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Experimental Investigation of Radio Signal Propagation in Scientific Facilities for Telerobotic Applications

Regular Paper

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Abstract Understanding the radio signal transmission characteristics in the environment where the telerobotic application is sought is a key part of achieving a reliable wireless communication link between a telerobot and a control station. In this paper, wireless communication requirements and a case study of a typical telerobotic application in an underground facility at CERN are presented. Then, the theoretical and experimental characteristics of radio propagation are investigated with respect to time, distance, location and surrounding objects. Based on analysis of the experimental findings, we show how a commercial wireless system, such as Wi-Fi, can be made suitable for a case study application at CERN.

Keywords Telerobot, Remote Control, Mobile Robot, Radio Signal Propagation, Wireless Communication, Tunnel Environments

1. Introduction

CERN (European Organization for Nuclear Research) and other similar scientific facilities have a need for remotely operated vehicles (mobile robots) to carry out remote inspections and radiation surveys in different areas, e.g., the Large Hadron Collider (LHC), to avoid or minimize the need for personnel to go inside the radiation areas and perform these tasks. Another similar situation is the use of help, search and rescue robots during disaster conditions [1] where humans cannot enter dangerous or harmful environments.

As the operations in hostile or radioactive environments are difficult to fully automate, the robots are equipped with teleoperation capabilities and some autonomy (intelligence) features may be added to ease the operator overload [2]. For these applications, the main wireless communication challenges to be considered are that the robot should be able to travel long distances in hostile or tunnel-like environments, and should be able to quickly transmit large amounts of data. Having a reliable communication link with the robot is essential to avoid the need for personnel access to recover the robot in the event of communication failure [3].

Using umbilical cables rather than a wireless system for the communication has some drawbacks. For instance, the Quince robot [1], which used an umbilical for communicating with the operator, became immobilized because of a communication failure on the third floor on its way back out after measuring radiation levels in the Fukushima nuclear reactor building [4].

Wireless communication avoids the cable disconnection problem typical of wired communication, which occurs when a cable is broken as a result of physical damage during operation. Therefore, wireless communication is preferable for remotely operating mobile robots in such environments.

However, underground tunnels are generally very challenging environments for radio communications [5, 6]. It is observed in [5] that the behaviour of radio signals is very different in underground mines compared to that in outdoor and Line of Sight (LOS) environments. In addition, the first step in increasing a wireless network performance is understanding the environment. Hence, there is a need to investigate how radio signals behave in scientific facilities such as at CERN, so as to properly design the wireless communication system and ensure reliability.

The contributions of this paper are two-fold:

1. Description of major wireless communication link requirements for typical telerobotic applications at CERN.
2. Experimental results giving temporal, spatial and environmental characteristics of radio signal propagation in an underground scientific facility.

The organization of the paper is as follows:

- First, the wireless network requirements for typical telerobotic applications related to CERN is presented and a case study application is considered.
- Then, current available wireless systems are compared and a specific wireless technology is selected for the case study application described in section 2.2.
- Following some theoretical background on radio signal propagation, the scope of the experiments to be conducted is defined.
- Then, during the experimental testbed, measurement parameters are described and signal propagation characteristics are analysed.
- Lastly, the results of the experimental tests are discussed in relation to commercially available wireless technology (Wi-Fi).

2. Wireless communication requirements

2.1. Wireless link requirements for telerobotic applications

According to the systems engineering approach [7], the user needs are studied first before identifying a solution. Therefore, the first goal is to obtain the requirements of the wireless communication system for various possible applications at CERN from the people who need these applications. Each application has different requirements for establishing a point-to-point wireless network between the telerobot and the teleoperator. The three main parameters which define these requirements are:

- Maximum admissible system latency (in milliseconds),
- Minimum data transfer rate (in Megabits/second),
- Maximum distance to be covered (in metres).

The system latency is a critical parameter in a real-time application. It is the amount of time taken by a data packet to travel from a source to a destination (host processing latency + network latency). It depends on the number of buffers between communication ends [8]. Network topology and coverage distance requirements (which are relevant to latency) are decided by the type of the application. Hence, these values were obtained by interviewing people requiring such applications.

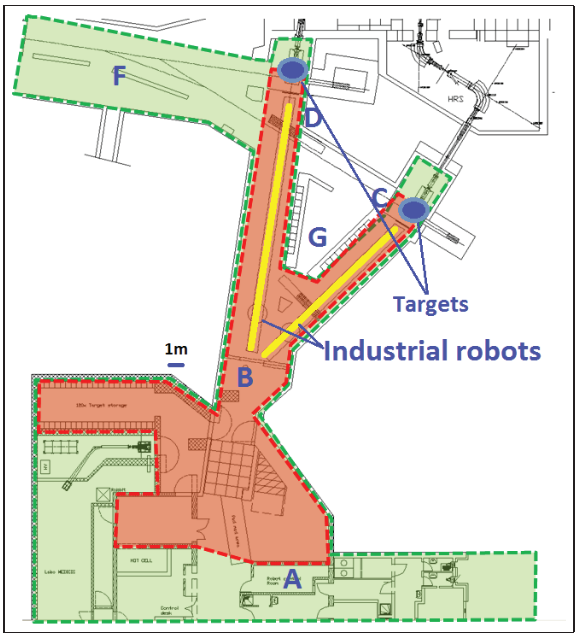

Figure 1. ISOLDE experimental facility at CERN

The data transfer rate is defined as the speed with which the data can be transmitted and is decided by the amount of data to be transmitted. For video transmission, one can refer to [9] to find a relation between the quality of the video and the data-rate required. It is recommended that at least two live video transmissions are necessary for a vision system used for remote handling [10].

