Experimental evaluation of fog computing techniques to reduce latency in LTE networks

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Funding information
European Horizon 2020 Programme, Grant/Award Number: 688624

Abstract
The changes in new mobile networks toward a full Internet protocol–based architecture have led to opportunities for service-oriented optimizations based on emergent technologies like fog computing, software-defined networking, or network function virtualization. This paper explores 2 ways of using these new technologies to reduce the latency in Long-Term Evolution (LTE) networks. Both solutions reduce the path that the data packets should follow from the base station (evolved Node B [eNB]) to the network components that connect to the servers. The first solution, called Fog Gateway, is based on the interception of the packets in the tunnel at the eNB and their redirection to local servers running the fog services. This solution is fully compliant with the current LTE architecture and only requires new components. The second solution, called General Packet Radio Service Tunneling Protocol Gateway (GTP), is based on splitting the eNB’s functionality to avoid unnecessary GTP encapsulation of the packets geared toward the fog services. This paper includes an analysis of the latency split in LTE networks, the evaluation of both solutions with experiments in an end-to-end LTE network testbed, and a discussion around their applicability in future fifth-generation networks. The results confirm that they are feasible to provide low-latency services and that they are compatible with some of the emergent paradigms (software-defined networking and network function virtualization) as well as with the studies on fifth-generation networks from the standardization bodies.

1 | INTRODUCTION

One big step in the deployment of services over the Internet was the migration from servers owned by the providers to shared infrastructures provided by third parties, creating the cloud computing paradigm. From a technological point of view, this evolution is about virtualization of the 3 main components of the infrastructure, namely, computing, storage, and networking, to deliver services at the application layer. From the point of view of exploitation, this is a new model that allows payment for use of the technology based on what you need. Today, this cloud computing paradigm is evolving to dominate the different ways in which on-demand services are offered over fixed and mobile networks: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).
The location of the physical resources offering the virtualized cloud only takes into account the requirement of the company demanding IaaS, PaaS, or SaaS. Location is usually external, but due to physical dependency, security, and economic or other technical or exploitation reasons, the resources can be partially deployed at the company’s premises following a hybrid architecture. For future networks, the location of the final users should also be considered to meet new requirements. For instance, services that require very low latency in the end-to-end path need to reformulate the architecture. Variants of cloud computing, like fog computing, address this challenge. Fog computing is based on locating a (large) number of nodes away from the main cloud data centers. It is worth noting that in mobile networks, there are other terms to refer to solutions highly related to fog computing, such as Mobile Edge Computing (MEC), cloudlets, or micro cloud.

In particular, in the case of mobile networks like Long-Term Evolution (LTE) networks and their evolution toward fifth-generation (5G) networks, the complex architecture of the network itself is an issue when trying to reduce latencies in the access to the cloud. The application of fog computing in this environment implies modifying the end-to-end standard path to locate instances of the cloud very close to the final users.

This paper presents 2 approaches to implement fog computing in mobile networks to reduce latency for critical services. The first proposal, called Fog Gateway, was presented in our previous work. More details about this approach are discussed in this paper, including possible evolutions toward 5G networks and alternative designs to improve the behavior and experimental validation of the proposals. The Fog Gateway implements a subnetwork at the aggregation point of several eNBs (evolved Universal Telecommunication Radio Access Network Node B) to process the General Packet Radio Service Tunneling Protocol (GTP) tunnels for the data plane. The subnetwork includes the Fog Gateway, the user equipment (UE) served by the Fog Gateway, and local servers to optimize some services. The Fog Gateway works by inspecting and forwarding GTP packets. The control plane will work as usual and completely independently from this component, which infers the required parameters by analyzing the data plane messages. Data plane processing is based on the tunnel endpoint identifier (TEID) of the GTP packets. This is done to route the Internet protocol (IP) packets to fog equipment without having to cross the entire core network.

The second approach, called GTP Gateway, tries to remove some limitations of the first approach regarding the management of GTP tunnels by splitting part of the functionality of the eNB in smaller functions. We propose some modifications in the eNB to avoid GTP encapsulation until it is really needed. To do so, a new component is deployed, which will be in charge of routing toward the fog services and the encapsulation in tunnels based on the information obtained from the eNB using a new control interface. That way, we save on costs in processing the traffic for local critical services, we solve some of the problems during the handover procedure of the Fog Gateway, and we are able to maintain the functionality without the need to analyze the data plane packets.

How these approaches could be applied to future-generation networks is also discussed, mainly focusing on network function virtualization (NFV) and software-defined networking (SDN). Both approaches can be implemented following the SDN paradigm that could be exploited to provide the identification of low-latency packets, the creation of new GTP headers, and the removal or modification of GTP headers prior to forwarding. However, to provide efficient implementations, several modifications to OpenFlow are also examined. The different components currently present in LTE networks, as well as their contributions to the latency, are considered to provide some insights on where the stack could be split to support virtual functions.

This paper is organized as follows. The next section discusses the LTE network architecture and the sources of delay present in the different segments of the LTE network. Section 3 describes the 2 solutions proposed in the paper: one that is based on the analysis of the data plane without any modification to the standard LTE network and another designed to work with the modified base stations and a new control interface. Section 4 presents the setup to perform realistic experiments to evaluate both proposals and the results of the measurements. Section 5 provides a comparison of the solutions, based on the results previously obtained, and an analysis of their applicability to future 5G networks. Some use cases where the work presented in the paper can be used are also provided. Section 6 positions our contributions with respect to related work. Conclusions and future work are discussed in Section 7.

