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Integration of Satellite and LTE for Disaster Recovery

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***Abstract*—Wireless communications are critical for public protection and disaster relief (PPDR) professionals during the emergency operations that follow natural or man-made disasters, scenarios in which both commercial and dedicated terrestrial networks often fail to provide the necessary support. The reason is threefold: they simply get destroyed by the disaster, they cannot sustain the sudden surge of network demand or they fail to deliver the necessary bandwidth and/or other QoS guarantees. Because LTE is expected to become the main wireless technology for broadband communication, a lot of studies have been devoted to assess its compliance for PPDR purposes and to find suitable architectural solutions able to meet mission-critical requirements. This approach is surely worthy, but it is based on the assumption that infrastructure-based terrestrial systems are reliable. As a consequence, in worst-case emergency scenarios appropriate guarantees can be provided only in the hypothesis of huge investment costs. Recent developments in satellite technologies are bringing the availability of non-terrestrial high performance channels, with better properties when comparing to LTE for what regards availability and reliability. On this basis, the paper proposes a network architecture based on the integration of satellite and LTE networks for both infrastructure-based and infrastructure-less scenarios. The proposal aims to provide field operators and people in distress with transparent accessibility, coverage guarantees and broadband performance when terrestrial infrastructures are lacking, and to expand their coverage, capacity and resilience otherwise.**

I. INTRODUCTION

Current technologies employed for PPDR purposes provide a rich set of voice-centric services that are of paramount importance for field operators, especially in the very early stages of the response; unfortunately, these systems are unable to sustain high-bandwidth data-oriented applications, for which there is an increasing demand from the PPDR community. Furthermore, due to the generalized lack of a common PPDR communication infrastructure between different PPDR entities (e.g. police corps, fire departments, ambulance services), operators often rely on commercial terrestrial networks for coordination and data-oriented communication [1].

To provide field operators with reliable, high performance communication channels, LTE is increasingly being chosen for next-generation public safety networks, for which both dedicated only and hybrid dedicated/commercial solutions have been proposed [2][3]. These approaches are valuable for day-to-day routine activities and major planned events, because they can offer great improvements to network capacity and in consequence to the range of services and applications that PPDR users can employ. Moreover, LTE is able to exploit spectrum holes through cognitive radio access techniques [4], providing increased transmission quality and coverage. However, in most major incidents and disasters, terrestrial mobile networks are overloaded or their infrastructures are damaged and thus out of service [5]. Even the deployment of ad-hoc mobile networks backhauled by infrastructure-based facilities cannot therefore offer adequate guarantees in the latter, worst-case scenarios.

This paper proposes an infrastructure-less approach to provide high-bandwidth connectivity through deployable LTE base stations, backhauled by new-generation satellite systems. This way, it is possible to provide coverage in the majority of the cases in which terrestrial infrastructures are damaged or destroyed by a disaster, without requiring field operators and civilians to employ special equipment. In infrastructure-based scenarios, this proposal provides PPDR operators with extended coverage, higher broadband capacity and greater resilience.

The remainder of the paper is organized as follows. Section II briefly presents the deficiencies of current PPDR systems. Section III details our proposal through the analysis of network architecture, properties and features. Section IV outlines the conclusions.

II. CURRENT PPDR SYSTEMS

In the European Union, PPDR communication is currently performed by means of different technologies, depending on the country or even on the specific region: TETRA, TETRA2, TETRAPOL, Analogue/Digital Mobile Radios and satellites. Their main purposes are the provision of specific voice capabilities, such as Group Calls and Direct Mode Operation (DMO), and the facilitation of voice calls when terrestrial networks coverage is lacking. Although these technologies are commonly used in the PPDR domain, they exhibit well-understood deficiencies, especially in relation to the PPDR community demands:

- Data Rate: current PPDR technologies do not offer broadband capabilities; in fact, the achievable data rates are always less than 30 kbit/s, with the exceptions of TETRA2, that allows for data rates up to 400 kbit/s, and satellite communications, for which data rates range

from 2.4 kbit/s to an aggregate of tens of Mbit/s. It is therefore impossible to exploit performance-demanding applications and data services in general [6].
- Availability: currently deployed networks often fail to guarantee operation in major incidents and disaster scenarios. Even in the absence of damage to terrestrial infrastructures, their coverage is far from being ubiquitous.
- Resilience: current infrastructure-based systems are not redundant and, in general, they are vulnerable to disasters and subsequent incidents (e.g. earthquakes often happen in series, posing a threat to terrestrial infrastructures even if the first event has left them partially or totally operational).
- Spectrum: to date, spectrum allocation is not harmonized between EU countries, affecting the interoperability of PPDR systems, especially in cross-border operations.

