Network-In-a-Box: A Survey about On-Demand Flexible Networks

Matteo Pozza, Ashwin Rao, Hannu Flinck, and Sasu Tarkoma

***Abstract*—One of the key features of next-generation mobile networks is the ability to satisfy the requirements coming from different verticals. For satisfying these requirements, 5G networks will need to dynamically reconfigure the deployment of the network functions. However, the current deployments of mobile networks are experiencing difficulties in exhibiting the required flexibility. At the same time, the research on connectivity provisioning in use cases such as after-disaster scenarios or battlefields has converged towards the idea of Network-In-a-Box. This idea revolves around fitting all software and hardware modules needed by a mobile network in a single or a handful of physical devices. A Network-In-a-Box inherently offers a high level of flexibility that makes it capable of providing connectivity services in a wide range of scenarios. Therefore, the Network-In-a-Box concept represents an alternative approach for satisfying the requirements of next-generation mobile networks. In this survey, we analyze the state-of-the-art of Network-In-a-Box solutions proposed by academia and industry in the time frame starting from 1998 up to early 2017. First, we present the main use cases around which the concept has been conceived. Then, we abstract the common features of the Network-In-a-Box implementations, and discuss how different proposals offer these features. We then draw our conclusions and discuss possible future research directions, including steps required to reach an even higher level of flexibility. The aim of our analysis is twofold. On one hand, we provide a comprehensive view of the idea of Network-In-a-Box. On the other hand, through the analysis we present the features that future mobile networks should exhibit to achieve their design goals. In particular, we show how the Network-In-a-Box fosters the transition towards the next-generation mobile networks.**

***Index Terms*—5G, Flexible Networks, On-demand Networks, LTE, Network-In-a-Box**

I. Introduction

The architecture of a 5G network has evolved into a well-defined design with a precise list of features. One of the key features of a 5G network is the capability to satisfy the requirements coming from different use cases. In short, 5G networks are expected to be flexible and adaptable [1]–[3]. At the same time, emergency and tactical networks are designed to be flexible and adaptable because the environment in which they will be deployed is largely unknown [4], [5]. Typically, such networks fall in the category of so-called Mobile Ad-hoc NETworks (MANETs).

Recently industry has boosted the development of emergency and tactical networks towards solutions that comprise a number of physical devices as small as possible with the main aim of increasing the practicability. Many organizations have pushed this idea to its limits, managing to launch on the market networks which are deployed through very few physical devices or even a single one, *i.e.* the so-called Networks-In-a-Box (NIBs) [6]–[8]. In most of the cases, a NIB can be configured to work either completely alone or together with other legacy network components, as well as with other NIBs [9], [10]. Moreover, usually there is no single technology for accessing the services offered because either many technologies can be used simultaneously or the technologies can be switched interchangeably [11], [12]. In addition, such networks are enriched with other features, like self-organization capabilities or provisioning of ad-hoc services.

In this paper, we analyze the state of the art of Networks-In-a-Box. In particular, we focus on the academic and industrial works that have been proposed from 1998 till the beginning of 2017. We do not limit our analysis to networks generated by exactly a single physical device, but we rather include academic and industrial proposals that exhibit flexibility as their own core property. In our analysis, we adopt a top-down approach, going from the motivations behind a NIB to its inner aspects. First, we consider the main use cases in which a Network-In-a-Box is used nowadays. This allows to justify the architectural choices that are performed in their design. Then, we explore how NIBs relate with the surrounding environment, so we focus on the technologies that are leveraged to communicate with users, the rest of the Internet, and other network components. Finally, we inspect inside NIBs to identify the common features whose combination provides a high degree of flexibility as outcome. The three parts are linked by a logical path: the use cases determine the technologies that are actually suitable for them, and the technologies determine the features that can or cannot be encapsulated in the final solution.

The main objective of this study is to explore the potentialities that are offered by NIBs and understand how they could be leveraged for the implementation of 5G networks. Indeed, the flexibility required by the next generation of mobile networks can be achieved by the inclusion of NIB's principles in such networks. We believe that the Network-In-a-Box can become the building block for generating flexible and adaptable networks. To this aim, we discuss the next steps that will allow to evolve from a traditional NIB, which is only suitable for specific scenarios, to a modular component, which can be leveraged in different contexts.

Figure 1 shows the structure of the survey. Section II defines the concept of Network-In-a-Box, showing the possible variations with which it can be found in literature and on the market. In Section III we explain the reasons behind the NIB concept by presenting the use cases that require it. Given the requirements of the use cases, in Section IV we describe the suitable technologies a NIB uses to communicate with external entities, *e.g.* end users and the Internet. The technologies adopted and the requirements of the use cases define the key features of a NIB, which we report in Section V. In Section VI

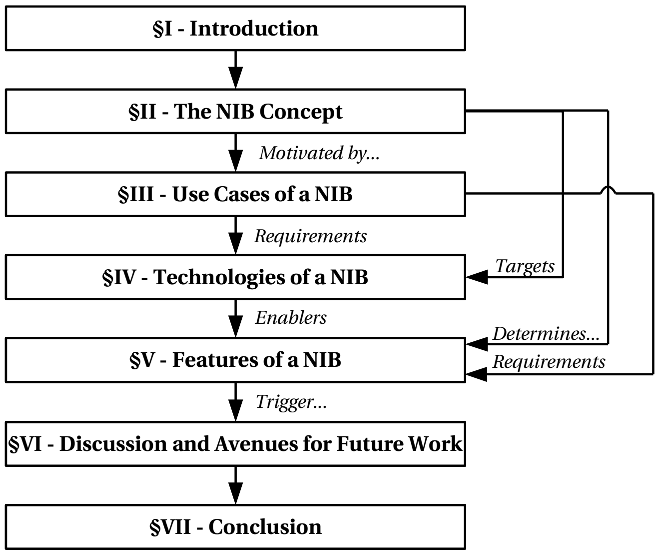


Fig. 1. **Structure of the Survey.** *After the introduction, the NIB concept is defined in §II. The use cases described in §III provide the reasons behind the NIB concept, the requirements that determine the technological options (§IV), and the features characterizing the NIB (§V). The technologies take into account also the communication targets prescribed by the NIB concept, and they enable the NIBs features determined the NIB concept. Such features trigger the discussion of their usage in tomorrow's networks (§VI), which is followed by the conclusion (§VII).*

we discuss how these features can be leveraged in tomorrow's networks, which are the risks associated, and which are the improvements that are expected in future NIBs. Finally, we conclude the study in Section VII.

II. The Network-In-a-Box Concept

Network-In-a-Box is a fairly recent expression for indicating a single physical device used to provide connectivity to a group of disconnected and potentially moving devices. A NIB allows devices to communicate with each other by offering services such as text messages, calls, and Internet connectivity. The design of a NIB is also focused on portability, so that NIB's users can freely move and the NIB can be moved on-demand as well. According to this principle, the NIB needs to be lightweight and to provide its services through wireless connectivity. For this reason, NIBs are also called "bring-your-own-coverage" solutions [10], [13].

An important use case of a NIB is the restoration of basic connectivity in an emergency scenario. Indeed natural or man-made disasters can seriously damage the already-deployed communication infrastructure, leading to a complete service disruption. Even if part of the communication infrastructure is not affected by the disaster, most of the time people are unable to communicate with each other because the survived infrastructure is overwhelmed by call attempts. In these cases, a NIB results in the quickest and easiest way to restore a basic communication service in the affected zone.

A NIB is also useful in case of high mobility of the communicating devices, like soldiers on a mission. In a battle scenario, soldiers cannot rely on a public communication infrastructure because it might be disrupted or controlled by the enemy. Instead, they can use a NIB in a backpack, keeping the network small, private, and secure. Section III contains a deeper analysis on the use cases of a NIB.

The term Network-In-a-Box started to appear in 2013 in some industrial proposals [14], [15], and it continued to spread in the following years [7], [16], [17]. Nevertheless, the idea of combining several network elements[1] in a few portable physical devices was conceived in academia, with the early works of Sanchez *et al.* [18] and Evans *et al.* [19]. In this paper, we do not limit the analysis to the proposals that strictly require a single physical device, but we rather consider the proposals in which the number of physical devices is small. These proposals exhibit the same features that are embodied in single-device Networks-In-a-Box, such as ease in deployment and self-organization. Henceforth, the expressions NIB, NIB solution, and NIB proposal are used interchangeably to indicate a network generated using a small number of physical devices.

The expression Network-In-a-Box appears with minor variations depending on what is actually encapsulated in each physical device. In some contexts the device may encapsulate just a part of a whole mobile network, *e.g.* Evolved Packet Core (EPC) [20]. As an example, in an after-disaster scenario, the survived telecommunication elements can be combined with complementary NIBs to recover the original network [21]. The term varies also depending on the technology that is used for providing the connectivity services, *e.g.* LTE [22], but these cases are just particular instances of the more generic concept.

In summary, we need to extend the original definition of a Network-In-a-Box to a more general one. We can rephrase the concept of Network-In-a-Box as a small set of physical devices in which the functions of an arbitrary number of network elements have been coalesced. In the borderline case, the whole network is coalesced in a single physical device; alternatively, just part of the network is embodied by the NIB.

The NIB concept has been designed to provide the services required in specific use cases, such as after-disaster scenarios. In the next section, we describe these use cases to understand their requirements and how a NIB satisfies them.

III. Use cases of a Network-In-a-Box

In the following, we briefly discuss the contexts in which a Network-In-a-Box is the most appealing solution. In particular, we focus on the three most important ones, which are: after-disaster scenario, challenging contexts such as flights or villages in developing countries, and battlefield. We also present some minor use cases in which a NIB can be leveraged, such as the setup of an enterprise network.

A. After-Disaster Scenario

Among all the possible use cases for a Network-In-a-Box, the most important one is connectivity provisioning in an after-disaster scenario. Most of the features of existing and proposed NIB solutions aim to satisfy the requirements of this use case,

[1] Henceforth, we use network element to refer to a generic infrastructural component of a telecommunication network, such as a switch, a gateway, or a middlebox.

and it still represents the main vertical from both academic and industrial perspectives.

Disasters such as earthquakes, tsunamis, and terrorist attacks trigger a sudden need for network connectivity, which is fundamental to ensure a good organization of the rescue operations [23]. For instance, the response by the rescue teams has to be as quick as possible because the chances of surviving drop after the first 72 hours from the occurrence of the disaster [24].

As highlighted by Jang *et al.* [25], a communication network involving firemen, medical staff, and survivors is essential in order to reach efficiency in the rescue operations. In addition, the survivors need to ask for help or to exchange information about their health status. Using the pre-existing cellular network for both needs is not a solution. Many studies have highlighted that the network infrastructure in a post-disaster scenario tends to be seriously compromised [15], [26]–[32]. In addition, even if the network survives the disaster, it has to deal with an excessive number of call attempts that are performed by the survivors. Kunz *et al.* [27] have reported that the mobile-originated traffic can increase 60 times more than usual in this kind of scenarios. This is the result of two simultaneous effects of the disaster: the need of people to communicate immediately, and the partial damage of the network infrastructure, which makes all the traffic to flow on the survived part only.

Given the described context, there are mainly two ways of facing the presented issues. The first one is repairing the original network infrastructure. Nevertheless, this approach is incompatible with the requirements on the response time because the complete restoration of the network may require months. The second one is the quick deployment of a ready-to-use network made by a few devices with minimum setup requirements. The Network-In-a-Box concept follows exactly this second paradigm, having proven to be the most effective way of providing support to both rescue team and population in an acceptable amount of time.

Please note that there are several ways in which a NIB can be used. The most straightforward approach is to use a NIB to provide connectivity to both rescue team and population. In this case, some traffic of the survived network is simply offloaded on the NIB. Nevertheless, the traffic originating from the population might be so high as to hinder the communication of the rescue team operators. For this reasons, prioritization can be applied on its data flow, or two different NIBs can be used alternatively, one for the rescue team and one for the population. Moreover, some works have pointed out that the links between the components of the network infrastructure are more likely to be damaged rather than the components themselves [33]. This means that we can use the already-deployed base stations through a NIB that acts as the core of the mobile network. In this way, the coverage and the capacity of the original base stations can be leveraged for both rescue operators and population support.

B. Connectivity Provisioning in Challenging Contexts

Even if Internet access is becoming more and more ubiquitous, there are still contexts in which connecting to the Internet is troublesome. The most glaring example are villages in developing countries, whose Internet connection is completely missing or significantly constrained. Accessing the Internet can greatly improve the development of these areas thanks to the enabled access to medical information and educational material [34]. Nevertheless, companies are usually not interested in deploying their communication infrastructure in these areas because the expected revenue is much lower than the actual expenditure [35]. Therefore, there is the need for a practical solution which is affordable both for local administrations, *i.e.* the service providers, and the end users, *i.e.* the villagers. A Network-In-a-Box, being a portable device with limited hardware capabilities, can address this need without requiring huge investments. Several NIB proposals focus on the cost efficiency of their design, representing an affordable solution for these scenarios [34]–[37].

Another challenging context is provisioning of connectivity in places where deploying an extension of the mobile network is cumbersome or impossible. This is the case of flights or ships because there are few means for providing connectivity on a platform several meters up in the sky or thousands of miles away from the coast. Also villages in areas with harsh climate conditions fall in this category [38]. In this context, the load generated is generally bounded because the population is almost stationary, *i.e.* there are not huge variations in the number of users to serve. In addition, the solution used to provide these connectivity services on flights and ships has to be as compact as possible since the space available is limited. Given the depicted scenario, a Network-In-a-Box seems to be the most appealing solution.

C. Tactical Network

Another relevant use case is offering support to soldiers on a mission. Soldiers need to communicate with each other in order to coordinate the operations among sub-groups of the same unity. Moreover, there might be the need to communicate with a central support station or headquarter for supervision or emergency requests.

Nevertheless, soldiers cannot rely on public infrastructure. Being in a battlefield, the public infrastructure could be seriously compromised, and therefore unavailable for the aforementioned needs. In addition, even if the already-deployed infrastructure is working, it might be hindered or monitored by the enemy. Commercial networks usually do not come with techniques to avoid interference or jamming, and they might also have security flaws that are not acceptable in military scenarios [15]. Soldiers need a private, small, and secure network which does not hamper their mobility, *i.e.* they need a highly-portable wireless system.

