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An eHealth-Care Driven Perspective on 5G Networks and Infrastructure

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Abstract. This work describes the advancements that next generation mobile networks can bring to emergency services on the basis of a fully 5G enabled medical emergency response scenario. An ambulance service combining autonomous driving, advanced on-board patient monitoring, remote diagnosis and remote control from the hospital is introduced, allowing increased levels of care during patient transport and improved early diagnosis, thus enhancing patient survival rates. Furthermore, it is shown that such an ambulance service requires a variety of different traffic types that can only be supported concurrently and with guaranteed quality of service by a high-performance network fulfilling all 5G key performance indicators. The scenario described combines a multitude of aspects and applications enabled by 5G mobile communications, including autonomous driving, ultra-high definition video streaming, tactile remote interaction and continuous sensing, into a compelling showcase for a 5G enabled future. A centralized radio access 5G network with space division multiplexed optical fronthaul using analog radio-over-fiber and optical beamforming is analyzed, fully supporting SDN and NFV for advanced network slicing and quality of service guarantee.

Keywords: ehealth, millimeter wave communications, radio-over-fiber, optical beamforming, multicore fiber

1 Introduction

In recent times, emergency medical services (EMS) have evolved compared to their predecessors, due to historical and socioeconomic forces as well as technological advancements [21]. In many countries of the world, EMS respond quickly to emergencies like accidents, traumatic injuries and medical issues. An ambulance is the “first room” of the hospital where a preliminary clinical diagnosis is formed and the patient is partially treated or prepared for treatment. All ambulances are connected to a call center where an emergency doctor gives medical advice to the paramedics and the ambulance nurses. However, this doctor is not a specialist and cannot fully diagnose a patient based on the limited amount of information available. Moreover, due to the lack of doctors, this medical assistance is inefficient as each doctor may need to support a number of ambulances. Consequently, the patients' treatment within the ambulances is limited. This reality will be utterly altered by the massive advancements that 5G communications will allow to be introduced to the health-care systems.

In the dawn of 5G, the future radio access networks (RANs) will provide guaranteed quality of service (QoS) with enhanced broadband connectivity to end users. The ITU-T FG-IMT-2020 standardization group claims that the 5G communications will bring revolutionary changes to the existing infrastructure by increasing the wireless capacity by 1000 and connecting over trillions of devices among several billions of people with ultra-low latency (<1 ms) [12]. Regarding the capacity requirements, it is expected that the data rates will vary between 100 to 1000 Mbit/s with a peak of 10 Gbit/s. With 5G, very reliable networks will be designed with no loss of connectivity and fast response times.

The carrier frequencies of the 5G communication signals will be located in the lightly licensed millimeter wave (mm-wave) bands, supporting high bandwidth [23]. Mm-wave bands support the use of large amount of small antennas with beamforming which is one of the major technologies to be introduced into these systems. In 5G systems multiple-input multiple-output (MIMO) technology can be realized, increasing spectral efficiency even further [24]. 5G will make the networks not only more reliable and faster but more intelligent. This is based on the fact that these networks will have the ability to connect not only people but sensors and machines to the internet with ensured QoS and low latency [18]. Guaranteed QoS can be achieved by network slicing and represents an additional crucial advance compared to 4G networks.

For example, today certain devices performing cardiac ultrasonography use 4G to transmit video data using a static wireless connection [5]. Due to the ultra low latency and support for fast mobility provided by 5G, the same process can be done in moving environments allowing the EMS to perform more complete diagnostics. Probes connected via 5G will run tests and send the results directly to the hospital. Furthermore, remote surgery will become feasible and thus the help provided by the EMS health care procedures to a patient inside the ambulance will immensely increase.

In order to achieve the goals of this concept, the scientific contributions of projects working on the realization of 5G networks are crucial. One of the projects carving the road towards 5G is the 2$^{\text{nd}}$ phase 5G-PPP project *blueSPACE* [6]. This project endeavors to establish new technologies that enable 5G networks with high performance in comparison to the existing ones with lower costs and energy consumption. *blueSPACE* elaborates on the concept of implementing analog radio-over-fiber (ARoF) fronthaul using optical spatial division multiplexing (SDM) with multicore fibers (MCF). Novel techniques such as the use of optical beamforming networks will be investigated leading to decisive capacity increase. The network management and allocation of resources will be conducted by a virtual orchestrator based on a centralized control plane featuring software defined networking (SDN) and network function virtualization (NFV).