Therefore, considering the need for having two good VGA quality videos and using H.264 coding at 30 $^{\text{frame}}/_{\text{s}}$, the data-rate required will be 1.7 $^{\text{Mb}}/_{\text{s}}$ [9] per video. Similarly, for other applications, the appropriate data-rate is calculated assuming typical data requirements. Table 1 summarizes the wireless communication requirements for various mobile robot applications at CERN.

2.2. ISOLDE vision system for remote handling

The ISOLDE (the Isotope Separator On-Line facility at CERN) experimental area is one of the high radiation areas at CERN with a radiation dose-rate of 100 mSv/h at 50 cm from the radioactive target after 1 $hour$ of decay [13]. Figure 1 shows the floor plan of the ISOLDE area.

Two industrial STAUBLI RX 170 robots are used to transfer the used targets [14] from the target irradiation supports (C,D) to the target storage area (G) and pick up new targets from (B), a target interchange point. These robots are preprogrammed and the operator selects the sequence of operations from a dedicated control room (A) outside the ISOLDE facility.

However, in some situations such as robot teaching, the operator has the need to visually monitor the robot's movements. For such real-time monitoring, it

	Application	Max. distance	Min. data-rate	Max. latency	Comments
1.	Remote measurements	500 m	512 kb/s	1000 ms	For measurements of radiation levels, temperature, oxygen and other sensory data transmission [11]
2.	Remote Handling (RH) tasks without haptic feedback	200 m	64 kb/s	100 ms	Remote control of robots in scientific facilities [2, 11]
3.	Vision system for RH	200 m	3480 kb/s	200 ms	For transmission of two good quality videos with VGA resolution [9, 10]
4.	RH with haptic feedback	200 m	128 kb/s	25 ms	Teleoperation with force feedback [12]
5.	ISOLDE case study	40 m	5120 kb/s	200 ms	For transmission of two good quality video with HD resolution (refer section 2.2 and [9])

Table 1. Requirements for some telerobotic applications at CERN

is desirable that a reliable wireless video transmission system mounted on a small mobile robotic vehicle, such as the KUKA Youbot [15], is used to transmit the live camera feeds monitoring the industrial robots. In figure 1, the red portions indicate the area where this application is needed.

The communication requirements for this application (given in table 1) are based on the HD transmission of two good quality videos so that the operator can observe the environment in more detail, including any small sparks in the Faraday cages inside the ISOLDE facility. In this paper, the vision system application at ISOLDE is used as a case study.

3. Comparison of various wireless technologies

Comparison of different wireless technologies is discussed in [16–20]. Table 2 shows a brief summary of specifications of some wireless technologies with the advantages and disadvantages with respect to the ISOLDE case study requirements.

Out of these available systems, a Wi-Fi-based system had been selected for first trials as it was readily available, widely studied and well used technology. Coded Orthogonal Frequency Division Multiplexing (COFDM)-based Wi-Fi technology can be well suited for tunnel environments [21] because it is specifically designed to combat the effects of multi-path interference (see section 4.1). However, owing to availability and cost limitations, a normal Wi-Fi system has been chosen for the experiments.

It appears from table 2 that a Wi-Fi system meets the requirements for the ISOLDE application, however, the specifications in table 2 are given for a normal indoor environment, whereas the CERN application will be in a tunnel environment including large metallic objects. As a result, experimental analysis is needed to verify the suitability of a Wi-Fi-based vision system in the ISOLDE area.

4. Radio signal propagation

4.1. Radio signal propagation theory

According to Shannon's capacity theorem [23], in a wireless system, the communication channel capacity C is related to the signal's received power P_R as follows:

$$C = Blog_2(1 + \frac{P_R}{P_N}) \qquad [\mathrm{Mb/s}] \qquad (1)$$

where, B is the bandwidth of the channel and P_N is the power of the noise in the channel. This indicates that the data-rate of the wireless network (which is a measure of the channel capacity C) depends on the received signal strength.

When a radio signal travels from a transmitter to a receiver through multiple paths subjected to reflections, diffractions and refractions in the surrounding environment, a phenomenon called multi-path propagation occurs. This leads to multi-path fading and constructive or destructive interference [24]. The multi-path fading can be either long-scale fading due to the shadowing effects caused by the obstacles or small-scale fading due to interferences of the multi-path components [25].

The attenuation in the power of the radio signal is defined as the path loss PL and is caused by many factors such as distance (free space loss), penetration losses through walls and floors, and multi-path propagation [26]. In particular, all walls, ceilings and other objects that affect the propagation of radio waves will directly impact the signal strength and the directions from which radio signals are received. The path loss can be modelled as a log-normal distribution [24]:

$$PL_d = PL_{d_0} + 10n\log(\frac{d}{d_0}) + \mathcal{X}_\sigma \qquad [\mathrm{dBm}]^1 \qquad (2)$$

where, PL_d is the path loss at a distance d, PL_{d_0} is the path loss at a reference distance d_0, n is the environment specific propagation constant, and σ_x is the variance of a zero mean Gaussian distribution $\mathcal{X}_\sigma$. The n and σ_x together define the environment and the $\mathcal{X}_\sigma$ represents the large-scale fading because of shadowing effects [25].