Between PPDR stakeholders, there is complete consensus on the paramount importance that voice services play in every disaster relief operations. It is also clear that data and video services have already started to play an important role for PPDR users [1]. PPDR operators need networks that offer high availability, high reliability, high security and faster data transmissions; capabilities that map respectively into coverage, resilience, security and data rate properties.

III. Integration of Satellite and LTE

In PPDR operations it is often essential to employ satellites or cellular repeater stations to provide wireless network coverage to field operators and people in distress. Traditionally, PPDR agencies have had to choose between the two; instead, we show that they can be employed together, exploiting the benefits of both and at the same time mitigating each technology specific issue. This approach has been chosen because satellites, today, are an almost ubiquitous mean to provide broadband connectivity; however, general-purpose User Equipment (UE) such as mobile phones and smartphones do not embed components to access satellite systems. Furthermore, the propagation delay imposed by satellites would yield unpractical the communication among field personnel. On the contrary, general-purpose UE is built to connect to commercial mobile networks, and it is already clear that LTE and LTE-Advanced are going to be the next standards for mobile devices.

We propose a hybrid architecture based on the integration between LTE and satellite technologies, whose key design requirements have been defined as:

- Accessibility: the deployed network(s) must be easily accessed by general UE.
- Coverage: in absence of adverse external conditions, it must be possible to deploy Incident Area Network(s) where terrestrial coverage is disrupted or absent.
- Performance: it must provide broadband access, at least to PPDR operators.
- Interoperability: it should permit concurrent exploitation of existing terrestrial networks, if operative in the disaster area.

The subsections that follow detail our proposal.

A. System architecture

In disaster scenarios, base stations may not be the only damaged network components, also aggregation channels and core infrastructures may be affected. Our proposal aims at being a solution in the worst-case (i.e. when an infrastructure-less network must be deployed and represents the only source of coverage), while adding capacity and functionalities when an infrastructure-based LTE network is still totally or partially operational.

As the general concept, we consider LTE to be the access technology while satellite the backhaul one; i.e. satellites are used as backhaul means to convey coverage through LTE base stations, as depicted in Figure 1. In this model, the Mobile Emergency Operations-control center (MEOC) provides First Responders (FRs) with a LTE Incident Area Network (IAN), thus representing a deployable (and mobile) LTE repeater station for field operators. A reliable satellite link serves as the backhaul medium between the MEOC and the Emergency Operations-control Center (EOC), which is non-mobile and represents the operations headquarters, in order for the former to be able to communicate with the latter independently from the geographical position. We consider the Incident Area Network provided by the MEOC to be an “atomic” element with which to compose the ad-hoc infrastructure-less network topology that will be presented now.

The state of network access on the field can be fully described with three cases:

- Persons have no connectivity to MEOCs or terrestrial networks, and are therefore unable to communicate.
- Persons can have connectivity with either a MEOC or a terrestrial base station.
- Persons can have connectivity with both a MEOC and a terrestrial base station.

These conditions are not necessarily fixed for the entire duration of the rescue operations: a person may shift between them at any time, for example if terrestrial congestion increases/decreases, if subsequent disasters damage network infrastructures or if MEOCs move. It is obvious that the first case must be always avoided.

Figure 2 shows the network architecture on a MEOC. By integrating both the E-UTRAN and the EPC subsystems, the MEOC can directly provide IP connectivity to UEs, and in case of necessity it can route data through its satellite link. Furthermore, this way no terrestrial core network is necessary, thus avoiding the presence of a single point of failure when a number of MEOCs are deployed.

B. Service Provisioning

People in distress may use their standard UE to ask for help, communicate their status and position, give a contribution to disaster recovery, and communicate with loved ones. If for whatever reason they are not able to rely on commercial terrestrial networks, they must connect to a MEOC when it provides them with LTE coverage. If, on the other hand, FRs use the terrestrial commercial networks as today often happens [1], they will congest them even more, especially in the presence of prioritization mechanisms; therefore, this option must be used as a last resort. Thus, connectivity (voice and text messaging at least) must be provided to people in distress that may be trapped, injured or dying and additional services (specific voice capabilities, text messaging and broadband data support) must be provided to FRs.

The latest LTE standard releases already contemplate the provision of services such as DMO and Group Calls [7]; in addition, external platforms such as the IP Multimedia Subsystem or service enablers defined by the Open Mobile Alliance can be employed to provide advanced voice services through LTE.