2 LTE AND SOURCES OF LATENCY

This section provides an overview of the LTE network functionality as well as some insights into the latency contribution of each of the elements involved both in the control and the data planes.

2.1 LTE architecture

The LTE architecture is provided by 2 different planes: one for control and the other for data. The control plane is used to register the users in the network, to manage the mobility inside the network, and to provide the appropriate configuration for the
data plane. The data plane is used to transport user data in the network. These data will be transported over bearers; the bearer concept is an abstraction used in LTE that refers to a data flow with a certain quality of service determined by the quality class indicator (QCI).

Figure 1 depicts the components of a basic LTE architecture, including the interconnection networks that are used between the base stations and the core network (backhaul) and the core network and the services (transport networks). The LTE base station is the eNB that provides the air interface functionality (we will use indistinctly the terms base station and eNB). The eNBs connect to other eNBs with the X2 interface and to the core network with the S1 interface. The basic components of the Evolved Packet Core (EPC) are the Mobility Management Entity (MME), the Serving Gateway (SGW), the Packet Data Network Gateway (PGW), the Home Subscriber Server, and the Policy Charging Rules Function.

The MME is in charge of the control plane procedures. It is connected to the eNB using the S1-MME interface and exchanges information with the UE using the non-access signaling procedures. Its main role is session and mobility management. It is the component that negotiates the registration of the users in the network.

The SGW is responsible for maintaining the data plane with the eNB via the S1-U interface and is the data plane anchor for the handover procedures. The SGW also establishes tunnels with the PGW, which is the component that routes the packets toward the Internet. The tunnels are transported with GTP, a protocol on top of User Datagram Protocol with a short header (8-12 bytes) that transports the UE IP packets. A tunnel is identified by its endpoints (IP of the SGW and the eNB) and the TEID.

The Home Subscriber Server stores the user database with the respective security settings for each of the users. The Policy Charging Rules Function provides the set of rules per user with the subscription details. It is the component in charge of enforcing the quality of service in the network, based on the rules and the application interface, which can be used by external applications to set up the type of service provided by the network.

The different sources of latency, depicted in Figure 1, which we have considered for the experiments of the paper, are as follows:

- Radio: in this segment, the UE and the base station have been considered together. The time consumed by these elements is $T_{\text{Radio}}$ and is affected by the type of base station and UE, as well as the radio frequency channel (we will indistinctly refer to it as radio frequency channel or channel) conditions. The base station eNB is connected to the EPC with the S1-MME interface that transports the control plane and the S1-U interface, in charge of the data plane. The radio access latency contribution varies considerably depending on the state of the radio channel; when the UE is transmitting in poor conditions, it is likely to trigger retransmissions due to packet loss.

- Backhaul: this contains all the networks between the base stations and the core network. The time consumed by this segment has been named $T_{\text{Backhaul}}$, which highly depends on the network’s configuration as it may include different types of communication technologies (fiber, copper, microwave links, etc). These networks are not necessarily owned by the mobile operator; hence, delays due to domain changes might be expected.

- EPC: this includes all the basic elements that are described later, mandatory to support the end-to-end communication. These components are centralized by the operator, and the time consumed by them is labeled as $T_{\text{EPC}}$.

- Transport: this consists of the different domains between the operator’s network and the cloud services. Here, again, the time introduced ($T_{\text{Transport}}$) varies highly when different operators and services are considered.

2.2 Latency contributions from the control plane procedures

Some of the procedures of the control plane also introduce delays in the user data. Some details on the impact of the energy saving states, handover, and attach procedures are provided.
The scheduling procedures in the base station have a relevant contribution to the latencies and are influenced by the number of concurrent users of the base station. Each time that the UE has data to send, it will ask the base station for a scheduling grant on where to transmit, a procedure that can take more than 4 ms.7

Another important part of the latency of the data plane is introduced by the transitions in the control plane state machines due to energy saving cycles. The UE has to monitor some broadcast channels to detect changes from the base stations, emergency notifications, and paging messages. This monitoring will drain the battery very quickly if it is done in each of the messages of the channels (which are sent every millisecond). To avoid this, LTE defines discontinuous reception (DRX) cycles that set the periodicity of the monitoring of broadcast channels. The duration of the cycle introduces an additional delay, which is the time that the UE needs to transit to the connected state. According to Maskey et al,8 the transition from energy saving can take between 20 and 50 ms.

The random access procedure, which is the first phase of the registration in the eNB, can also introduce delays. The effect of this procedure in the data plane is more evident in mobility events, which is when the UE is already transmitting data in a base station and has to change to a different one. These mobility events are provided by the handover procedures, which will also increase the latency on the data plane. There are several types of handover, the main ones being the X2 handover (when the X2 interface exists between the involved base stations) and the S1 handover (rest of the cases), which normally consume more time. During the procedure, there will be delays introduced by the negotiation between the base stations. The main contributions will come from the random access procedure to the destination base station (if the handover succeeds) and normally also the retransmissions due to more than likely poor channel conditions (which are the cause of the handover). Some figures on X2 performance are provided in the work of Alexandris et al,9 which estimates that the delay will oscillate between 20 and 55 ms.