The received signal power P_R is equal to the difference in the transmitted power P_T and the path loss PL_d over a distance d,

$$P_R = P_T - PL_d \qquad [\mathrm{dBm}] \qquad (3)$$

The path loss is a major component in the analysis and design of the telecommunication system [27].

[1] dBm (dBmW) is the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW).

	Wireless Technology	Max. data-rate	Max. distance	Average Latency	Merits	Demerits	Cost (€)	Typical applications
				Wireless Local Area Networks (WLAN)				
1.	Wi-Fi 802.11n	108-600 Mb/s	100 m	1-100 ms	Readily available, High data-rate	Latency can be high	10s	Internet
2.	Wi-Fi with COFDM [21]	18 Mb/s	5 km	50 ms	Long range, Low latency	Expensive	1000s	Communication in Tunnels
3.	WirelessHD [22]	1 Gb/s	20 m	1 ms	Very low latency, Very high data-rate	Short range	100s	HD video transmission
4.	Bluetooth v2.0	1 Mb/s	10 m	10 ms	Low latency	Low data-rate, Short distance	10s	Fast data sharing
5.	Zigbee	256 kb/s	70-100 m	5 ms	Very Low latency	Low data-rate	10s	Wireless sensor networks
6.	WiMAX	75 Mb/s	50 km	10-50 ms	Very Long distance, High data-rate	Infrastructure limitations	10000s	Wireless broadband

				Cellular Networks			
	Cellular Technology	**Max. downlink data-rate**	**Max. distance**	**Average Latency**	**Merits**	**Demerits**	**Availability**
1.	2.5G (EDGE)	236.8 kb/s	> 1 km	1000 ms	Long range	Low data-rate, High Latency	Presently available in CERN underground facilities
2.	3G (UMTS)	2 Mb/s	> 1 km	200 ms	Long range	Low data-rate, High Latency	Presently available in CERN underground facilities
3.	4G (LTE)	100 Mb/s	> 1 km	20 ms	Long range, Low latency	Infrastructure limitations	Not available in CERN facilities

Table 2. Performance characteristics of commercially available communication systems with reference to CERN requirements

4.2. Radio signal propagation in tunnel environments

Much literature exists for radio signal propagation in tunnel environments [5, 6, 28–30]. Experimental studies on radio propagation characteristics in tunnel-like environments date back to 1975; Emslie et al. [31], focus on the path loss of radio signal at frequencies in the range of 0.2 to $4GHz$ along a tunnel, and from one tunnel to another around a corner. Reference [5] provides a detailed analysis of wired and radio communication systems in underground mines or tunnel facilities where the tunnels are not straight leading to different forms of turns (e.g., U turn, angle turn). In [6], the authors investigate the communication considerations from the perspective of in-mine and mine to surface communications separately, and provide a detailed overview of all types of possible communication systems.

In [30], the authors recommend a wireless system operating at a frequency greater that $2GHz$ in underground tunnel facilities because the transmission loss becomes very small over a frequency of $2GHz$ in a coal mine tunnel of width $4m$ and height $3m$. Therefore, a Wi-Fi system operating at $2.4GHz$ should be a reasonable choice for underground scientific facilities.

Scientific facilities such as those at CERN, exhibit the characteristics of underground tunnel structures and complete non-Line of Sight (NLOS) conditions with special properties such as heavy metal objects in the surroundings. The presence of thick concrete blocks (for shielding gamma rays, which also makes it difficult for the radio waves to penetrate) and large objects with metallic surfaces such as the dipole or quadrupole magnets, contributes to the characteristics of these environments. All these characteristics have different effects on radio signals [5]. For the facilities having obstructed indoor environments, multi-path effects have to be taken into account in the propagation of radio waves [25].

Boutin et al. [29] analyse the NLOS propagation in tunnels and compare the characteristics of path amplitude and delay spread in a received signal from multiple paths. They suggest that further narrow-band and wide-band measurement campaigns should also be undertaken in galleries with different configurations as the wireless propagation in underground mine tunnels can be a challenge to model accurately in view of the complexity of the environment. Signal propagation simulation tools such as WISE [32], predict the received signal in an indoor RF channel. However, such tools rely on many parameters and are limited to outdoor and LOS situations.

One of the observations by Chou et al. [33] suggests that for a wireless link there is a trade-off between the maximum achievable data-rate and the packet delivery latency. The latency of radio propagation in scientific facilities was not studied in the literature.

The two main motivations for conducting the experimental analysis are:

1. According to [29], using the theories and analysis available in the literature, it is not very simple to quickly predict the signal propagation behaviour in underground environments because the characteristics for each environment are very different.
2. No study was found that analyses the effects on radio signal latency in scientific and tunnel facilities.

Therefore, experiments have been conducted to investigate the spatial, temporal and environmental characteristics of radio signal strength and latency in a scientific facility at CERN.

4.3. Communication quality measurement parameters

The quality of communication links is a function of many variables including location, distance, direction and time [34]. To estimate the distance coverage of radio signal propagation, we must analyse the Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) at the receiver end. The latency of the communication network can be measured by using the Round Trip Time (RTT) metric. The definitions of the three metrics to be measured are given below.

