi antenna on both sites.

The yagi antenna typically has a 30-degree azimuth, which means that the signal power is aimed in a single direction; this in conjunction with the design of the antenna increases the power and distance over which the signal can propagate (typically up to 3km at a speed of 11Mbps). Site testing showed that the yagi antenna, although deemed to be directional by the manufacturer, did in fact allow connection through 360° without difficulty.

4.1.3 Tower Crane Mounted WNC

The location of a WNC centrally in the site was not deemed necessary or thought to be practical in the original design of the system. However the following factors required such a solution to be investigated:

- large spoil heaps of hardcore;
- commencement of superstructure;
- variation in working levels; and
- size of the site.

Once the superstructure commenced it was apparent that there was a possibility to use the tower cranes as a means of providing a centrally located WNC. The tower cranes were being used to construct the shear cores and as such were ideally located to provide such coverage. Although the tower cranes are provided with power, this was via a generator. Therefore, to ensure a continuous and uninterruptible power supply, the WNC was re-designed to the same specification as the rig-based WNC but with the addition of 12Ah sealed lead acid battery. The unit and antenna were located 12m up a tower crane to provide high level signal coverage to both divert the signal around the superstructure but also allow the signal to be passed over the spoil heaps and into lower working areas of the site (Fig.7).

FIG.7: Tower crane mounted WNC.

Throughout the construction of the Wembley Stadium, the importance of the tower crane mounted WNC increased. This was due to the continuing construction works that led to the isolation of the piling contractors site offices and yard, which were effectively cut-off from the remainder of the site. Although this provided the required solution, the need to maintain a battery supply within the units was deemed a drawback. Especially with the core function that the tower crane WNC had in the overall system.

5. WLAN PERFORMANCE

There are many factors that can be used to measure the performance of wireless networks. In pure computing terms (Jinyang, et al. 2001), some of which are as follows:

- throughput (packets of data per second);
- losses (lost packets);
- link quality (quality of wireless link);
- signal strength; and
- delivery rates (number of successfully completed packets).

However, the nature of the research was not to determine performance in such terms but rather on the practicality and functionality of the WNC system in a construction environment.

5.1 Signal Propagation

The variability of radio signals can be directly attributed to the environment through which they pass, with steel having the most detrimental effect on the propagation of the signal causing it to reflect, refract and diminish in quality. The signal quality and strength were measured at static points on both construction sites using the software included with the WLAN cards.

Signal quality is a measurement of the number of data packets that have been transferred between two points on the network and is measured by an algorithm running on the wireless cards and WNC. As this represents the actual data on the network, this was deemed to be a more important value in consideration of performance, than signal strength. On both sites, the signal quality remained relatively static in the range of 80% - 100%, with no loss of data reported.

The strength of the signal on both sites, whilst greatly improved by the changes made to the system was still highly variable, in some cases ranging between 40% and 80% at a single location within a matter of seconds. Other locations were found to have a more static signal strength, however this was also found to fluctuate around 5 to 10% over a few minutes. Whilst revisiting the same points only a day later could result in a different range of signal strengths being achieved. Such variations in signal strength were thought to be caused by the ever-changing environment and the movement of small to medium sized machinery such as dump trucks, excavators, and earthmovers.

5.2 Wireless Network Cells

The WNC have met their design requirements and have shown to be highly reconfigurable and suit the changing nature of the construction site especially with respect to changes in working areas. No problems have been encountered with the quality or operation of any of the units throughout the contracts, which have proved to be very stable. The use of crush and water resistant enclosures was also found to be invaluable, particularly when de-rigging, resulting in no loss over hardware over a two-year period.

5.3 WLAN Management

One burden of implementing WLAN in the construction environment is the requirement to provide some form of support and management to the system (Baxevanaki, et al. 2001). One of the main factors in the design of the WNC was to enable them to be easily manageable. Where used, battery powered WNC require the use of dedicated personnel to exchange the batteries every two days. This procedure takes approximately 10-20 minutes dependent on their location. Such a requirement can be eliminated totally with the use of a rig-based WNC.

The use of a rig-based WNC also reduces the amount of management with respect to the relocation of WNC as this is effectively carried out by the rig. There is however, a requirement to manage the availability of signal to specified working areas and understand the work sequence of other contractors, both demolition and superstructure, which may affect the signal. Such management issues were more apparent at Wembley than Kings Cross, which was due to the majority of work being underground at Kings Cross during the piling works contract.