The remainder of this manuscript is structured as follows: section 2 describes a future 5G city consisting of fully automated systems that communicate with increased throughput, low latency and high QoS. Section 3 showcases a scenario where a patient needs to be transferred to a hospital by an autonomous ambulance. Section 4 discusses the involved traffic types and the centralized RAN supporting such a scenario. Finally, Section 5 summarizes the article.

2 A Future, Fully 5G Enabled City

Figure 1 shows a city in the future where full 5G coverage is implemented. The control station is the most important aspect of the architecture since it is in charge of the circulation within the city and connects the nodes of the network that need to communicate. This is achieved both in the optical and wireless domain. A fiber optic network is deployed underground, connecting all the important network nodes of the city and establishing connectivity with high bandwidth that enables 5G [8]. Households are connected to the network either through fiber to the home (FTTH) or through lamp posts in the city that provide high-capacity wireless broadband access [22].

Fig. 1. The urban environment of a future city where all the infrastructure is 5G enabled. Vehicles are fully autonomous and receive signals from lamp posts, traffic lights and base stations throughout the city. The lamp posts also enable 5G broadband wireless access. The control station is responsible for the management of all public infrastructures, including communications and traffic.

All cars are autonomously driven and each car is connected to the control station through the network and ad-hoc to the surrounding traffic and road infrastructure, allowing both central traffic flow management and local on-the-spot optimization. The dense network of 5G enabled lamp posts along the roads and intelligent traffic lights at the junctions assure ultra reliable vehicular communications. Autonomous 5G cars will bring major changes to the transportation systems of the future. Traffic jams will be reduced to a minimum due to the orchestrated traffic control provided by the network. For each car, a reliable and fast route will be chosen to arrive to its destination. Consequently, fuel consumption will be decreased leading to reduced CO_2 emissions into the atmosphere. The total number of car accidents will be significantly reduced since 5G autonomous cars will always keep a safe distance from the neighbouring cars with a variable speed depending on road and traffic conditions. Furthermore, these cars will be able to respond quickly and effectively to abrupt traffic changes such as immediate breaking within ms, compared to the perception response time (PRT) of a human driver that ranges on average between 1.6 to 3 s [14].

The cars and the majority of the devices and systems within the city are connected to its wireless network. Mm-wave high capacity signals arrive to the end users with low latency. However, mm-waves suffer from high attenuation due to path losses and their coverage is significantly reduced in non-line-of-sight (NLoS) connections. Consequently, high gain mm-wave MIMO antennas are installed in base stations (BS) around the city. Most of these antennas are placed on top of the tallest buildings assuring LoS. The locations of the BS are selected so that they can provide broad coverage to different users. The mm-wave signals carrying information that are essential for all the main functionalities of the city are centrally generated in the optical domain, travel through the optical distribution network and arrive at the respective radio node from where they are wirelessly distributed. For such a 5G network scenario where the signal that needs to be transmitted through the air is generated far away from the antenna, the existence of hybrid photonic-wireless links is certain. This is due to the fact that these links allow the transmission of high bandwidth multi-channel signals in long distances with very low attenuation comparing to RF coaxial cables.

3 A 5G Enabled Health Care Emergency Scenario

One important variable that affects the patients' fate and chance of survival is the response time of the EMS [17]. Furthermore, the range of health care and emergency measures that can be performed while the patient is being transferred to the hospital, i.e., the range of medical procedures available on the spot, is a key parameter that affects many aspects of the healing process. With 5G, both variables will be optimized, radically increasing the amount of positive outcomes on patients' treatment.

3.1 Coordinated Emergency Response

In case of an emergency, a central coordination center receives the emergency report – typically as an alert from the general public or from connected response or monitoring services on patrol –, performs an initial emergency assessment and notifies the required response services, including – as shown in Fig. 1 –

medical, police and fire fighting services. Additionally, going beyond the typical scenario of today, the central city control is alerted, to coordinate emergency response with traffic control, communications infrastructure and other relevant public services, infrastructures and institutions.

