LONDON UNDERGROUND COMMUNICATIONS

GROUP 17

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ABSTRACT

"Tube commuters hit by 'rush hour from hell'." [1]

It was a title in the daily BBC news on the seventh of February 2011. Signal failure has caused a huge frustration to Londoners, especially those who choose underground railway or Tube as their main means of transportation.

London Underground (LU) is the oldest underground railway in the world[2]. With 402km/249miles in length of networks[3], it has become the 2nd longest metro in the world[4]. On average, 1065 million passengers are carried each year[3], showing how important the Tube is to Londoners.

However, London's underground railway is lacking communications in terms of cellular network coverage, unlike its counterparts in Glasgow, Washington DC, Stockholm, Beijing, Tokyo and Moscow. At present, there is hardly any mobile phone connection that is the simplest communications technology available on the Tube, let alone the 4th generation cellular wireless standards[5].

Underground communications is useful to Londoners in many ways. Apart from being a platform for exchange of ideas, some research has shown that 6 out 10 passengers would like to have mobile phone coverage on the Tube[6]. The figures are expected to increase prominently with the upcoming Olympic Games in 2012.

However, further research has shown that a lack of credible proposals from suppliers has been the main factor of the delay of implementation of underground communications network by London's underground authorities[7] .

The report should draw readers' understanding, first on communications system in general, then the impediments to the existence of underground communications, before arriving at a solution to this problem.

Given the extensive nature of research that has been performed, and the substantive nature of the outcome, it is suggested that the report should be submitted as a proposal paper for TfL to further improve their services.

Hopefully the report will give an insight to all readers about communications technology in general and how it is useful to our lives!

1) What Is Communications system?

Communications system is a system consisting of two ends, transmitter and receiver, in between which there is a channel. Antenna is a transducer, which is a device that transmits and receives radio waves. It converts radio waves to electric signal by induction and vice versa.

Nowadays mobile phones use full duplex (i.e. the use of two different frequencies simultaneously) to transmit data. This means mobile phones can process two frequencies together, one is for transmitting signal (talking) and one is for receiving signal (listening). The network coverage of mobile phones is determined by the number of 'cells'. Cells are small partitions that a city is divided into, whereby each cell consists of a tower and a small building with radio equipment. Mobile phones operate within cells and can switch cells as they move around to enable continuous conservation. Same frequency can be reused in non-adjacent cells.

Typically there are 832 radio frequencies in a city, which can be divided into 395 full duplex voice channels and 46 control channels. The available number of frequency is increased by 2G technology with digital transmission methods. The most popular one is GSM, which stands for Global System for Mobile communications. Voice data is compressed by an analogue-to-digital converter so that less space is taken and less travel time. GSM uses encryption (for security) and operates in 900MHz or 1800MHz. The main network providers in the UK, like T-Mobile and Orange, work on the 1800MHz bandwidth while O2 and Vodafone use 900MHz bandwidth[8].

Within the bandwidth, each frequency is identified by Mobile Telephone Switching Office and signal transmitted from each user is differentiated by a specific code. This specific code or System Identification Code (SIC) is assigned by the network provider and is searched by control channel when the phone is switched on. When a phone call is made, the mobile phone sends SID along with registration request to Mobile Telephone Switching Office (MTSO) which will keep track of your phone location and save it in the database[9]. When a phone call is made to you, the MTSO will search your location, before picking an available frequency pair for your phone to receive the call.

By setting a resonant frequency, only certain bandwidth(s) will be allowed to work with this antenna[10]. Radio waves are more reliable because it travels at higher speed and low energy loss through air. However, it is not penetrable, where signal is absorbed by rocks and soils and partially reflected when it encounters a surface. So it makes underground communications difficult.