For what regards broadband data support, the optimal solution is for FRs to have a dedicated channel (i.e. high priority) with the MEOC via LTE that provides broadband data capabilities; MEOCs network capacity in excess (i.e. low priority) can be therefore provided for people in distress. MEOCs have thus a twofold function: they provide a dedicated PPDR network for FRs and additional network capacity for people in distress. This prioritization can be realized through LTE bearers. A bearer is an IP packet flow that defines a specific quality of service (QoS) between a gateway and a UE. A user can be associated with multiple bearers; for example, a FR might be engaged in an emergency voice (VoIP) call while at the same time performing a file upload. A VoIP bearer with dedicated resources would provide the necessary QoS for the voice call, while a best-effort bearer would be suitable for the file transfer. The same concept applies for different users, i.e. it is possible to assign by default dedicated bearers to FRs and best-effort bearers to civilians. In fact, when a UE connects to a LTE network, it gets an IP address by the P-GW and at least one default bearer is always established, whose parameters are assigned on the basis of subscription data retrieved from the HSS.

C. Infrastructure-based and infrastructure-less topologies

Our proposal contemplates the possibility to extend infrastructure-based networks if terrestrial LTE infrastructures are still operational, and to deploy completely infrastructure-less networks otherwise, as shown in Figure 3. Normally, the X2 interface is established between one eNodeB and some of its neighbor eNodeBs in order to exchange signaling information. Its initialization starts with the identification of a suitable neighbor, a process that can be manually performed or automatically carried out by LTE Self-Organizing Network (SON) features. Specifically, the Automatic Neighbor Relation function makes use of UEs to identify neighbor eNodeBs: an eNodeB may ask a UE to read the global cell identity from the broadcast information of another eNodeB for which the UE has identified the Physical Cell Identity (PCI) [8]. Once the IP address of a suitable neighbor has been identified, the initiating eNodeB can establish a transport level connection; then it must trigger the X2 Setup procedure, which enables an automatic exchange of application level configuration data that is core of another SON feature: the automatic self-configuration of the PCIs. Once this procedure has been completed, the X2 interface is operational. This way, it is possible to deploy MEOCs that automatically attach to already existing terrestrial eNodeBs, thus extending the terrestrial infrastructure. In the same way, it is also possible to automatically interconnect different MEOCs in an infrastructure-less topology. When a UE has the possibility to attach to different eNodeBs, such network topologies may be very useful to shift traffic from heavily congested MEOCs to less congested ones, thus augmenting the overall system efficiency, and to provide stronger resilience by the presence of different available paths in order to reach a remote host.

An additional LTE eNodeB on each MEOC is an option that may be considered to provide a long-range channel for inter-MEOC communication, when these are not deployed near each other; without providing connectivity and capacity to users on the field, their range may be much more extended comparing to a typical LTE eNodeB used to provide coverage to people in distress and FRs. In absence of these dedicated channels, or if MEOCs are deployed even farther, the satellite backhaul channels may be used among MEOCs, although this solution would add the time for two additional satellite hops to the overall transfers.

D. Handover

FRs are expected to move in the disaster area, and their specific movements cannot be predicted in advance. When civilians, on the other hand, are not able to rely on commercial terrestrial networks, they must be able to shift to a MEOC when it provides LTE coverage in their area. Therefore, transparent handover provision is an important requirement. With LTE, this can be accomplished through both its S1 and X2 handover procedures. When a UE moves between one cell and another, handover through the X2 interface is triggered by default, unless there is no X2 interface established or the source eNodeB is configured to use S1 handover instead [8]. X2 handover should be performed if the UE is moving between terrestrial eNodeBs. When moving between MEOCs cells or between a MEOC and a terrestrial eNodeB, a S1 handover procedure must be performed instead. In these cases, in fact, the source and target eNodeBs are served by different MME/S-GW nodes, and S1 handover is thus required.

E. Spectrum Remarks and Interoperability with Legacy Technologies

LTE have been designed to support as many regulatory requirements as possible, and in consequence it is able to operate in a number of different frequency bands. While from a commercial standpoint most European LTE networks are being deployed in Bands 3 (1800 MHz), 7 (2600 MHz) and 20 (800 MHz), EU still lacks a harmonized frequency band dedicated to PPDR purposes. This fact clearly represents an issue for cross-border operations and Pan-European service provision; furthermore, it may happen that equipment from one country is not able to work in others. To help to overcome these issues the proposed architecture may allow for a local spectrum harmonization of the deployed IANs, also through on-demand (i.e. by MEOCs configuration) spectrum alignment with the frequency bands used by terrestrial networks in the specific geographical area of the disaster, feature that may ease accessibility, reduce signal interference and allow for cross-border interoperability. In alternative, under the hypothesis of proper EU regulatory enforcements, the hybrid spectrum management approach proposed in [3] may provide PPDR operators with sufficient guarantees.