The most time-consuming procedure of the control plane is the Attach procedure that is used to register the UE in the network. The measurements obtained in our previous work6 show that the procedure can take up to 1 second. This procedure will normally have a low impact on the data plane, as it is done once at the beginning of the connection, but it is important as it includes the negotiation of the default data plane tunnels. Additional data plane tunnels can be established during the process or employing dedicated bearer establishment procedures.

### 2.3 Data plane behavior

The components that can introduce more variability in the data plane delay are the backhaul (between the eNBs and the EPC) and transport networks (between the EPC and the services). The main reason for this variability is because neither of them is necessarily managed by the operator, who might lease the access to these networks. Additionally, current EPC networks run over dedicated hardware infrastructures (such as Advanced Telecommunications Computing Architecture [ACTA]), and operators normally own a few of them so there will be many base stations connecting from different geographical locations to these central elements.

In the case of the backhaul, different technologies might be used to provide connectivity to the base stations, principally depending on its location. For example, base stations located in rural areas are likely to use microwave links, as fiber is probably not available, whereas stations in dense urban environments will probably be connected with fiber. Furthermore, there is a clear trend toward adding capillarity to the network by increasing the number of base stations; hence, the heterogeneity of the access will increase. Zhang et al10 provide an overview of the effects of the different backhaul technologies to understand their aggregated effect. The delay introduced by the backhaul network can be on the order of tens of milliseconds.

The transport network delay will depend on the service and the geographical location of the servers, which is the main reason for introducing fog computing techniques into the network. Most approaches propose moving these cloud servers to the edge of the operator’s network, namely, the SGi interface, whereas others study the location of the services close to the radio access, which is the focus of the different architectures proposed in Section 3.
2.4 | End-to-end latency

Following our previous definitions, the end-to-end delay \( T_{e2e} \) of an LTE network will be the time consumed by the radio plus the EPC and transport and backhaul networks. It could be defined as follows:

\[
T_{e2e} \approx T_{\text{Radio}} + T_{\text{Backhaul}} + T_{\text{EPC}} + T_{\text{Transport}}.
\]

This sum of latencies can worsen in the case of communications between UEs connected to the mobile network, as the packets will have to cross the core network and backhaul twice. This will occur even when the peers are connected to the same base station. We can estimate the peer-to-peer delay \( T_{p2p} \) as follows:

\[
T_{p2p} \approx 2 \times (T_{\text{Radio}} + T_{\text{Backhaul}} + T_{\text{EPC}}).
\]

This latency could be improved by introducing architectures that take the server closer to the base stations, cutting down the time consumed on the transport and backhaul in the peer-to-peer communications within the same cell and enabling the possibility of exploiting this server to offer advanced services locally.

Additionally, although there are several studies providing figures on the latency split on LTE systems, the results vary considerably from one source to another. For instance, in the Nokia Siemens Networks Technical Report, the end-to-end latency is calculated at 20 ms. The authors provide a split between the network's different elements (UE, eNB, and EPC); half of the delay is consumed in the radio access. Laner et al measured the end-to-end latency in live networks and found that it is around 33 ms in LTE networks. In order to establish a proper baseline for comparison purposes, some figures regarding the end-to-end latency on the experimental setup will be provided in Section 4.

3 | TWO LATENCY REDUCTION ARCHITECTURES

In this section, 2 different approaches are provided to support fog computing in LTE networks. The first approach is the Fog Gateway, which was introduced in our previous work and consists of an intermediate component to be introduced between the EPC and base stations without modifying any element of the architecture. The other approach discussed is the GTP Gateway that requires modification in the base stations. The GTP Gateway decouples part of the functionality of the eNB to reduce the latency of the system by avoiding unnecessary overhead. A discussion about the evolution of the architectures toward 5G networks is also provided at the end of the section.

3.1 | Fog Gateway

The proposed architecture for the Fog Gateway is depicted in Figure 2. The standard components of the network remain untouched, but an additional element, the Fog Gateway, is deployed between the eNB and the SGW. In order to offer an enhanced behavior in the case of handover, the gateway will also analyze the X2-U traffic. This traffic corresponds to data links between base stations that are used in the event of handover. When the handover procedure starts, the source eNB will forward the traffic received from the SGW to the target eNB using this interface.

The Fog Gateway will analyze all the packets of the data plane (S1-U) to decide if they should be forwarded as they are to the SGW or if the GTP header has to be removed in order to forward them to the fog services. The packets from the X2 (transported over GTP in the data plane of that interface, called X2-U) will then be analyzed to maintain the bearer information updated, but
they will always be forwarded to the corresponding eNB. The idea behind the component is to avoid sending data across the core network when necessary. There are 2 assumptions that will make the Fog Gateway process a GTP packet locally.

- The transported IP header contains the IP of a UE, which is known by the gateway.
- The transported IP header contains the IP of a service, which is reachable from the gateway.

Figure 3 depicts a message sequence chart of 2 scenarios (destination IP inside or outside the fog network). The main advantage of this gateway is that it can work just by analyzing the data plane and without introducing any additional modification to the standard LTE architecture.