A Network-In-a-Box is usually designed to fulfill these needs. Indeed, security in communication can be achieved using an independent physical device as communication hub, carried in a backpack by a soldier, for example. In this way, it is much more difficult to attack the network because it depends only on the NIB, *i.e.* without relying on additional infrastructure that is easier to attack. Moreover, a NIB solution reduces the need to communicate with external entities because the control traffic can be handled internally by dedicated modules [39]. Thanks to this lack of external dependencies, the reliability of the communication is further improved.

D. Miscellaneous use cases

There are some other use cases in which a NIB represents a valid solution. The first one is the setup of an enterprise network for companies whose workplace changes frequently, like mining and oil companies. A network among co-workers is needed in order to coordinate operations, or in case of emergency requests for unexpected events. For this kind of enterprises, mobility of the workers and minimum network setup time are key factors in deciding the most appropriate solution. Bringing a set of Wi-Fi access points is too cumbersome to setup, especially if the working site is particularly huge [17]. Therefore, a Network-In-a-Box results in a good trade-off between portability and coverage.

The choice of a NIB solution might be driven by privacy and economical aspects as well. Indeed, for some companies reducing the traffic through the public infrastructure has two main advantages. On one hand, it allows to keep communications inside the company's network, avoiding potential information disclosures that might happen when traffic goes outside. On the other hand, the reduction of external traffic reduces the costs associated with the usage of public infrastructure [17]. A NIB is also particularly appealing when its wired counterpart is cumbersome to setup, *e.g.* a company working in buildings close to each other. Finally, adopting a private NIB as the enterprise network eases the provisioning of company-specific services, *e.g.* a pager service for employers, because there is no need for dealing with public infrastructure's stakeholders [22].

In addition, a Network-In-a-Box is an attractive solution to deal with sudden increases of traffic load, *i.e.* flash crowds. Indeed, when popular events occur, such as concerts and sports events, mobile operators have to face peaks in the usage of the network, which lead both to traffic congestion and signaling storms [40]. In this case, several NIBs can be leveraged to offload part of the mobile-originated traffic [17], [41]. The portability of the solution allows mobile operators to deploy a set of NIBs for the duration of the event and remove the NIBs when the event is over.

The requirements characterizing the described use cases, *e.g.* high-bandwidth communication, and the communication targets of the NIB concept, *e.g.* end users and external networks, determine the technologies that are suitable for a NIB. In the next section we describe such technologies, highlighting their popularity and the motivations behind such popularity.

IV. Technologies of a Network-In-a-Box

In this section, we deal with the technologies that are leveraged by a Network-In-a-Box in order to communicate with other entities. From a high-level perspective, we can recognize three targets with which a NIB communicates. The first target is represented by the end users of the connectivity services. The second target is any kind of external network, such as the Internet. The third target is represented by any pre-existent infrastructure components or other NIBs. A NIB can communicate with these entities for multiple purposes, such as load balancing or role assignment, *i.e.* carrying out the tasks of the damaged entities.

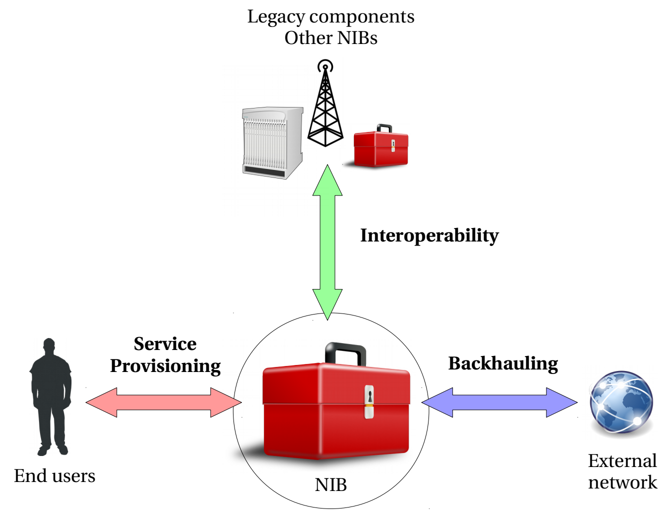


Fig. 2. **The three communication channels of a Network-In-a-Box.** *The service provisioning channel corresponds to the set of technologies used to provide services to mobile users. The backhauling channel is used to connect to external networks (e.g. Internet). The interoperability channel is used to communicate with legacy components or other NIBs. Please note that some channel may be deactivated or absent, depending on the configuration.*

For each target, we can abstract a communication channel between the NIB and the target. In our context, a channel represents the set of interfaces or technologies that are used to communicate with the target. Following the definition, a channel is represented by a Wi-Fi connection, or an Ethernet cable, or both at the same time, for example. Therefore, we can identify three main communication channels: service provisioning, backhauling, and interoperability channel. The service provisioning channel corresponds to the interfaces that allow the final users to communicate among each other through the NIB. The backhauling channel corresponds to the technologies that the NIB leverages to connect to the Internet. Finally, the NIBs may be configured to deal with elements of a pre-existent network, *e.g.* eNB, HSS, P-GW, or with other NIBs through the interoperability channel. The channels are shown in Figure 2.

Please note that none of the channels is mandatory because their presence depends on the setup of the NIB and on the purposes for which it has been deployed. Indeed we could be in a context in which we only require communication among a group of close devices, *e.g.* rescue operators or soldiers, without needing to connect to external networks or other NIBs. At the same time, we could have a NIB connected to a legacy base station, or to a legacy P-GW, removing the need for service provisioning and backhauling respectively. In the following, we present the state-of-the-art technologies used for the three communication channels.

TABLE I
COMPARISON ON TECHNOLOGIES FOR SERVICE PROVISIONING

Work	**Wi-Fi**	**2G**	**3G**	**4G**
Absolute [41]			✓	✓
Airspan AirSynergy [42]				✓
Amarisoft Amari LTE/OTS 100 [43]				✓
Anand *et al.* [34]		✓		
Andersson *et al.* [44]	✓			✓
Argela AMoN [45]			✓	
Aricent [16]				✓
Athonet PriMo Cube/Light [6]			✓	✓
Azcom AZP/AZN [11]	✓		✓	✓
Bai *et al.* [46]	✓			
Berioli *et al.* [47]	✓	✓	✓	
Casoni *et al.* [29]				✓
Chemring TS SmartLink [7]			✓	
Del Re *et al.* [48]	✓	✓		
Fairwaves UmSITE [49]		✓		
Fazli *et al.* [50]	✓	✓		
Ghaznavi *et al.* [51]		✓		
Gomez *et al.* [52], [53]				✓
Guevara *et al.* [54]		✓		
Hackett *et al.* [55]	✓			
Heimerl *et al.* [36]		✓		
Iland *et al.* [56]		✓		
Islam *et al.* [57]	✓			
Jang *et al.* [25]	✓			
Lindgren *et al.* [38]	✓			
Project Loon [58]				✓
Nokia Ultra Compact Network [59]				✓
NuRAN Wireless GSM NIB [60]		✓		
Parallel Wireless HNG and CWS [13]	✓		✓	✓
Polaris Networks LTE NetEPC [20]				✓
Qiantori *et al.* [61]	✓			
Quortus ECX Tactical/Core [10], [62]		✓	✓	✓
Ranberry B1000 [9]				✓
Sakano *et al.* [63]	✓			
Shao *et al.* [5]		✓		
Sysmocom sysmoBSC/IP [14]		✓		
Tecore Networks NIB [8]		✓	✓	✓
Telrad BreezeCOMPACT 1000 [64]				✓
Vodafone Instant Network Mini [65]		✓		
Wypych *et al.* [66]		✓		
Yate LTE Lab Kit [67]				✓

A. *Service Provisioning*

When dealing with NIB solutions, connectivity services are always provided by means of wireless technologies. This is due to the use cases around which the NIB concept has been developed. Indeed, all use cases need a solution that preserves the mobility of the end users, possibly avoiding the hindrance of cables.

A NIB is usually equipped with one or many radio interfaces to support a certain number of technologies simultaneously. These radio interfaces are usually lightweight external devices which are plugged in the NIB rather than internal components of the single physical device [9], [12]. The main advantage is that the antenna can be placed in a position where the signal is strong (*e.g.* on top of a roof) while keeping the NIB in a more comfortable and safe place. Moreover, this allows to easily substitute the antennas with more powerful ones without the need for upgrading the whole NIB.

As we can see in Table I, the technologies that are currently used by NIB solutions are mobile technologies, *e.g.* 2/3/4G, and Wi-Fi. There are two reasons for which these technologies have been adopted, and they are both linked to the main use case of NIBs, *i.e.* connectivity provisioning in after-disaster scenario. The first one deals with the support to rescue operators, while the second is related to the support to survivors. Please note that the proposals either focus on the rescue operators only, or on the population only, or on both at the same time. Even if designed for different purposes, the set of technologies suitable for one group of users is practically the same for the other one as well.

In the past, public safety forces such as first-aid operators, police, and firefighters have leveraged technologies like P25 [68], TETRA [69], or TETRAPOL [70] for organizing rescue operations. Nevertheless, two main issues have arisen using these technologies. First, there is a lack of standardization among different countries on the frequency range reserved for public safety. Indeed, some countries have reserved bands, while others prefer to use commercial bands [71]. In addition, there are interoperability issues between TETRA, which is used in Europe, and P25, which is used in the U.S.A. [29], [72]. This is a problem both for vendors, which have to develop and maintain many versions of the same product, and for rescue forces, because they have to buy specialized and expensive equipment. Second, the data rate offered by these technologies is very limited despite some use cases require broadband connectivity. Examples of such use cases are telemedicine and downloading 3D maps of buildings in an on-demand fashion [10], [73]. For these reasons, LTE and Wi-Fi have recently received attention from public safety stakeholders. Compared to Wi-Fi, LTE has the advantage of offering a greater coverage. In addition, it works on dedicated spectrum bands, avoiding the risks associated with the usage of ISM band, *e.g.* overcrowding and security issues. For these reasons, 3GPP has included public safety functions in LTE specifications from Release 12 on, such as Push-To-Talk (PTT) and group call services [74].

When considering survivors of a disaster, the technological choice is driven by different considerations. Survivors need connectivity services in order to ask for help. At the same time, the telecommunication infrastructure is likely to be compromised, completely down or overwhelmed by call attempts. In this case, what drives the technological choice for an additional temporary network is the popularity of the technology [4]. Indeed, if the technology is widespread, there is no need to deploy specific terminals and train users, but survivors can rather leverage their own devices [61]. For this reason, mobile technologies (2/3/4G) and Wi-Fi are the best candidates in these contexts. In addition, 2G is a low-power technology, both from the end users' perspective and the service provider's one [66]. Moreover, all the subsequent mobile standards offer backward compatibility to 2G. Therefore, its adoption ensures a wide set of users and minimizes the power consumption of both mobile devices and NIB, which is of fundamental importance in an emergency context.

Some proposals include both Wi-Fi and one or more cellular technologies at the same time. This design choice is supported by the willingness to separate the rescue operators' network from the one given to survivors. In other cases the combination is chosen to offer connectivity to the highest possible number of users in the disaster area, *i.e.* both Wi-Fi-only and cellular-only terminals. In addition, nowadays mobile phones are also Wi-Fi capable, opening new opportunities to boost connectivity performance by using both technologies simultaneously [75], [76]. Nevertheless, offering two ways of connecting requires a separated antenna for each technology. In some circumstances, the transport and the deployment of an additional antenna can result in an excessive hindrance.

When considering rescue teams, the purchase of dedicated terminals might be out of discussion due to the constrained budget that public safety organizations have [10], [61]. In this case, a NIB offering backward compatibility with TETRA or P25 is the best choice to allow a smooth transition from the previous system to the new one. Some proposals offer this kind of support [41], [47], but they require an additional antenna.

Even when considering the other use cases, the preferred technologies are the same. When providing connectivity services to remote villages or on flights, the key factor that determines the technology to adopt is its popularity as in both cases the aim is to provide services to the widest possible set of users. Therefore, Wi-Fi and cellular technologies are the typical choices. Instead, when dealing with military contexts, Wi-Fi technology is not suitable because of the unreliability of the ISM band. LTE is the best choice because the technology comes with both a built-in security model and a high data rate, which is needed in case of on-demand download of information, *e.g.* floors of buildings.

TABLE II
COMPARISON ON TECHNOLOGIES FOR BACKHAULING

Work	**Satellite**	**μwave**	**Cable**	**2/3/4G**	**Wi-Fi**
Absolute [41]	✓				
Andersson *et al.* [44]	✓				
Argela AMoN [45]			✓		
Athonet PriMo Cube/Light [6]	✓				
Azcom AZP/AZN [11]			✓		✓
Bai *et al.* [46]	✓			✓	
Berioli *et al.* [47]	✓				
Casoni *et al.* [29]	✓				
Cisco NERV [77]	✓		✓	✓	
Del Re *et al.* [48]	✓				
Fairwaves UmSITE [49]			✓		
Fazli *et al.* [50]	✓				
Gomez *et al.* [53]	✓				
Huang *et al.* [21], [78]	✓	✓	✓		✓
Iland *et al.* [56]	✓				✓
Islam *et al.* [57]	✓				
Jang *et al.* [25]	✓				
Nakamura *et al.* [73]					✓
Nokia Ultra Compact Network [59]	✓	✓	✓		
NuRAN Wireless GSM NIB [60]			✓		
Parallel Wireless HNG and CWS [13]	✓		✓	✓	
Qiantori *et al.* [61]					✓
Quortus ECX Tactical [10]	✓	✓		✓	
Ranberry B1000 [9]	✓		✓	✓	✓
Sakano *et al.* [63]			✓		
Sato *et al.* [79]	✓		✓	✓	
Shao *et al.* [5]	✓	✓			
Sysmocom sysmoBSC/IP [14]			✓		
Tecore Networks NIB [12]	✓	✓		✓	✓
Uchida *et al.* [80]	✓				
Yate LTE Lab Kit [67]			✓		

Legend: Satellite; Microwave (μwave); Ethernet, fiber, or cable (Cable).