Because the legacy PPDR networks listed in Section II are already operational in a number of EU countries and are already under development in others, multimode UE may be adopted by FRs in order to allow the exploitation of existing PPDR infrastructures, where those are deployed. LTE also supports interworking and mobility with networks using other technologies, namely GSM, UMTS, CDMA2000 and WiMAX. This allows the interoperability with legacy terrestrial commercial networks, if deployed and operational in the disaster area.

F. Networks range, Data Rate and QoS

The range limit of wireless repeaters is primarily determined by cell size, system configuration, signal penetrability and expected number of users. Theoretically, the coverage offered by common LTE base stations may range from 15 km to 100 km [9]. In practice, these values vary. In urban/suburban areas, single cell coverage typically ranges between 0.5 km and 3.5 km, because both the propagation loss and the average user density are high. In rural areas, the nominal single cell coverage typically ranges between 25 km and 50 km; however, the actual coverage is easily affected by environmental conditions that rise the propagation loss (e.g. when obstacles as hills are present between eNodeBs and UE). Considering the peculiarities of a generic emergency situation, the main factors that hinder coverage of a deployed LTE cell are the possibility of high propagation losses (especially when the disaster strikes an urban area) and the certainty of a very high user density, both in the spatial and temporal domains. Therefore, we consider ranges between 0.5 km and 1.5 km in urban areas, between 1 km and 2 km in suburban areas, and between 1 km and 10 km in rural areas to be appropriate estimations for a deployable LTE eNodeB to be used in emergency scenarios. Satellites, on the other hand, are theoretically able to provide global coverage, depending mainly on their orbit type:

- Geosynchronous Orbit (GEO) satellites are deployed at 35.786 km above the Earth's equator. They permanently orbit in the same sky area, allowing ground-based antennas to remain fixed in one direction. These satellites offer the greatest coverage, but being very far from Earth they also exhibit the highest propagation delay.
- Medium Earth Orbit (MEO) satellites orbit at altitudes comprised between 2000 km and 35.768 km. A greater number of satellites is necessary to provide a coverage comparable to GEO solutions. The lower orbit, however, allows better transmission performance.
- Low Earth Orbit (LEO) satellites orbit at altitudes comprised between 160 km and 2000 km. These solutions could provide the least propagation delay. However, an even greater number of satellites must be put in orbit in order to offer a coverage that is comparable to GEO and MEO solutions.

For what regards data rate, LTE can theoretically reach an uplink value of 75 Mbit/s, while 326 Mbit/s can be reached in downlink with a 4x4 MIMO antenna without error control coding. However, simulations and trials have showed [10] that realistic LTE average throughput values stop between 17 Mbit/s and 33 Mbit/s. The data rate provided by a satellite backhaul depends primarily on its orbit type; because propagation delay plays a key role in the realistically achievable data rates, GEO satellites usually offer the least performance. We consider as the reference for latest MEO systems the O3b solution [11]; it uses the Ka-band frequencies between 17.8 and 19.3 GHz in the downlink and between 27.6 and 29.1 GHz in the uplink. These satellites compose a MEO constellation at a height of 8063 km. Each satellite circles the earth within 4 hours and, for a fixed point on Earth, a new satellite rises every 45 minutes. O3b uses a make-before-break mechanism to ensure seamless handovers, in which a ground terminal temporarily enjoys a simultaneous connection to two satellites. Every satellite possesses 12 spot beams, able to deliver a data rate of up to 1.2 Gbit/s each, with a bandwidth of up to 216 Mhz. To achieve such high data rates, the satellite dishes of terminals have to have a diameter that is between 3.5 m and 4.5 m, facilities that cannot be embedded in a UE but can be installed on a MEOC. For future LEO constellations, L-3 Communications estimated that data rates up to 3.75 Gbit/s should be achievable between a LEO satellite and a ground station [12], using Ka-band frequencies. However, to date no LEO constellation able to offer broadband capacity is operative.