There are 2 main functions in the gateway: tunnel database building and packet routing. Tunnel database building creates a database with information of the UEs to route the packets appropriately. The packet routing function decides whether to process the packets locally or forward them to the SGW. The following subsections provide more details on the implementation of these blocks.

### 3.1.1 Tunnel database

The tunnel database is built based on the information received from the data plane. The database will provide bindings between the tunnels (defined by their TEID, eNB IP, and SGW IP) and the UE IP. Every GTP packet received in the FGW (independently of where it comes from) will be analyzed to see if the tunnel is recognized or not. The tunnels will be indexed by their TEID.

If the TEID is new, it will be stored in the database along with the rest of the tunnel information and the UE IP that is in the GTP inner IP header. In case the TEID is previously known, the eNB IP and the SGW IP will be checked again, as they could have changed due to a handover procedure. In the case that the packets are coming from the SGW, the only thing to be done is to update the database with the information of the packet. This information is very important to enable fast communications between different UEs, as it provides the necessary information to craft packets for the downlink tunnels.

When a handover procedure is detected via the X2-U interface, the database should keep track of the information of the old TEID as well as the new one until the handover is finally completed. There will be 3 different tunnel identifiers for the downlink (source eNB–SGW, source eNB–destination eNB, and destination eNB–SGW). This is the main limitation of the approach: in order to work properly, the gateway needs the presence of downlink data during the entire procedure.

After this procedure is completed, the packets from the eNB to the SGW will be passed to the packet routing function. The packets going to an eNB (from the SGW or from an eNB via the X2-U interface) will normally be forwarded to the eNB. The database should also include mechanisms to remove old entries in order to avoid increasing its size too much.

### 3.1.2 Packet routing

The packet routing function is the component that decides which packets are processed locally and which ones are sent to the SGW. It will receive the packets from the tunnel database function and from the fog services. All the packets received by the packet routing function will be analyzed in order to decide how the packet should be treated and/or routed.

The packets coming from the tunnel database building function will always be GTP. The packet routing function will analyze the destination IP address of the inner IP header in the GTP packet. The destination IP can be any of the following:

- An IP belonging to a fog service. In that case, the GTP header will be removed, and the packet will be forwarded toward the service.
An IP belonging to a UE that is in the database. This is the case when 2 UEs establish a peer-to-peer communication. In that case, the GTP header will be changed to match the information present in the database for the UE. After the change, the packet will be forwarded to the appropriate eNB.

- Other cases. The destination of the packet is not reachable by the Fog Gateway; hence, it will be forwarded, without any modification, to the SGW.

Finally, in the case of packets from the fog services, the function will check whether the destination address belongs to a known UE. If so, the information from the UE will be retrieved from the database, and the packet routing function will craft a GTP packet with that information. This new GTP packet will be forwarded to the eNB in which the UE is camped.

3.2 | GTP Gateway

The Fog Gateway provides a simple approach to support low-latency services; the cost of this functionality is the introduction of an additional delay due to packet decapsulation and database construction. In certain handover situations, the Fog Gateway can introduce packet loss in the fog services. As mentioned before, this can occur when there is no downlink data from the SGW during the handover procedure. These limitations could be resolved by introducing some modifications in the standard LTE architecture.

The GTP Gateway is a nonstandard evolution of the Fog Gateway. Its architecture is depicted in Figure 4. The modification consists in decoupling the tunneling functionality from the eNB. The modified eNBs will generate IP data directly from the PDCP layer, and the encapsulation will only be done when necessary. The GTP Gateway will act as a default gateway: it will forward packets for the local subnetwork to the appropriate peers and will encapsulate with GTP the packets being sent outside the local subnetwork.

The control plane of the base station remains as it is; the main change comes in the data plane that now generates IP packets. The information about the tunnels has to be sent explicitly by the base station. To do so, there is an additional interface with the SGW that has been labeled as T1-C in Figure 4. The role of this interface is to notify the GTP Gateway of the TEID, the endpoint IPs, the traffic flow templates (TFTs), and the bearer ID. All this information will be used by the gateway to craft the appropriate GTP headers when necessary. Additionally, T1-C can also be used to notify handover procedures in progress, removing the possibility of data loss in the fog services.

The 2 main scenarios of operation for the gateway are depicted in Figure 5. When the UE is sending data to an IP of the local subnetwork, the GTP Gateway will forward the packet to the destination. This will happen with packets for fog services and for packets to other UEs registered within the same GTP Gateway. When the packets are going outside the local subnetwork, the GTP Gateway will access its database to gather the required information for the tunnel. Then, the gateway will add the GTP header with the appropriate information and forward it to the SGW.

In this approach, there is no unnecessary encapsulation/decapsulation: the GTP headers will be created only when necessary. Furthermore, as the information regarding the tunnels is sent from the modified eNB, the gateway is able to anticipate when a handover procedure is in progress. Again, the control plane of the base station remains as it is in current standard networks.