After initial set-up and following the changes made to the system after testing, the management of the signal strength and availability was performed on an ad-hoc basis at both sites. This was largely due to the flexibility in the WNC configuration, which meant that as users found problems with connection to the system, they could be resolved by the repositioning or installation of another WNC.

Basic monitoring of each WNC can be carried out at the site offices utilising software provided with the WLAN equipment. This indicates the current status of each of the WNC and whether they are active. Such limited information is all that is needed to ensure that the system is functioning as required and can take as little as five minutes twice a day.

6. THIN-CLIENT DEVICES AND SOFTWARE

6.1 Windows CE Tablet Computers

Windows CE tablet computers were used on both sites as the primary hardware for data collection. These were chosen because of their relatively large screen size (800 x 600 pixels) compared to a typical PDA (240 x 320 pixels) and the need to provide touch-screen capability. Other important considerations were:

- transflective screen which could operate both indoors and outdoors;
- use of a built-in WLAN card with no protrusions;
- ability to provide thin-client capability; and
- robustness.

As each tablet computer was purchased ‘off-the-shelf’, the software for the WLAN card had to be installed onto each device separately, after which the units were ready to be used. Each unit has an IP rating of IP54 providing for limited water and dust protection and a semi-rugged construction screen with the manufacturer stating that they could survive a drop of 1m onto concrete. Whilst this rating is not the highest, the unit cost of £900 is approximately a quarter of that of a fully rugged device of the same size. To date, the tablet computers have been operating for 18 months with a low failure rate typically one every twelve months of operation. This coupled with the fact that such technology is ever-changing, suggests that semi-rugged devices may be a more cost-effective solution than fully rugged devices.

Another factor considered for their use was the requirement for the units to be operated by the site staff and the rig drivers inside the cabs. Purchasing devices with transflective screens meant that the devices could be fully interchangeable between the rig and site users as necessary

6.2 Software and Personnel

Bespoke process orientated software was written for the capture of pile construction information (Ward, et al. 2002) utilising a Microsoft Access database. Due to the difference in contract requirements, the personnel undertaking the data capture tasks at each site were different. ‘Pile managers’ were employed to undertake all data capture at Kings Cross and were semi-experienced ‘site engineers’ with some knowledge of construction and piling. At Wembley the decision was made to utilise the site staff to undertake the data collection. This difference in personnel selection was due to the following factors:

1. Difference in contract requirements between Kings Cross and Wembley;
2. The differing nature of the piling work at each site;
3. Ability of the contract to support the cost of dedicated ‘Pile managers’.

The difference in personnel between sites, and their data collection tasks, required the development of different front-end programs to collect the data. The use of a specific ‘Pile Manager’ at Kings Cross meant that a single interface could be used for collecting all data relating to the construction of pile. However, the use of site staff at Wembley meant that individual process orientated front-end programs had to be created to match the work being carried out on site. Table 1 shows the difference in approach between sites, with a minimum of three personnel used at Wembley for data collection, against one at Kings Cross. This did not affect the structure of the underlying database, which remained the same at both sites, which was due to the process-orientated approach adopted in the creation of the original system design (Ward, et al 2002).

TABLE 1:Personnel used for data capture at each site

Site	**Process**					
	Casing	Drilling	Strata Log	Bentonite	Cage	Concrete
Wembley	Rig Driver	Rig Driver	Foreman	N/A	Ganger	Ganger
Kings Cross	Pile Manager					

The flexibility in the original database design provided the possibility of designing any user interface to match any particular site without affecting the underlying structure or compromising the possibility of future cross-contract analysis. However, this could prove to be a future problem if individual site managers were to request the development of individual front-end programs for each specific site or person undertaking the data collection. To provide a certain level of control it is therefore necessary to create a standard set of interfaces or profiles, which can be selected by the site or project manager at an early stage in the contract. This would enable data collection to be tailored to suit the needs of the site, the personnel undertaking the data capture and the requirements of the contract without compromising the data analysis requirements of the company.

6.3 Operation

6.3.1 Battery power

Each tablet computer was equipped with a 1.8Ah Lithium-ion battery that provided approximately four hours continuous use (as stated by manufacturer). This meant that the users would need to replace the battery out on site during the day, something the manufacturer stated was catered for by providing a blinking yellow indicator when the battery required replacing, and the ability to hot-swap the batteries with the use of an internal backup battery. However, initial trails showed this not to be the case. Although the battery indicator would blink after approximately 4 hours use, hot swapping of the battery would cause the re-setting of the tablet computers to the factory setting. This effectively caused the loss of all previously installed WLAN drivers, rendering the tablets unable to re-connect to the server without being brought back into the site office and the WLAN drivers re-installed. This problem was caused by two elements:

1. The nature of windows CE devices, which operate wholly on memory requiring power to maintain state.
2. The inability of the tablet computer to swap over to backup battery when hot-swapping when the main battery is low.