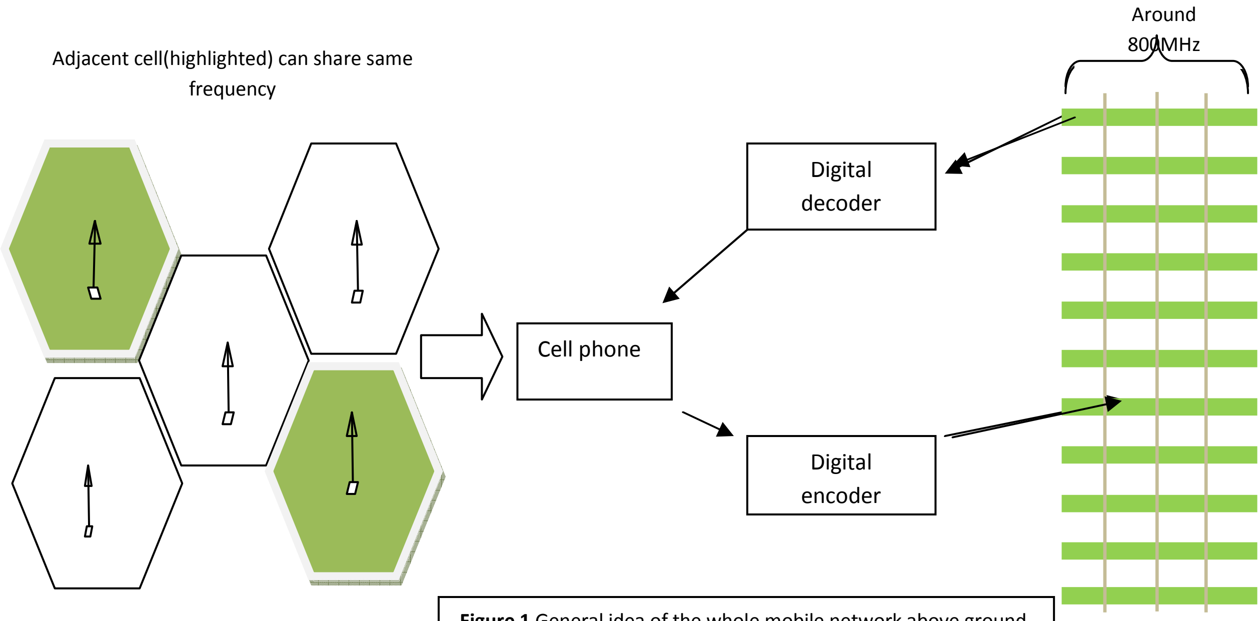


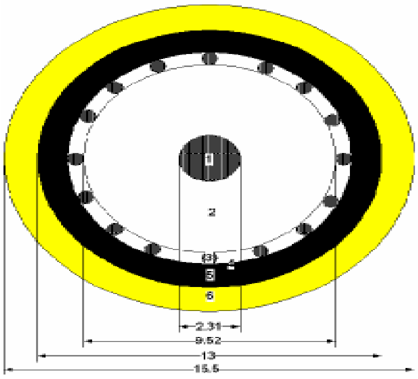
Figure 1 General idea of the whole mobile network above ground. Cells are like hexagon shape and not overlap with each other; cell phone uses two frequencies in the bandwidth.

2) Leaky Cables

One solution that we can use is leaky cable. Leaky cable is a normal coaxial cable, with periodic apertures/slots, for it to emit and receive radio signals. Having this property, it can function as an antenna where it can distribute radio waves at places where the placement of discrete antenna is not feasible (in our case, the LU). Typically, there are a few types of leaky cables[11], which are determined by the structure of their outer conductors: braided, axial slotted and periodically slotted coaxial cable[12].

Figure 2 General internal structure of a leaky cable.[9]

1 Inner Conductor
2 Dielectric
3 Outer Conductor
4 Tape
5 Inner Jacket
6 Outer Jacket



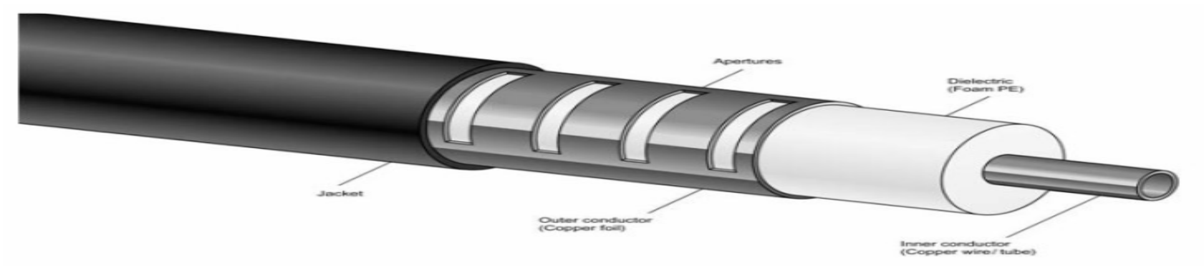


Figure 3 General outer structure of leaky cable (with periodic apertures)[13]

Inner conductor is usually made of copper wire. There are several types of dielectric that can be used, depending on the radio wave velocity. Generally it is made of polyethylene with a permittivity about 1.25[14], the ratio sufficient for radio wave permeability**.** The outer conductor, made of copper foil, is the layer at which the arranged apertures are made.