3.3 | Evolution toward 5G

This section provides an overview on how future 5G networks could leverage the aforementioned solutions. The SDN paradigm could be employed to implement these new architectures, and a discussion on the design of such implementation is provided. Additionally, some insights regarding the virtualization of the protocol stack are also given.
3.3.1 SDN design

Software-defined networking is one of the promising paradigms for future mobile networks; the idea behind the paradigm is the provision of network functionality that could be run over programmable switches. Both of the approaches previously described could be implemented as SDN applications. To do so efficiently, several modifications have to be introduced in the standards. The basic modifications are GTP header parsing, matching, and modification; these will enable forwarding the tunnels toward the Fog Gateway, based on the TEID. Using the TEID, the bearers from a particular user can be identified; hence, in order to differentiate the fog services from the rest, they should be transported in a dedicated bearer. The traffic going over dedicated bearers is determined by a specific TFT, which is a traffic rule that is to define which packets will be transported over the bearer. The dedicated bearer for the fog services will be defined based on a TFT rule that will match the fog subnetwork. This bearer could have associated a new type of QCI defined for low-latency services.

The provision of GTP support in OpenFlow is discussed in many research papers. The standard 1.5.1 does not yet support this protocol, but there are fields (such as the Tunnel ID) employed by other tunneling protocols (eg, Generic Routing Encapsulation and Multiprotocol Label Switching) that could be exploited. The idea is to provide fast paths for the GTP packets based on the TEID. Observing the proposed architectures, it can be concluded that the analysis of the inner IP header of the GTP packets could also be useful. This support will improve the service differentiation that could help provide more efficient switching of the packets, helping to identify packets going to local peers or services, to operator services, to the Internet, etc. Additionally, it will also be useful for the integration of legacy equipment.

3.3.2 Stack virtualization

Another important trend in the design of future-generation networks is the virtualization of the network's components. This enables deploying network solutions in bare metal servers and the under demand composition of dedicated networks. The services can be provided by combining the minimal number of functions that they require. This aspect is reflected in the design of the GTP Gateway, which provides a functionality that is normally present in the stack of the eNB as a standalone function. A local service, which is very frequent, is a sensor network connected to a gateway, for instance, and could be composed by adding the functionality up to the PDCP. Following this division, more functions could be identified across the stack, for example, compression, retransmissions, or scheduling.

4 EXPERIMENTAL EVALUATION

This section describes the setup employed for the characterization of the proposed solutions. Then, a baseline is established by analyzing the latency split in the elements of the setup. Experimental results are provided for the Fog Gateway and the GTP Gateway architectures.

4.1 Experimental environment

The experimental environment is PerformNetworks, which is a testbed that combines commercial equipment with instrumentation and research solutions. Two main components from the testbed are employed in the validation setup: the Keysight LTE T2010A box and the Polaris Networks EPC Emulators.
TABLE 1 T2010A configuration for the data plane baseline

| Parameter                          | Configured Value                |
|-----------------------------------|---------------------------------|
| Frequency (Band 20 FDD) DL        | 806 MHz, UL 847 MHz             |
| Bandwidth                         | 10 MHz                          |
| Power                             | −61 dBm/15 KHz                  |
| Uplink modulation                 | 22-64 QAM                       |
| Downlink modulation               | 22-64 QAM                       |
| Antenna configuration             | SISO                            |
| Maximum retransmissions           | 7                               |

Abbreviations: DL, downlink; FDD, frequency-division duplexing; QAM, quadrature amplitude modulation; SISO, single-input single-output; UL, uplink.

TABLE 2 Channel configuration

| Conditions | Fading Profile | Noise Power, dBm/KHz |
|------------|----------------|----------------------|
| Ideal      | None           | None                 |
| Medium     | EVA70          | −80                  |
| Bad        | EVA70          | −70.5                |

EVA70, Extended Vehicular A 70Hz.

The T2010A box is an LTE conformance testing unit that is normally employed by UE manufacturers to validate their products. The box provides full LTE end-to-end connectivity with commercial devices. This type of unit provides the functionality for the eNB and the EPC as well as channel emulation (fading effects and noise). The unit employed for the experiment has been extended to implement the S1-MME and S1-U interfaces to communicate with standard core networks. In all the experiments, the unit acts as an eNB capable of emulating controlled mobility conditions with commercial UEs. Additionally, commercial off-the-shelf base stations have also been used to produce the baseline results. The base stations employed are small cells, much more limited in terms of configuration parameters, which can offer results closer to the ones on the market. The common basic configuration of the T2010A for the experiments is provided in Table 1.

In order to characterize different radio channel conditions, the T2010A unit has been configured with different fading and noise profiles. Table 2 summarizes the channel conditions employed in the experiments. EVA70 is a fading profile, i.e., Extended Vehicular A with a 70-Hz maximum Doppler frequency, defined in the standards (see the 3GPP Technical Report15).

The EPC Emulators are also a testing solution, designed to validate the implementation of EPC network elements and base stations, that offers carrier-grade performance for up to 300 users. The emulator enables the deployment of multiple instances of core network components, providing standard communication interfaces that can be fully configured (even to generate negative behaviors). The emulators also support the introduction of artificial network impairments in the different transport interfaces that are used to emulate the behavior of the transport and backhaul networks.