B. Backhauling

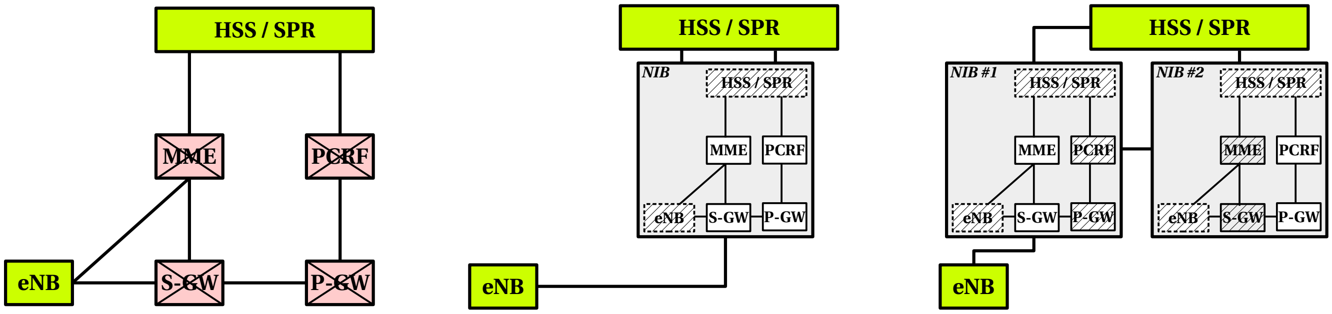
The backhauling of a NIB corresponds to the means the NIB uses to connect to any external network. In most of the cases the backhaul link is required to communicate with entities that are geographically remote, *e.g.* rescue team headquarters, or to provide access to the Internet. Nevertheless, in some contexts the backhaul link is not required or even desired. This happens when the services offered by the NIB are actually instantiated on the NIB itself, or on a server that is linked directly to it. PTT services for rescue teams and soldiers, or employee-specific services for enterprises, are examples of services that do not require a connection to external networks.

The technology which is mostly adopted for backhauling is satellite connection. The main advantage of this technology is the ubiquitousness, *i.e.* the possibility to establish a connection everywhere without the need for wires or additional infrastructural components. In this way, a connection is always feasible, even after a disaster, or on a battlefield because the satellite system is untouched by such events. Following this principle, some projects propose satellite-based messaging systems that allow Commercial Off-The-Shelf (COTS) smartphones and tablets to communicate directly without even the need of intermediate devices such as a NIB [41], [57]. A satellite connection is reliable because satellites are always-on systems, and it offers a good data rate.

Nevertheless, satellite communication has some drawbacks as well. It incurs high delays, which can cause issues with protocols such as TCP. A satellite connection also requires specialized equipment, *i.e.* antenna dishes, which are usually expensive and unpractical to move [79], [81]. In addition, satellite connection is characterized by asymmetrical transmission rates, *i.e.* the download data rate is much higher than the upload rate [73], [82]. This can become an issue in situations where soldiers or rescue team operators are streaming what they see from their helmet, for example. Finally, some nations prohibit the use of satellite for purposes such as telemedicine [73].

To overcome the issues brought by satellite connection, some proposals use multiple backhaul links [10], [11]. Indeed, the equipment constituting the NIB solution can be selected depending on the specific situation. As an example, if we cannot carry a satellite dish with us, we can fall back to the other technology. As we can see in Table II, the technologies that are used in combination are microwave, Ethernet or fiber, mobile technologies, and Wi-Fi.

Finally, some proposals do not rely on satellite connection at all, but they rather use alternative means. The preferred choices are Ethernet cable, optical fiber and long-range Wi-Fi, but other technologies are used as well, like microwave and mobile technologies. Both cable and Wi-Fi offer a high data rate, but they also come with significant drawbacks. A cable connection limits the movement of the end users, making it unsuitable for



(a) Compromised deployment (b) Backward compatibility (c) Interoperability with other NIBs

Fig. 3. **Usage of interoperability channel.** *In an after-disaster scenario, some core elements might have been damaged, e.g. Mobility Management Entity (MME), Serving Gateway (S-GW), Packet Data Network Gateway (P-GW), and Policy and Charging Rules Function (PCRF) (a). In such cases, they can be replaced by a NIB connected to the survived network elements, allowing to restore the connectivity (b). Instead on a single NIB, two or more NIBs may be also configured to work together in order to balance the load for example (c).*

NIBs used by soldiers on a mission, for example. Long-range Wi-Fi requires line-of-sight between the two antennas, and this can compromise the mobility of the network. In addition, it might be subject to interferences because it works in the ISM band. It also prevents the choice of Wi-Fi as technology for service provisioning, even if some workarounds are possible, *e.g.* using 2.4GHz for service provisioning and 5GHz for backhauling [61]. Nevertheless, these two technologies can still be used for backhauling when providing connectivity to remote villages. Indeed, the mobility of the network is not required in such contexts. When dealing with connectivity provisioning on flights, both cable and Wi-Fi are unsuitable. An alternative is to leverage air-to-ground LTE [83]. On one hand, the approach offers a good data rate and it is comparatively cheap; on the other hand, it cannot be applied when flying in areas without coverage, *e.g.* oceans.

C. Interoperability

The interoperability channel can be considered in two different ways. The first one is to see it as an added value, *i.e.* the NIB is able to cooperate with other entities if this is required by the context. In other words, the functioning of the NIB is independent from the presence of external entities. The second way is to consider it as a requirement, *i.e.* the NIB requires the channel to provide connectivity services. In this case, the NIB encloses just a part of the network functions, and it relies on other components. As an example, Huang *et al.* [21] propose a physical device that connects to the pre-existent base stations in order to restore the original mobile network.

Rather than focusing on the technologies used, in this section we deal with the entities with which a NIB can communicate using the interoperability channel. We can identify two sets: entities of the telecommunication infrastructure that are already deployed, and other NIBs. A Network-In-a-Box may support the communication with other network components for several reasons. For example, the NIB is not able to generate a fully fledged network on its own, but it rather needs the cooperation with some other devices. Alternatively, the interoperability channel is leveraged to allow flexibility in the setup of the NIB. Considering an after-disaster scenario, some components of the original mobile network might be still operational. In this context, the best choice is to use such components together with an emergency device that acts in place of the damaged ones. In this way we can leverage the already deployed operational components, which are dimensioned for the local population, and reduce the effort required to the NIB. The possibility to flexibly assign roles to the NIB is offered by many proposals [9], [12], [16], [20], [62].

An additional feature of some NIBs is the interoperability with other NIBs. The two NIBs are connected through standard interfaces, *i.e.* each NIB sees the other as a pre-existent legacy infrastructural component, or through a dedicated interface, *i.e.* the device detects the other one is a NIB. The latter case enables additional configuration options, such as load balancing and dynamic assignment of roles. Nevertheless, the interface that allows detection and communication with another NIB is not standardized, *i.e.* the implementation is vendor-specific. This implies that interoperability between NIBs of different vendors is not guaranteed. The standardization of a cross-NIB interface is expected in the near future.

The described technologies enable the NIB to exhibit some features. For example, a satellite connection allows flexibility in the installation of the network because it allows ubiquitous connection to remote networks. At the same time, the use cases mentioned in Section III require some features from the NIB. Indeed, the NIB is required to host use-case-specific services, which are installed and provided on-demand. Also the NIB concept itself requires some additional features, such as the ability to be as independent from external entities as possible. In the next section, we describe the most relevant features of a NIB and how they are correlated with the NIB concept, the use cases addressed, or the technological choice.

V. Features of a Network-In-a-Box

In this section, we go through the main features that characterize NIB proposals. The most important ones are the ease of deployment, *i.e.* the reduced effort needed to bring the NIB to a certain place, and the provisioning of edge

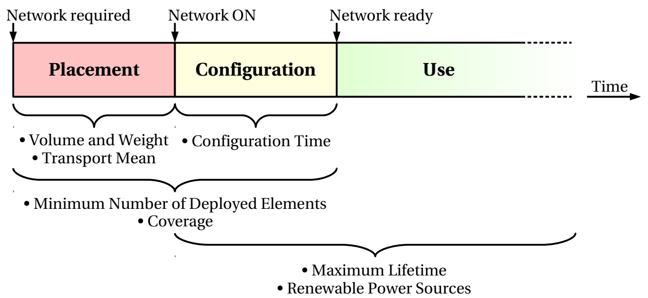


Fig. 4. **Three phases in the lifetime of a NIB.** *The first phase represents the time frame between when a network is required and when the network components are physically placed. The second phase is the time interval required to configure the network, while the third phase is the actual usage of the network. The figure shows which features of the NIB influence the duration of which phases.*

services, *i.e.* services deployed directly on the NIB. Then, we take a look at the SON principles followed by current NIB solutions since a high autonomy of the network implies both less maintenance and shorter time to make it operational. We also discuss capacity and Quality of Service (QoS) assurance. Finally, we present the approaches adopted to keep the costs of NIB solutions as low as possible.

Please note that the list of features used in this section does not correspond to any official feature list for NIBs, but we rather crafted the list by analyzing the data presented in both industrial documentation and academic articles. In particular, data such as volume, weight, and maximum lifetime are explicitly mentioned in the majority of the documents describing the NIBs. Instead, aspects such as the implementation of edge services or SON features are NIB-specific, *i.e.* they are reported only if the NIB implements them but their absence is not stated. In this case, our approach consists in selecting aspects that are common to a large group of NIBs.

A. Ease of Deployment

What makes a NIB different from a traditional wireless network is the reduced amount of time that incurs between when the network is needed and when it is fully operational, *i.e.* how easy is to deploy it. Figure 4 shows the phases in the lifetime of a NIB. The deployment time comprises the first two phases, *i.e.* the physical placement of the network components and the network configuration. For this reason, when analyzing the ease of deployment of NIB proposals, we mostly focus on aspects of the physical devices such as their number, their weight and volume, how they are brought to the desired place, and how much configuration time they need. Moreover, we will also consider aspects such as coverage extension, lifetime, and support for renewable power sources. Even if they are not directly related with the ease of deployment, they provide a measure on how much we can rely on our NIB, especially in the long term.

Table IV shows the data gathered from our analysis. Given the heterogeneity of the values of each category, we grouped them using labels as described in the legend in Table III. When the data is not available, *e.g.* a NIB is presented without stating the weight, the corresponding label is blank. Further details on the analysis process are available in the following paragraphs.

1) Minimum Number of Deployed Elements: The driving factor in the practicability of a NIB is the number of physical devices that need to be deployed. Most of the times a NIB consists in a combination of several devices. For example, including large antennas in the same physical device makes the NIB difficult to transport so they are typically separated.

In our analysis, we counted the minimum number of deployed elements required by each proposed solution. We consider each device that executes software to provide some functionalities of the network as a distinct element of the solution. Therefore, each computing node executing some software is counted in, while bare-metal antennas, satellite dishes, or battery packs are not considered.

Many NIBs correspond to a single-device design [12], [45]. This choice maximizes the practicability of the solution, but it comes with some disadvantages as well. First of all, the single device constitutes a single point of failure: in a battlefield, this might become a problem because the enemy can tear down the communication among the soldiers focusing on a single objective. Second, the coverage offered by a single physical device is both limited and difficult to customize, making it hard to deal with coverage holes caused by the current deployment.

Other solutions comprise a handful of devices. These designs typically include a device that provides wireless connectivity and performs the initial signaling processing, and a separate device which cares about core functionalities and provisioning of dedicated services [41]. The devices used to provide wireless connectivity are easy to carry and deploy, while the core component is usually more bulky because of the presence of a satellite antenna. The choice of using few devices can be considered a good trade-off between practicability and flexibility in coverage.

Finally, many academic proposals present designs involving a higher number of devices, *i.e.* four or more. Most of them consist in MANET designs, where each deployed node both provides connectivity services and routes the traffic coming from other nodes [46]. The advantage is the improved coverage extendability because the components can be deployed to maximize the covered area and eliminate coverage holes caused by huge buildings. On the other hand, several physical devices imply a longer deployment time. In addition, the configuration of the whole network is more complex, as well as detection and recovery of faults.

2) Volume and Weight: Even if the number of deployed elements is limited, both volume and weight of the NIB have to be considered when assessing its practicability. If the single device is too bulky or too heavy, it is better to have more than one device, making the transport less cumbersome.

Usually the volume of NIBs is reported by describing width, height and depth, but this does not allow to easily compare the different proposals. Therefore, we converted all the volume descriptions in liters to get a single value for each NIB. Liters are used to measure backpacks' and baggage's capacity, so the conversion allows to easily compare the solutions with everyday examples.

TABLE III
LABELS USED IN TABLE IV

Label	Deployed Elements (#)	Volume	Weight	Configuration Time	Coverage	Maximum Lifetime
A	1	< 10 L	< 8 kg	< 15 min	> 5 km	> 5 h
B	2-3	10 - 20 L		15 - 30 min	1 - 5 km	
C	MANET	> 20 L	>= 8 kg	> 30 min	<= 1 km	< 5 h

We subdivide the proposals in three categories: less than 10 liters, between 10 and 20 liters, and more than 20 liters. The proposals that fit in less than 10 liters are usually simple base stations or Remote Radio Head (RRH) units which are used to extend the coverage and route the traffic back to a separated core component. Alternatively, the core component alone usually fits in less than 10 liters as well [11], [14]. Sometimes volume values do not include batteries or external antennas, but they rather focus on the actual NIB device. In such cases, the total volume of all the components might be more that what is specified in our analysis.

Some proposals fit in the category 10-20 liters. These NIBs can be installed on a mast or traffic light and they consist of boxes that include the antenna(s) [64]. Nevertheless, these solutions rely on both cable backhauling and cable power.

The solutions having a volume higher than 20 liters comprise the equipment required for a wireless backhaul, *e.g.* a satellite dish [47]. The volume might require a vehicle for transportation and deployment. On one hand a vehicle enables a faster deployment compared to a backpack solution; on the other hand, streets and roads might be unusable for terrain vehicles during natural disasters.