$RSSI$: Corresponds to the received strength of the signal. The signal strength mainly depends on the antenna output power and the distance between the transmitter and the receiver.

LQI: Shows the quality of wireless connection. There are several definitions for LQI and it usually refers to the percentage of packets transmitted successfully.

RTT: Round trip time for a packet to travel from the transmitter to the receiver.

Both the $RSSI$ and LQI are nonlinear with respect to distance as there are many other factors affecting link quality such as reflections and interference. If there are too many wireless stations in a wireless network, interferences may occur resulting in loss of messages. Reference [35] explains why RSSI alone is not enough as a measurement parameter as the interference experienced on a link cannot be inferred via $RSSI$ measurements, but can be measured by the LQI. Therefore, both $RSSI$ and LQI are needed for link quality assessment, and RTT is needed for latency measurement.

5. Experimental setup

Since there is relatively little propagation measurement data available for underground environments, it is important to take into account the impact of various environmental characteristics so that several simulations of link qualities using empirical values can be performed [29]. Conducting experiments at ISOLDE was not allowed during its operation as it is a highly radioactive area [13]. Therefore, experiments are conducted in a tunnel area called ECN3 (shown in the figs. 2 and 3) which was not in operation and hence was available for tests.

Figure 2. ECN3 tunnel area at CERN - location of the transmitter (Point A in figure 6)

Figure 3. ECN3 tunnel area at CERN - view from the tunnel entrance

Even though the ISOLDE and ECN3 facility areas are different, using ECN3 as the test facility allowed experimented and analytical techniques to be developed, and will provide information on how well results obtained in one facility (ECN3) can be applied to another one (the ISOLDE area).

5.1. Methods and materials

In these experiments one static wireless transmitter (ProSafe Dual Band Wireless-N Access Point WNDAP350 [36]) and five compact Wi-Fi receiver stations are used (Zyxel NWD2105 [37]). The transmitter [36] uses IEEE 802.11n 2.4GHz standards with maximum transmit power $P_T = 20\,\text{dBm}$ and a maximum data-rate of 144.44 Mb/s. The receiver [37] had a receive sensitivity threshold R_S of -64 dBm at Mb/s and -82 dBm at 11 Mb/s.

The transmitter was fixed at point A in figure 6 and the receiver stations were mounted at different positions on a KUKA Youbot mobile robot as shown in figure 4. The omni-directional capability in Youbot [15] made it the best choice for the experiments because of space and size restrictions in the environment. As for the CPU, a computer running on Ubuntu in the Youbot is used.

The values of $RSSI$ and LQI were obtained by using the $iwconfig$ command in Linux. Each $RSSI$ and LQI sample is measured at 100 Hz sampling rate for 1s, and then averaged to diminish statistical temporal fluctuations. $\overline{RSSI} = \frac{1}{100} \cdot \sum_{i=1}^{100} RSSI_i$, $\overline{LQI} = \frac{1}{100} \cdot \sum_{i=1}^{100} LQI_i$. The values of the measured $RSSI$ and LQI, and the method of measurement depend on the manufacturer of the wireless device. For Zyxel NWD2105, the $RSSI$ is equal to the received power in dBm, $RSSI = P_R$, and the LQI is the percentage of successfully transmitted packets.

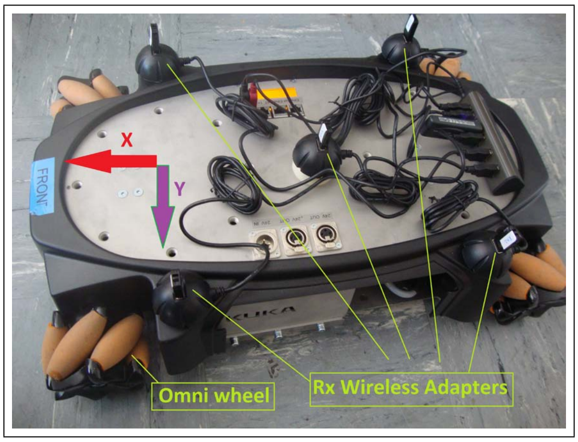

Figure 4. The Youbot mobile robot used in the tests

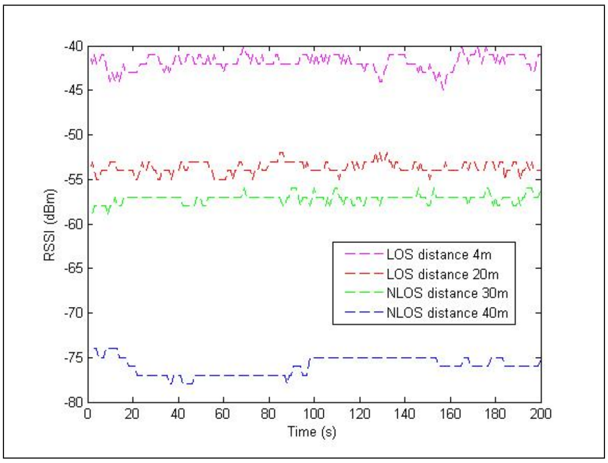

Figure 5. RSSI variations with time at various distances

$$LQI = \frac{No.\ of\ successfully\ transmitted\ packets}{No.\ of\ total\ transmitted\ packets} \quad [\%] \quad (4)$$

The *ping* command provides the RTT values for the respective receivers. The maximum number of bytes able to transfer at a time using *ping* is 65527 bytes (512 kilobits). The RTT reading for each receiver is the average of 10 samples. The average of the results from all receivers has been obtained, so that the results were not device-dependent.

