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High-Speed Mobile Communications in Hostile Environments

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Abstract. With the inexorable increase in the use of mobile devices, wireless connectivity is expected by users anywhere, anytime. In general, this requirement is addressed in office buildings or public locations through the use of Wi-Fi technology but Wi-Fi is not well adapted for use in large experiment halls and complex underground environments, especially those where radiation exposure is an issue, such as the LHC tunnel and experimental caverns. 4G/LTE technology, however, looks to be well adapted to addressing mobility needs in such areas. We report here the studies CERN has undertaken on the use of 4G/LTE in the LHC tunnel, presenting results on the data throughput that can be achieved and discussing issues such as the provision of a consistent user experience.

1. Introduction

The increasing usage of smartphones, tablets, laptops and other wireless devices has led to a rise in the demand for wireless access to data networks.

This demand is primarily in homes, offices, trains, shopping malls and meeting points, where the deployment of wireless networks is today a standard practice. However, there are environments where there is a demand but where the deployment of wireless services is not straightforward. Along with mining caves and subway tunnels, CERN's underground facilities, which host large particle accelerators and detectors, are a good example of an area posing significant problems for the deployment of a standard wireless network.

2. CERN overview

CERN, the European Organization for Nuclear Research, is today the world's leading particle physics laboratory. The laboratory's raison d'être is the provision of particle beams to specialist experiments and, to this end, CERN operates a series of underground particle accelerators, notably the Proton Synchrotron complex (PS), the Super Proton Synchrotron (SPS), and the flagship Large Hadron Collider (LHC).

The LHC is installed in a 27 km long tunnel located 50 to 150 m below ground, with four enormous caverns hosting the huge detectors of the major experiments. When the accelerator is running, the tunnel is exposed to ionising radiation and areas of the experimental caverns are exposed to high magnetic fields. Standard electronic devices cannot be installed directly in the tunnels given the risk of radiation damage and the type and/or location of device that can be installed in the caverns is also restricted. Furthermore, the significant access restrictions imposed for Safety reasons means that, even for radiation-hard devices, the number installed in the tunnels must be minimised and they must be capable of being controlled remotely.


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Despite these significant restrictions, advanced communication networks must nevertheless be provided since high-speed data connections are essential to the operation of CERN's accelerators, not only during normal operations but also, and perhaps even more so, during maintenance and repair activities.

For example, radiation surveys and other environmental measurements in the LHC tunnel are carried out using TIM, the Train Inspection Monorail, which is a device mounted on a monorail installed in the tunnel which must transmit data wirelessly and where the ability to provide one or more video feeds, preferably at high-definition, is highly desirable as a supplement to the basic transmission of measurement results. Moreover, machine maintenance and upgrades is greatly facilitated if the person on site in a tunnel can benefit from remote support by experts elsewhere.

3. Wi-Fi technology

Wi-Fi is now ubiquitous in office and residential environments. Wi-Fi is also performant with the latest standard, 802.11 ac wave 2, expected to deliver throughput of up to 3.5 Gbps. Sadly, this solution is not applicable to CERN underground tunnels.

As the output RF power of an AP is limited many would be needed in the tunnel. Further, with Ethernet as the link-layer protocol, network switches must be located within a limited distance and so a rather large amount of other equipment would also be necessary in order to provide full Wi-Fi coverage. It is not possible to ensure that all of this equipment is adequately protected from ionising radiation so a permanent standard Wi-Fi installation is not feasible. A temporary Wi-Fi coverage was provided during the first two-year LHC upgrade (LS1) over an existing VDSL network in the LHC tunnel. This, though, required the installation of nearly 300 access points and their removal at the end of the upgrade period; which represents a significant effort in terms of both time and money that we would like to avoid. Additionally, due to VDSL throughput limitations, such a temporary installation is limited to the relatively low throughput of 10 Mbps.

A further issue for Wi-Fi services is that, at least with today's network configuration at CERN, roaming between different Wi-Fi access points causes an interruption which is especially problematic for real time services. Although solutions to address this issue exist, the feasibility of their deployment for installations in the accelerators tunnels is yet to be demonstrated.

4. The LTE standard

Long Term Evolution, or LTE, is the 4th generation mobile network standard initially defined in 2009 by the Third Generation Partnership Project. An advance on UMTS technology, it introduces new features which provide a much improved end-user experience whilst maintaining backward compatibility with older mobile technologies. Key amongst these are

- uplink and downlink modulation schemes are orthogonal, so to reduce interference issues, improve link capacity and spectral efficiency;
- LTE devices support some Multiple Input Multiple Output (MIMO) schemes, leading to higher throughput and/or reliability;
- and the target round time trip is below 10ms, to allow the use of real-time services.

LTE is also a pure IP network and provides no support for traditional circuit switched voice calls. For this reason LTE-Advanced, an enhanced version of the standard, introduces Voice Over LTE (VoLTE) services. LTE-A is currently deployed in very few areas around the world, but it is already targeted as a key technology to deploy at CERN.