When dealing with the weight, we divide the proposals in two categories: the solutions that demand less than 8 kg, and the ones that demand 8 kg or more. The choice of this value is linked with the maximal weight of a cabin baggage, which is typically around 8 kg. This gives an idea about the practicability of a solution since carrying 8 kg can be considered an accessible operation regardless of the transport mean adopted.

3) Configuration Time: The configuration time corresponds to the time frame between the end of the deployment of the NIB solution and its full functioning. Therefore, it consists of the time needed to configure the already-deployed devices to provide the desired connectivity services. NIB solutions aim to reduce this timeframe as much as possible for several reasons. First, the timeliness of the solution is of vital importance, both in an after-disaster scenario and in a battlefield because a delay in the service provisioning might imply a loss of human lives. Second, a reduced configuration time implies a lower Operating Expenditure (OpEx).

We divided the solutions in three categories according to the time required: less than 15 minutes, between 15 and 30 minutes, and more than 30 minutes. The proposals that require up to 15 minutes follow the “plug&play” paradigma, *i.e.* minimum human intervention is needed for making the network operational. An automatized configuration process is fast and less error-prone. On the other hand, a low configuration time is typically linked with a very limited number of devices. Indeed, the network complexity increases with its number of components, and obtaining an automatic reliable configuration of the whole network is hard to achieve. Nevertheless, deployments with many hardware devices also have some advantages. We can configure the network to achieve the desired level of coverage or fault tolerance.

4) Transport Mean: The way in which the network is physically deployed is part of the design of a NIB. This is a fundamental aspect when considering after-disaster scenarios or soldiers on a mission. The preferred way of carrying the NIB is through a comfortable mean, *i.e.* a transport method that does not hinder movement [9]. Backpacks, suitcases, luggages, or wearable objects fall in this category. These transport means allow to deploy the network in any human-reachable place. On the other hand, having the whole network in a single backpack or suitcase limits its coverage flexibility and capacity.

The transport means described so far require a human to reach the deployment spot. In some cases this might require too much time, *e.g.* a shipwreck in the middle of the ocean, or it might be too dangerous, *e.g.* fire in a building. Moreover, the network might be constrained by surrounding buildings or hills. To overcome these issues, some NIBs leverage an aerial platform, like Unmanned Aerial Vehicles (UAVs), weather balloons, kites, and Low-Altitude Platforms (LAPs) [23], [54], [66]. The advantages are fast deployment and wide coverage. Moreover, the high altitude of the NIB maximizes the number of line-of-sight connections with the end users, reducing the risks of coverage holes. Nevertheless, there are disadvantages in using these transport means. The remote control of the position requires an additional radio interface. In some cases, the position is not even adjustable, *e.g.* weather balloons. In both cases, weather conditions affect the effectiveness of the solution.

Some solutions leverage a vehicle, either terrain (*e.g.* a van) or aerial (*e.g.* an helicopter) [29], [77]. A vehicle is more robust to weather conditions, and it is human-driven, so there is no need for an additional radio interface. It also requires lower deployment time if compared to a backpack solution. At the same time, roads and streets might be damaged in after-disaster scenario and battlefield, making the adoption of a terrestrial vehicle more cumbersome. This issue can be avoided considering aerial vehicles, but this has a dramatic impact on the costs of the NIB as well.

There are also a few proposals that leverage different approaches together. The ABSOLUTE project [41] leverages both kite platforms for RRH functionalities and suitcases for the core functionalities. The main drawback is a higher cost

TABLE IV
FEATURES RELATED WITH EASE OF DEPLOYMENT

Work	**# EL**	**VOL**	**WEI**	**TIME**	**COV**	**LIFE**	**Transport mean**				**RPS**
Absolute AeNB [41]	B							✓			
Absolute PLMU [41]	A						✓				
Abush-Magder *et al.* [32]	A										
Amarisoft Amari LTE/OTS 100 [43]					C						
Anand *et al.* [34]	C										
Andersson *et al.* [44]	C									✓	
Argela AMoN [45]	A	B	C		B		✓				
Aricent [16]	B										
Athonet PriMo Cube/Light [6]	A				C		✓				
Azcom AZP/AZN [11]	A	A	A								
Bai *et al.* [46]	C										
Berioli *et al.* (BGAN) [47]	A	C		A		C	✓				
Berioli *et al.* (DVB-RCS) [47]	A	C		B					✓		
Casoni *et al.* [29]	A				A				✓		
Chemring TS SmartLink [7]	A	A	A	A	B		✓				
Cisco NERV [77]	A			B		A			✓		
Del Re *et al.* [48]	C							✓	✓		
Dhekne *et al.* [84]	A							✓			
Evans *et al.* [19]	C										
Fairwaves UmSITE [49]		B	C				✓				✓
Fazli *et al.* [50]	A		A		C	C	✓				
Ghaznavi *et al.* [51]	A										✓
Gomez *et al.* [52]	A									✓	
Guevara *et al.* [54]	A							✓			
Hackett *et al.* [55]	B			A		A	✓				
Heimerl *et al.* [36]										✓	
Huang *et al.* [21], [78]	B										
Huawei eLTE Rapid System [85]	B			B	A						
Iland *et al.* [56]											✓
Islam *et al.* [57]	C										
Jang *et al.* [25]	C										
Lindgren *et al.* [38]											✓
McCarthy *et al.* [86]	C										
Nakamura *et al.* [73]				C							
Nokia Ultra Compact Network [59]							✓				
NuRAN Wireless GSM NIB [60]		B	C				✓				
Polaris Networks LTE NetEPC [20]	B										
Project Loon [58]	C				A			✓			✓
Qiantori *et al.* [61]					B	C		✓			
Quortus ECX Tactical [10]	A						✓		✓		
Ranberry B1000 [9]	A	C			A	C	✓				
Sakano *et al.* [63]	A	C		C	C				✓		
Sanchez *et al.* [18]	C										
Sato *et al.* [79]	C										
Shao *et al.* [5]	C										
Sohul *et al.* [87]									✓		
Sysmocom sysmoBSC/IP [14]		A	A								
Tachwali *et al.* [88]	A										
Tecore Networks LYNX/NIB [8], [12]	A	A	A	B			✓				
Telrad BreezeCOMPACT 1000 [64]	A	B	C	B	A						
Telrad BreezeWAY EPC [89]	B										
Trotta *et al.* [30]									✓		
Uchida *et al.* [80]	C										
Verma *et al.* [90]	C										✓
Vodafone Instant Network Mini [65]			C	A	C	A	✓				✓
Wypych *et al.* [66]					B			✓			
Yarali *et al.* [82]	C								✓		
Yate LTE Lab Kit [67]	A										

For each NIB, the labels A,B,C refer to the value ranges of the features described in Table III. The label is missing when no data is available for the feature. For example, we do not have information about the coverage radius for the proposal in [12].
Legend: Number of deployed elements (# EL), Volume (VOL), Weight (WEI), Configuration time (TIME), Maximum lifetime (LIFE), Renewable Power Source (RPS).
Icons: Rugged case, backpack, wearable; Unmanned Aerial Vehicle, weather balloon, kite, Low Altitude Platform; Terrestrial or aerial vehicle; Fixed preventive deployment.

of the solution and the additional complexity of configuring the different components.

Finally, some works deploy NIB together with the traditional network infrastructure. This approach is followed when the NIBs are deployed for connectivity provisioning in villages because they act as the traditional network, so they do not need to be carried on-demand but they are stably deployed [36]. The approach is also adopted to improve the response to disasters. The NIBs are deployed in quiet times so that the base stations can use them in case of issues in the link to the core network [44], [52]. This approach has the advantage that coverage and deployment can be studied off-line, *i.e.* before disasters. On the other hand, the functioning of the network depends on the impact of the disaster.

5) Coverage: The coverage radius offered by a NIB is related to the ease in deployment. Indeed the number of NIBs required to provide coverage to the whole area of interest depends on the coverage radius of each single NIB.

We divided the proposals in three categories: up to 1 km, up to 5 km, and more than 5 km. A 1-km radius is suitable for all the contexts in which the end users correspond to a small group of people close to each other. The typical use case is soldiers on a mission, or rescue operators working in the same quarter [65]. This is also applicable for mobile networks using picocells [91].

When we consider a radius up to 5 km, the NIB is suitable for small villages or medium/large working sites. However, this radius is insufficient when considering huge natural disasters; in this case, some solutions offer a radius which is higher than 5 km. This coverage is required in huge working sites as well, such as mining sites [17]. Offering high-radius coverage typically requires heavy equipment, which may affect the portability of the NIB solution.

6) Maximum Lifetime: The quality of a portable network also depends on how long the services provided last. This aspect matters only for NIB solutions that are self-powered, *i.e.* they do not need any power wire in order to work.

We divide the NIBs depending on their lifetime: less than 5 hours, and 5 hours or more. The first group of solutions are suitable for short-timespan contexts such as military missions, rescue operators providing first aid, and sport events or concerts. The main reason for providing less than 5 hours of service is to avoid the need for a heavy battery pack, *i.e.* the short service time is balanced by an improved portability of the solution. The solutions offering longer service time are more suitable for long-term rescue operations, *e.g.* rescuing survivors in a disaster area. On the other hand, such solutions require either heavy batteries or a power generator. In the latter case, there are two disadvantages: we must use a vehicle as transport mean, and we have higher costs due to the fuel required by the generator.

7) Renewable Power Source: Few proposals discuss the use of renewable power sources, which can dramatically extend the lifetime of the NIB. The only renewable power source that has been considered is solar energy [49], [51], [56], [58], [65]. The drawbacks of using solar panels are the additional hindrance of their transport and the variability in the energy provisioning due to the dependency on weather conditions and daytime.

TABLE V
CLASSIFICATION OF THE WORKS BASED ON THE TYPOLOGY OF EDGE SERVICES PROVIDED.

Category		**Works**
General purpose		[20], [62], [46], [38], [92], [93], [17]
Public safety	Communication	[7], [21], [25], [41], [10], [32], [51], [77], [57], [53]
	Health	[51], [21], [47], [41], [48]
	Monitoring	[46], [41], [77], [32]
Security		[7], [94], [45], [10]

B. Edge Services

Instead of leveraging a remote server, most of the services are deployed directly on the physical components of the NIB. We call them *edge services* because they are deployed at the edge of the network. Edge services include general-purpose services as well as services that are specifically designed for some use cases, *e.g.* services required in an emergency scenario [4]. An example is Push-To-Talk communication, which allows people joining a group to talk with each other in a walkie-talkie fashion. The logic of the service resides mostly in the NIB and just minimally in the devices using it. This allows to keep the dependency between the NIB and the end-user devices low, avoiding the need for specialized terminals.

Deploying services on the NIB instead of using a remote server is supported by two motivations. The first one is to increase the fault tolerance of the network by avoiding the dependency on the backhaul link [95]. The second is that the services provided are local, *i.e.* they are used only by those who are connected to the NIB [44], [47]. In this context it makes no sense to have traffic going back and forth through the Internet. Instead, providing these services directly from the NIB allows to keep the transmission delay low and it reduces the volume of the traffic on the backhaul link [96].

The idea of deploying services on the NIB is in line with Mobile Edge Computing (MEC) [97], a technology that pushes services on the edge of the network in order to reduce the traffic from the core network [17]. While MEC prescribes openness to 3rd-party services, NIBs are usually not open to new services. NIB services are often hard-coded and targeted for the aims for which the NIB has been designed. Nevertheless, many recent works have recognized the flexibility that such openness would bring to NIB solutions and they propose platforms for 3rd-party applications based on Network Function Virtualization (NFV) [12], [72], [85]. This approach allows to use the same NIB solution for different use cases, and it also opens new optimization opportunities [98], [99].

In the following, we describe the services that are typically offered by NIBs. As shown in Table V, we group them in three categories: general purpose, public safety services, and security services.

1) General Purpose: We label as "general purpose" the services which are not use-case specific, or which are implicitly used by other services. This is the case of services that ensure basic data communication, like Domain Name System (DNS) and firewall services [17], or which improve the fault tolerance of the network [93]. Voice over LTE (VoLTE) support [20], [62] and phone call smart routing [46] fall into this category as well. In line with MEC aims, some works also propose a service for caching popular contents, allowing to reduce the traffic on the backhaul link [38], [92].

2) Public Safety: Many works focus their attention on providing public safety services due to the relevance of the use case. In addition, public safety and military use cases share some requirements, *e.g.* group communication or localization, so providing one service for one use case automatically addresses the requirements of the other as well. In general, we can distinguish three sets of services: communication services, health services, and monitoring services.

a) Communication Services: they address both the demand of rescue teams and survivors. NIBs provide PTT and group call services to allow rescue team members to communicate in a walkie-talkie fashion [7], [62]. Therefore the NIB acts as a server on which PTT and other group services are provided. This kind of server is called Group Communication Service Application Server (GCSAS) and it has been standardized by 3GPP [71], [100]. Some proposals offer services for survivors, such as broadcasting of emergency messages and satellite-based messaging systems [53], [57]. Given the importance of such communication services, 3GPP has recently standardized the provisioning of LTE services when base stations are detached from the core [101].

b) Health Services: they automatize medical assistance provided by rescue team operators. Nevertheless, there is no common agreement on the services to provide. The work of Ghaznavi *et al.* [51] proposes a message-based service for finding suitable blood donors. Instead, the works of Berioli *et al.* [47] and Del Re *et al.* [48] focus on tasks such as localization and triage of survivors.

c) Monitoring Services: few proposals offer monitoring services, like gathering and processing of data coming from deployed sensors [46] and video surveillance [77]. These services aim to both forecast natural disasters as well as monitor their evolution. The number of works that focus on such services is limited though.

3) Security: Security services are required when using a NIB for implementing a tactical network. In particular, one of the most important requirement is to have a network robust against interference [15]. The most straightforward way an enemy has to hamper the communication in a tactical network is to generate a signal on the same frequencies used by the NIB. Despite the easiness and the effectiveness of such attacks, there are few works that focus on preventing it [7].

TABLE VI
CLASSIFICATION OF THE WORKS BASED ON THE SELF-ORGANIZING FEATURES EXHIBITED.