Upon notification from the emergency coordination center, an autonomous self-driving ambulance rushes to pick up the patient. The central control office arranges the fastest route to the pick up point and ensures that all the traffic lights are green when the ambulance it is on its way. Moreover, the light poles and the traffic lights alert the autonomous cars to pull over, clearing the way and securing the passage for the ambulance. Thus, the probability of a car accident between the ambulance and a civilian car decreases [19], while the average speed of the ambulance can increase and thus initial response times become significantly faster.

The map of Fig. 2 shows that the ambulance picked up the patient in need and its imperative that it returns to the hospital as fast as possible. The control center again calculates the optimum journey and controls the ambulance through the network. For instance, even though in terms of distance the fastest way for the ambulance is to follow the diagonal road towards the hospital, however the construction works would not allow it to proceed. Thus, the second best path, indicated in the figure, is chosen and all the cars and traffic lights get notified.

In life threatening situations where special medicine, blood or medical equipment are urgently needed and are not available in the ambulance by default, drones are used [20] to ferry such supplies on demand from the hospital to the ambulance, potentially saving valuable minutes in the time between response and initial treatment. More specifically, drones residing on the roof of the hospital are connected to the 5G network. When they are activated by the hospital, they receive the necessary medical aid and autonomously fly to the ambulance where they attach to it and contribute to the support of the patient [9].

3.2 5G Enabled Autonomous Ambulances

The ambulances that are 5G enabled are radically different from the ones that are deployed today. Figure 3 illustrates the comparison between the two vehicles. At the top there is the typical ambulance staffed with two paramedics and a driver. These health-care vehicles provide on-board life support and only local monitoring. At the bottom of the figure, it is portrayed a fully 5G supported autonomously driven ambulance. It is manned with two paramedics with increased space since the driver's compartment is added to the main cabin. Moreover, this 5G vehicle features full connectivity to the hospital, including remote monitoring, consultation and interaction with medical personnel and robotics. The autonomous driving is enabled by the full connectivity to road infrastructure and local traffic. Finally, aerial support is granted by autonomous drones. Such an ambulance will increase dynamically the effect of EMS to positive outcomes in patients' healing processes.

5G ambulances carry devices and medicine that the current ones possess such as a first aid kits and a portable automatic cardiac defibrillator for emergency

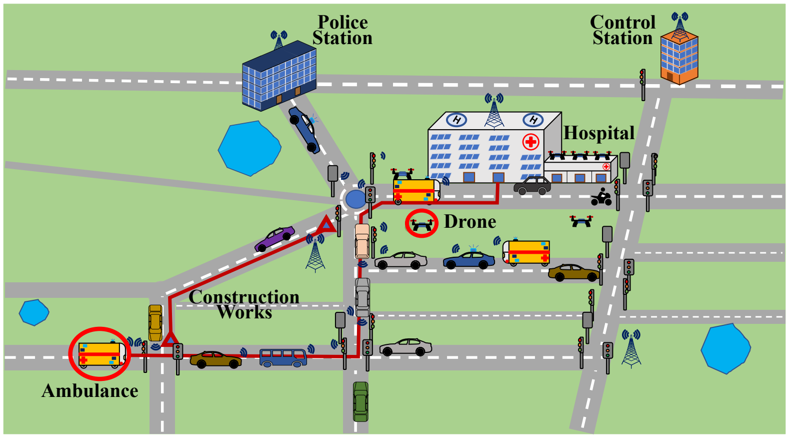

Fig. 2. An emergency health-care scenario based on the future 5G enabled city of Fig. 1. The ambulance need to transfer a patient to the hospital and the fastest route is chosen based on the traffic and the construction works; all the nearby cars are alerted for the presence of the ambulance. A drone transports medical supplies from the hospital to the autonomous ambulance.

treatment of cardiac arrest; however their technology is far more advanced. The medicine container of the ambulance is connected to the network and has an embedded computer calculating the exact portion of medicine needed to be given to the patient depending on his physiology. In addition, the most important characteristic of this vehicle that makes it supersede the ambulances deployed today is that 5G will enable the doctors at the hospital not only to monitor but also to remotely control all the medical instruments inside it. The ultra-low latency and high QoS that 5G offers will allow the specialists to perform these processes from the hospital.