5. CERN's underground mobile network infrastructure

Today, various mobile and radio services are offered in CERN's underground facilities, including GSM and UMTS for standard communications, TETRA and TETRAPOL for critical safety operations. To

ensure a consistent and proper propagations of signals in tunnels, these networks are transmitted via an antenna cable infrastructure.

An antenna cable is a coaxial cable whose outer conductor has periodical slots from which the Radio Frequency (RF) signals travelling in the cable are radiated over the air. As any other antenna, the cable is a passive device, hence it is quite easy to manufacture a cable that can be installed in the accelerator tunnels and exposed to radiations. CERN's antenna cable was built to resist to at least 10 years of LHC operation [1].

It should be noted that CERN's indoor RF infrastructure—the antenna cable network, splitters and combiners—is common to all of the different radio services, which run on different frequency bands ranging from 400 to 900MHz. This is quite an achievement and required both a careful network design and significant effort to identify compatible RF devices.

In the case of the PS and SPS tunnels, the base stations, i.e. the equipment generating the RF signals, are deployed on surface; from there they feed the RF infrastructure in the tunnels. This solution avoids the burden of strict access constraints for maintenance or upgrades. Unfortunately this architecture cannot be applied to the LHC case due again to the unusual size and radiation levels of this accelerator.

As shown in the following picture, the LHC tunnel is accessible through 8 pits, each more than 3 km from the next.

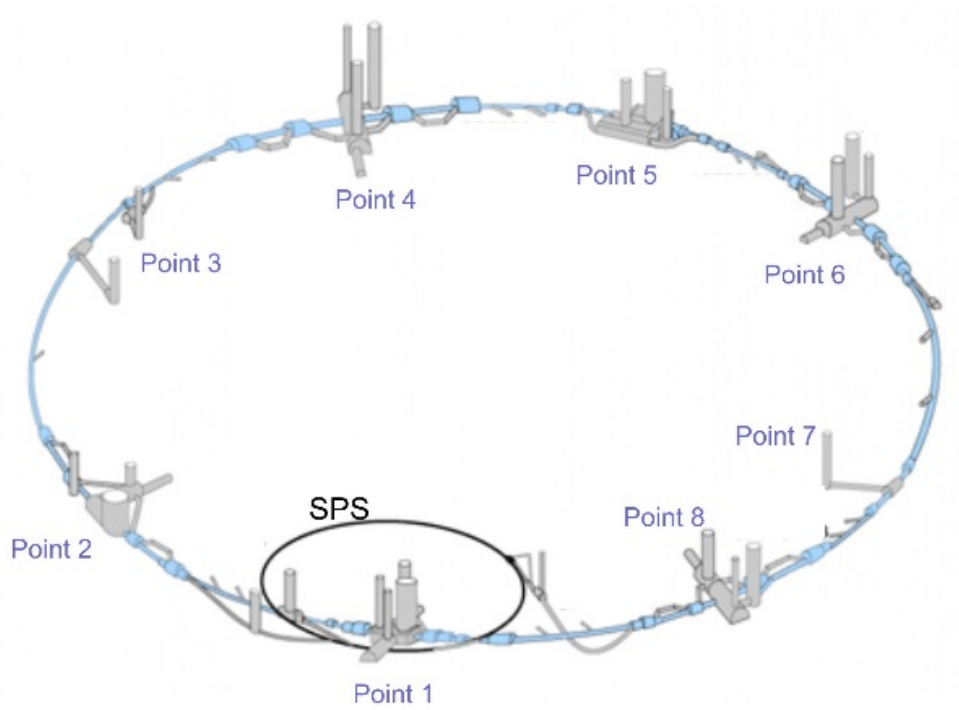

Figure 1. The 8 LHC tunnel access pits.

Because of the RF signal attenuation along the antenna cable infrastructure, a deployment of 8 surface base stations would not guarantee acceptable network coverage throughout the 27 km tunnel. To address this issue, the repeating system depicted in the following picture is deployed.