Category	**Works**
Self-configuration	[9], [56], [32], [29], [45], [87], [42], [55], [47]
Self-optimization	[20], [80], [79], [41], [30], [88], [87], [48], [18], [19]
Self-healing	[33], [52], [56], [87]

Some proposals focus on other security functions, such as detection and mitigation of attacks [94], network admission control [45], and encryption of the communication [10]. Nevertheless, the number of works that focus on security services is limited. One reason is the adoption of LTE as the technology for service provisioning. LTE comes with strong built-in security features, making it a suitable choice on a battlefield. Another reason comes from the emergency network use case. Despite the main focus is the provisioning of connectivity services to a set of users as wide as possible, some studies have highlighted how attacks take place even in after-disaster scenarios [94].

C. Self-Organizing Network Principles

The effectiveness of a NIB is also measured by its ability to autonomously adapt to the context of use. An example of such ability is changing frequency when the default one is crowded. Another example is self-configuration, *i.e.* deciding autonomously the services provided by each network device. Networks with such capabilities are called Self-Organizing Networks (SONs).

There are several reasons for which NIBs exhibit SON features. First, the primary users of a NIB, like rescue teams or soldiers, are not network experts, therefore an automatic configuration avoids the costs of training specialized personnel and lowers the configuration time.

Second, the use cases for a NIB require the new network to integrate with pre-existing ones. As an example, when considering an after-disaster scenario, the NIB should not interfere with the commercial mobile network of the area. SON functions supporting communication establishment with nearby base stations and backup configurations in case of EPC faults have been standardized [27].

The capability of a network to self-organize is measured along three directions: self-configuration, self-optimization, and self-healing. As shown in Table VI, we leverage the same classification in our analysis: for each direction, we list the proposals that offer functions related with it. In the following, we discuss each direction by describing the corresponding functions.

1) Self-Configuration: A network exhibits self-configuration features when the procedure to get the nework up and running is partially or completely automated.

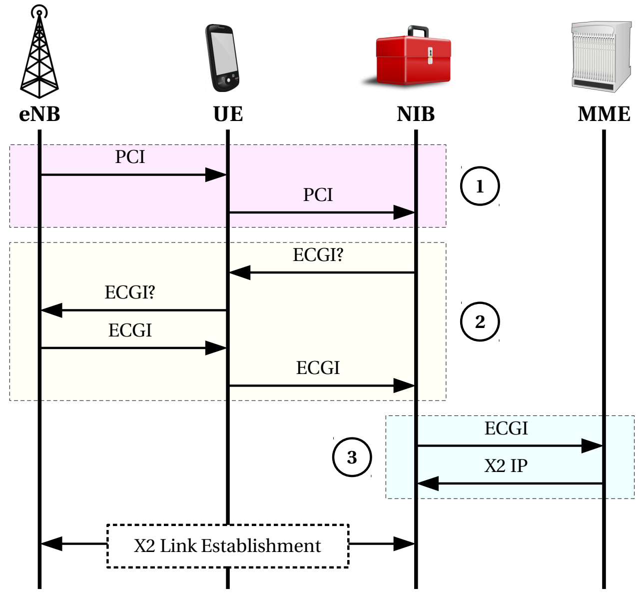


Fig. 5. **Automatic Neighbor Relation (ANR) in an LTE scenario.** *The UE is connected to the NIB, and it provides to the NIB measurement reports, which contains Physical Cell Identifiers (PCIs) of neighbour cells (1). If one PCI is unknown, the NIB asks to the UE to fetch the E-UTRAN Cell Global Identifier (ECGI) of the cell (2). Once obtained the ECGI, the NIB asks the X2 IP address of the eNB owner of the cell to the MME (3). Finally, the NIB and the eNB establish a X2 link.*

Therefore, self-configuration is linked with configuration time because the more the network configuration is automatized, the smaller the time required for the configuration is.

Among the SON functions offered by NIBs, three of them belong to this category. The first function deals with the ability of automatically electing the main node, called EPC node. The main node provides the core functionalities, such as authentication and routing, and it offers backhaul connection to the Internet. Examples of NIBs offering such feature are the work of Iland *et al.* [56] and the proposal in [9].

The second function is Automatic Neighbor Relation (ANR), which is a function standardized by 3GPP that allows base stations to configure with base stations nearby without requiring manual intervention [102], [103]. The functioning of ANR is depicted in Figure 5. A NIB leverages this function to get the network topology and use a neighbor base station for backhauling, for example. Among the self-configuration functions, ANR corresponds to the most popular one [29], [42], [45], [56], [87].

The third function corresponds to the so-called "plug&play" capability, *i.e.* the NIB autonomously configures itself once switched on. Such degree of autonomy is hard to achieve and just a small number of NIBs offer this feature [42], [55], [56].

2) Self-Optimization: A network exhibits self-optimization features when it changes dynamically to improve the services provided. What triggers such changes are events like an increase of the traffic load, a high level of interference, or the perception of a weak signal. When these events happen, the network can perform load balancing, or adjust the antenna direction to maximize the Signal-to-Noise Ratio (SNR) [18], [77].

TABLE VII
CLASSIFICATION OF THE WORKS BASED ON THE MAXIMUM NUMBER OF CONNECTED USERS SUPPORTED.

Max connected users	Works
10 - 100	[11], [45], [7], [85]
100 - 500	[64], [9], [16]
> 500	[20], [8], [89], [63]

While just a single proposal implements some form of load balancing [20], NIB designs mostly focus on providing cognitive radio capability [18], [19], [30], [41], [48], [79], [80], [87], [88]. Cognitive radio is a technology that allows to dynamically change the frequency used for communicating based on the congestion of the frequency in use. This flexibility can be achieved by using either multiple antennas or reconfigurable antennas [104]. Cognitive radio allows a more efficient usage of the spectrum, *e.g.* by leveraging unused frequencies reserved for television [15], as well as easier integration of new wireless networks in crowded scenarios. On the down side, it requires the end-user devices to dynamically change the frequency in use. Since widespread mobile phones do not come with this ability, cognitive radio cannot be applied for service provisioning, unless specific terminals are used instead. For this reason, it is mostly used in the links between the NIB components or for backhauling [79].

3) Self-Healing: A network exhibits self-healing features when it detects faults and actuates mitigation techniques. Most of the NIBs do not include such features because NIBs typically provide communication services for short periods. Nevertheless, the few self-healing features focus on dynamic assignment of roles, *i.e.* activating services on a spare component when a sudden failure of another component occurs [105], [106]. Examples of such functions are the services described in Section V-B or the services provided by the EPC in an LTE network.

Dynamic role reallocation is useful when the NIB is deployed in hazardous environments, in which one of the components might become unavailable, or when it is used together with the already-deployed network infrastructure. As an example, some solutions leverage a preventive deployment of the NIBs, which are activated in case base stations experience issues in communicating with the core network [52]. In this case, the EPC network functions are implemented leveraging NFV, a key technology for enabling network flexibility [99]. NFV allows to consider the network functions as applications that can be installed, migrated, and downloaded in an on-demand fashion. Many NIBs implement mobile core functions leveraging NFV technology [12], [17], [20], [29], [41], [56].

D. Capacity and QoS

A NIB serves a number of end users that depends on the use case for which the NIB is adopted. For example, when considering rescue team operators, the number is small, but if we extend the services to survivors then the number becomes very high. In addition, serving a user implies some guarantees on the service provided, for example guarantees about its availability regardless of the number of other simultaneous users. For this reason, NIBs are focused not only on offering connectivity to as many users as possible, but also on the Quality of Service (QoS) they are able to ensure.

There are two reasons for which capacity and QoS are important. First, if the NIB substitutes the crashed telecommunication infrastructure in an after-disaster scenario, it might have to handle an enormous amount of simultaneous call attempts [4], [27]. Moreover, rescue workers or soldiers need high-speed communication links for downloading 3D maps/floor plans of buildings or videoconferencing [10], [32]. In this context, QoS assurance, *i.e.* offering guarantees on the provisioning of a QoS level, is of fundamental importance [4], [24], [107]. In the following, we present which are the typical capacity levels provided, and how QoS assurance is achieved.

1) Capacity: It corresponds to the maximum number of connected users a NIB is able to handle simultaneously. A connected user transits between idle state, in which the network reserves some resources but no services are requested, and active state, in which the user requests a service, *e.g.* a phone call. Therefore, the requests that might be performed by a connected user at any time need to be taken into account in the network.

Table VII shows our grouping of the NIB. We have divided the NIBs in three categories depending on the supported number of connected users: between 10 and 100, between 100 and 500, and more than 500. NIBs that handle less than 100 connected users are suitable for both soldiers on a mission and rescue teams [7], [45], [85]. They are also suitable for connectivity provisioning in small flights because the number of passengers is limited. Most NIBs fall in this category.

Nevertheless, there are three contexts in which the limit of 100 connected users becomes a bottleneck. First, an enterprise network can have a very high number of employees in the same geographical area, *e.g.* an enterprise network covering several buildings. Second, intercontinental flights and cruises have hundreds of passengers. Finally, the number of inhabitants of villages in developing countries can exceed one hundred. In these cases, an upper-bound of 500 connected users is sufficient to satisfy the connectivity requirements [64].

When considering an after-disaster scenario or flash crowds, we deal with a number of users higher than 500. For this reason, some NIBs work with higher numbers of simultaneously connected users [20], [89]. Handling more connected users necessarily implies more resources, so a trade-off is needed. Depending on the use case, a solution which handles a smaller number of simultaneous users might be more appealing because of the constrained price.

2) QoS: Quality of Service is essential when considering tactical networks or public safety. Since the NIB solution is a collector of traffic towards the Internet, some mechanisms of prioritization are required to avoid the collapse of the network [108]. Nevertheless, QoS assurance requires to define a QoS model, which includes privilege categories and rules to apply when requests of different categories are competing. The presence of a built-in QoS model is the reasons behind the success of LTE [74]. Indeed, it offers the bearer abstraction, *i.e.* a data flow labeled with certain QoS guarantees. In addition, LTE leverages Access Classes (ACs) to divide users by priority. In case of overload, users from certain access classes have a guaranteed access to the connectivity services, while requests from lower-priority access classes are rejected. This mechanism is known as access class barring [27]. Bearer prioritization and access class barring consist in the most straightforward way of enforcing QoS when dealing with a number of connection attempts higher than the available capacity [71].

Another way of providing QoS assurance is to provide broadband connectivity and bound the maximum number of connected users. This is the approach adopted in [16]: the maximum number of connected users is not high, but the solution is able to provide 200 Mbps both in uplink and downlink. Similarly, other works offer a high data rate and limit the maximum number of users to few hundreds [9], [11].

Finally, there are works that provide their own QoS model crafted for a specific use case. The work of Huang *et al.* [33] proposes to prioritize the phone calls on their urgency, *i.e.* rescue workers will have a higher priority compared to survivors. Instead, Berioli *et al.* [47] propose to differentiate on the usage pattern of the connectivity services. For example, call attempts have higher priority compared to web browsing.

E. Cost Efficiency

Most of the NIB are focused on the cost efficiency of the proposed solution both in terms of Capital Expenditure (CapEx) and OpEx [18], [38]. Reducing the costs is important for two reasons. The first one is the lack of economic incentives in the public safety market for the limited revenue opportunities [4], [87]. Second, the Non-Governmental Organizations (NGOs) that deploy networks in developing counteries have very constrained budgets. At the same time, mobile operators do not extend their networks in such areas since the Return of Investment (RoI) is too low [35], [36].

The idea of using just a few physical devices allows to reduce both CapEx and OpEx [81]. In addition base stations correspond to the most expensive component of a mobile network [71], and we are experiencing a gradual shift towards limited-range small-/micro-/pico-cells due to their limited price [5], [109]. A NIB is typically equipped with one of these small portable base stations, therefore keeping the whole price of the NIB constrained. Finally, NIBs provide their connectivity services using technologies which are supported by COTS devices. Therefore, users can access these services using widespread devices, *e.g.* smartphones. This allows to limit the costs of the devices as well as the training for using such devices [61], [95].

NIBs leverage other techniques to further reduce costs. One is the adoption of Software-Defined Radio (SDR) technology, and the second is the support for general-purpose hardware. We grouped the proposals adopting the two techniques in Table VIII.

TABLE VIII
CLASSIFICATION OF THE WORKS BASED ON THE COST-EFFICIENCY APPROACH ADOPTED.

Approach	**Works**
Software-Defined Radio (SDR)	[12], [64], [51], [41], [30], [110], [56], [48], [34], [19], [42], [43]
General-purpose hardware support	[16], [62], [38], [56], [34], [111], [19], [43]

A software-defined radio is a radio system in which the processing of incoming and outgoing signals is implemented through software functions [104]. In traditional radio systems, the processing of the signal, *i.e.* amplification, filtering, Fast Fourier Transformation (FFT), is performed by specialized hardware. In SDRs, amplification and digital-to-analog/analog-to-digital conversion are implemented in hardware, while all the remaining functions are implemented in software. This reduction in the hardware requirements implies a reduction in the costs of the equipment [34], [112]. In addition, SDR systems allow flexibility in the customization of the software functions without requiring to upgrade the hardware. As an example, while traditional radio systems work on a fixed set of frequencies, SDRs can be tuned to work on a chosen frequency by issuing software commands to a reconfigurable antennas, *i.e.* an antenna that can change the frequency used for communication in a dynamic fashion [104]. SDR and reconfigurable antennas consist in an affordable alternative to the purchase of different antennas for different frequencies. They also consist in a key enabler for implementing cognitive radios.

Some NIBs run on general-purpose hardware combined with SDR systems [16], [43], [56]. These NIBs leverage COTS equipment, such as laptops, to create bubbles of coverage. Mobile networks are typically implemented using expensive, non-customizable appliances for high traffic loads, often resulting in over-provisioning of the mobile network [40], [99]. Since public safety and Non-Governmental Organizations cannot afford such appliances, the adoption of a NIB working on general-purpose hardware represents an affordable alternative for satisfying their requirements.

Both SDR technology and general-purpose hardware support come with drawbacks in performance. Signal processing in hardware is faster than its software equivalent. Similarly, COTS laptops are slower than dedicated hardware appliances. However, the main limitation consists in the number of users they can serve. In contexts with a small number of users, *e.g.* rescue team network and mobile network in developing countries, the adoption of SDR and general-purpose hardware support is a good approach to reduce the cost of the NIB.