5.2. Experiments carried out

The variations of signal strength, link quality and the latency in the wireless channel were investigated for temporal, spatial and environment-based characteristics. The three types of experiments conducted were:

1. Temporal characteristics: Time variation of $RSSI$ and LQI was measured for around 90 minutes at various distances in the ECN3 tunnel. The RTT variation with the amount of data transmitted was also observed.
2. Spatial characteristics: The mobile robot was moved from one point to another point over a distance of around 50m through variations in space, such as LOS and NLOS situations, passing nearby metallic objects. The robot was moving at a speed of 0.2 m/s.
3. Environmental characteristics: The mobile robot was moved under a reinforced concrete block and near to large metal objects and the $RSSI$ variations were noted.

Figure 6 shows the floor plan of the ECN3 tunnel area and the location of the transmitter and the receiver (Youbot) indicating the path the mobile robot used to travel a distance of 37m in X direction (LOS) and 28m in Y direction (NLOS). Each experiment was conducted twice and the readings were averaged.

6. Results and discussions

Changes in RSSI and LQI with respect to time, distance and environment variations are detected. The RTT variations were measured with respect to the distance and the quantity of the data transferred. The results of these experiments are described in the following sections.

6.1. Temporal characteristics

In [34], the authors say that it is highly possible to conserve the quality of a wireless link within an hour and they observed $RSSI$ variation within $5 - 6$ dBm in a day, however this was in an indoor environment. With the measurements shown in figure 8, the $RSSI$ variation over a period of 90 minutes at point B in the ECN3 tunnel had a mean of 23.22 dBm and a variance 8.75 dBm.

Figure 5 shows the temporal variation of $RSSI$ at different distances from the transmitter. It can be observed that as the receiver was farther from the transmitter, the frequency of $RSSI$ variations with time got smaller but the magnitude of variation became larger.

The variation of RTT with distance and quantity of data transmitted (at a distance of 40m) can be observed in figure 7 and a linear fit for this variation is given by the equation:

$$RTT = 0.0001bits + 2.3 \qquad [\text{ms}] \qquad (5)$$

This result correlates well with the observations in [10] where the RTT was observed as $1s$ for transmission of five good quality video images at 2 Mb/s each over a distance of $50m$.

6.2. Spatial characteristics

The received signal power $RSSI$ and the link quality LQI with respect to the distance have been analysed in order to understand the spatial characteristics of the radio signals in underground CERN facilities. It can be observed in figure 9 that the decay of $RSSI$ with distance followed the log-normal distribution as expected [24].

The points in the figure 9 correspond to the physical location points in figure 6. As soon as the robot entered the NLOS region (point D), the decay became more rapid with distance compared to the LOS region. As the receiver moved further into the deep NLOS region (point F to point G), the wireless network became unreliable because the $RSSI$ values reached very near to the sensitivity threshold of the receiver (-82 dBm).

The linear regression method described in [24] was used to derive the empirical path loss constants. The n value was

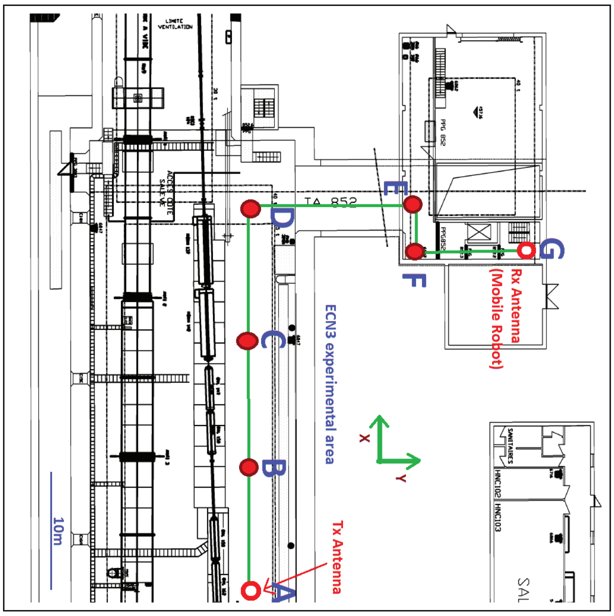

Figure 6. Floor plan of ECN3 tunnel

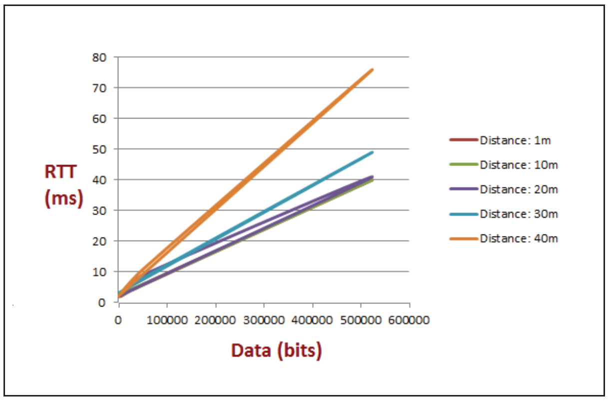

Figure 7. RTT variation with quantity of data at various distances

obtained by equating the derivative of mean square error estimate J_n of the path loss constant to zero, $\frac{dJ(n)}{dn} = 0$. The formula for J_n is:

$$J(n) = \sum_{i=1}^{k} (P_{d_i} - P_{d_0} - 10n \log \frac{d_i}{d_0})^2 \qquad (6)$$