However, the usage of leaky cable is not as easy as it seems. Since Underground stations are further apart, one long leaky cable has to be installed. Otherwise, the radio wave connection between the controller over ground and the mobile phones would fade away as the train moves. Furthermore, there are other main aspects that we have to look into when we deal with leaky cable which are frequency bands and the coupling loss.

As mentioned above, every network provider in the UK has their own frequency range for GSM. The question is 1) How are we going to ensure that, by using this leaky cable, these radio frequencies would not interfere to each other and from other sources? 2) What is the design of the leaky cable that we have to look into to overcome this problem?

Another problem is coupling loss. Coupling loss can be defined as the ratio between the power received by the half-wavelength dipole antenna and the transmitted power in the cable[8]. How are we going to guarantee that when the wave is radiated from one medium to the other, there would not be significant losses in power that would disrupt the connection? These are the things that we are trying to solve and hopefully would be able to reach to a solid conclusion.

A) ***Technicality of Leaky Cable***

In this part, periodically-slotted coaxial cable is analysed theoretically in more detail including equations and explanations. We will discuss the properties of the slotted coaxial cable, including the basic principle of frequency bandwidth expansion, coupling characteristic and the field distribution. All these important parameters will help us understand how exactly the leaky coaxial cable propagates the signal in the underground telecommunications system.

As we have discussed before, the signals transmitted and distributed in the leaky coaxial cable are in the ultra-high frequency wave range (from 300MHz - 3GHz) and travel at the speed of light. Unlike the usual coaxial cable, the leaky coaxial cable implemented in the underground tunnel does not only work as a normal cable but also functions as an antenna in the tunnel. Based on the theory of the ray diffraction, each slot of the radiating cable can work as an antenna spreading the signal out in the tunnel.

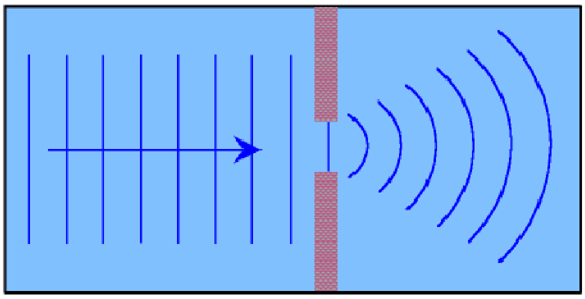


Figure 4 Radio waves will behave as the picture when they pass through the slots.

B) ***Field distribution***

Since each dimension of the slot is relatively smaller than the wavelength of the frequency, the radiation of the signal can be consider as a magnetic dipole in the free space[15] .Therefore the leaky cable will behave as long arrays of the magnetic dipoles. Considering radiation in free space, the total electric field can be expressed as:

$E_t = \sum_{n=1}^{N} E_0 \times e^{j_n(k\times d\times cos\theta - \beta_g\times d)}$ (1) where

ß$_g$ and k are the wave numbers in the cable;

E_0 is the field amplitude of a single slot;

d is the distance between each slot;

θ is the angle of the direction;

By letting k*d*cosθ - ß$_g$ *d= 2nЛ (n is any integer), we can find out at which angle we can get the maximum total electric field and the radiation pattern of different angles. Therefore, by this equation we can find out where to place our leaky cable to maximise the signal.

C) Frequency bandwidth

In the study of leaky coaxial cable with periodic slots, the two major parameters are frequency bandwidth and coupling loss. The relationship between frequency bandwidth and the period of the magnetic current distribution is determined by:

$$-\frac{c}{1+\sqrt{\varepsilon_r}}\frac{m}{p} < f < -\frac{c}{\sqrt{\varepsilon_r}-1}\frac{m}{p}$$, m = -1, -2, -3 ... (2) Where

c, speed of light;
ϵ_r, relative permittivity of the dielectric material between the coaxial conductors;
p, period of the magnetic current distribution;
m, m^{th} harmonic component of the periodic source expressed in Fourier series generates the m^{th} spatial harmonic in free space;
By applying this formula, we can define each parameter to set up the frequency band of the leaky cable.

D) Coupling characteristic

Coupling loss is the loss of energy when transferred from a circuit to another. In this context, it refers to the energy distribution between the cable inside the slots and the space outside the slots.