In Table IX we have listed the software and the hardware tools used for implementing NIBs. Despite the advantages of LTE, the most used technology is GSM thanks to the OpenBTS software suite [115]. OpenBTS is mature, it relies on SDR, and it has also led to the launch of commercial NIBs [37]. Instead, LTE implementations are either incomplete or hard to customize [110]. Nevertheless, a significant number of works leverage tools such as OpenAirInterface [113] and OpenLTE [114] to offer LTE connectivity.

Looking at the hardware, there are two important aspects to highlight. The first is that the antennas Inmarsat BGAN are widely adopted for obtaining a satellite connection [47], [50], [82]. The second is that Ettus USRP platform is the most used platform for implementing an SDR-based system. This equipment acts as a bridge between the bare-metal antenna and the platform processing the signal. The main advantage is that it works with a huge variety of frequencies, so it can be used to provide different wireless technologies.

A NIB exhibits the presented features to address the needs of the use cases discussed in Section III. A key question is if and how we can leverage these features to satisfy the requirements of tomorrow's networks. In the next section we present the points of contact between what is offered by a NIB and what is needed by forthcoming 5G networks. In addition we discuss what could be improved in NIBs to fully achieve the aims for which they have been originally designed as well as to open them to new use cases.

VI. DISCUSSION AND AVENUES FOR FUTURE WORK

Two important properties of a NIB are its adaptability to the environment and its independence from external elements, *i.e.* the NIB is self-sufficient. In the following, we describe the evolution NIBs are experiencing to improve the achievement of such properties. In addition, we discuss the role of NIBs in next-geneartion mobile networks. Finally, we discuss the security issues that a wide adoption of NIBs implies.

A. Technological Flexibility

We define technological flexibility the ability to provide a service independently from a single technology. For example, NIBs implement backhauling either using a single fixed technology, or using a fixed set of technologies simultaneously, or using multiple interchangeable technologies. In the first case, there is no technological flexibility because backhauling requires a specific technology. Instead, backhauling is independent from a specific technology in the other two cases, *i.e.* the NIB is more flexible from the technological perspective. Currently NIBs come with a single or a small set of technologies used for service provisioning and backhauling. However, the interoperability with multiple technologies improves the effectiveness of the rescue operations [30], [88], [125]. For this reason, NIBs are required to provide their connectivity services through a high number of technologies simultaneously, *e.g.* through several NICs on the same NIB [87], [108].

Nevertheless, offering a high number of technologies does not correspond to a complete solution. We argue that NIBs should pursue radio technology independence, *i.e.* the capability of supporting radio technologies in an on-demand fashion. This corresponds to the next step in the evolution of networks that started with Software-Defined Networking (SDN). SDN allows the management of network devices through a standardized interface, allowing heterogeneity in the

TABLE IX
SOFTWARE AND HARDWARE TOOLS LEVERAGED BY NETWORK-IN-A-BOX SOLUTIONS.

Group	Sub-group	Name	Description	Works
Software tools	LTE	OpenAirInterface [113]	eNB and EPC implementations	[110], [111]
		OpenLTE [114]	eNB and EPC implementations (partial)	[110]
	GSM	OpenBTS [115]	GSM-to-IP full implementation	[36], [51], [26], [116], [54], [56], [34]
		OpenBSC [117]	BSC, MSC, HLR functions	[66]
	Call switch	Asterisk [118]	PBX, VoIP gateway	[47], [50], [116], [34]
		FreeSWITCH [119]	PBX, VoIP gateway	[36], [56]
	Traffic management	Iproute2 + tc tools	Control of TCP/IP traffic and QoS enforcement	[47], [50]
		OpenVPN [120]	VPN implementation	[108]
		relayd + Polipo	Client-backhaul network bridge + requests caching	[55]
	Other	JXTA [121]	Programming language for P2P apps	[24]
		OpenWRT [122]	OS for wireless network nodes	[55]
Hardware tools	Satellite antenna	Inmarsat BGAN [123]	Lightweight and portable satellite dish	[50], [47], [82]
		DVB-RCS VSAT	High-bandwidth satellite dish	[47]
	Programmable radio device	ip.access nanoBTS	Pico-cell base station	[50], [66]
		Ettus USRP [124]	Hardware platform for SDR	[51], [116], [54], [48], [111]

The listed software tools are all open-source. Details on software and hardware used by commercial solutions are largely unavailable.

network devices. Nevertheless, the fixed interface promoted by SDN is inflexible, *i.e.* it does not allow modifications. For this reason, network appliances today offer customization options on the control interface using languages such as P4 [126]. The same language allows to define network-layer protocols that are used interchangeably by network devices [127]. However, the flexibility stops at the network layer because the lower-level technologies are fixed. Radio technologies should be supported as "network apps" that can be downloaded, activated, and deactivated when needed. This allows a NIB to offer backward compatibility with P25- or TETRA-compliant devices, for example. Until now only few works offer similar capabilities [11] [128].

Many works highlight the relevance of supporting multiple radio technologies [32], [42], [81], [82]. Nevertheless, different radio technologies work on different frequency bands, requiring specific antennas. The differences in the antenna used represent a major obstacle to the achievement of radio technology independence because we are forced to carry a set of antennas and select the right one depending on the technology adopted. An alternative to this approach is the adoption of reconfigurable antennas, which can be reprogrammed to work on a different frequency [19], [104], [129]. Such antennas improve the ease of deployment because they can be used for a wide set of radio technologies. In addition, some works have explored simultaneous transmission and reception through the same antenna, therefore avoiding the need for different frequencies [130]–[132].

B. Control Plane Delegation

After the deployment, the NIB is either configured locally or remotely. Remote control becomes fundamental when many NIBs are required, for example in case of a huge disaster area or flash crowd. Nevertheless, a NIB should not depend completely on the instructions coming from an external entity, especially when using it in an emergency scenario where the disaster is ongoing because the link with such external entity

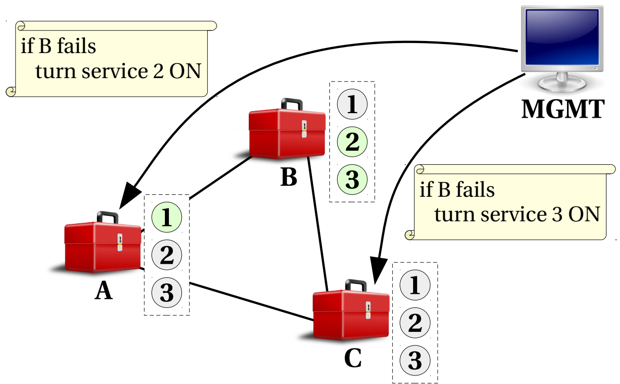


Fig. 6. **Example of Emergency Plan.** *NIB A is providing service 1, while NIB B is providing services 2 and 3. The management platform (MGMT) injects the emergency plan in NIBs A and C. In case of failure of NIB B, NIB A starts providing service 2, and NIB C starts providing service 3.*

might fail. Therefore, a trade-off between dependence and independence is required [133].

We argue that NIBs should encapsulate a level of autonomy which is steered by external instructions. In other words, NIB solutions should include some low-level control plane functionalities which are driven by high-level remote instructions. This control plane delegation has two advantages. The first one is the decoupling between NIB control plane and remote control plane. The key idea is that the local control plane can take autonomous decisions based on the remote instructions. Therefore the communication between the NIB and the remote management platform is reduced. The second one is that a local execution of the control plane functionalities allows a higher reactivity of the system [134].

Many works have explored control plane delegation both for reliability purposes and for reducing the usage of high-delay backhaul links [39], [106], [135], [136]. For example, the work of Sedef Savas *et al.* [137] discusses the usage of switches as suitable locations for a part of control plane functionalities. Instead, the work of Du Toit *et al.* [138] describes a content-replication distributed system in which the system components receive remote instructions and perform limited tasks independently as well.

The independence of the NIB is further improved with the installation of emergency plans, *i.e.* collections of actions that a NIB performs in case of malfunctioning in the network, as depicted in Figure 6. For example, if a NIB detects that a neighbor NIB is not working, then the NIB provides the network services that were provided by the faulty NIB, *e.g.* by switching ON the corresponding EPC functions [99], [139]. The installation of such plans takes place before using the NIB in real scenarios. This opens new perspectives on designing plans to optimize the network resulting from the actuation of the emergency plan. Some recent works follow this direction [105], [106].

C. *Towards 5G Networks*

We believe that NIBs can foster the transition towards 5G networks because they can be leveraged for implementing four capabilities required in 5G networks, *i.e.* network flexibility, network heterogeneity, Mobile Edge Computing, and Licensed Shared Access.

1) Network Flexibility: 5G networks are expected to satisfy the requirements of use cases such as self-driving cars and e-Health. Nevertheless, the requirements characterizing these use cases can be very different: for example, self-driving cars require high-bandwidth communication, while e-Health requires low energy consumption. For this reason, 5G networks will be able to adapt to satisfy the specific requirements of the use cases for which they are needed [1], [2], [140].

We define network flexibility as the ability of a network to provide its services without requiring a static deployment, *i.e.* a configuration in which services cannot be migrated or scaled. 5G networks require a high level of network flexibility since they require to tailor the provisioning of network services, such as communication security or mobility management, to the specific use cases. We might need to scale the network, *i.e.* instantiating or removing replicas of a certain service, or we might need to rearrange the provisioning of the services, *i.e.* re-instructing each network element on the services to provide. Nevertheless, the network elements that are leveraged for providing such services are constrained, limiting the possibilities of rearranging the provisioning of the services. For example, the network elements which are not equipped with a base station cannot help in improving coverage.

In this context, we can use NIBs as network elements to achieve the desired flexibility. Indeed, a NIB is able to provide all the services required by a mobile network, but it can also disable them selectively when it is working together with other network elements, as described in Figure 3. Therefore, a group of connected NIBs allows great flexibility in the arrangement of the services provided. We might instruct each NIB in providing a different set of services, as well as replicating some services in many NIBs. Additionally, the coverage can be expanded or reduced on-demand by activating or deactivating the radio module in each NIB. In summary, leveraging NIBs in place of general-purpose servers removes constraints in distributing the provisioning of the services in the network, ultimately making the network more flexible.

2) Heterogeneous Networks: A Heterogeneous Network (Het-Net) is a wireless network provided by antenna elements with possibly overlapping coverage areas. A typical example is a mobile network generated by a macrocell and a set of picocells deployed in the same area. The concept can also be extended to the coexistence of different wireless technologies in the same area. The reasons for having a Het-Net is that it provides connectivity services to a broader set of customers in the same area than a traditional wireless network, *i.e.* with a single antenna and a single technology supported.

The Het-Nets concept has existed for many years and 3GPP has standardized some of its features [91]. Nevertheless, 5G Het-Nets will come with a much bigger amount of limited-coverage base stations to supply the connectivity needs from a constantly growing population of customers. In addition, base stations will be added and removed on-demand to satisfy the variable demand from the customers, *e.g.* during a concert. Therefore, a huge variability in the group of active base stations is expected, with a lot of base stations joining and leaving the network dynamically. In this context, the base stations have to exhibit SON features since a manual configuration of each single base station, in terms of frequency and technology to adopt, is unfeasible [133], [141].

The SON features of NIBs can satisfy the requirements of 5G Het-Nets. NIBs with "plug&play" capabilities can be used in place of traditional mini/micro/picocells, so when the NIB is switched ON, it agrees with the neighbor base stations on the frequencies and technologies to use. Since a NIB is able to provide a much bigger set of services than a base station, the remaining services can be configured to be activated in case of malfunctioning with the core network, *e.g.* through an emergency plan. Therefore, a 5G Het-Net can also achieve a higher level of fault tolerance through the adoption of NIBs.

3) Mobile Edge Computing: NIBs are closely related with the concept of Mobile Edge Computing, which prescribes the deployment of third-party services in facilities placed to the edge of mobile networks. This approach has two advantages: first, it reduces the traffic towards the core network; second, it allows to offer delay-sensitive applications. Some NIBs are open to third-party applications allowing the customer to deploy the services required for specific use cases [12], [72], [85]. In addition, a NIB corresponds to a device deployed at the edge of the network because users are connected directly to it. A NIB is suitable for flash crowds because it can be leveraged for both traffic offloading and provisioning of event-specific services, *e.g.* instantaneous replay. In line with this approach, the work of Madhavapeddy *et al.* [96] proposes to deploy cloud services in home gateways to reduce latency.

4) Licensed Shared Access: A NIB is also suitable for offering Licensed Shared Access (LSA) [109], *i.e.* sharing the available spectrum dividing it by time, geographical extension, and frequency to maximize the efficiency. This opens opportunities to offer rental services to incumbent users who need the spectrum for a limited context, *e.g.* duration of a sport event. LSA can be leveraged by public safety organizations to obtain some long-term revenue. Indeed, national organizations can reserve frequency bands for public safety and rent them to mobile operators during quiet times [87]. Some NIBs allow to tune the frequencies used for service provisioning, making them good candidates to offer LSA [109]. If we consider running third-party services while offering LSA, then the offer for the incumbent users is further enhanced. Indeed, in case of a popular event, an incumbent user rents a portion of the spectrum for the event and runs a NIB offering event-specific services. The same idea can be leveraged by organizations such as hospitals or universities. Indeed, they can rent a portion of the spectrum and deploy their business-specific services on a NIB instead of using remote servers [22]. In case of popular events, the organizers can deploy some NIBs in the place and rent them to mobile network operators willing to offer their own services [142].

D. Security Considerations

From the security perspective, there are two aspects to consider. The first one is the combination of flexibility and security in NIB, *i.e.* how to perform download and execution of third-party applications in a secure way. The second one is dealing with the potential usage of a NIB as attack vector, *e.g.* rogue base station collecting private information.

One of the promising features of NIBs is the openness to business-specific services, which are installed in an on-demand fashion. This implies the execution of third-party software, opening the door to a huge variety of security issues. In addition, NIBs will download and install radio technologies to flexibly adapt to the context of use. An attacker can leverage this capability to harm people [143].

