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Use of wireless, ad-hoc networks for proximity warning and collision avoidance in surface mines

Venkataraghavasivanagashashank Sabniveesu[a], Ajay Kavuri[a], Rahul Kavi[a], Vinod Kulathumani[a], Vladislav Kecojevic[b]* and Ashish Nimbarte[c]

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This article describes the use of wireless communication technology in an easy-to-use *ad hoc* mode to address concerns of timely proximity warning and collision avoidance in surface mines and also describes the design of a cloud-based logging framework for long-term vehicular traffic analysis in mines. For timely warning about approaching vehicles at large distances (10–100 m), a GPS system is integrated with Wi-Fi (IEEE 802.11a/b/p) radios in an ad hoc mode, where information about approaching vehicles is known as soon as they come into range. A communication range test is performed in an actual surface mine setting to characterise the distances at which warning can be reliably received using each of the IEEE 802.11 family of radios. A zone-based proximity warning system is designed using low power IEEE 802.15.4 radios for detecting obstacles and vehicles at much smaller distances (<10 m), and marking them into zones around the vehicle. Both the proximity warning system and the Wi-Fi-based collision avoidance system were evaluated for feasibility at an operating surface coal mine in the southern United States. Finally, the design of a cloud-based logging framework is described and can be used for long-term data collection from GPS and other sensors.

Keywords: surface mine safety; RF-based zoning; Wi-Fi; collision avoidance; range tests; performance evaluation; IEEE 802.11a/b/p; V2V systems

1. Introduction

Despite the record of progress achieved in the United States with respect to reducing fatal and non-fatal injuries in surface mines, both the number and severity of these injuries remain unacceptable. A large fraction of these injuries in surface mines are caused by collisions involving large haulage equipment such as trucks, dozers and front end loaders [1–3]. There are two main contributing factors for these collisions: (i) the massive size of these vehicles, which causes several blind spots surrounding the vehicle for the driver and (ii) the sheer momentum of these vehicles, which makes it hard to manoeuvre these vehicles and often necessitates a long response time to avoid collisions [4]. The objective of this research was to investigate the use of different kinds of wireless networks in a distributed ad hoc mode for providing timely warning about

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nearby personnel and vehicles, and to evaluate their performance using tests in an operating surface mine.

For timely warning about approaching vehicles at large distances (10–100 m), we designed a GPS system integrated with Wi-Fi (IEEE 802.11a/b/p) radios in an ad hoc mode. The use of an ad hoc mode for Wi-Fi networks avoids the need for a cellular or long-range multi-hop network where GPS data would first be transmitted to a central processing unit and the vehicle locations would be then broadcast from that central system. Instead, in the proposed approach, information about approaching vehicles is known as soon as they come into communication range of each other. This also keeps the display for equipment operators free of clutter, as only information about nearby vehicles is displayed. One of the overlooked aspects when designing a GPS-based warning system is the effective distance range at which GPS locations of nearby vehicles can be received using wireless communication. In this research, we systematically investigate the packet reception characteristics and the received radio signal strength at different source–destination distances for IEEE 802.11 a, b and p radios, inside an actual surface mine. The topology of a surface mine is different than that of regular roads and contains deep pits, high obstacles and sloped muddy roads. By characterising effective communication range for 802.11 radios in these surroundings, we are able to determine the effectiveness of such collision warning systems for operation in surface mines.

One of the goals of this research was to design a system that will be able to provide a warning to a vehicle operator when another equipment or personnel comes close, and also to accurately determine the location as one of the several zones around the vehicle. For areas that are closer to the equipment, GPS data are not precise enough to provide a location indicator. Hence, we use an RF-based system. Specifically, we have utilised the Telos platform [5], which consists of a 2.4 GHz IEEE 802.15.4 radio [6]. This is the same radio used by ZigBee devices, but we do not utilise the ZigBee protocol here. RF-based tagging systems have been previously used for proximity detection in surface mines, but existing systems are typically designed only to detect the presence of other vehicles or personnel in the nearby vicinity and not to pinpoint a location or direction. However, in this article, we show how multiple RF devices embedded on the truck along with the received radio signal strength indicator on the radios can be used to accurately identify the zone in which an obstacle is detected.

In order to facilitate collection of long-term data about locations of different vehicles, we have designed a cloud-based data logging system. This system could potentially be used to collect data from any sensor installed on the truck, but this system has been currently integrated with a GPS that tracks the location of trucks. This system uses a Garmin GPS [7] device attached to a Windows Tablet running the .NET framework [8]. Upon installation, the GPS would log location coordinates locally as well as establish a remote connection to an FTP server and upload the data. Long-term data collected from this GPS system can be used to analyse vehicle trajectories in the mine and to assess near misses. The system thus has the potential to devise better guidelines for vehicular traffic in surface mines.

2. Review of existing technologies

Given the importance of the collision problem in surface mines, there has been extensive research in the past decade on proximity warning technologies for vehicles [9–13]. A summary of these technologies is provided as follows.

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Ultrasonic sensors: Ultrasound devices typically operate at 40–250 kHz and emit a short burst of ultrasonic waves, which are reflected back when they hit a hard surface [14]. The echo time is then used to estimate distances of obstacles. However, ultrasound systems require direct line of sight and any object in their path will cause a proximity alarm. This is likely to cause false alarms. Moreover, the range of these devices is typically very short (<10 m). As a result, these sensors are typically used for parking assistance in regular vehicles, but they are mostly unsuited for proximity warning in large surface mine vehicles.