The σ_x value was calculated by substituting the estimated n value in the following equation:

$$\sigma^2 = \frac{J(n)}{4} \qquad (7)$$

The reference distance used in calculations was $d_0 = 5\,\text{m}$ and the received power at the reference distance was $P_{d_0} = -32\,\text{dBm}$. The path loss constant n and the variance of the Gaussian distribution σ_x calculated using the experimental data from figure 9, are shown in table 3. The obtained path loss constants for the LOS, NLOS and deep-NLOS regions in ECN3 correspond to the outdoor region, obstructed factories region and obstructed in building regions in [24].

These empirical values which correspond the environmental characteristics of ECN3 tunnel can be useful in predicting the distance range of the wireless network in tunnel areas similar to ECN3. It is assumed that the propagation characteristics of ISOLDE experimental area are similar to ECN3 area, therefore the derived log-normal fit can be used in the analysis of the case study application.

Location	Path loss exponent, n	Variance σ_x
LOS (Point A to D)	2.54	1.77
NLOS (Point D to E)	3.02	1.52
Deep NLOS (Point F to G)	4.36	2.72

Table 3. Experimental values of path loss constants

Figure 10 shows the behaviour of LQI versus distance. When the robot entered the deep NLOS region (point F), the link became unstable with very poor connectivity and the LQI decreased linearly with distance d. The linear-fit equation for LQI variation with distance greater than 38 m was:

$$LQI = -1.57d + 160 \qquad [\%] \qquad (8)$$

According to [38], the Packet Reception Ratio PRR which is equivalent to LQI, should be at least 85% to consider the link as being of a good quality. Applying the threshold of 85% LQI for a good connection, the distance range for a good quality wireless link in the ECN3 tunnel was 48m from the point A.

6.3. Environmental characteristics

Radio signals suffer significant attenuation near some metallic surfaces due to reflections [5]. According to [24], the expected path loss for radio waves obstructed by a 4m metal object is $10 - 12\,\text{dBm}$. To analyse the characteristics of metallic reflections and obstructions, the robot was made to pass a metre wide metallic obstruction as shown in figure 11. Figure 12 shows the observed changes in $RSSI$ caused by the reflections and obstructions due to metal objects. The end-to-end variance in $RSSI$ was 8.2 dBm, which is consistent with the values in the literature [24].

Obstructions by reinforced concrete walls can also deteriorate the radio signal strength as the radio waves find it difficult to penetrate through walls and reinforced concrete materials. The expected path loss because of obstruction by a 0.6 m square reinforced concrete pillar is 12-14 dBm [24]. Figure 13 shows a half metre thick concrete block used for the experiments. The mobile robot was driven between two concrete blocks and the changes in $RSSI$ due to the obstruction by these blocks were noted as shown in figure 14. The $RSSI$ variance observed was 17.2 dBm which compares to the $13 - 20\,\text{dBm}$ path loss due to a concrete block wall in [24].

7. Implications for the case study application

In this section, the question of whether a Wi-Fi system can be suitable for the case study application at ISOLDE is discussed. As defined in [27]: "If the estimated received power is sufficiently large (relative to the receiver sensitivity), the link budget is said to be sufficient for