The general coupling loss is defined as:

$$\text{Coupling loss (dB)} = -10\log\frac{p_r}{p_t} \quad (3)$$

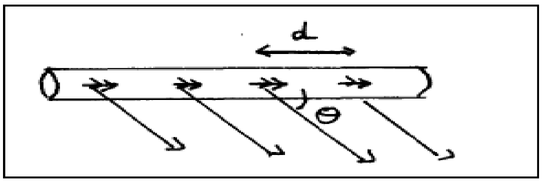


Figure 5 Radiation of equivalent magnetic dipoles

The coupling loss varies along the cable; it depends on the period of the slots, the slots number in each period, (with or without the radiation of high harmonics), and the different inclined slotted angle. Based on previous research[16], it is noted that the higher the period of the slots, the larger the coupling loss would be while suppressing out the high order harmonics will stabilise and flatten the coupling loss (which is what we want) in comparison to the cable with the high order harmonics. Furthermore, as the inclined slotted angle increases, the coupling loss will increase as well. From these, we can conclude that for a leaky cable to act as a better antenna, it would have high periodic slots at an inclined angle.

E) General Implementation of The Whole System in the Underground

We have mainly talked about leaky cable previously. Now we are going to merge it with the whole system so that the signals from the base stations can be sent to the mobile phones in tunnel back and forth. Nowadays we generally have two types of technology for mobile networks in the world

- GSM(Global System for Mobile Communications)
- CDMA (Code division Multiple Access) - A form of multiplexing, which is one transmission channel being used to allow a number of signals to pass through. Applied in 2G and 3G technology.

In the UK, both are these are used in the mobile network. However the frequency band of CDMA is very close to the GSM900. These two systems may interfere with each other particularly between the downlink of CDMA (870-880MHz) and the upper link of GSM (890-915MHz)[17].

The distribution system consists of leaky cables, transmission lines, Point of Interconnection (POI) platform and Low Noise Amplifiers (LNA). The POI platform consists of couplers, filters combiners and splitters. The function of POI is basically to combine multi-band signals and to eliminate the inter-system interference. For the downlink operation, POI combines multiple signals while for the upper link, it divides the mixed signals from the leaky cables into signals in different bands.[14]

In order to ensure that the signals are strong enough to reach mobile phones underground, we need to amplify the signals. So, amplifiers can be placed before passing them to POI. A variety of signals from both GSM and CDMA will be filtered into POI platform from base transceiver stations before being sent to leaky cables. The signals will be first split and then routed to POI platform which are placed in stations, and tunnels[14]

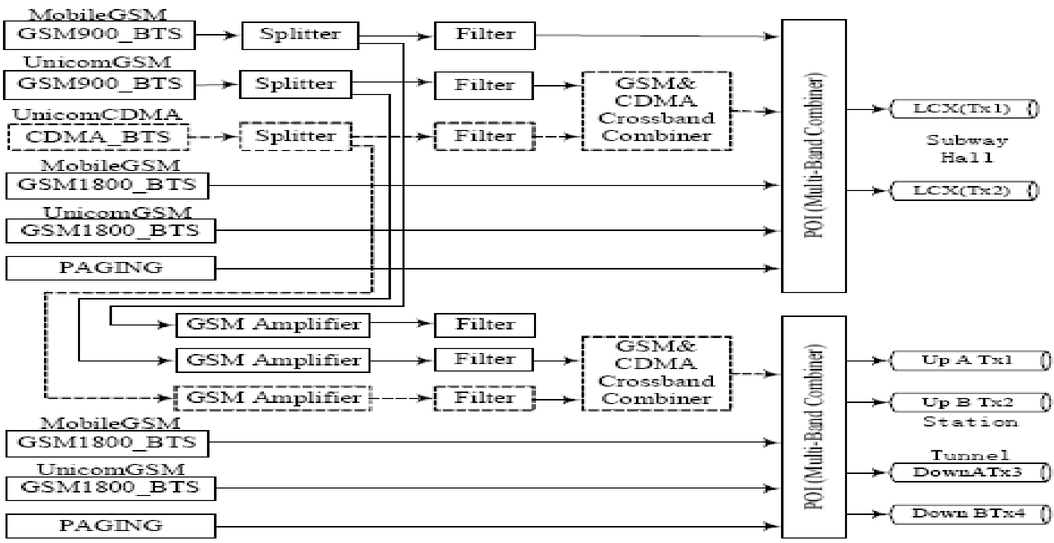


Figure 6 Down link of the system

For the upper link, POI platform will divide mixed signals from leaky cables into different frequency band. The signals are then filtered and sent to the corresponding base transceiver stations. This division function is convenient to make different systems share a common leaky cable so that the cost of leaky cables is reduced[14].