Pulsed radar and LIDAR-based systems: Radars [15] and Lidars [16] are two other promising technologies that have been used for proximity warning. They operate similarly, in concept, as ultrasound echoing, but have a larger range and are much more accurate in distance measurements. However, they also suffer from false alarm issues as they can get triggered by the detection of any obstacle in their path. For example, on large trucks, they can get blinded by obstacles such as the large tyres or large dumps of soil and rocks. There are also chances of missed detections – for example, when personnel walk directly under their field of view, they remain undetected [15,17]. Moreover, these systems are often expensive, and installing them on surface mine trucks that operate in rugged environments is quite challenging.

Camera-based systems: Advances in computer vision with respect to object recognition have led to the use of cameras for detecting collisions in vehicles [9,13,18]. However, camera-based systems depend upon adequate lighting and do not perform well in the presence of fog, dust and dirt on the lenses. Moreover, when multiple cameras are used, reliable pattern recognition algorithms are needed to point accurately to an obstacle and present the correct view on a terminal; it is not feasible for a driver to shift through multiple screens all the time. Designing such reliable systems are challenging. Therefore, cameras are typically used as complementary systems to other proximity detection technologies; for example, if an obstacle is detected by radar in a given direction, the camera view from that side is projected on the terminal.

RFID and electronic tag-based systems: The key idea in these systems is that devices that are embedded on vehicles and personnel periodically emit electromagnetic waves. These devices can also sense signals transmitted by other devices, and when devices are close enough, the signal strength is sufficient to cause a proximity alarm. These systems are easy to deploy, do not depend on line of sight and typically have a range of 12–18 m. But existing systems are typically designed only to detect the presence of other vehicles or personnel in the nearby vicinity and not to pinpoint a location or direction [19]. One of the systems that we designed for this research is also an RF-based proximity warning system that uses IEEE 802.15.4 radio operating the 2.4 GHz frequency. However, we show in this article how multiple RF devices embedded on the truck, along with the received radio signal strength indicator on the radios, can be used to accurately identify the zone surrounding the vehicle in which an obstacle is detected.

GPS-based systems: GPS devices can provide location estimates with an accuracy of 3–4 m. Therefore, GPS devices along with some form of wireless communication are increasingly being used for detecting approaching vehicles and for collision avoidance [20–24]. In this research, we have used a GPS-based system for collision detection from larger distances (>10 m). At very close distances, the GPS systems are not accurate enough to correctly estimate the direction in which a nearby obstacle has been detected, although they can estimate that there is an object nearby. Therefore, for closer distances, we have used an RF-based system. Secondly, as noted earlier, some form of wireless communication is needed so that GPS locations of nearby vehicles and objects

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can be communicated to other approaching vehicles. For this research, we evaluated three Wi-Fi-based standards in an actual surface mine setting to understand their effectiveness in communicating the locations from a sufficient distance such that there is enough time for drivers to react.

3. Investigation of IEEE 802.11 radios in an ad hoc mode for GPS data communication

GPS-based proximity warning systems are increasingly being recommended for collision avoidance and vehicular safety, in the context of regular personal vehicles as well as heavy mining trucks. The basic idea in these systems is to use a GPS receiver along with some form of wireless communication module on each vehicle to provide updates about its location to other vehicles. These updates can be provided in two ways: (i) a centralised cellular or long-range communication infrastructure can be used to communicate data from each vehicle to a processing centre and then re-broadcast data from there to all the vehicles and (ii) GPS data can be communicated in a decentralised peer-to-peer manner only to vehicles that are nearby. The former approach is more cumbersome and expensive: it involves excessive set-up costs inside surface mines as well as high cost for data usage. Therefore, for this research, we used the latter mechanism by utilising IEEE 802.11 (Wi-Fi) radios in an ad hoc mode. In this mode, two Wi-Fi radios can communicate with each other as soon as they come within communication range of each other.

The Wi-Fi Alliance defines Wi-Fi as a wireless local area network product based on the IEEE 802.11 standards. IEEE 802.11 is a set of media access control (MAC) and physical layer (PHY) specifications for implementing wireless computer communication in the 2.4,5 and 60 GHz frequency bands. The IEEE 802.11 family consists of a series of standards that use different modulation techniques and frequency bands, but use the same underlying communication protocol. In this research, we specifically consider the IEEE 802.11 a, b and p series for evaluation.

The 802.11a specification is an amendment to the IEEE 802.11 family that uses the same frame format and link layer protocol as the original 802.11 specification, but operates in the 5.8 GHz band and uses the orthogonal frequency division multiplexing (OFDM) technique for signal modulation. The advantage of 802.11a is the use of the 5 GHz frequency instead of the crowded 2.4 GHz ISM band, where interference from other devices often can be found.

IEEE 802.11b is an amendment of IEEE 802.11 that uses the direct-sequence spread spectrum with data rates of 5.5 and 11 Mbps in the 2.4 GHz range. One disadvantage is the use of the 2.4 GHz frequency where many other devices operate, such as Bluetooth devices and Wi-Fi routers that may cause wireless channel interference. However, in mining environments, we do not expect this interference.

