Tunnelling and Underground Space Technology 43 (2014) 157–170

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Underground wireless networking: A performance evaluation of communication standards for tunnelling and mining

Gareth A. Kennedy *, Michael D. Bedford

Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9EZ, United Kingdom

ARTICLE INFO

Article history:
Received 19 December 2013
Received in revised form 14 April 2014
Accepted 12 May 2014
Available online 7 June 2014

Keywords:
Wireless networks
Microwave propagation
Tunnelling
Mining

ABSTRACT

Tests on both commonly-used and new wireless communication standards operating in the 2.4 GHz and 5 GHz bands (IEEE 802.15.1 Bluetooth, and IEEE 802.11g, 802.11n and 802.11ac Wi-Fi) were carried out in a variety of underground tunnels. In general, it was shown that wireless data communication in tunnels shows significantly increased throughput vs. range characteristics compared to open space or office environments, however, transmission is largely restricted to line-of-sight paths. Particular attention has been given to the effect of tunnel cross-sectional area, the presence of cross-cuts, a comparison between 2.4 GHz and 5 GHz, and the relative effectiveness of those standards that employ MIMO. Tests also investigated tolerance to loss of line-of-sight. It is anticipated that the results presented here will provide guidance for planning wireless networks for use in mining and transport tunnels, or for temporary use in drains, sewers or service tunnels such as those carrying cables and pipework.

1. Introduction

While the migration of data networks from wired to wireless technologies is well advanced in the business and industrial sectors, this progression has been much slower in tunnelling, mining, and other underground applications. Although, the underground sector has seen the use of wireless networking for certain projects in recent years, e.g., tunnelling construction (Nielsen and Koseoglu, 2007), commonly, both tunnelling and mining do not make full use of the benefits offered. In addition, when wireless technologies are used, the infrastructure often adheres to older, lower-performance standards. Yet utilization of wireless networking in the underground environment offers the potential for major benefits in productivity and safety. Applications – which include communication, both for operational use and in emergency situations, environmental monitoring, maintenance and control of plant, and personnel tracking for safety considerations – are discussed in Section 2.

Wireless networking has not yet been fully embraced in underground application, in part, due to the limited availability of adequately robust equipment or of equipment that meets the legal requirements, for example, for use within a potentially explosive atmosphere such as coal mines. However, it is also true that the adoption of wireless networking in tunnels and underground mines has been hindered by a lack of understanding of how these systems operate in the subterranean environment. Accordingly, while a wireless network for an office or factory can be planned with relative ease, the same is not true of an underground system. The work described in this paper was conducted to provide some guidance on the performance of wireless links in tunnels to assist in planning such networks in the underground environment. In particular it involved an experimental characterisation of the underground performance of IEEE 802.15.1 Bluetooth and IEEE 802.11x Wi-Fi (specifically 802.11g, 802.11n and 802.11ac) communication standards.

2. Applications

Although the primary purpose of this paper is to provide guidance for those who have a requirement for wireless data communication underground, it is also appropriate to discuss the growing range of applications in which wireless networking can be exploited in this environment. It should be noted that this discussion is limited to tunnels and similar linear spaces since the propagation in larger underground spaces, e.g., shopping malls and underground car parks, follows a similar pattern to the well-know model of indoor propagation than to the less-well understood model of tunnel propagation that is the subject of this paper.

2.1. Tunnel boring

In this section the requirements of tunnel boring are discussed although some of the same issues apply to the working areas of mines, for example the coal face, which are in a state of constant

* Corresponding author. Tel.: +44 1326 371876.
E-mail address: G.A.Kennedy@exeter.ac.uk (G.A. Kennedy).

http://dx.doi.org/10.1016/j.tust.2014.05.005
0886-7798/

change so are less able to be served by wired networks than the fixed access tunnels in mines. In most cases, tunnel boring machines (TBMs) are driven from an integral control cabin using laser guidance although newer experimental techniques such as the use of robotic total stations – e.g., (Shen et al., 2012) – require the use of wireless networks. Increasingly there is a requirement to monitor TBMs and other elements of plant such as conveyors and pumps from a surface control centre and to use such a communication link to provide additional information to the TBM operator as described, for example, in Mao et al. (2013). The use of wireless sensor networks (WSNs) in this sector has also seen growth in the past decade. It is interesting to note, for example, that a construction project in London used a WSN in an adjacent London Underground tunnel to monitor any disturbances caused to that tunnel (Cheekiralla, 2004).