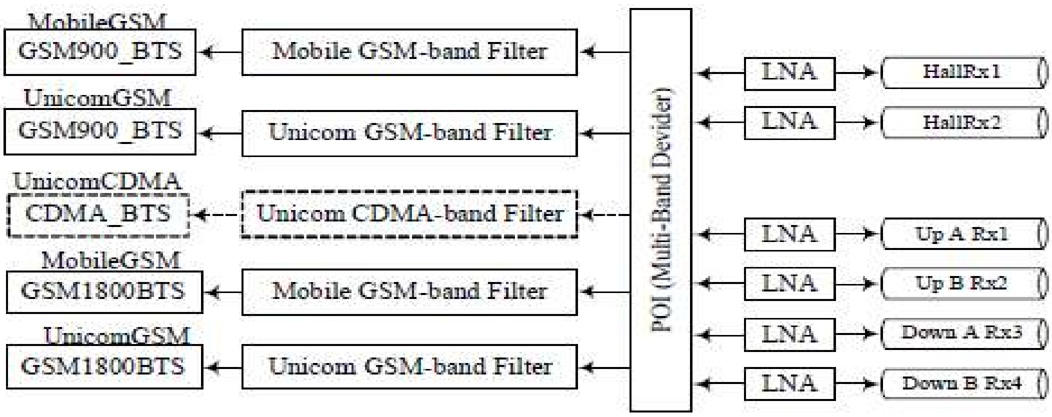


Figure 7 Upper link of the system

3) COST

According to communications requirements of subway train control system and the characteristic of leakage wave communications, 2 leaky coaxial cables are required for the communications between left-going train and right-going train respectively. As leaky coaxial cables are required to be installed on both sides of the railway, the total length of leakage cable is twice as long as the railway. In the meantime, receivers and in-train receivers are also required[18]. However, the main cost of communications lies on the leakage cables[19].

On the other hand, the power consumed in communications is weak current, and the total weak current consumption only takes up 2% of the total power consumption in the subway system. Therefore the power consumption cost could be ignored as compared to other parts[20].

In choosing the specification of leaky coaxial cables, the construction environmental factor, equipment parameters and system expansion requirements should all be taken into consideration. The price of radiated leaky coaxial cables for underground communications system is around US$1,000-US$10,000 per kilometer. Taking other communications charge into consideration, the communications cost for each meter in tunnel is within US$2,000-US$20,000. Therefore, Piccadilly Line (76 KM) needs at least US$152,000-US$1,520,000[21].

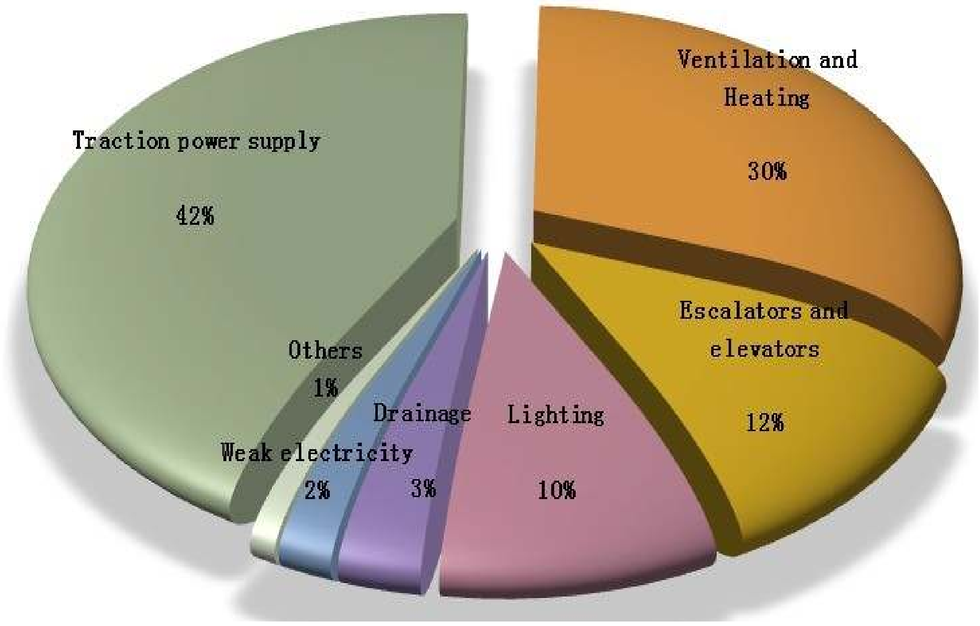


Figure 8 The energy distribution of the Underground system.