For example, a robotic device consisting of multiple probes that are able to compose the clinical overview of the patient is installed within the future 5G ambulances. It is is a multi-sensing instrument and has a direct connection to the hospital [4]. This device performs more well-informed diagnostics than the ones currently used and is able to transmit the data in real time over 5G connections. Measurements such as blood type, oxygen and sugar levels, blood pressure and cardiograms showing the current status of the patient are directly sent to the hospital for further analysis and treatment planning. Furthermore, this robotic device can also perform small surgical procedures on a patient that can be supervised and controlled by the experts at the hospital. This means that doctors can make a surgery without having to go to the operating room and while their patient is inside the moving environment of a vehicle.

While the ambulance transfers the patient, an emergency doctor at the hospital supervises the first medical treatment steps while watching through the high resolution cameras embedded inside the vehicle [11]. At the point where the probes send the preliminary results describing the medical condition of the pa-

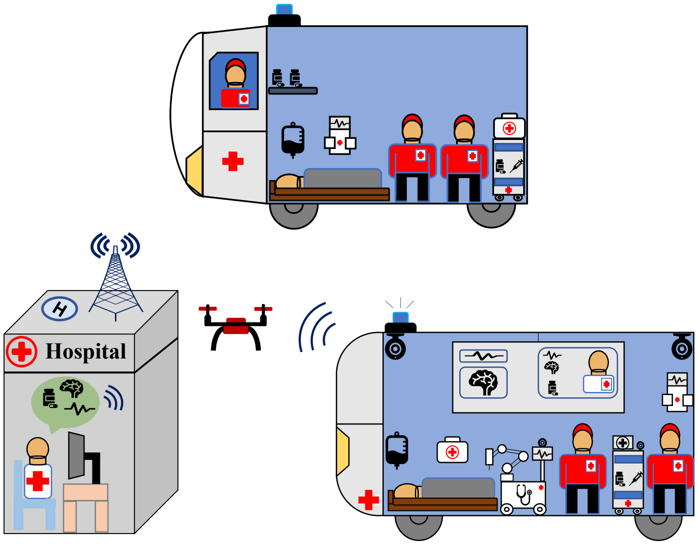

Fig. 3. Comparison of ambulance vehicles today (top) and with full 5G support (bottom). Top: typical ambulance vehicle of today, manned with driver and paramedics, fitted with life support and local on-board monitoring. Bottom: ambulance concept with full 5G support, featuring full connectivity to the hospital, including remote monitoring, consultation and interaction with medical personnel and robotics, as well as autonomous driving, full connectivity to road infrastructure and local traffic as well as aerial support from autonomous drones.

tient, the emergency doctor can make a preliminary diagnosis. In a further step, the doctor sends all the results to a specialist who connects to the ambulance from a workstation installed in his office. The doctor can examine in detail the patient by the multi-sensing robotic probe and even perform a surgical process.

Consequently, doctors can already immediately diagnose the patient's health status and specify the treatment that needs to be given long before the patient arrives at the emergency rooms (ERs) of the hospital. This will grant time for the hospital to make an efficient medical preparation targeting the source of the patient's medical issue. Furthermore, by converting the ambulance into a small ER, the load of the actual ERs within the hospital will be reduced critically.

4 The 5G Network Overview

The scenario depicted in the previous section and the wide range of diagnostic, interaction and communications facilities hosted in the 5G enabled ambulance highlight the presence of many different traffic types and traffic flows with different service requirements in the same locations and at the same time. Joint support for these traffic types can only be provided by a network meeting the full 5G KPIs and a guaranteed QoS for each type requires careful network design to support isolation of the traffic types during transport in the network. For these reasons, the future networks need to be designed with slicing mechanisms where different services coexist without affecting each other. Based on ITU-R [13], there are three different generic traffic categories that 5G will support and are categorized as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine type communications (mMTC). Each traffic category is briefly analyzed below.