The 802.11p supports wireless access in vehicular environments and contains enhancements required to support Intelligent Transportation Systems applications [25]. The standard uses the 5.9 GHz ISM band and enables car-to-car or vehicle-to-vehicle communication. Similar to IEEE 802.11a, 802.11p radio is based on matured OFDM technology. The MAC layer functionality is slightly modified to include provision for rapid communication of DSRC devices with no need for authentication or authorisation processes as in the original 802.11 standard.

An often overlooked aspect when designing a GPS-based warning system is the quality of wireless communication and the effective distance range at which GPS

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locations of nearby vehicles can be received inside a surface mine. The topology of a surface mine is different than that of regular roads and contains deep pits, high obstacles and sloped muddy roads, which cause a hidden line of sight for the wireless radios being used leading to poor reception (Figure 1). At the same time, some other conditions are more relaxed when compared with regular roads: (i) the number of vehicles per unit area is much lower thereby reducing channel contention and (ii) the chances of interference from other devices such as Wi-Fi routers and Bluetooth devices are also lower. For this research, we systematically investigated the packet reception characteristics and the received radio signal strength at different source–destination distances for IEEE 802.11 a, b and p radios, inside an actual surface mine. By characterising effective communication range for 802.11 radios in these surroundings, we are able to determine the effectiveness of such collision warning systems for operation in surface mines and identify the appropriate 802.11 radio type to use. We first describe our system set-up and then present the results of our evaluation.

The system that was assembled for testing consists of the following hardware components (Figure 2):

(1) GPS sensor: The Globalsat BU-353 was used as the GPS module for the system [26].
(2) Processing: Each GPS device was attached to an Alix 1e [27] single board computer that has a 500 MHz AMD Geode CPU and 256 MB SDRAM. This board has a mini-PCI slot for inserting the wireless card.
(3) Wi-Fi module: The *UNEX CM9-GP* mini-PCI wireless card [28] was used as the Wi-Fi module that has support for IEEE 802.11 a, b, g and p standards.
(4) Antenna: A 9dBi dual band 2.4 GHz/5 GHz antenna was attached to the wireless card for communication.

Software components include the following:

(1) GPS programme: This programme periodically samples the GPS coordinates at 5 Hz and sends it to the Alix board using a socket programme.
(2) Data Broadcast and Reception: This module utilises the underlying communication network to broadcast the GPS data as well as receive GPS data from other transmitters within communication range. Each transmitted packet has a unique sequence number and timestamp. The received data are processed to compute the packet reception rate and the received signal strength (RSSI).

Figure 1. Topology at surface mine with sloped terrain and sharp hairpin bends (the figure on left shows a spoil pile causing hidden line of sight for the 802.11 radio while the figure on the right illustrates sloped terrain and the partial line of sight).

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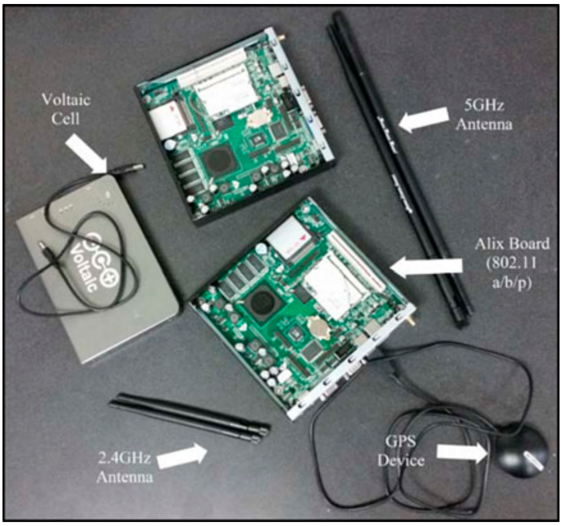

Figure 2. Components of Wi-Fi for range test at a surface mine: GlobalSat BU-353 GPS device, Alix single board computers, dual band antennae, Unex 802.11 wireless cards and Voltaic cells to power the system.

(3) Ad hoc network: Each device is configured to belong to a Wi-Fi network in an ad hoc mode with the same cell ID. This allows data communication without having to explicitly join a network when devices come into contact. The process of joining a network is time consuming (with a latency of several seconds) and will result in long delays. By setting up an ad hoc mode, this latency can be avoided.

The topology of a surface mine consists of sloped terrains with berms at the edge of vehicular pathways. As noted earlier, this causes several hidden-line-of-sight scenarios at intersections for both drivers as well as the propagation of 802.11 radio waves. In many of these cases, the pathways are sloped with hairpin bend intersections where vehicles cannot see each other and must rely on location warnings with adequate response time. Figure 1 shows the hairpin intersections at slopes and the hidden-line-of-sight scenarios. To characterise the performance of IEEE 802.11 inside a surface mine, we conducted range tests using a sender–receiver pair of the above system under the following different topological conditions: (i) Line of sight, (ii) Non line of sight, (iii) On an inclined hair pin bend with receiver at the bottom and (iv) On an inclination with receiver at the top. Sender and receiver were separated by distances in steps of 9 m. Sender transmission rate was fixed at 5 Hz with each packet about 100 bytes.

In Figures 3–6, we show the packet reception rate for IEEE 802.11 a, b and p radios under these conditions and the corresponding RSSI values that indicate the strength of radio reception. The data shown in these figures were derived from several trials by systematically sending and receiving data from different distances. The points shown are medians over these trials. Approximate trend lines have been devised to better show the pattern in this data.