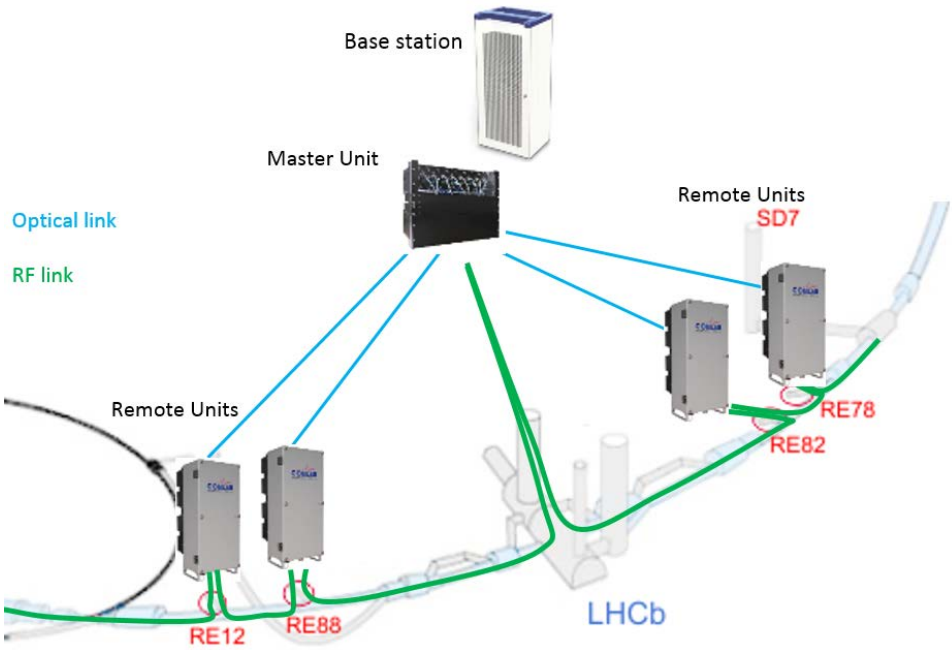

Figure 2. CERN mobile networks repeating system.

Eight surface base stations feed the RF infrastructure providing network coverage in the pit areas. In parallel, four base stations installed in the even main pits feed a local Master Unit (MU); each of which converts the base station signals from RF to optical, and dispatches the signals above to four Remote Units (RU). The RUs are installed in “alcoves” of the LHC tunnel, dedicated areas shielded from the accelerator-generated radiation. From these alcoves, the RUs convert the optical signal back into RF and inject it into the RF infrastructure thus providing network coverage for the rest of the tunnel.

This infrastructure, together with the introduction of LTE technology, holds out the promise of a high bandwidth, radiation resistant mobile data network for the LHC tunnel.

6. Pilot LTE deployment

To explore the capabilities of such a network, a pilot LTE service was deployed in a section of the LHC tunnel (LHCb detector cavern and LHC8 tunnel area) in 2014.

In order to ensure compatibility with the existing communication services (2G, 3G, TETRA, TETRAPOL) as well as to meet the target radio coverage parameters (-90 dBm Received Level for 2G, -80 dBm Received Signal Code Power and -6 dB Chip Energy over Noise Spectral Density Ec/No for 3G) the rest of CERN indoor RF infrastructure had to be upgraded and retuned. In order to avoid the risk of Passive Inter Modulation (PIM) with several signals with different power levels and frequencies traveling on the same cable, roughly 75 wide band power splitters were installed in the relevant sections of the RF infrastructure. Some hundreds of N-type jumper connectors had to be replaced with 7/16-type models. More than 50 combiners for TETRA (425 MHz) and 2G/3G (900 MHz) had to be replaced to enable transmission of LTE 800 MHz signals. Similarly, some tens of indoor antennas deployed in caverns and alcoves also had to be adjusted. Furthermore, the attenuation level between the mobile operator Base Station and CERN MU, necessary to limit the uplink noise, had to be retuned after a new link budget study.

One more issue that had to be addressed is that the LTE 800 signal generates interference case with the accelerator cavities of the LHC. Fortunately, these are located in one specific tunnel sector and so, to eliminate this interference, the LTE 800 MHz signal bandwidth was been reduced in that sector of

the tunnel, and RF terminators installed in the antenna cable to isolate that sector from the rest of the network.

The Swissqual Qualipoc tool was employed to assess the performances of this pilot. The tool was running on a Samsung Galaxy S5G900F. In the LHCb detector cavern where the LTE received power level (Reference Signal Received Power) was of the order of -100 dBm, the network provided 70 Mbps download and 14 Mbps upload. At the bottom of the tunnel pit, where better LTE coverage is available (RSRP ≈ -80 dBm), 70 Mbps download and 30 Mbps upload was registered. However it must be noted that these results are limited by the measuring tools. Meaning that the LTE network is able to provide even higher throughput than what a user equipment can handle. This is more visible with LTE-A: the measuring tool could not run at more than 100 Mbps because of its design limit.

7. Conclusions

The availability of high speed wireless networks in CERN's underground caverns and tunnels is essential for the operation and maintenance of the accelerators and experiments. Unfortunately, active electronic devices cannot easily be installed in such areas because of the exposure to ionising radiations. Even where such devices can be installed, the strict underground access constraints make it troublesome to access the facilities, a consideration that limits the number of devices that can be installed. For these reasons, although Wi-Fi technology is an excellent solution for homes and offices, it cannot be implemented in CERN tunnels as a vast part the network would be exposed to radiations.

LTE, on the other hand, is not only capable of delivering high throughput, but can be designed so that active network equipment is not installed directly in the tunnels, with only a passive antenna cable exposed to radiation. Our tests at CERN have demonstrated that such an installation can indeed meet the requirements for data transmission, offering very high speed, real time, mobile services.

Following the positive outcome of these tests, a full deployment of LTE technology will be undertaken in the second half of 2015. We will also be deploying a brand new system to monitor the performance of the LTE services and trigger real time alarms in case of faults.

Overall, we confidently expect these deployments to deliver improvements in efficiency for the accelerator maintenance and repair teams and so contribute to the successful operation of the LHC accelerator and the LHC experiments during Run 2.

References

[1] A. Gerardin, "Mechanical tests on GSM-VHF cable," CERN EDMS 1077149 v.1, Geneva, 2010.