Additionally, all the components of the setup are synchronized with a highly stable Global Positioning System (GPS) clock that is exposed by an IEEE 1588 (Precision Time Protocol) server. The time measurements have been extracted from the systems with tools developed for the different scenarios. These tools can analyze ping traces in the different interfaces of the core network, in the base stations, and even in the eNB stack, to obtain estimates on the round-trip time (RTT). More details on the testbed methodology are provided in the work of Zayas et al.16

4.2 Database baseline

The first set of experiments consisted in a characterization of the different delays on the LTE network data plane.

4.2.1 Experiment design

Figure 6 depicts the setup employed for this set of experiments. The UE was a commercial LTE Universal Serial Bus (USB) dongle connected to a laptop. The LTE Emulator refers to the previously described T2010A. The EPC Emulators provided the basic elements described in Section 2.

This first setup was used to characterize the behavior of the latency under different radio channel conditions. Two additional setups were used to estimate the time consumed by each of the segments of the network: one based on the same LTE Emulator
Figure 6: Baseline experiment setup. eNB, evolved Node B; EPC, Evolved Packet Core; LTE, Long-Term Evolution; RF, radio frequency; UE, user equipment.

Table 3: Round-trip time (RTT) split time comparison

| RTT, ms | COTS Small Cells | T2010 Equipment |
|---------|------------------|------------------|
|         | Median           | MAD              |
| $T_{c2e}$ | 28.775          | 11.830           |
| $T_{Radio}$ | 28.223          | 11.577           |
| $T_{EPC}$  | 0.227            | 0.229            |

Abbreviations: COTS, commercial off-the-shelf; MAD, median average deviation.

Figure 7: Cumulative distribution function (CDF) baseline comparison under different channel conditions. LTE, Long-Term Evolution; RTT, round-trip time.

4.2.2 Baseline results

Table 3 provides a summary of the results obtained with the T2010A equipment and the commercial small cells. The table provides the median and median average deviation of the RTT for the different segments of the network; as mentioned before, $T_{Backhaul}$ and $T_{Transport}$ are approximately 0.

The difference between the time obtained in the 2 solutions is due to the configuration of the conformance testing equipment, which has been set up to allocate all the resources for the UE. In general, both latencies are lower than what they would normally be in a public network. The experiments were done with a single UE; hence, the scheduling decisions are easy. Most of the delay in the system is introduced by the radio link, and the EPC processing time is negligible. Again, this figure would be worse in commercial networks due to the number of users.

Figure 7 depicts the cumulative distribution function for the end-to-end RTT under different channel conditions (described in Table 2). For these measurements, several impairments have been introduced in the EPC interfaces: in the S1-U interface, a mean delay of 15 ms has been considered; for the SGi, the mean delay considered was 30 ms. As expected, when the radio conditions get worse, the RTT gets higher; this is mainly due to the retransmission procedures at the medium access control level.


4.3 Fog Gateway evaluation

4.3.1 Experiment design

To evaluate what the behavior of a Fog Gateway implementation could be, the setup depicted in Figure 8 shows the scenario that was employed to evaluate the Fog Gateway architecture. This can be used to estimate the potential improvement introduced by the gateway: a collocated EPC does what the Fog Gateway is supposed to do, that is, decapsulate the GTP packets and send them to the actual server.

This model does not reflect the trade-off of the solution, which is that the packets going outside the fog will suffer an unnecessary decapsulation.

4.3.2 Fog Gateway results

Figure 9 depicts the results obtained for the Fog Gateway scenario under different channel conditions. The median value of the delay is 12.5 ms, which is mainly the radio contribution. An estimate of the additional delay introduced by the solution when routing packets to the SGW will be $T_{EPC}$ that is on the order of microseconds. The number of users connected to the gateway will increase this value, although we do not expect this number to grow much. A single base station will support less than 750 simultaneously, not all of them transmitting simultaneously. This type of gateway exploits geographical proximity; hence, less than a hundred base stations will be a reasonable estimation.

4.4 GTP Gateway evaluation

4.4.1 Experiment design

Figure 10 depicts the setup employed for the GTP Gateway. The time measurement has been inside the LTE Emulator, more concretely in the PDCP layer of the stack, which is the one handling the IP packets received from the UE. The T1-C interface in charge of storing the GTP information in the gateway is not modeled. The assumption that the bearers have been established in advance was made for all the experiments.
FIGURE 10  General Packet Radio Service Tunneling Protocol (GTP) Gateway experiment setup. eNB, evolved Node B; EPC, Evolved Packet Core; LTE, Long-Term Evolution; MAC, medium access control; PDCP, Packet Data Convergence Protocol; PHY, physical layer; RF, radio frequency; RLC, radio link control; UE, user equipment

FIGURE 11  Cumulative distribution function (CDF) General Packet Radio Service Tunneling Protocol (GTP) Gateway under different channel conditions. RTT, round-trip time

4.4.2  Results

Figure 11 depicts the results obtained for the GTP Gateway evaluation. The median value of the delay is 12 ms, with results similar to those provided in the previous section.

The GTP Gateway does not introduce any trade-off in the data plane, which works in the same way as a standard LTE network, the only difference being the split of the functionality in different components and the introduction of overhead in the control plane (due to the new T1-C interface).

5  DISCUSSION OF THE RESULTS

5.1  Comparison of solutions

Figure 12 provides a comparison between the proposed architectures and the behavior of standard LTE networks. A summary of the results is also provided in Table 4. Both solutions compare well with the standard network, reducing the end-to-end latency, mainly by avoiding the transport and backhaul delays.