In Figures 3(a) and 3(b), we show the packet reception percentage and RSSI, respectively, for the line-of-sight scenario. Under this scenario, the graphs show a

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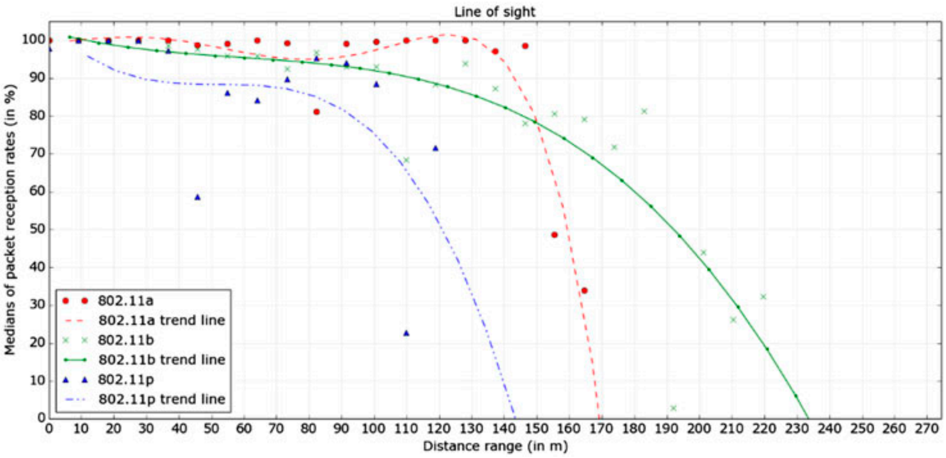

Figure 3a. Median packet reception rate as a function of source receiver distance (direct line of sight).

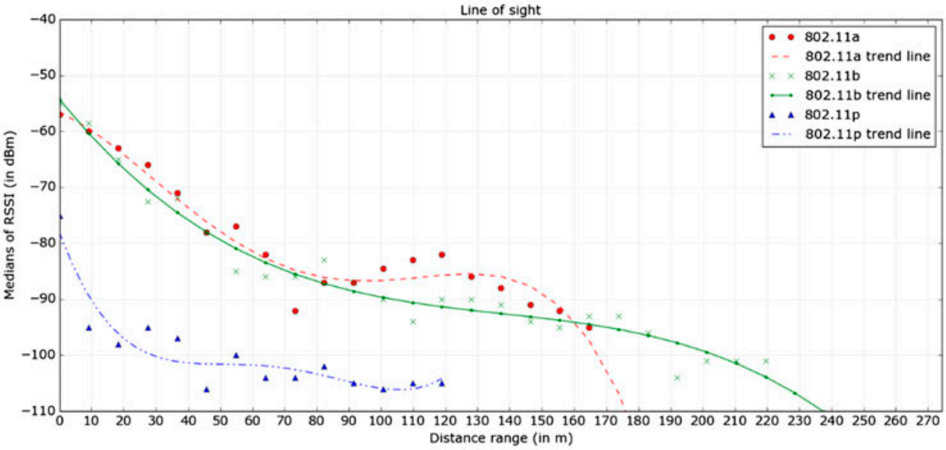

Figure 3b. RSSI trend as a function of receiver distance (direct line of sight).

steady deterioration in signal quality and packet reception for all three radios. However, it can be noted that 802.11b and 802.11a have a much larger reception range than 802.11p under these conditions. Also, we note that RSSI and packet reception rate drop off steeply for 802.11a radios after a certain distance, but 802.11b is able to get weak signals at much greater distances.

In Figures 4(a) and 4(b), we show the packet reception percentage and RSSI, respectively, for the sloped terrain scenario where the receiver is at the bottom of an inclined pathway. In Figures 5(a) and 5(b), we show the packet reception percentage and RSSI, respectively, for the sloped terrain scenario where the receiver is at the top of an incline. In sloped terrains, 802.11b is observed to have a much larger packet reception range compared to the other two radios. Both 802.11a and 802.11p have

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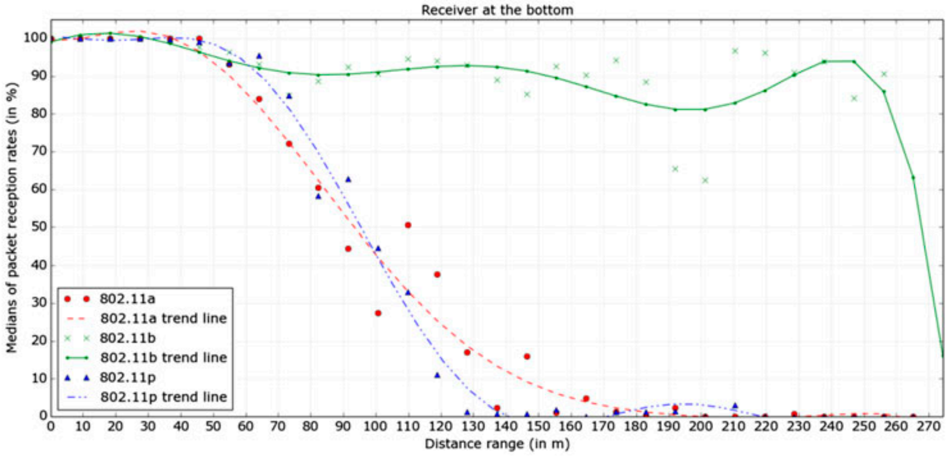

Figure 4a. Median packet reception rate as a function of source receiver distance (receiver at the bottom of incline).