For QoS purposes, the overall latency plays a key role, especially when considering the usage of satellites as backhaul means. For the LTE access part, thanks to its IP-based architecture, the initial packet data connection typically takes around 50 ms, and between 10-15 ms of roundtrip latency is needed for subsequent transfers. The propagation delay between the eNodeB and the UE does not pose any issue to delay-sensitive applications; in fact, even at a distance of 100 km, the eNodeB needs less than a millisecond to reach the UE. At that distance, however, performance would be significantly impaired by the propagation loss. On the contrary, a GEO satellite backhaul takes *at least* 500-550 ms for a Round Trip Time (RTT), whereas with a MEO solution this value can be reduced to an average of 200 ms [13], depending on the orbit height. LEO satellites typically need less than 100 ms for a RTT, also depending on the orbit height; however, because of the data rate deficiency stated above, current LEO constellations may only be considered as part of the legacy PPDR systems presented in Section II. An estimation of the total average latency needed for a complete, remote connection made through the LTE subsystem backhauled by satellite is represented in Figure 4. In it, the GEO propagation delay is optimistic on purpose, resulting in a mean RTT of 600 ms with GEO satellites and of 230 ms with MEO satellites. Especially in the PPDR context, where stringent QoS guarantees are often needed, the total latency experienced by the user is a very important parameter.

The usage of satellites as backhaul mediums implies that QoS may be strongly affected by TCP, known to perform badly when employed on links with high propagation delay. While also in PPDR operations UDP is preferred for general video streaming, a good number of applications require reliable data delivery [1]. If GEO satellites are employed, specific TCP solutions [14] should be used; instead, with MEO and LEO systems it is possible to maintain the usage of common TCPs (e.g. TCP Cubic) with a limited QoS degradation [13].

In the proposed architecture, the identified bottlenecks are therefore:

- The LTE access subsystem for what regards coverage.
- The LTE access subsystem for what regards data rate if it is backhauled by MEO satellites, while the situation may invert if GEO satellites are employed.
- The satellite backhaul subsystem for what regards latency QoS.

Overall, new-generation Ka-Band MEO satellite constellations offer a high-performance and valuable medium to backhaul LTE connections for PPDR purposes.

G. Indoor and Tunnel Network Provision

In PPDR operations, it is not infrequent to meet an indoor or tunnel scenario. In order to provide coverage in those cases, the proposed architecture allows for two different approaches. In general, the FRs UE should embed the possibility to act as repeaters, in order to extend network range and to create a redundant number of network paths.

The first option is to deploy picocells and femtocells inside buildings and tunnels, respectively; these may be directly connected to a MEOC, to other eNodeBs that in turn reach the MEOC, or to some FRs UE acting as a bridge. The second option is to create a network chain by deploying the necessary number of FRs, forming a network path from the MEOC into the building or tunnel; this way, their UE may provide connectivity indoor and traffic may be routed outside through multiple hops.

IV. CONCLUSIONS

To address the vulnerabilities of terrestrial infrastructure-based networks in major incidents and disaster scenarios, we proposed a hybrid network architecture that integrates LTE and satellite technologies for PPDR purposes. It is based on deployable mobile units that bring LTE coverage to the disaster area through a satellite backhaul. The architecture is designed in order to provide easy connectivity, extended coverage and high performance guarantees. Furthermore, it allows for both infrastructure-less and infrastructure-based service provision, without requiring extensive configuration. This way, existing dedicated and commercial terrestrial infrastructures can be leveraged, and at the same time sufficient reliability from unexpected events can be provided. We conclude by noting that the proposed architecture has the potential to permit interoperability with legacy cellular technologies, to ease cross-border operations and to provide communication in disasters that include both outdoor and indoor scenarios.