In order to overcome this problem, users were provided with an on-site power point in which the tablet computers were plugged into whilst the main battery was exchanged.

To reserve battery power, users were requested to suspend the tablet devices when not in use. This had to be carried out manually as the use of the wireless card effectively meant that automated power saving operations, which suspend the device after a period of no use, did not work because the wireless card was always deemed to be active.

6.3.2 Connectivity

Users connected to the server via the Microsoft RDP protocol using terminal services. This effectively provides each tablet with thin-client desktop capability. Suspension of the tablet computer to reserve battery power effectively meant that the user could not be seen by the server, causing the server to automatically disconnect the user from their session but leaving it open for them to reconnect when they powered the machine back on. The need to disconnect and reconnect proved frustrating to the users and in some instances they were not re-connected to their old session but provided with a new session by the server. This had the effect of taking up duplicate licences and duplicating connections. This problem was managed by ensuring users disconnected from sessions before suspending the tablet computers.

Once the initial set-up and configuration of the WNC at each site was carried out, users experienced no problems with the connection between the tablet and WLAN. The design of the wireless network and changes made after testing provided for seamless connectivity between the user and the server, even when moving between WNC coverage areas.

7. USER PERSPECTIVE

Initial testing with users at Kings Cross resulted in some negative feedback relating to the system. This was caused by the initial lack of signal strength, apparent loss of signal and requirement of the user to manage the connection between the tablets and the server. However, changes made to the wireless network configuration enhanced the users perspective of the reliability of the wireless network. Although this could be due to the removal of the burden and management of the WNC by the creation of the rig-based WNC it is thought that the use of a more powerful directional antenna and increased reliability of the signal across the site is the main factor. The use of the rig-based WNC generates a signal wherever the rig is working which is often at the same location as the user undertaking the data capture.

Comparison of user perspectives between sites showed no difference in their attitude towards data collection. However, the 'Pile managers' at Kings Cross showed more of an interest in assisting with diagnostics when problems occurred and trying different approaches to improve the system. It is believed that this can attributed to the role of the person undertaking the data collection. The main role of pile managers was to collect data whereas data collection at Wembley was in addition to the users operational role in the construction of the pile. This suggests that a greater level of management will be required on sites where workforce driven data capture is used rather than 'Pile managers'.

Irrespective of the type of user undertaking the data collection, the use of wireless mobile computers on the site requires all users to undertake one or more of the following tasks during their work:

1. operate the data collection software;
2. monitor and ensure connectivity to wireless network;
3. connect to the server as necessary; and
4. ensure continuous power to the unit and hence state.

The monitoring and connectivity of the wireless network can largely be removed from users only if adequate coverage and management of the WNC is carried out before and during the contract. However, the users are still required to understand why they may not be getting access to the server, which may be caused by loss of signal or loss of server connection. It is for this reason that training must be provided on the basics of how the wireless network operates on the site, in addition to how to operate the data collection software.

8. COST BENEFIT ANALYSIS

To determine the benefit of the system to the company, a simple cost benefit analysis was carried out for the Kings Cross contract. This took the form of comparing the cost of implementing the system against the value of the contract and cost of remedial work, caused by defects. The value of remedial work on the Kings Cross site was compared to the known value of defective work across other company sites to provide a baseline cost of defective work (Table. 2)

TABLE 2: Cost analysis for Kings Cross Implementation

Contract Value	£10,500,000
Number of piles	575
Average Cost per Pile	£18,000
Baseline cost of remedial work (**X**) (0.97% of Contract Value)	£102,000
Actual cost of remedial work (**Y**)	£20,000
System implementation (**Z**)	£20,000
Saving (X-Y-Z)	**£62,000**

Table 2 indicates a 75% reduction in the cost of remedial work at Kings Cross, reducing the baseline percentage to 0.2% of contract value. Based on a company turnover of £50M this equates to a possible saving of £385,000 per annum if the system were used throughout the company.