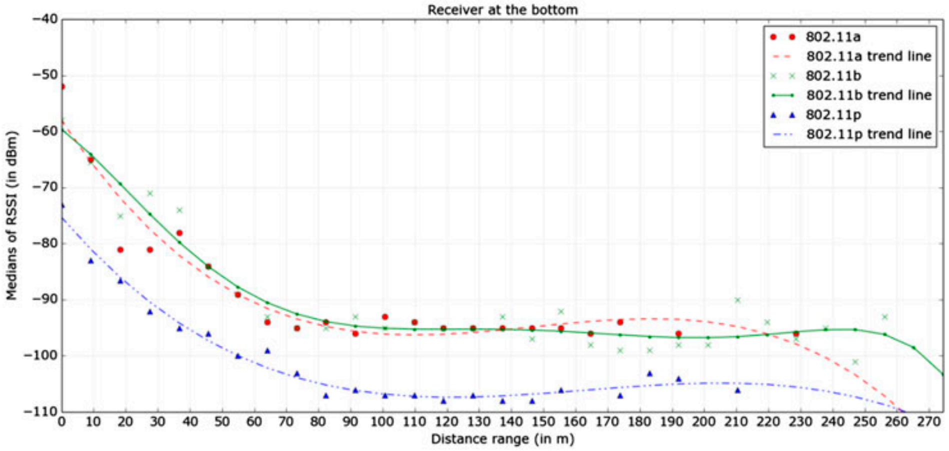

Figure 4b. RSSI trend as a function of receiver distance (receiver at the bottom of an incline).

similar characteristics with lower packet reception range. Also, we observe that RSSI values are relatively stronger when the receiver is at the bottom.

In Figures 6(a) and 6(b), we show the packet reception percentage and RSSI, respectively, for the hidden-line-of-sight scenario. Under this scenario, when the sender and receiver are blocked by a high mound of rocks, all three radios seem to be affected with lower packet reception range. The RSSI values are also relatively weaker. However, in this scenario, 802.11b is able significantly outperforms the other two radios in terms of communication range.

In Table 1, we list the approximate reception range at which more than 75% of the packets are received on average for each of the scenarios. We observe that with IEEE 802.11b, even in the worse condition (hidden line of sight), packets can be received at

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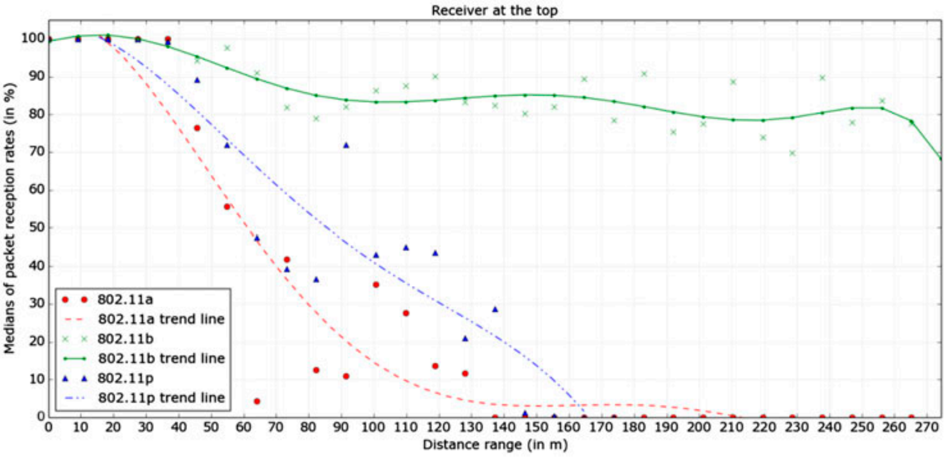

Figure 5a. Median packet reception rate as a function of source receiver distance (receiver at the top of an incline).

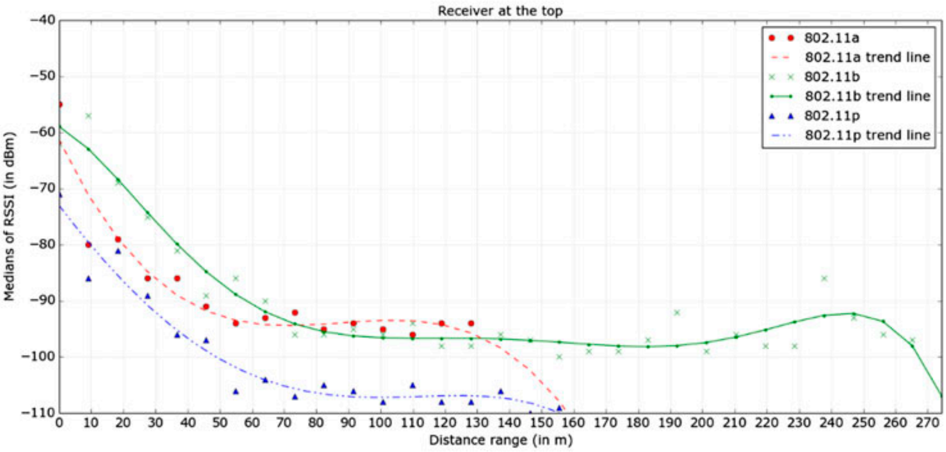

Figure 5b. RSSI trend as a function of receiver distance (receiver at the top of an incline).

a distance of 73 m from each other, providing adequate reaction time for the drivers. At a speed of 32 kmph, this gives drivers about 9 s of reaction time.