The delays introduced by the Fog and the GTP are very similar, which is something that we expected. The GTP encapsulation time is negligible compared to the delays introduced by the rest of the functionality of the LTE network.

As stated in Section 3, the comparison with other research is difficult because the figures change considerably even when comparing the basic split per component. Furthermore, most related works provide qualitative analysis (such as those by Lobillo et al., Mäkinen, and Li et al.) and/or focus on other parameters (scalability or elasticity of the network).

The main advantages of the Fog Gateway are the fact that it builds the database just by examining the data plane and the compatibility with standard core networks. The GTP Gateway is an evolution for future networks: if the services are located close to the base station, there is no need to encapsulate the data until necessary. In both cases, the localization of services close
to the base station mitigates the effects on the data plane, which will have the foreseen explosion of Internet of Things (IoT) devices. The security in the interfaces is not compromised. Although not specified by the standards, the data plane is normally protected using Internet Protocol Security. In order to introduce an intermediate component, it will therefore be sufficient to establish Internet Protocol Security between the eNB and the gateway and between the gateway and the SGW.

The main limitation of the Fog Gateway approach is that both the uplink and downlink data tunnels have to be known to communicate with the Fog. If a handover occurs without any downlink traffic, the tunnel database might enter in an inconsistent state, which could cause packet loss in the downlink of local services. The dedicated bearers are ignored by the solution, which does not know anything about the TFTs required to differentiate the different bearers.

The main drawback to the GTP Gateway is that the architecture requires modifications of the base stations; hence, it cannot be deployed using commercial off-the-shelf network elements, and the appearance of a new control interface between the GTP Gateway and the base station increases the signaling messages on the network. On the other hand, the introduction of this signaling removes the possibility of packet loss due to handover as the interface will share the results.

5.2 Applicability to future networks

The solutions presented here can be applied to future-generation networks. For instance, in the 3GPP Technical Report, the data plane stack of the next-generation networks remains almost equal (a new sublayer is added on top of the PDCP). The principles of the FGW Gateway will be applied to the new transport protocol (not decided yet); the ones from the GTP Gateway will be applied over the new sublayer on top of the PDCP, which will be the one responsible for the data plane encapsulation. Furthermore, the S1-U interface still appears as an alternative in the new architecture: the standardization body plans to maintain the compatibility with the ongoing LTE deployment.

As mentioned in Section 3, both approaches are implementable using the SDN paradigm. Additional support in OpenFlow must be added to provide this support efficiently. The GTP Gateway is perfectly aligned with the NFV philosophy. Indeed, the deployment of this gateway function could be optional; for instance, in the deployment of dedicated networks for sensors, it might not be necessary.
5.3 | Use cases

The services that can be deployed in the proposed solutions have to be discussed. While the architectures are more than suitable to accelerate peer-to-peer communications, especially in mission-critical environments such as in the work of Zayas et al.\textsuperscript{23} it is more difficult to deploy content-based services (such as video or music on demand), as they will require techniques to cache content in the servers. This problem has been covered in different research papers, such as by Oueis et al.\textsuperscript{24} and Braun and Monteiro.\textsuperscript{25} The use cases proposed cover low-latency peer-to-peer communications. In particular, we cover one of the scenarios described in the work of García-Pérez et al.,\textsuperscript{26} which shows an emergency situation where paramedics communicate with each other and with a hospital where there are specialists. In this scenario, we can consider several different use cases for the proposed fog solutions, as follows:

- IoT gateways, which can be used to gather information from patient sensors
- Vehicle-to-vehicle or vehicle-to-infrastructure communications between the different ambulances
- Multicast communications between the paramedic and other paramedic/s and hospital/s.

The use of medical sensors on chronic patients and even on healthy people is increasing. The upcoming IoT explosion can be improved with the use of fog techniques. Some of the use cases for IoT communications based on MEC are described in the work of Sabella et al.\textsuperscript{27} Introducing fog systems can greatly reduce the signaling and traffic toward the core network in sensor network deployment. In many cases, the sensors communicate with a local gateway. The introduction of fog techniques can benefit this scenario. The gateway could be moved to the fog while the sensors can directly use any of the new low-consumption LTE modems (such as category 0 or Narrowband IoT\textsuperscript{28}). This will reduce the latency of communications, which can be significant for certain scenarios; most importantly, it will reduce the traffic toward the core network, as the sensors will communicate directly with the fog, and the fog will be the one communicating with external networks.

Latency reduction when avoiding transit to the core network can benefit vehicle-to-vehicle scenarios. These scenarios can be covered using device-to-device techniques,\textsuperscript{29} which enable functioning without coverage. In these scenarios, the fog can be used in the assisted access. Another possibility is to locate servers for vehicle networks in the fog.\textsuperscript{30} The main challenge for these scenarios is the appropriate management of the handover procedures, which can be very frequent due to the mobility of the vehicles. The connectivity among different operators using the fog also has to be covered, and this could be handled by associating fog domains per operator.