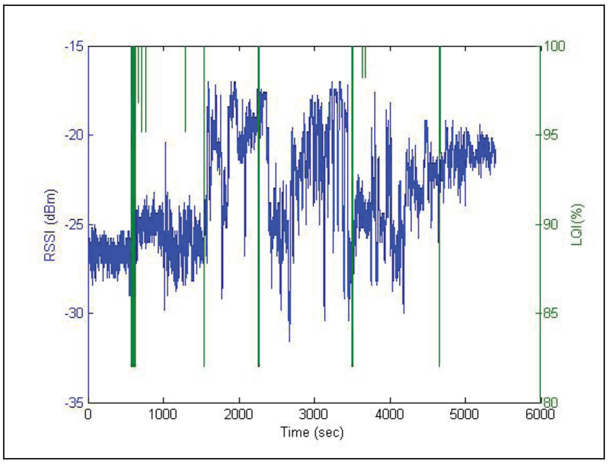

Figure 8. RSSI and LQI variations with time

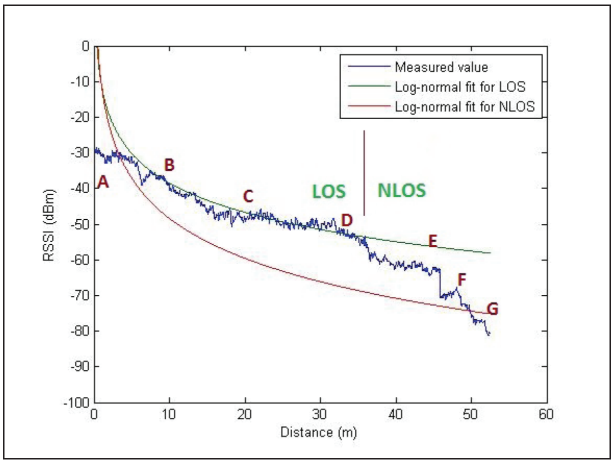

Figure 9. RSSI versus distance in ECN3

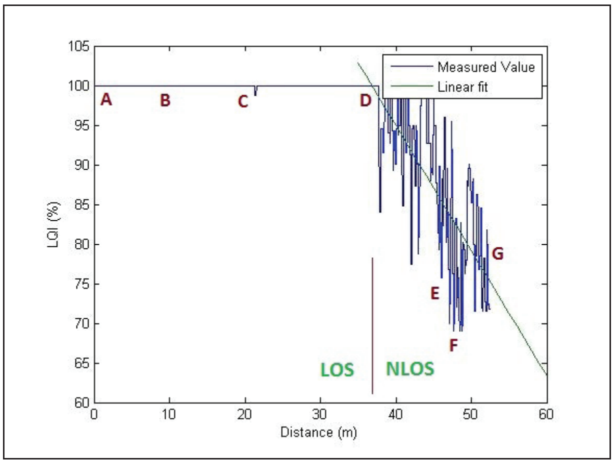

Figure 10. LQI versus distance in ECN3

sending data under ideal conditions". The amount by which the received power exceeds receiver sensitivity is called the link margin.

$$Linkmargin = P_R - R_S \tag{9}$$

Figure 11. Metallic objects used for tests

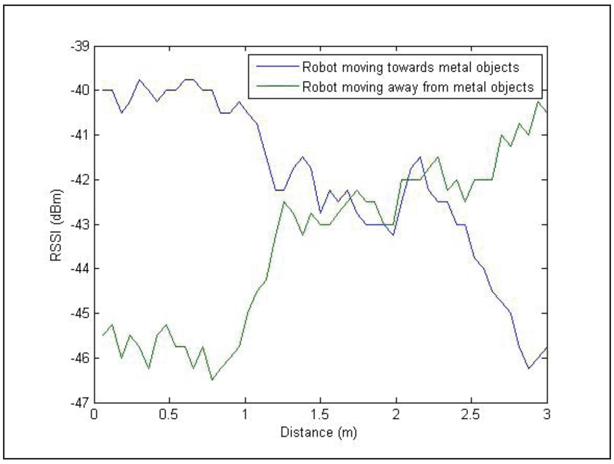

Figure 12. RSSI variation because of metallic objects

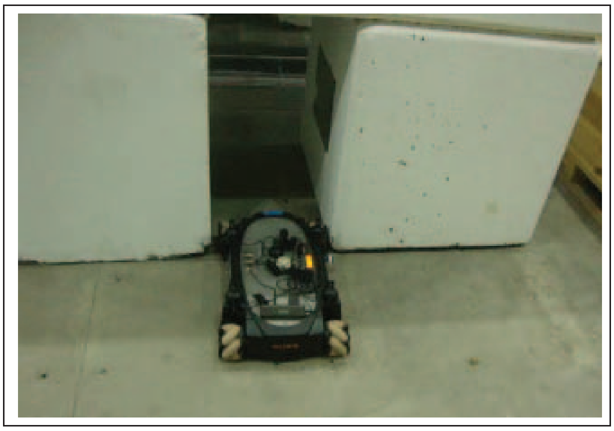

Figure 13. Thick reinforced concrete block used for tests

The wireless communication range and link quality can be improved by one or more of the following approaches [27]:

- Increase the "transmit power P_T" of the transmitter.
- Have enough link margin considering the path loss of the environment.
- Relocating or repositioning the antennas.

Among these possibilities, reference [27] recommends that an adequate link margin is factored into the link budget to overcome the multi-path fading when designing a wireless system.

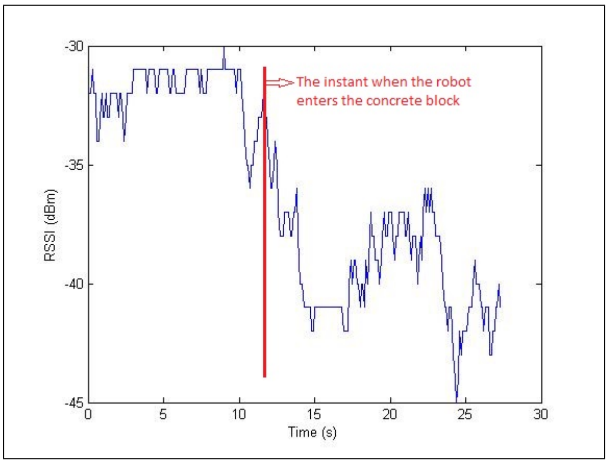

Figure 14. RSSI variation because of concrete block

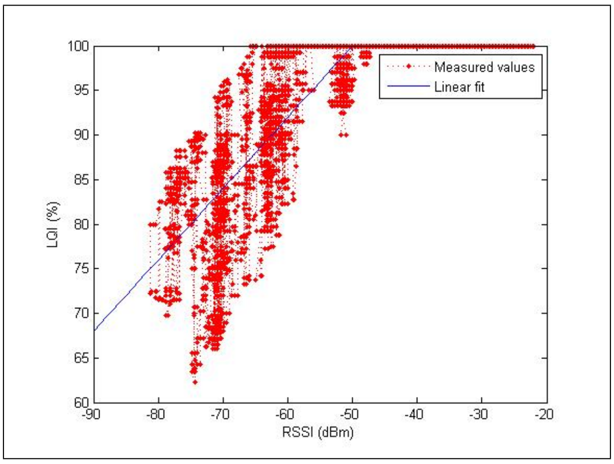

Figure 15. LQI with RSSI

7.1. Distance range prediction

Let us assume that for the case study application the transmitter antenna is located at a point which ensures LOS connectivity to all the points where the receiver robot can be placed. A link margin of 18 dBm is required to ensure 99% link availability (as a percentage of time) in LOS conditions [27].