Our findings show that although IEEE 802.11p (DSRC) radios are recommended for vehicular networks and intelligent transportation systems, the higher frequency (5.9 GHz) of these signals makes them less suitable for use in surface mine conditions. IEEE 802.11b signals are better suited. The concern of potential interference in the 24 GHz range with IEEE 802.11b is unlikely to be of impact in surface mines with much lower traffic and external interference.

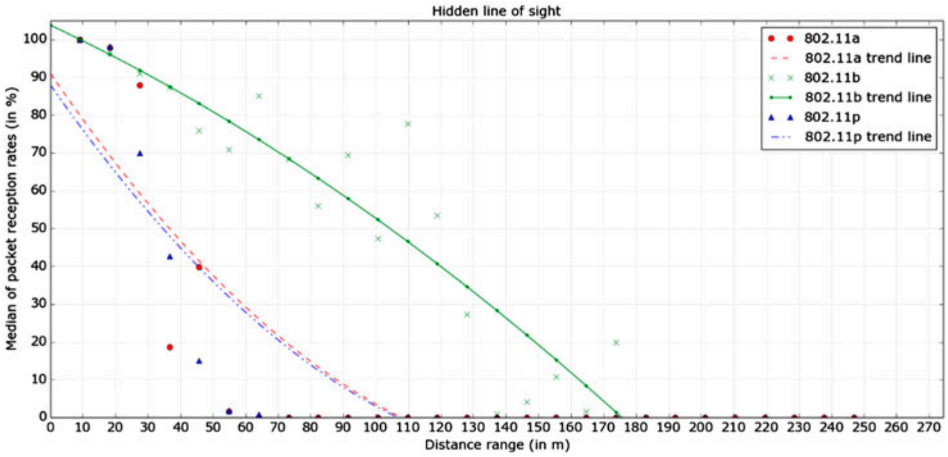

Figure 6a. Median packet reception rate as a function of source receiver distance (hidden line of sight; sender and receiver are separated by a large mound of soil and rock).

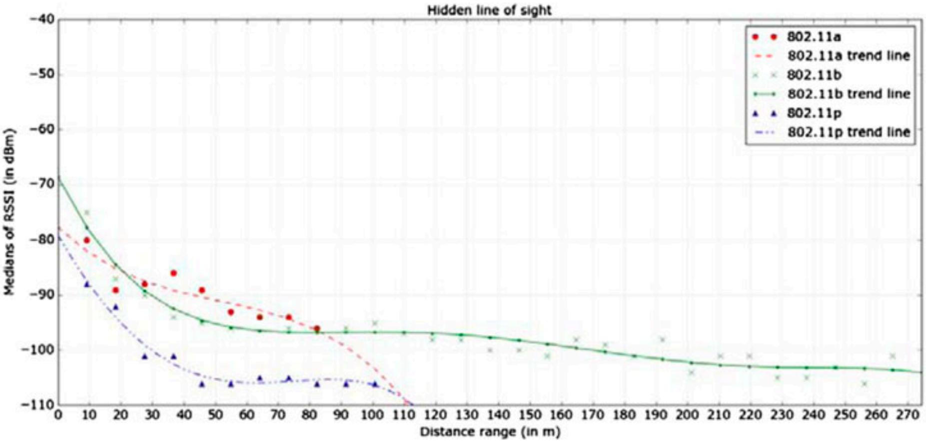

Figure 6b. RSSI trends as a function of source receiver distance (hidden line of sight; sender and receiver are separated by a large mound of dirt and rock).

Table 1. Average distance at which more than 75% packets are received under different topological conditions in for each of the three radios.

	802.11 b	802.11 a	802.11 p
Direct line of sight	152 m	152 m	98 m
Receiver at top	183 m	76 m	76 m
Receiver at bottom	183 m	91 m	76 m
Hidden line of sight	73 m	36 m	36 m

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4. Design of IEEE 802.15.4 radio-based proximity zoning system for near-field objects

The objective of this system is to provide a warning to the vehicle operator when an object comes close to the vehicle and classify the object into one of the several zones around the vehicle. The zoning feature can potentially be used to optionally turn on a camera to visualise the particular area for more details.

For our test deployment of the RF-based proximity system, we used 4 TelosB motes [5] as our RF sensors and installed them on four sides of a CAT 769 haul truck. These are used as zone-marker motes. We divided the truck into eight proximity zones as shown in Figure 7(a). The Telos platform consists of a Texas Instruments MSP430 microprocessor along with a 2.4 GHz IEEE 802.15.4 radio (Figure 7(b)). This is the same radio used by ZigBee devices, but we did not utilise the ZigBee protocol here.

A mobile mote (whose location was to be tracked) acts as a transmitter and sent out a beacon message once every 200 ms, i.e. at 5 Hz. The 4 zone-marker motes act as receivers of beacon messages sent out by mobile motes. All the zone-marker motes that received this message recorded the received signal strength for the message (RSSI). The RSSI recorded by each zone marker is then transmitted wirelessly to a base station mote that is located inside the truck. The base station continuously sorts incoming messages based on their RSSI. The RSSI values from the motes were averaged over a moving window of 3 s. These RSSI values are used to classify the mobile object into one of the eight zones around the vehicle.