The work of Baldini *et al.* [144] lists the security issues of systems based on software-defined radio and cognitive radio technologies. In particular, the work highlights the importance of securing the download channel, *i.e.* the link through which the NIB retrieves software, and ensuring the trustfulness of the software executed. The framework presented in [143] aims to protect an SDR-enabled system by verifying the source and the integrity of the code. 3GPP has worked on the concept of Trusted Environment (TrE) [145] for Home eNBs (HeNBs), *i.e.* small cells deployed in houses. The TrE isolates the functions that are running on the HeNB from each other and from the external environment preventing unauthorized accesses and external tampering.

The security threats that concern NIBs are not limited to a single technology, but are rather related with wireless security in general because of the technological flexibility offered by such appliances[2]. In particular, an attacker can leverage a NIB to perform a rogue base station attack. The works in [147], [148] show how to set up a fake GSM base station to collect personal data, *e.g.* IMSI. Alternatively, the attacker can deny network services to the connected devices, as in the works of Dondyk *et al.* [149] and Shaik *et al.* [150]. In the first one, the authors create a fake Wi-Fi access point that does not provide any Internet connectivity, but it is able to elude the connectivity checks performed by the operating system. In the second one, the authors show how to set up a fake LTE base station that disables connectivity services in the mobile phone[3]. A rogue base station can also be leveraged to perform a Man-In-The-Middle (MITM) attack. The work of Zhang *et al.* [152] describes how to set up a fake UMTS base station that connects the UE to a network which is different from the default one, leading to unaware use of expensive roaming services. Finally, the work in [153] describes a MITM attack in WiMAX networks that exploits the lack of synchronization between the user and a legitimate base station to spoof the identity of the user.

The major concern with the described attacks is that the tools required are accessible to anyone. No expensive hardware appliances are required, and the majority of the software tools are open-source, as shown in Table IX. The work of Bilogrevic *et al.* [154] also shows that the low cost of femtocells lowers the barriers to attacks in LTE networks. The only obstacle is the domain-specific knowledge that the attacker

[2]For further information, the work of Zou *et al.* [146] is a comprehensive and updated survey about wireless security.

[3]Additional details on the security aspects of LTE can be found in the survey of Cao *et al.* [151].

requires to perform the attack. However, next-generation NIBs will allow customers to select technologies and applications which are automatically downloaded, installed, and activated. In such context, no domain-specific knowledge is required, and performing attacks will become even easier. In addition, the technological flexibility allows attackers to perform a plethora of attacks through the same physical device, lowering the economical barriers to such threats.

To conclude, the innovations brought by NIBs come with some drawbacks. We need some mechanisms to prevent misuses before next-generation NIBs are released to the public. The concerns on harm to citizens suggest a tight interaction between NIBs producers and governmental agencies. One way of regulating the usage of NIBs is to allow the activation of technologies only after the governmental agency has granted the permission. On one hand, such approach reduces the ease of performing attacks. On the other hand, it hampers the usage of NIBs for research purposes.

VII. Conclusion

In this paper, we have analyzed the Networks-In-a-Box, *i.e.* networks characterized by a low number of physical devices. Such networks are designed to provide on-demand connectivity to rescue operators and survivors in after-disaster scenarios, or to support soldiers in the battlefield. We have shown that flexibility is a key feature for satisfying the requirements of these use cases. Such flexibility is expressed in terms of ease of deployment, technological richness, and openness to the external environment through backward compatibility and execution of third-party software packages. The next generation of mobile networks needs to incorporate these features because they are expected to satisfy the requirements coming from different use cases. Therefore, Network-In-a-Box is a key concept to boost the transition towards 5G networks.

While the Network-In-a-Box concept is well known in industry, it has received limited attention in academia. We believe that more resources should be allocated in research for studying and enhancing the NIB concept. In particular, technological flexibility is achieved by adopting SDR technology and programmable antennas, but their combination in NIBs has still to be studied. In addition, the security of NIBs needs to be studied to prevent misuses from malicious users. To conclude, this paper represents a set of research guidelines for designing the components of tomorrow's mobile network. Indeed, we strongly believe Networks-In-a-Box will be a fundamental part of forthcoming 5G networks.

Acknowledgment

This work has been supported by the Nokia Center for Advanced Research (NCAR) and the Business Finland TAKE-5 project.

References

[1] Next Generation Mobile Networks (NGMN), "5G White Paper," https://www.ngmn.org/fileadmin/ngmn/content/downloads/Technical/2015/NGMN_5G_White_Paper_V1_0.pdf, Feb 2015, last access: Feb 2018.

[2] Ericsson, "A vision of the 5G core: flexibility for new business opportunities," https://www.ericsson.com/publications/ericsson-technology-review/archive/2016/a-vision-of-the-5g-core-flexibility-for-new-business-opportunities, 2016, last access: Feb 2018.

[3] Nokia, "5G use cases and requirements," https://www.ramonmillan.com/documentos/bibliografia/5GUseCases_Nokia.pdf, 2016, last access: Feb 2018.

[4] J. S. Huang and Y. N. Lien, "Challenges of emergency communication network for disaster response," in *Communication Systems (ICCS), 2012 IEEE International Conference on*, Nov. 2012, pp. 528–532.

[5] Z. Shao, Y. Liu, Y. Wu, and L. Shen, "A rapid and reliable disaster emergency mobile communication system via aerial ad hoc bs networks," in *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*, Sep. 2011, pp. 1–4.

[6] Athonet, "Enterprise, Mission Critical and Public Safety," http://www.athonet.com/athonet/enterprise-mission-critical/, last access: Feb 2018.

[7] Chemring Technology Solutions, "Smartlink - Quicker response through increased collaboration," http://www.chemringts.com/~/media/Files/C/Chemring-TS-V2/documents/02467-smartlink.pdf, 2014, last access: Feb 2018.

[8] Tecore Networks, "Network in a box (NIB)," http://www.tecore.com/product/nib/, last access: Feb 2018.

[9] Ranberry, "Ranberry B1000 - Mobile rapidly deployable 4G/LTE network-in-a-box - Slides," http://www.slideshare.net/ranberry/ranberry-b1000-mobile-rapidly-deployed, 2014, last access: May 2017.

[10] Rethink Technology Research for Quortus, "LTE: a robust solution for public safety," https://www.quortus.com/download/lte-a-robust-solution-for-public-safety/, 2015, last access: Feb 2018.

[11] AZcom Technology, "AZP and AZN Series Small Cell Platforms," http://www.azcom.it/wp-content/uploads/azp-and-azn-series-small-cell-platforms.pdf, last access: Feb 2018.

[12] Tecore Networks, "LYNX Network in a box (NIB)," http://www.tecore.com/product/lynx-network-in-a-box-nib/#tab-35, last access: Feb 2018.

[13] ParallelWireless, "HetNet Gateway and Converged Wireless System," http://www.parallelwireless.com/products/, last access: Feb 2018.

[14] Sysmocom, "sysmoBSC/IP data sheet," https://www.sysmocom.de/downloads/sysmobsc-ip-data-sheet.pdf, 2013, last access: Feb 2018.

[15] Elektrobit, "LTE - Solution for Public Safety and Defense Applications," https://tapahtumat.tekes.fi/uploads/d947b274/Hulkkonen_Ari-4794.pdf, 2013, last access: Feb 2018.

[16] Aricent, "Development of a LTE 'Network-in-a-box' Solution for the Public Safety Market - A Case Study," http://www3.aricent.com/epc-lte-network-in-a-box-case-study/, 2014, last access: Feb 2018.

[17] Nokia Networks, "LTE Network in a box," https://onestore.nokia.com/asset/200194/Nokia_Network-in-a-Box_White_Paper_EN.pdf, 2015, last access: Feb 2018.

[18] R. J. Sánchez, J. B. Evans, G. J. Minden, V. S. Frost, and K. S. Shanmugan, "Rdrn: A prototype for a rapidly deployable radio network," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 2, no. 2, pp. 15–22, Apr. 1998. [Online]. Available: http://doi.acm.org/10.1145/584017.584019

[19] J. B. Evans, G. J. Minden, K. S. Shanmugan, G. Prescott, V. S. Frost, B. Ewy, R. Sanchez, C. Sparks, K. Malinimohan, J. Roberts, R. Plumb, and D. Petr, "The rapidly deployable radio network," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 4, pp. 689–703, Apr 1999.

[20] Polaris Networks, "LTE NetEPC," http://www.polarisnetworks.net/lte-netepc.html, last access: Feb 2018.

[21] J.-S. Huang, Y.-N. Lien, and C.-L. Hu, "Design of contingency cellular network," in *Network Operations and Management Symposium (APNOMS), 2012 14th Asia-Pacific*, Sep. 2012, pp. 1–4.

[22] Telefonica, "LTE in a Box - Your own LTE network for your Enterprise," https://www.telefonica.com/documents/26188/319484/Stand_LTE_in_a_Box.pdf/f3a62052-fac0-40ed-aacc-b1add3232789, last access: Feb 2018.

[23] "Nokia Saving Lives - Intelligent solutions for worldwide rescue operations," https://networks.nokia.com/innovation/nokia-saving-lives, last access: Feb 2018.

[24] Y. N. Lien, L. C. Chi, and Y. S. Shaw, "A walkie-talkie-like emergency communication system for catastrophic natural disasters," in *2009 10th International Symposium on Pervasive Systems, Algorithms, and Networks*, Dec. 2009, pp. 309–314.

[25] H.-C. Jang, Y.-N. Lien, and T.-C. Tsai, "Rescue information system for earthquake disasters based on manet emergency communication platform," in *Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing: Connecting the World Wirelessly*, ser. IWCMC '09. New York, NY, USA: ACM, 2009, pp. 623–627. [Online]. Available: http://doi.acm.org/10.1145/1582379.1582514

[26] P. Crane and M. Nowostawski, "Rapidly deployable GSM network," *Postgraduate Day*, p. 27, 2010.

[27] A. Kunz, I. Tanaka, and S. S. Husain, "Disaster response in 3gpp mobile networks," in *2013 IEEE International Conference on Communications Workshops (ICC)*, Jun. 2013, pp. 1226–1231.

[28] E. Monticelli, B. M. Schubert, M. Arumaithurai, X. Fu, and K. K. Ramakrishnan, "An information centric approach for communications in disaster situations," in *2014 IEEE 20th International Workshop on Local Metropolitan Area Networks (LANMAN)*, May 2014, pp. 1–6.

[29] M. Casoni, C. A. Grazia, M. Klapez, N. Patriciello, A. Amditis, and E. Sdongos, "Integration of satellite and lte for disaster recovery," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 47–53, Mar. 2015.

[30] A. Trotta, M. D. Felice, L. Bedogni, L. Bononi, and F. Panzieri, "Connectivity recovery in post-disaster scenarios through cognitive radio swarms," *Computer Networks*, vol. 91, pp. 68 – 89, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128615002510

[31] K. Miranda, A. Molinaro, and T. Razafindralambo, "A survey on rapidly deployable solutions for post-disaster networks," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 117–123, April 2016.

[32] D. Abusch-Magder, P. Bosch, T. E. Klein, P. A. Polakos, L. G. Samuel, and H. Viswanathan, "911-now: A network on wheels for emergency response and disaster recovery operations," *Bell Labs Technical Journal*, vol. 11, no. 4, pp. 113–133, 2007. [Online]. Available: http://dx.doi.org/10.1002/bltj.20199

[33] J.-S. Huang, Y.-N. Lien, and Y.-C. Huang, "Network topology planning for contingency cellular network," in *Proceedings of 17th Mobile Computong Workshop*, 2012.

[34] A. Anand, V. Pejovic, E. M. Belding, and D. L. Johnson, "Villagecell: Cost effective cellular connectivity in rural areas," in *Proceedings of the Fifth International Conference on Information and Communication Technologies and Development*, ser. ICTD '12. New York, NY, USA: ACM, 2012, pp. 180–189. [Online]. Available: http://doi.acm.org/10.1145/2160673.2160698

[35] Nokia, "The remote and rural connectivity - A new community-based network model," https://www.cambridgewireless.co.uk/media/uploads/resources/Small%20Cell%20Group/29.06.17/SmallCell-29.06.17-Nokia-Enrico_Gattinotta.pdf, 2017, last access: Feb 2018.

[36] K. Heimerl, S. Hasan, K. Ali, E. Brewer, and T. Parikh, "Local, sustainable, small-scale cellular networks," in *Proceedings of the Sixth International Conference on Information and Communication Technologies and Development: Full Papers - Volume 1*, ser. ICTD '13. New York, NY, USA: ACM, 2013, pp. 2–12. [Online]. Available: http://doi.acm.org/10.1145/2516604.2516616

[37] "Endaga - Community Cellular Networks," https://www.endaga.com/, last access: Feb 2018.

[38] A. Lindgren, A. Doria, J. Lindblom, and M. Ek, "Networking in the land of northern lights: Two years of experiences from dtn system deployments," in *Proceedings of the 2008 ACM Workshop on Wireless Networks and Systems for Developing Regions*, ser. WiNS-DR '08. New York, NY, USA: ACM, 2008, pp. 1–8. [Online]. Available: http://doi.acm.org/10.1145/1410064.1410066

[39] J. Spencer, O. Worthington, R. Hancock, and E. Hepworth, "Towards a tactical software defined network," in *2016 International Conference on Military Communications and Information Systems (ICMCIS)*, May 2016, pp. 1–7.

[40] M. Pozza, "Solving Signaling Storms in LTE Networks: a Software-Defined Cellular Architecture," Master Thesis, University of Padua, http://tesi.cab.unipd.it/53297/1/tesi_Pozza.pdf, Jun 2016, last access: Feb 2018.

[41] ABSOLUTE Project Consortium, "Aerial base stations with opportunistic links for unexpected & temporary events," https://cordis.europa.eu/project/rcn/106035_en.html, 2015, last access: Feb 2018.

[42] Airspan, "AirSynergy - Outdoor Urban Small Cell with Integrated Wireless Backhaul," http://www.airspan.com/products/airsynergy/, last access: Feb 2018.

[43] Amarisoft, "Amari LTE 100 / Amari OTS 100 Software 4G network on PC," https://www.amarisoft.com/software-enb-epc-ue-simulator/, last access: Feb 2018.

[44] K. Andersson and V. P. Kafle, "Disaster-resilient mobile network architecture," in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, Jan. 2014, pp. 157–162.