- eMBB: Focuses on signals with enhanced throughput, low latency and high connection density. This type of service can be useful for receiving very high definition video signals from the hospital to the 5G ambulance [25].
- URLLC: This use case assures the transmission of very reliable signals capable of controlling machines with very low latency and location precision. Thus, this type of traffic enhances the driving autonomy of the ambulance and the drone. Low latency is also very important in the case where there is a conflict in bandwidth allocation between cars in the same area causing confusion in the network and a probable accident [1]. Remote robotics also depend on this type of service. In order for remote surgeries to be performed inside the ambulance, signals have to enable the robots with very low latency.
- mMTC: Requires the transmission of low bandwidth signals, assuring low energy consumption and enhanced coverage [10]. The traffic infrastructure of the 5G city is controlled by mMTC signals. For example, this service is used for non time cricitcal vehicle to vehicle (V2V) and vehicle to everything (V2X) communications.

In Table 1, each signal transmitted or received by the ambulance is classified by the applicable traffic service. Based on the three definitions, the traffic types have vastly different capacity and QoS requirements. However, the signals that support the 5G services of the ambulance scenario may have combined properties. For instance in the case of medical probes, characteristics from both the mMTC and eMBB are combined. This is because the probes transmit signals that consume low power but also in the case where ultrasound scan data are transmitted, the high bandwidth of eMBB signals is essential. This is shown in Fig. 4 highlighting the fact that support for different traffic types is crucial.

Table 1. 5G Traffic Service Categories of the Different Applications in the Patient Transfer Scenario

Signal Traffic Types	eMBB	URLLC	mMTC
Autonomous Driving		x	
Traffic Lights/Traffic Control			x
Vehicle to Vehicle Coordination		x	
Drone Control	x	x	
4k Video Remote Interaction	x	x	
Medical Sensing	(x)		x

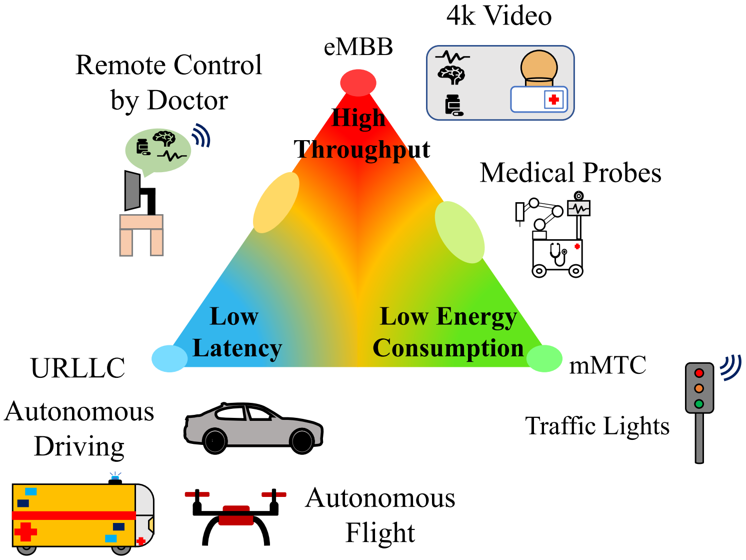

Fig. 4. The different signal traffic use cases applied at the ambulance scenario; for some applications signals have properties from multiple traffic services.

In 5G networks, isolation between different traffic types and different traffic flows and independent guarantee of QoS are achieved though network slicing [26]. Flexible network slicing is achieved by the combined contribution of both software defined networking (SDN) and network function virtualization (NFV) [15]. With SDN the control plane of the network is decoupled from the data plane which is responsible for forwarding the data traffic. This gives the ability to centralize the control of the network using transparent interfaces. With NFV, all the hardware-based network services and functions are moved to a virtualized environment. 5G networks will be supported and controlled by cloud orchestrators and virtual machines that use both SDN and NFV.

Figure 5 shows the physical network infrastructure of the city scenario. The control station functions as central office of a highly centralized RAN with a pool of virtualized baseband units (BBUs) [2]. The combination of generating flexible carrier aggregated signals (e.g. OFDM signals) with ARoF fronthaul allows the centralization of the network's complexity at the control station. Since no framing and digitization are involved for the ARoF fronthaul signal generation, the network may operate with low latency. Thus, this type of network not only offers maximum flexibility for capacity assignment, but also enables SDN and NFV. With NFV, granular network slicing can be obtained and for each traffic signal type a guaranteed QoS is achieved meeting the traffic type specific requirements.