For the ISOLDE area, a link margin that corresponds to the inevitable $RSSI$ fluctuations due to temporal variations and objects within the LOS has to be considered. This means that for the receiver used in tests with sensitivity threshold $R_S = -82$ dBm, a strong wireless connection 99% of time with an $RSSI$ stronger than -64 dBm is maintained in LOS situations.

The variation of LQI with respect to the $RSSI$ in the ECN3 tunnel is shown in figure 15. A linear fit for LQI with respect to the $RSSI$ was applied for $RSSI$ values less than -40 dBm.

$$LQI = 0.8RSSI + 140 \qquad [\%] \tag{10}$$

It is evident from figure 15 that to achieve a completely stable and reliable connection where $LQI = 100\%$, the $RSSI$ should be greater than -57 dBm in a 95% confidence interval. This $RSSI$ value corresponds to a distance of 35 m in figure 9.

To satisfy the distance requirement of the case study application, an $RSSI$ value of -57 dBm is required at 40 m distance. In figure 9, at 40 m, the $RSSI$ value is -60 dBm. Therefore, the need for having an additional 3 dBm in the link budget can be solved by increasing the transmitter power from 20 dBm to 23 dBm, the legal limit of maximum transmitter power (equivalent to 200 mW) in Europe for the 2.4GHz ISM band. Therefore, a more powerful transmitter or a receiver with better sensitivity threshold, according to theory, can be used to solve the problem of meeting the distance range requirements of the ISOLDE vision system application.

7.2. Data-rate and latency prediction

For the ISOLDE application, a data-rate of 5 Mb/s is required to transmit two HD quality video images. This means that within one second 5120 kbits should have been transmitted. Applying the data requirement at 40 m distance in equation 5, the RTT value is obtained as 514ms, which can lead to two inferences.

1. 5120 kbits of data can be transmitted within one second, therefore, this system will satisfy the data-rate requirement.
2. Since the $RTT = 2 * Latency$, the system latency is 257 ms at 5120 kb/s, therefore, a latency requirement of 200 ms is not achieved.

However, when transmitting multiple packets with less data in each packet, the latency requirement can be met. Assuming that data are sent at 4 Mb/s, the system latency will be 200ms which meets the latency requirements for the case study application but not the data-rate requirement. Therefore, there is a trade-off between the latency and data-rate requirement in a wireless application.

Table 4 summarizes the requirement and the observed possibilities for the case study application at ISOLDE.

	Distance	Data-rate	Latency
Needed	40 m	5 Mb/s	200 ms
Achievable with present system	35 m	5 Mb/s	257 ms
Present system + more transmit power	40 m	5 Mb/s	257 ms
Present system + less data-rate	40 m	4 Mb/s	200 ms

Table 4. ISOLDE case study application: Needs and calculated requirements

8. Conclusions and further work

This study attempted to characterize radio signal propagation in a typical underground scientific facility for a telerobotic application. Initially, the wireless communication requirements for typical telerobotic applications at CERN and similar scientific facilities are discussed. Considering the requirements for the application of wireless video transmission, we attempted to answer the question of whether readily available wireless technologies such as Wi-Fi, offer adequate performance and can be used for the case study application. Experiments have been performed to analyse the temporal, spatial and environmental characteristics of the radio signal propagation in the ECN3 tunnel area at CERN using link quality measurement parameters such as $RSSI$, LQI and RTT.

The data-rate requirement for the ISOLDE case study application can be met with the present Wi-Fi-based system used for the experiments. The distance requirement can be met only under LOS conditions, whereas the latency requirement can be met only if the quality of the transmitted videos is reduced. With all the observations, the conclusion is that the Wi-Fi devices used in the experiments can be used for the ISOLDE vision system application only if there is a trade-off between the latency and data-rate requirements, or if a powerful wireless transmitter and receiver (with better transmit power and receive sensitivity) should be required.

The HD video is needed because the video quality is sufficient enough to inspect small cracks in the target or the beam dump in the ISOLDE area. As inspecting a crack with a delay is acceptable, for such inspection, the latency requirement does not need to be met strictly, but the data-rate has to be strictly met. On the other hand, for teleoperation of the robot, the HD video may not be strictly required and so the video quality can be reduced to meet the strict latency requirements but with a trade-off to the data-rate.

Even though the experiments were conducted in the ECN3 tunnel area, the results have given intuitive meaning with regard to how to design a better wireless system in the ISOLDE facility. The ISOLDE area will be available for tests during the long shut down period (May 2013 - March 2014). For further studies, the use of directional antennas (on both the transmitter and the receiver robot) will be examined so that the radio signals from the transmitter are concentrated only to the receiver, thereby increasing the received signal strength.

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