Current research into augmented reality systems to assist personnel involved in the maintenance of mining machinery is noted (Michalak, 2012) with the potential for such systems to also be used in tunnel boring projects. Although this prototype used local data storage, there are clear benefits in ensuring network access to a central up-to-date data repository and, potentially, linking the underground personnel to the surface allows assistance to be sought from remote equipment manufacturers. The advantage of allowing service engineers to be physically decoupled from a wired data connection cannot be over-stated.

Finally, wireless networking can provide an important role in providing communication between personnel in the tunnel. The requirements are much the same as for emergency communication and are discussed in Section 2.3.

2.2. Operational use

Much of the communications infrastructure in operational tunnels such as transport tunnels and the main access roadways in mines (as opposed to the working areas that, by definition, are in a state of constant change) are usually provided by cables. However, while operational needs of such tunnels can often be met using wired networks, it is becoming increasingly necessary in public spaces to provide access to the Web via WiFi networks. The communication standards discussed here are suitable to provide public WiFi hotspots in tunnel type environments such as the platforms of underground railway stations. This technology has also been used to provide an underground navigation system that provides a similar function to a smart phone's GPS capability on the surface (Lee et al., 2011).

For maintenance, upgrade and inspection of infrequently accessed tunnels such as sewers and cable conduits, a wired communication infrastructure will not generally be available, therefore personnel will be reliant on wireless communications. The requirements are much the same as for emergency communication as discussed in the next section.

2.3. Emergency use

Incidents such as fires, explosions or earthquake can render an underground environment's normal wired communication infrastructure inoperable. Accordingly, emergency services will often require wireless communication following a serious incident in a tunnel or mine operation. Although rescue services are equipped with VHF or UHF radio equipment that is effective above ground, such radios have a very poor range in tunnels. The use of leaky feeder cables (Delogne, 1982) is commonly used to extend the range of VHF and UHF systems. The microwave frequencies used by wireless networking standards, on the other hand, provide a much greater range, without expensive leaky feeder systems, in such environments and further offer increased bandwidths. Leaky feeders are a fixed cable that is also susceptible to damage during a fall or explosion.

Although hand-held "walky-talkies" operating on a microwave frequency can provide effective person-to-person communication, improved performance and additional facilities can be provided using a wireless data network through the increased bandwidth available. Voice communication can be transmitted across such a network using VoIP (voice over IP) and it is also possible to exchange photographs, video streams or other data, as well as allowing a surface controller to monitor the tunnel environment or the rescue personnel's vital signs. Several companies provide ruggedized equipment for creating a temporary network and, by positioning stations along the tunnel to act as relays, greater ranges can be achieved. Such a system, including both wired and wireless segments, is described in Wenfeng et al. (2007).

Using a wireless-based personnel tracking system to track miners – e.g., (Zhang et al., 2009) – can reduce the time taken for rescuers to reach any casualties. The same technology would be applicable to use in tunnel boring projects.

3. Previous work

3.1. Radio propagation in tunnels

The propagation of radio waves in tunnels has been studied by several researchers at a range of frequencies from LF to microwave. For example, extensive studies were carried out at UHF and microwave frequencies (Legace et al., 1975; Davis et al., 1983). The conclusion drawn was that propagation is favourable at these frequencies, where under the right conditions tunnels will act as lossy dielectric waveguides (Emslie et al., 1975). The various studies (Boutin et al., 2008; Choudhury and Jha, 2011; Delogne, 1982; Djadel et al., 2002; Emslie et al., 1975; Hwang et al., 1998; Mahmoud and Wait, 1974; Nerguizian et al., 2005; Zhang and Hwang, 1998) contain combinations of experimental results, modal analysis, and ray tracing techniques. In the light of the use of 2.4 GHz and 5 GHz for wireless networking, the authors of the current paper previously undertook a detailed investigation of the propagation at these frequencies in the underground environment. Favourable performance was noted under a wide variety of conditions and good correlation with waveguide theory was demonstrated. These positive results provided the impetus for the programme of work described in this paper.

3.2. Performance of wireless communication standards

As an alternative to radio propagation studies, the performance of the commonly used wireless communication standards has been reasonably well characterised for office environments. In many cases, though, practical evaluations have been presented in technical consumer or business publications, often as plots of throughput vs. distance, for equipment adhering to the same standard. While this is potentially useful as part of a comparative review of commercially available equipment, the lack of a formal peer review process places an element of doubt on the rigorousness of the test procedure and comparisons between different networking standards are rarely published. Other sources of information include network planning guides that are published by major equipment manufacturers although there's an element of doubt as to whether such publications are always entirely impartial. Some more rigorous work (Davies et al., 2008) describes a numerical modelling approach to indoor performance prediction, providing results in terms of received signal strength. Dama et al. (2011), on the other hand, provides a comparison of an experimental evaluation of data throughput and signal strength modelling of an IEEE 802.11n