In both the traffic lights and the lamp posts there are fibers connected originating from the network. However, it is yet unclear the nature of the wireless signal that is going to be transmitted to the cars. The cars may receive sig-

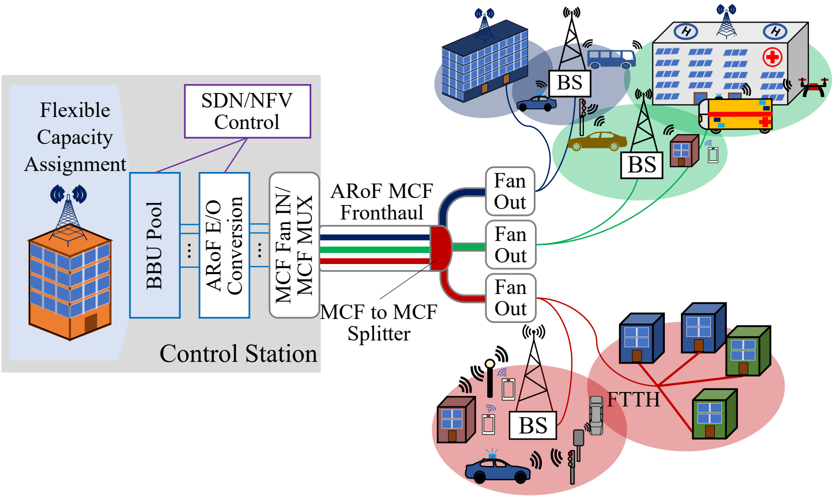

Fig. 5. Cetralized RAN architecture with SDN and NFV providing control and virtualization of the BBU pool. Carrier aggregation and multicore fiber enable the signal delivery to different communication cells.

nals either through visible light communications (VLC) or via transmitted RF signals [7]. For the purposes of this paper all the wireless communications are conducted by mm-wave antennas in the radio frequency (RF) domain.

At the control station, an integrated beamforming network will be adding true time delays to the generated optical signals. MCF is used for the transport of signals from or to the MIMO antennas. MCF allows the use of numerous optical channels increasing the signal traffic quality [16]. The opto-electrical upconversion takes place at photodiodes (PD) close to the transmitting antennas where wireless signals at specific radio frequencies (f_{RF}) are generated by optical heterodyning [3]. The end users within the city receive signals with low latency and with beamforming high precision user tracking can be applied.

5 Conclusions

In this paper, possible improvements to medical emergency response services enabled by 5G mobile networks are discussed. A coordinated emergency response scenario is illustrated, showcasing the substantial improvements to response time and patient support during transport to the hospital, compared to the current state. Vehicular autonomy and remote diagnosis and control are the key parameters that will drastically increase the positive outcomes of emergency response services in the health sector.

Autonomous ambulances connected to a 5G centralized network will offer fast and reliable patient transfers to the hospitals whilst paramedics can provide extensive medical services within the vehicle. 5G will increase the medical interaction during the patient's transfer by enabling enhanced bidirectional communications between the ambulances and the hospitals, allowing a remote specialist to virtually be in the vehicle. Robotic probes connected to the network will send an analytic overview of the patient's physical health to the hospitals. Low latency and high QoS will allow the specialists at the hospital to remotely control these multi-sensing probes. Thus, the doctors, can perform a plethora of medical tests as well as some minor surgical processes. In addition to the above, the high definition video interaction with the paramedics will allow the doctors to perform improved diagnosis and decide for the patient's treatment before arrival at the hospital.

The signals controlling all the processes of the ambulance are generated and transmitted within a centralized RAN. A control station using SDN and NFV is responsible for traffic flow the management and quality of service guarantee. Support for different traffic types (eMBB, URLLC and mMTC) is assured through the use of ARoF and MCF within a fully SDN and NFV enabled network, allowing dynamic and flexible network slicing.

The described medical emergency response scenario showcases how advances in the health care sector depend on full support of the 5G KPIs and how the combination of applications enabled by 5G combine to drastically advance a scenario not necessarily intuitively regarded as depending on 5G mobile networks.

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