Finally, the proposed solutions can be extended to support multicast communications, especially when implemented using SDN technology. Long-Term Evolution networks provide broadcast technologies, namely, the evolved Multimedia Broadcast Multicast Service, but it is geared at broadcasting/multicasting to a large number of users in different cells. To implement a smaller multicast functionality, the gateway used could produce copies of the packets received from the data source and send them to the different peers of the communication.

6 | RELATED WORK

Mobile Edge Computing and fog computing are relatively recent topics that are gaining increased attention from the research community. The research possibilities around the technologies are wide and span many different areas; in the work of Mao et al.,\textsuperscript{31} a detailed survey on the different aspects of MEC is provided. To position our paper regarding related work, we first summarize complementary approaches that were presented with the paper that originated this work,\textsuperscript{6} then we provide a comparison of our work with the solutions related to latency reduction.

There are many publications about the problem of application orchestration and MEC orchestration. It is a very important aspect, as the localization of the servers requires that coordination with each other is improved. For instance, Hegyi et al.\textsuperscript{32} analyzed these problems in the context of cellular IoT deployment with virtualized infrastructures. A more generic work is presented by Brito et al.\textsuperscript{33} where the idea of programmable fog nodes to support Industrial IoT applications with cyber-physical systems in order to reduce latency and increase throughput was introduced.

Security aspects are considered in many papers, as moving functionality to the edges of the network might arise security risks. Pacheco and Hariri\textsuperscript{34} proposed a framework to ensure security in the whole environment of cloud-based applications, including the fog components. The system is oriented to IoT applications. The second proposal\textsuperscript{35} explores the introduction of a fog layer to implement security mechanisms in large mobile wireless sensor networks. In particular, they implement intrusion detection with selective forwarding.
There are also approaches, for instance, CloudWare,\textsuperscript{36} that focus on the client side. It is a middleware to predict changes in the context of a mobile application in order to decide on the use of computation offloading with MEC according to these changes and to the available resources in the UE (e.g., battery). The paper is not specifically oriented toward reducing latency but toward saving resources and is implemented on Android devices.

Other approaches such as that by Mehta et al\textsuperscript{37} are focused on bandwidth optimization rather than latency reduction. The authors analyze when the network operator can benefit from allocating intermediate data centers close to the edge of the network for high-bandwidth-demanding applications. The main concern is bandwidth, and the validation of the approach is done with analytical models.

Regarding the particular problem of latency reduction in mobile networks, there are some related approaches. The proposal by Heinonen et al\textsuperscript{21} also focuses on GTP tunnels to improve the flexibility of the core network. The authors propose a dynamic GTP termination mechanism that combines cloud-based GTP with a fast GTP tunnel implemented with dedicated hardware. Depending on the user's requirements (or other policies defined by the operator), the system switches from a cloud-based SDN SGW implementation to a fast path one. Compared with the proposal by Heinonen et al,\textsuperscript{21} our proposal is not focused on the elasticity of the network per UE; we provide service differentiation to many UEs simultaneously. In addition, we do not need dedicated hardware, because the FWG and the SDN support can be implemented in general-purpose hardware available at the edge of the network. In the work of Lobillo et al,\textsuperscript{17} several femtocell architectures are analyzed in a qualitative fashion. The main difference with this paper is the use of components to communicate both with the control and data planes in the LTE femto architecture.

There are other proposals dealing with different aspects of latency, which are more related to MEC than to FOG. The proposal by Mäkinen\textsuperscript{18} centers more on the service side. The authors analyze the business case as well as some technology and service designs. Li et al\textsuperscript{19} present an analysis of the different architectures to support mobile edge in future 5G networks, also providing some insights on data caching and the overall system performance. In the work of Cau et al,\textsuperscript{20} experimental results on the NFV deployment of EPCs are given, and the scalability and the setup time of the solution are analyzed in depth.

7 CONCLUSION

In this paper, we have presented 2 uses of fog computing to reduce latency in LTE networks. The Fog Gateway solution provides a very simple approach, analyzing the data plane packets to reduce the latency of the ones going to fog services. The second option, named GTP Gateway, can provide similar performance while removing unnecessary encapsulation/decapsulation of the base station outgoing packets. The solutions employed can be combined with SDN and NFV techniques to support the services over dedicated switches, improving the flexibility of the network.

Both approaches have been compared in a realistic environment using commercial equipment and conformance testing infrastructure, showing the potential benefits of each solution in comparison with the standard LTE network. They can be used to enable different scenarios such as network sensors, vehicle-to-vehicle, or multicast communications. Both solutions are compatible with the standardization bodies' current studies and are aligned with some of the paradigms foreseen in 5G networks.

As for future research, we expect to evaluate how the solutions could be used to provide multicast services and to validate the solutions at scale. To do so, we are currently producing prototypes and tools to execute trials with emergency services. Additionally, we foresee the exploitation of the SDN/NFV paradigms to produce efficient implementations of the gateways.

ACKNOWLEDGEMENTS

The work described in this paper has received funding from the European Horizon 2020 Programme under grant agreement 688624 (Q4Health project).

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**How to cite this article:** García-Pérez CA, Merino P. Experimental evaluation of fog computing techniques to reduce latency in LTE networks. *Trans Emerging Tel Tech*. 2018;29:e3201. [https://doi.org/10.1002/ett.3201](https://doi.org/10.1002/ett.3201)