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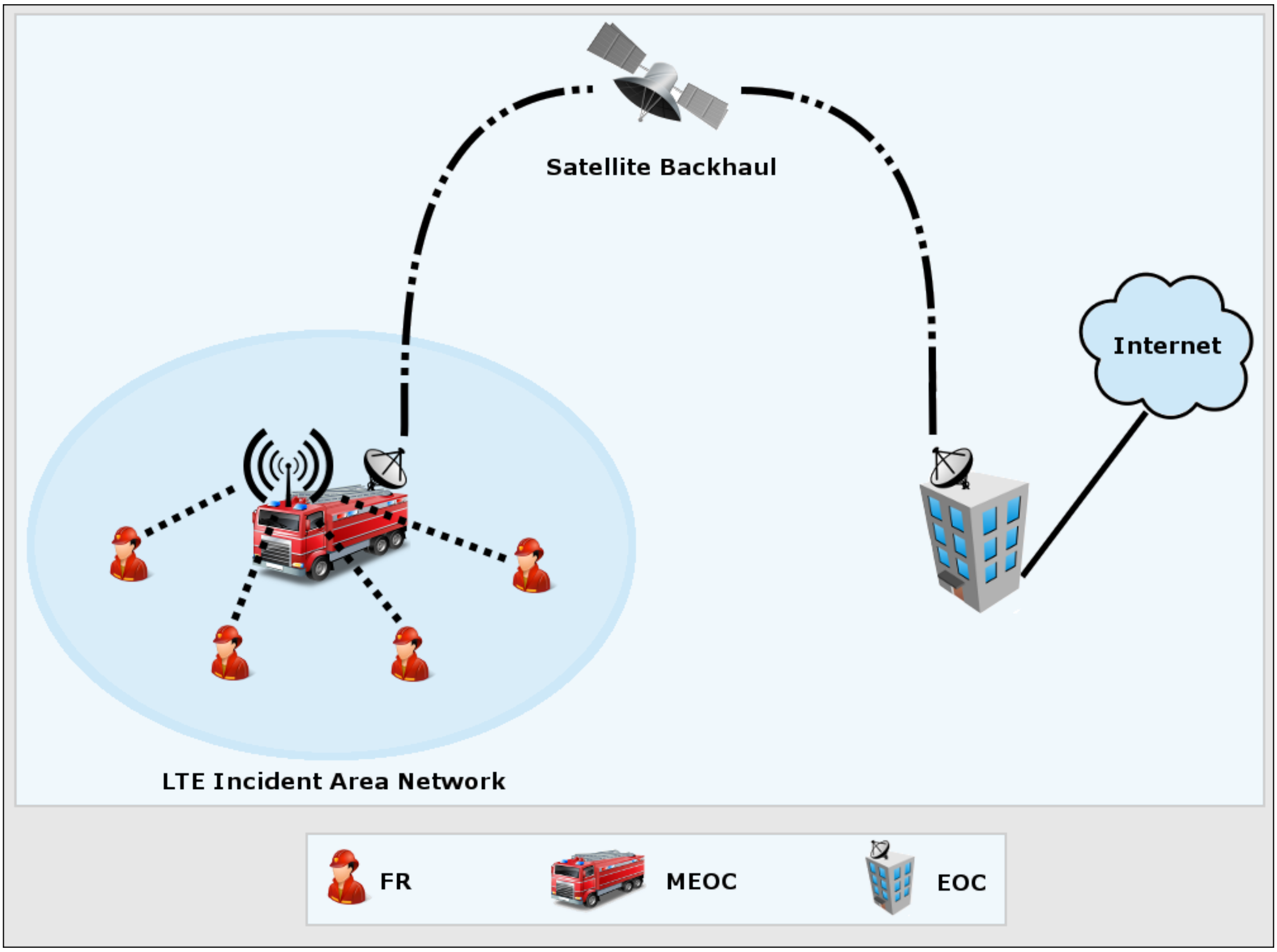