When the mobile mote is inside one of the zones tagged by a zone-marker mote (i.e. zones 1,3,5,7 in Figure 7(a)), the RSSI values from those motes are clearly dominant compared to RSSI values from other motes. We observed an almost 100% accuracy when classifying motes into only one of these four zones. When the motes are in the other zones, there is no clear dominant RSSI value from any given zone-marker mote. We utilise this fact in classifying whether a mobile mote is in zone 1,3,5,7 or in

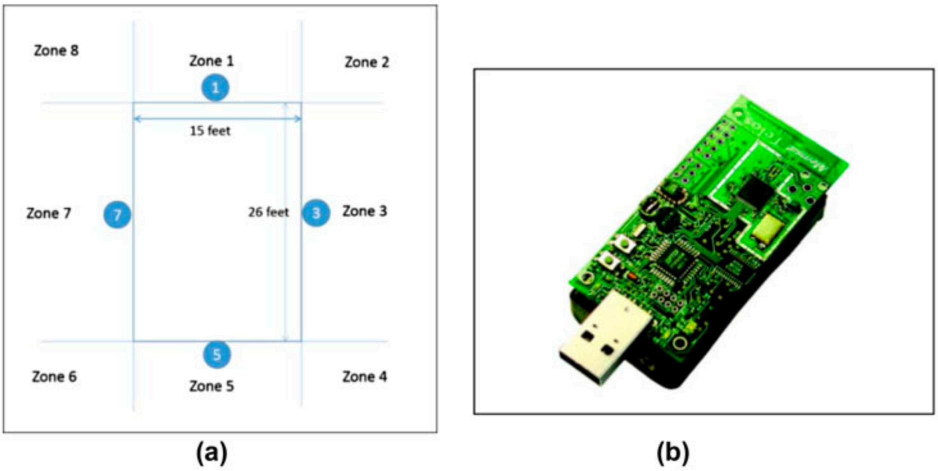

Figure 7. (a) Schematics of mote deployment and zones surrounding a CAT 769 haul truck (the 4 blue circles indicate zone marking motes deployed in zones 1, 3, 5 and 7, respectively). (b) TelosB mote used for proximity sensing and zoning; it contains a TI MSP430 microcontroller along with an IEEE 802.15.4 radio.

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zone 2,4,6,8. We compute the difference in the top two RSSI values at any instant and then take a moving average over the last 3 s.

Let $R_a(t)$ and $R_b(t)$ denote the highest and second highest RSSI recorded for the mobile mote at time t. Let $Z_a(t)$ and $Z_b(t)$ denote the zones representing these RSSI values, respectively. Let $R_d(t) = |R_a(t) - R_b(t)|$. Let $MA_3(R_d(t))$ denote the moving average of $R_d(t)$ between time t and time $t-3$. In Figure 8(a), we have shown a distribution of this moving average $MA_3(R_d(t))$ at different distances from the truck. The blue dots represent the distribution of $MA_3(R_d(t))$ when the mobile mote is in zones 1,3,5 and 7, which are zones tagged by a zone-marker mote. The red dots represent the distribution of $MA_3(R_d(t))$ when the mobile mote is in zones 2,4,6 and 8, which are zones not tagged by a zone-marker mote. The figure shows that the differences in two highest RSSIs are much higher when the mobile mote is in zones 1,3,5 and 7. We use this fact to determine threshold $\alpha(t)$.

If $(MA_3(R_d(t)) > \alpha(t))$, we classify the mote as belonging to zone Z_a(t); otherwise, we classify the mobile mote as belonging to the zone between $Z_a(t)$ and $Z_b(t)$. For our particular system test, we chose $\alpha(t)$ to be equal to 10 dB. The classification accuracy obtained using this scheme is shown in Figure 8(b) for distances of 3, 6 and 9 m from the truck. As observed in Figure 8(b), we get almost 90% accurate zoning and about 10% times, the zones are classified as the directly neighbouring zone. At a distance of 12 m, it is observed from Figure 8(a) that we cannot correctly distinguish between neighbouring zones and the precision of the system decreases to that of a 4-zone system as opposed to an 8-zone system.

Our results show that IEEE 802.15.4 radios can be reliably used for proximity detection and zoning at short distances. This system can adequately complement GPS-based systems that are better suited for distances greater than 10 m away from a vehicle.

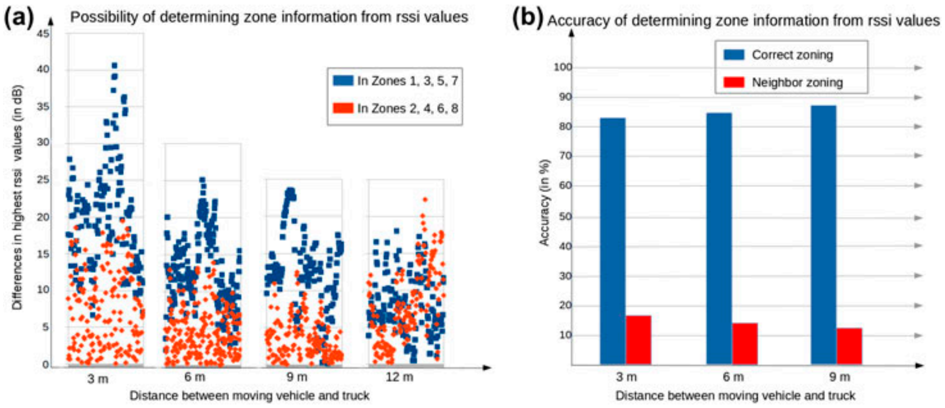

Figure 8. (a) Difference in RSSI values between highest and second highest zone (the blue dots represent the distribution when mobile mote is in zones 1, 3, 5 and 7 which are zones tagged by a zone marking mote while the red dots represent the distributions when the mobile mote is in zones 2, 4, 6 and 8). (b) Accuracy of determining zone information based on RSSI values.