4) COMPARISON

Until now we have only evaluated the leaky coaxial cable. However, there are still two other signal transmission technologies which can be chosen for the project. The wireless sensor network (WSN) for mobile underground coverage is possible by using either electromagnetic (EM) waves system or magnetic induction (MI) system. There are pros and cons for each technology.

The traditional terrestrial wireless technology uses EM waves, mainly microwave. But EM wave can no longer be propagated in air in an underground environment. WSN has three main problems in the underground situation, namely high path loss, dynamic channel condition and large antenna size. Firstly, the EM waves will be heavily attenuated by soil, rock and water.

Because space is limited in the underground tube stations, the power available for the equipment will also be limited, and hence causing transmission range of EM waves to be likely less than 4 metres. Moreover, the path loss varies dynamically, depending on the soil properties such as water level and soil density, which will also be dramatically different depending on time and location. This channel condition means that there will be a difficulty designing a network with reliable connectivity and high power efficiency. In order to reduce the path loss, the frequency of EM waves can be lowered. But this means larger antennas are needed for signal transmission, which doesn't satisfy the small sensor size requirement of a limited space[22].

Instead of the troublesome EM waves system, MI system could be a better form of wireless underground sensor network (WUSN) because MI communications system can resolve the three major problems faced by the EM waves system. Basically the transmission and the reception occur by using a coil of wire (see Figure 9).

Unlike EM waves transmitter, we don't have to consider the radiation power of MI transmitter. The ratio of transmitting and receiving power is nearly one, if the resistance of the coil is small. This feature ensures almost no transmission power lost to the surroundings[23]. This technology is not affected by the dynamic channel condition because magnetic permeability of different components of soil is relatively constant so the channel condition remains the same for most of the time.

The system operates with small-sized coils so there is no need for big antenna, thus saving space. For MI system, if the transmission distance increases by d, then the magnetic field strength decreases by a factor of d^3[24]. It thus makes MI and EM wave systems hard to be applied in the real world due to their short transmission ranges, both less than 10 metres[25]: "the MI system provides larger transmission range (around 10 m) than that of the EM wave system (around 4 m)"[26]. Currently there is no technical solution to improve their transmission range and thus making the leaky coaxial cable the most practical solution.

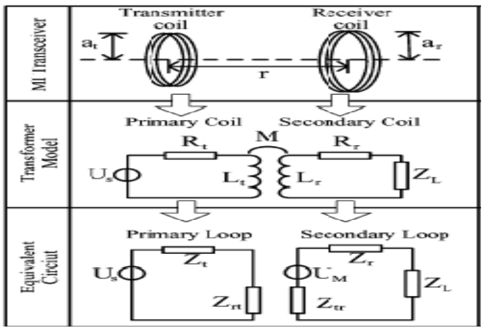


Figure 9 MI communications channel model[27]

5) CONCLUSION

Over the past 20 years, the 80% mobile phones ownership has grown to 80%, demonstrating our continuing reliance on mobile communications. However, the most important mass transport system to the economy, the LU, is not covered by mobile networks.

The lack of signal reception in tunnels and underground stations is due to the fact that radio waves cannot travel through walls – which can be overcame by the use of leaky cables.

Such approaches have already been implemented in some countries. Therefore, the delay in solution implementation in this country could be due to a number of factors; underdeveloped technology is certainly not one of them.

Security can be one such factor. Considering the geological conditions of the channel, as the oldest railway in the world, the network could be too old and too fragile to support any installation of new devices. Besides, Londoners are heavily dependent on tube; therefore any engineering service will disrupt the daily service. Hence, any upgrade to the system should be thoroughly planned to avoid any further disruptions. Apart from that, using phone underground may cause signal interference with other equipment, just like using mobile phone in flight will interfere with the operation of some avionics instrument installed on aircraft[28] .

However, with technological advancement, we are positive that these problems could be overcame as long as there is adequate funding for further research to improve the suggested solution and substantial support given by both the authorities and the general public.

With that, science and technology hopefully will succeed in achieving its ultimate purpose of making our lives easier!

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