Fig. 1. Single Reference Deployment

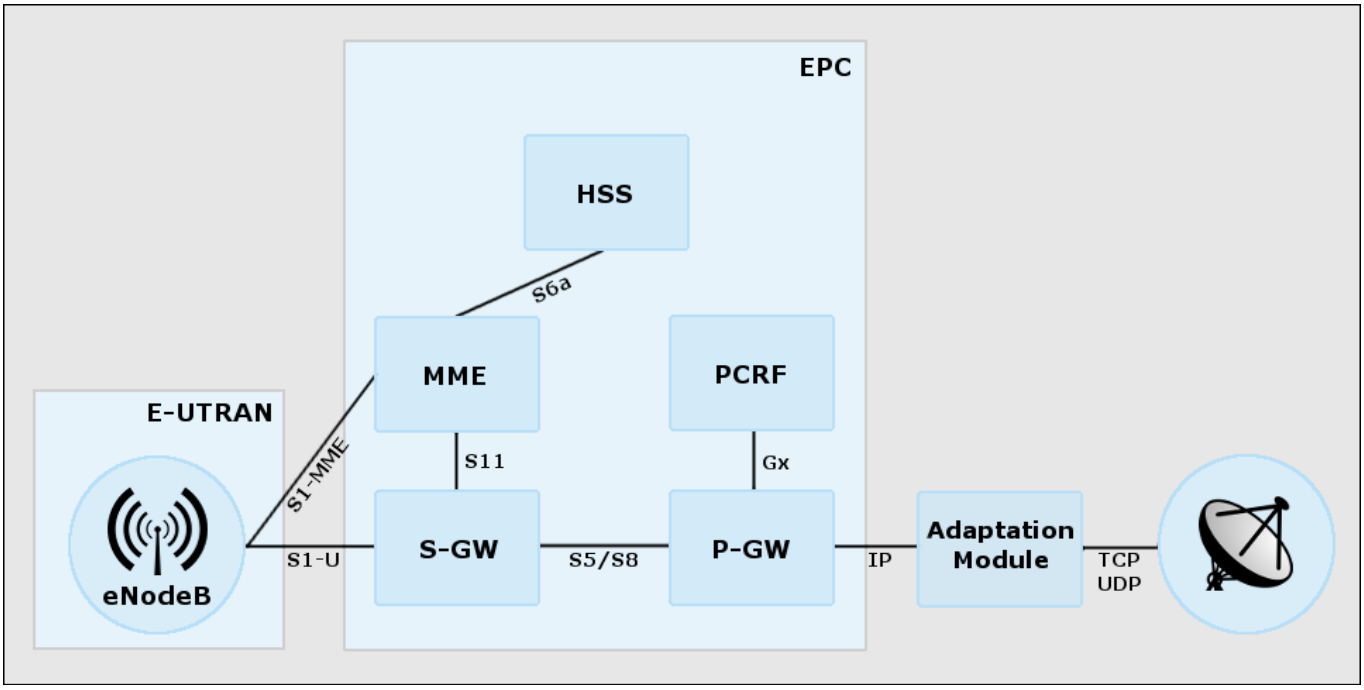

Fig. 2. MEOC Network Architecture

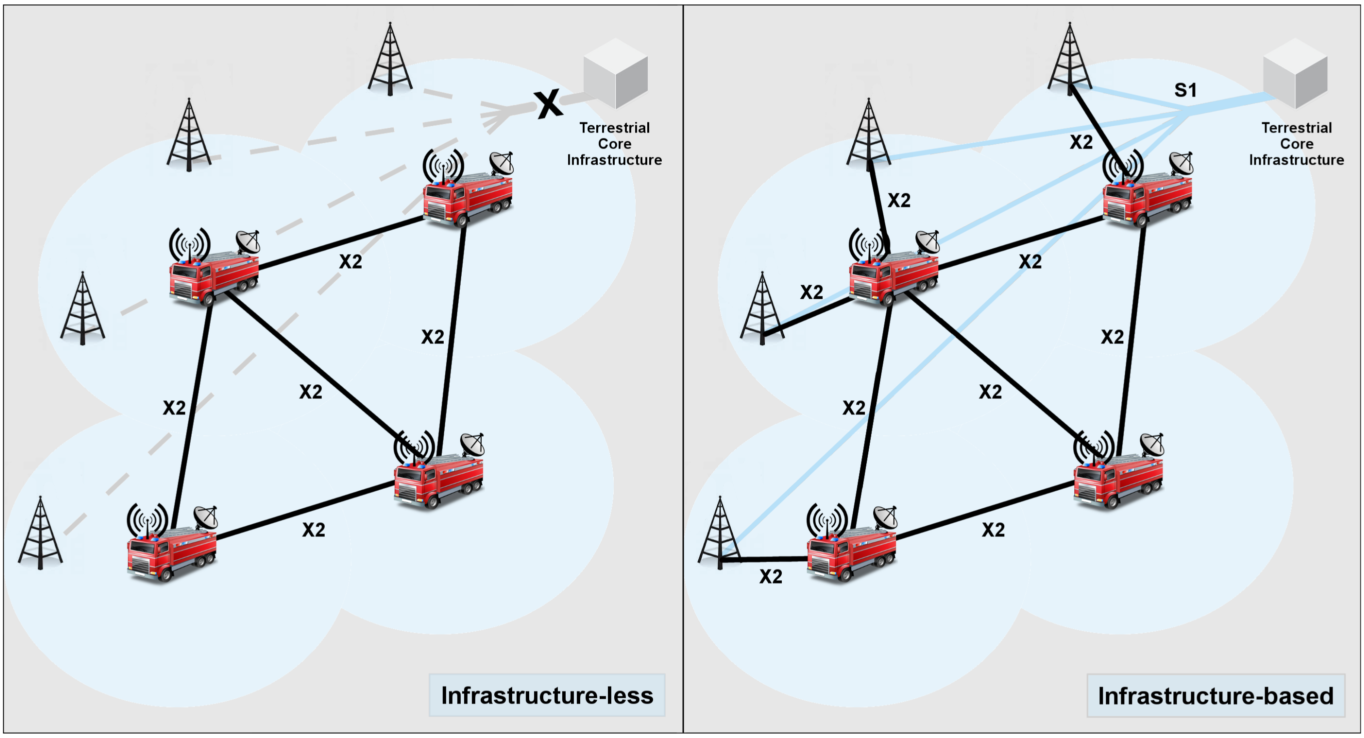