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5. Cloud-based data logging system for surface mines

While the two systems described above are meant for proximity warning in real time, there is also a need for long-term analysis of vehicular traffic in the mine. GPS location data that is collected from all the trucks in surface mine over several months will enable a detailed traffic analysis that can be used to understand near-misses in collision that were not caught by the real-time system. It will also point out traffic distribution in the mines along with median speeds in various areas.

In order to facilitate long-term data collection from sensors in the mine, we designed a cloud-based data logging system (Figure 9). This system could potentially be used to collect data from any sensor installed on the truck, but we have only integrated this with a GPS that tracks the location of trucks. For this purpose, we have used a Garmin GPS device attached to a Windows Tablet running the .NET framework [8]. Upon installation, the GPS would log location coordinates locally as well as establish a remote connection to an FTP server and upload the data. Some of the features of this system are as follows:

(a) *Speed-based logging rate*: Logging all the data periodically (even at a 10-s interval) would generate a huge amount of data, which is not cost effective (Internet Service Providers and cloud services charge based on data transferred). For example, if each log is 100 bytes long, logging at 1 Hz would generate 360 Kbytes per truck per day. On the other hand, decreasing logging frequency will prevent the data from being useful when vehicles come closer. Hence, we have designed a speed-based differential logging service that logs and transmits data proportional to the speed. No data are transferred when the vehicle is idle and the data rate is progressively increased with speed and is transferred at 1 Hz at speeds of 40 kmph and above. This results in effective data usage; on a normal working day, this results in about 50 Kbytes of data per truck.

(b) *Tolerates intermittent connection*: It is not feasible to assume that network connection is always available in a mine. So our service logs data locally, and

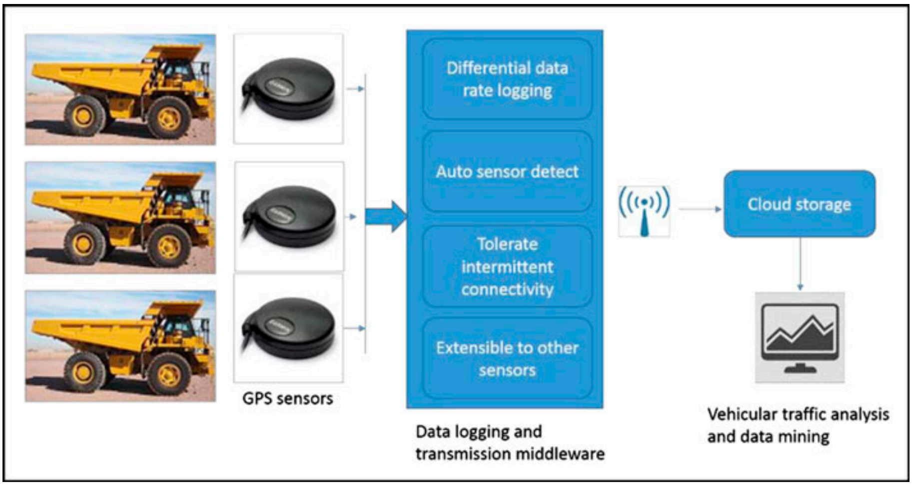

Figure 9. Cloud-based logging framework for long-term data collection and traffic analysis inside surface mine.

whenever a connection is available, it uploads the data.

(c) *Auto package installer and auto sensor detect*: The service can be installed with an easy-to-use package installer and starts itself automatically when a GPS device is detected.

6. Conclusions

In this article, we have described three different use cases of wireless communication technology aimed at addressing concerns of timely proximity warning and collision avoidance in surface mines. We first characterised the performance of a family of IEEE 802.11 standards inside an actual surface coal mine for communicating GPS data to nearby vehicles. We observed that the IEEE 802.11b standard operating in the 2.4 GHz range outperforms 802.11p and 802.11a standards, in terms of the effective distance at which GPS data can be reliably received. We then described an IEEE 802.15.4 radio-based system for proximity zoning of tagged objects at distances of less than 10 m. Our system is shown to be able to reliably classify nearby objects into one of the eight zones surrounding a CAT 769 truck. The 802.15.4 radio-based proximity zoning system can thus adequately complement Wi-Fi-GPS based systems that are better suited for collision avoidance at distances greater than 10 m away from a vehicle. Finally, we presented the design of a cloud-based framework for logging GPS data over long durations from vehicles in the mine. This system can be used for long-term vehicular traffic analysis, detecting near misses, and for designing better and safe traffic guidelines in surface mines.

In terms of extensions to this work, we would first like to augment our wireless range studies to include the presence of wireless interference from other trucks. We are also currently studying effective user interface designs that can display the proximity warnings and GPS data in an intuitive manner without extensive distractions. Finally, once the long-term, cloud-based logging framework is deployed on multiple trucks, we would like to use this data for performing traffic analysis and understanding vehicular driving patterns.

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