Although the use of pile managers constantly monitoring the construction, would be expected to have a beneficial impact on reducing defects, the use of a common source of data and automated auditing by the system over the WLAN as construction of the pile progresses, is believed to be the main contributory factor in the reduction of remedial work.

It is not only the cost of the system that should be considered but also the perception that such a system provides to clients and the ability to show that site level data collection can be successfully carried out. This in-turn realises the prospect of additional work being granted on the basis of having a sound system to monitor the construction of the work and an improvement in contract performance.

9. FURTHER WORK AND CONCLUSIONS

9.1 Further Work

It is inevitable that some battery powered WNC will be required on larger sites, as such it is imperative that an easier form of monitoring the WNC is developed. This could take the form of a web-based interface, which could provide information such as the input power the WNC and highlight those WNC that require imminent battery replacements. This could be enhanced with the use of wireless low cost PDA devices being provided to staff and alerts made via the WLAN. Alternatively a GSM dial-up to alert staff by text message on their mobile phone could be used.

Keeping track of the location of the WNC on the site is also an important role, which could be assisted by providing a graphical interface of the site layout or an aerial photograph onto which the system manager could drag and drop WNC and rigs. Such a visual aid may also prove beneficial in highlighting potential problems in signal deterioration or quality from future superstructure work.

The use of the tablet computers providing a larger screen size than that of a PDA, allow for greater flexibility in design of user interface and inter-changeability between pile manager, site user and rig user. However, this comes at a cost to battery consumption. Low power consumption devices and PDA's, particularly those for mobile WLAN use are available. However, this is usually at the cost of screen size, which has a large drain on battery power. Therefore the provision of a tablet that can be operated throughout a whole day, thereby reducing the burden on the user to manage the device state is still required; alternatively investigations into the use of a PDA for limited tasks should be investigated.

The need to tailor data capture requirements for particular contracts, clients and users has been highlighted. This suggests that efforts should be made towards providing a standard set of interfaces or user profiles from which the project manager can tailor the data collection to meet such requirements at the start of the contract. However, the need to ensure a common underlying database structure throughout the company remains the priority.

Problems associated with connection to the server via the wireless network have been exacerbated by tablets which require power saving operations to be carried out. Therefore, the need to provide an alternative mechanism for the data capture should be explored. It is envisaged that a web-based data collection system could be developed based on the work already carried out. Such a system would require the user to be in control of the data transfer between the tablet and the server, may require some form of short-term data storage on the tablet but would eliminate the cause of duplicate sessions and the need to retain particular software platforms on the server. Such a web-based system would also allow for remote clients or head-office personnel to connect into the site server to monitor progress. However, it is important that security is taken account of in such a configuration.

9.2 Conclusions

The use of reconfigurable WNC to provide wireless mobile coverage for data capture on the construction site has proved successful. Although the design of the wireless network allows for reconfiguration and portability to overcome obstructions, the following factors should be considered on any implementation of site WLAN:

- spoil heaps;
- variation in platform/piling level;
- construction of superstructure;
- uncontrolled space, public private and on-site;
- size of the site.

When using WLAN on the site, it is essential that user coverage be maintained. This will reduce the burden on the user to ensure that wireless connection is available. However, the nature of radio-based technology is such that some intermittent loss of signal has to be accepted, unless a large amount of redundancy is introduced into the system, which would in-turn increase maintenance requirements.

The use of rig-based WNC, which allow for permanent power supply from the battery on the rig has proved successful. With the rig effectively becoming the WNC, it is only necessary to maintain a signal over to each working area to ensure that users have full connectivity to the server.

The use of windows CE tablet devices has been explored and their suitability for the site verified. The ability to utilise a single device such as a tablet in many applications such as pile manager, rig and site user has been shown to be beneficial. However, the current lack of battery power requires that the mobile user be actively involved in maintaining the state of the device. Irrespective of the role in which the tablet is used, there is still a requirement for the user to connect and re-connect to the server via the terminal services interface.

The ability of site personnel to conduct data collection tasks both as a primary task and secondary task to their day-to-day work has been explored. This research indicates that those users who undertake the data collection as their main task are more likely to be pro-active in the control and improvement of the system. This suggests that sites which specifically employ ‘pile managers’ to undertake data collection would have a lower overhead for managing the system to those which utilise site staff in the data collection role.

A cost benefit analysis shows that the value of remedial work as a percentage of turnover has reduced from 0.97% to 0.2% with the implementation of the SHERPA system. This would equate to a possible saving of £385,000 in remedial works cost should the system be implemented throughout the company.

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