Fig. 3. Infrastructure-based vs Infrastructure-less Topologies

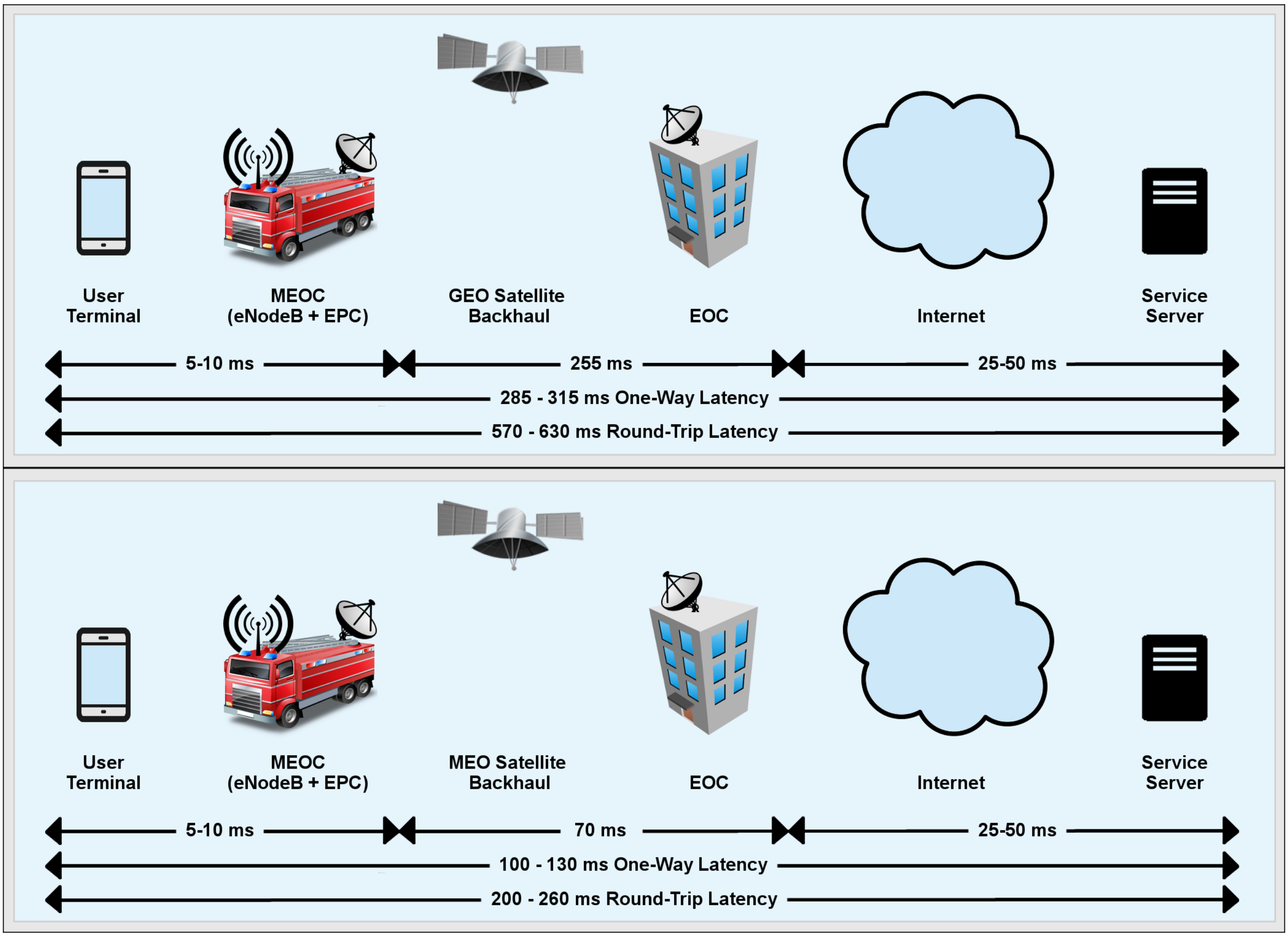

Fig. 4. End to end latency comparison between GEO and MEO satellite backhauls