[45] Argela, "AMoN - Autonomous Mobile Network," http://www.argela.com.tr/brochures/AMoN_UMTS_%20DataSheet_v2_2016.pdf, 2016, last access: Feb 2018.

[46] Y. Bai, W. Du, Z. Ma, C. Shen, Y. Zhou, and B. Chen, "Emergency communication system by heterogeneous wireless networking," in *Wireless Communications, Networking and Information Security (WCNIS), 2010 IEEE International Conference on*, Jun. 2010, pp. 488–492.

[47] M. Berioli, J. M. Chaves, N. Courville, P. Boutry, J.-L. Fondere, H. Skinnemoen, H. Tork, M. Werner, and M. Weinlich, "WISECOM: A rapidly deployable satellite backhauling system for emergency situations," *International Journal of Satellite Communications and Networking*, vol. 29, no. 5, pp. 419–440, 2011.

[48] E. D. Re, S. Jayousi, S. Morosi, L. S. Ronga, M. D. Sanctis, E. Cianca, M. Ruggieri, E. Falletti, A. Iera, G. Araniti, and C. Sacchi, "Salice project: Satellite-assisted localization and communication systems for emergency services," *IEEE Aerospace and Electronic Systems Magazine*, vol. 28, no. 9, pp. 4–15, Sept 2013.

[49] Fairwaves, "UmSITE - A complete mobile network in a single tower mounted base station," https://fairwaves.co/products/, last access: Feb 2018.

[50] E. H. Fazli, M. Werner, N. Courville, M. Berioli, and V. Boussemart, "Integrated gsm/wifi backhauling over satellite: Flexible solution for emergency communications," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, May 2008, pp. 2962–2966.

[51] I. Ghaznavi, K. Heimerl, U. Muneer, A. Hamid, K. Ali, T. Parikh, and U. Saif, "Rescue base station," in *Proceedings of the Fifth ACM Symposium on Computing for Development*, ser. ACM DEV-5 '14. New York, NY, USA: ACM, 2014, pp. 53–62. [Online]. Available: http://doi.acm.org/10.1145/2674377.2674392

[52] K. Gomez, L. Goratti, T. Rasheed, and L. Reynaud, "Enabling disaster-resilient 4g mobile communication networks," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 66–73, Dec. 2014.

[53] K. Gomez, S. Kandeepan, M. M. Vidal, V. Boussemart, R. Ramos, R. Hermenier, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, Q. Zhao, Y. Han, S. Rehan, N. Morozs, T. Jiang, I. Bucaille, T. Wirth, R. Campo, and T. Javornik, "Aerial base stations with opportunistic links for next generation emergency communications," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 31–39, April 2016.

[54] K. Guevara, M. Rodriguez, N. Gallo, G. Velasco, K. Vasudeva, and I. Guvenc, "Uav-based gsm network for public safety communications," in *SoutheastCon 2015*, Apr. 2015, pp. 1–2.

[55] T. M. Hackett and S. G. Bilén, "Implementation of a rapidly deployable, mobile communications system prototype for disadvantaged environments," *Procedia Engineering*, vol. 159, pp. 158 – 166, 2016, humanitarian Technology: Science, Systems and Global Impact 2016, HumTech2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1877705816322974

[56] D. Iland and E. M. Belding, "Emergenet: robust, rapidly deployable cellular networks," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 74–80, December 2014.

[57] M. K. Islam and L. Rongke, "Beidou communication (beicomm) device for rescue in disaster," in *The First International Conference on Future Generation Communication Technologies*, Dec. 2012, pp. 89–93.

[58] "Project Loon - Baloon-Powered Internet For Everyone," https://x.company/loon/, last access: Feb 2018.

[59] Nokia, "Ultra Compact Network establish coverage in minutes," https://onestore.nokia.com/asset/200315/Nokia_Ultra_Compact_Network_Executive_Summary_EN.pdf, 2016, last access: Feb 2018.

[60] NuRAN Wireless, "GSM network-in-a-box," http://nuranwireless.com/solutions/gsm-network-in-a-box/, last access: Feb 2018.

[61] A. Qiantori, A. B. Sutiono, H. Hariyanto, H. Suwa, and T. Ohta, "An emergency medical communications system by low altitude platform at the early stages of a natural disaster in indonesia," *Journal of Medical Systems*, vol. 36, no. 1, pp. 41–52, 2012. [Online]. Available: http://dx.doi.org/10.1007/s10916-010-9444-9

[62] Quortus, "ECX Core," https://www.quortus.com/products/ecx-core, 2015, last access: Feb 2018.

[63] T. Sakano, Z. M. Fadlullah, T. Ngo, H. Nishiyama, M. Nakazawa, F. Adachi, N. Kato, A. Takahara, T. Kumagai, H. Kasahara, and S. Kurihara, "Disaster-resilient networking: a new vision based on movable and deployable resource units," *IEEE Network*, vol. 27, no. 4, pp. 40–46, Jul. 2013.

[64] Telrad, "BreezeCOMPACT 1000," http://www.telrad.com/wp-content/uploads/2015/04/BreezeCOMPACT1000-Datasheet-A4.pdf, 2015, last access: Feb 2018.

[65] Vodafone, "Instant Network Mini," http://www.vodafone.com/content/index/what/technology-blog/the_vodafone_foundat.html, last access: Feb 2018.

[66] T. Wypych, R. Angelo, and F. Kuester, "Airgsm: An unmanned, flying gsm cellular base station for flexible field communications," in *Aerospace Conference, 2012 IEEE*, Mar. 2012, pp. 1–9.

[67] "YateBTS LTE Lab Kit," http://yatebts.com/products/lte_lab_kit, last access: Feb 2018.

[68] Project 25 - Technology Interest Group, "What is P25 Technology?" http://www.project25.org/index.php/technology/what-is-p25-technology, last access: Feb 2018.

[69] ETSI, "TErrestrial Trunked RAdio (TETRA)," http://www.etsi.org/technologies-clusters/technologies/tetra, last access: Feb 2018.

[70] TETRAPOL, "Official website," http://www.tetrapol.com/, last access: Feb 2018.

[71] Nokia Networks, "LTE networks for public safety services," https://onestore.nokia.com/asset/200168/Nokia_LTE_for_Public_Safety_White_Paper_EN.pdf, 2014, last access: Feb 2018.

[72] A. Kumbhar and İ. Güvenç, "A comparative study of land mobile radio and lte-based public safety communications," in *SoutheastCon 2015*, Apr. 2015, pp. 1–8.

[73] M. Nakamura, S. Kubota, H. Takagi, K. Einaga, M. Yokoyama, K. Mochizuki, M. Takizawa, and S. Murase, "Development of long-range and high-speed wireless lan for the transmission of telemedicine from disaster areas," *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, no. 1, p. 724010, 2007. [Online]. Available: http://dx.doi.org/10.1155/2008/724010

[74] T. Doumi, M. F. Dolan, S. Tatesh, A. Casati, G. Tsirtsis, K. Anchan, and D. Flore, "Lte for public safety networks," *IEEE Communications Magazine*, vol. 51, no. 2, pp. 106–112, February 2013.

[75] Alcatel-Lucent, "Blending Wi-Fi and cellular - Introducing Wireless Unified Networks," http://www2.alcatel-lucent.com/landing/blending-wi-fi-and-cellular/, 2015, last access: Feb 2018.

[76] O. Galinina, A. Pyattaev, S. Andreev, M. Dohler, and Y. Koucheryavy, "5g multi-rat lte-wifi ultra-dense small cells: Performance dynamics, architecture, and trends," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 6, pp. 1224–1240, June 2015.

[77] Cisco, "Network Emergency Response Vehicle," http://www.cisco.com/c/dam/en_us/solutions/industries/docs/gov/NERV_AAG.pdf, 2016, last access: Feb 2018.

[78] J. S. Huang, Y. N. Lien, and C. F. Wang, "Design of multi-path network topology for contingency cellular network," in *2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, Nov. 2015, pp. 103–108.

[79] G. Sato, N. Uchida, N. Shiratori, and Y. Shibata, "Performance analysis of never die network based on software defined disaster resilient system," in *Network-Based Information Systems (NBiS), 2015 18th International Conference on*, Sep. 2015, pp. 64–70.

[80] N. Uchida, K. Takahata, Y. Shibata, and N. Shiratori, "Never die network based on cognitive wireless network and satellite system for large scale disaster," *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications*, vol. 3, no. 3, pp. 74–93, Sep. 2012.

[81] S. Ghafoor, P. D. Sutton, C. J. Sreenan, and K. N. Brown, "Cognitive radio for disaster response networks: survey, potential, and challenges," *IEEE Wireless Communications*, vol. 21, no. 5, pp. 70–80, October 2014.

[82] A. Yarali, B. Ahsant, and S. Rahman, "Wireless mesh networking: A key solution for emergency & rural applications," in *Advances in Mesh Networks, 2009. MESH 2009. Second International Conference on*, Jun. 2009, pp. 143–149.

[83] Nokia, "Using air-to-ground LTE for in-flight ultra-broadband," https://onestore.nokia.com/asset/185856/Nokia_A2G_Strategic_White_Paper_EN.pdf, 2016, last access: Feb 2018.

[84] A. Dhekne, M. Gowda, and R. R. Choudhury, "Cell tower extension through drones: Poster," in *Proceedings of the 22Nd Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '16. New York, NY, USA: ACM, 2016, pp. 456–457. [Online]. Available: http://doi.acm.org/10.1145/2973750.2985275

[85] Huawei, "eLTE Rapid System," http://e-file.huawei.com/en/~/link.aspx?_id=597019C3976A4D3E92CE6B7B8CD7FC58, last access: Feb 2018.

[86] B. McCarthy, C. Edwards, and M. Dunmore, "The Integration of Ad-hoc (MANET) and Mobile Networking (NEMO): Principles to Support Rescue Team Communication," Oct. 2006.

[87] M. M. Sohul, M. Yao, X. Ma, E. Y. Imana, V. Marojevic, and J. H. Reed, "Next generation public safety networks: A spectrum sharing approach," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 30–36, March 2016.

[88] Y. Tachwali, F. Basma, and H. H. Refai, "Cognitive radio architecture for rapidly deployable heterogeneous wireless networks," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp. 1426–1432, Aug 2010.

[89] Telrad, "BreezeWAY EPC," http://www.telrad.com/wp-content/uploads/2015/04/BreezeWAY-Datasheet-A4.pdf, 2015, last access: Feb 2018.

[90] H. Verma and N. Chauhan, "Manet based emergency communication system for natural disasters," in *Computing, Communication Automation (ICCCA), 2015 International Conference on*, May 2015, pp. 480–485.

[91] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3gpp heterogeneous networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 10–21, June 2011.

[92] E. Baştuğ, M. Bennis, and M. Debbah, "Proactive caching in 5g small cell networks," in *Towards 5G: Applications, Requirements and Candidate Technologies*. John Wiley & Sons, 2016, ch. 6.

[93] P. K. Jaggi and A. K. Singh, "Opportunistic rollback recovery in mobile ad hoc networks," in *Advance Computing Conference (IACC), 2014 IEEE International*, Feb. 2014, pp. 860–865.

[94] J. Cucurull, M. Asplund, S. Nadjm-Tehrani, and T. Santoro, "Surviving attacks in challenged networks," *IEEE Transactions on Dependable and Secure Computing*, vol. 9, no. 6, pp. 917–929, Nov. 2012.

[95] Chemring Technology Solutions, "Smartlink - Rapidly deployable secure cellular comms," http://www.chemringts.com/~/media/Files/C/Chemring-TS-V2/documents/smartlink-defence.pdf, 2015, last access: Feb 2018.

[96] A. Madhavapeddy, T. Leonard, M. Skjegstad, T. Gazagnaire, D. Sheets, D. Scott, R. Mortier, A. Chaudhry, B. Singh, J. Ludlam, J. Crowcroft, and I. Leslie, "Jitsu: Just-in-time summoning of unikernels," in *12th USENIX Symposium on Networked Systems Design and Implementation (NSDI 15)*. Oakland, CA: USENIX Association, 2015, pp. 559–573. [Online]. Available: https://www.usenix.org/conference/nsdi15/technical-sessions/presentation/madhavapeddy

[97] ETSI, "Mobile Edge Computing (MEC); Framework and Reference Architecture," http://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/01.01.01_60/gs_MEC003v010101p.pdf, 2016, last access: Feb 2018.

[98] A. Jain, S. S. N., S. Lohani, and V. M., "A comparison of sdn and nfv for re-designing the lte packet core," in *2016 IEEE Conference on Network Function Virtualization and Software Defined Networks*, Nov. 2016.

[99] M. Pozza, A. Rao, A. Bujari, H. Flinck, C. E. Palazzi, and S. Tarkoma, "A refactoring approach for optimizing mobile networks," in *IEEE ICC 2017 SAC Symposium SDN & NFV Track (ICC'17 SAC-11 SDN&NFV)*, Paris, France, May 2017, pp. 4001–4006.

[100] 3GPP, "Group Communication System Enablers for LTE (GCSE_LTE)," 3rd Generation Partnership Project (3GPP), TS 23.468, Mar. 2017.

[101] ——, "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access - Annex K: Isolated E-UTRAN Operation for Public Safety," 3rd Generation Partnership Project (3GPP), TS 23.401, Mar. 2017.

[102] ——, "Automatic Neighbour Relation (ANR) management - Concepts and requirements," 3rd Generation Partnership Project (3GPP), TS 32.511, Apr. 2017.

[103] 4G Americas, "Self-Optimizing Networks: The Benefits of SON in LTE," http://www.5gamericas.org/files/2914/0759/1358/Self-Optimizing_Networks-Benefits_of_SON_in_LTE-July_2011.pdf, 2011, last access: Feb 2018.

[104] P. S. Hall, P. Gardner, and A. Faraone, "Antenna requirements for software defined and cognitive radios," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2262–2270, July 2012.

[105] D. Hancock and J. van der Merwe, "Hyper4: Using p4 to virtualize the programmable data plane," in *Proceedings of the 12th International on Conference on Emerging Networking EXperiments and Technologies*, ser. CoNEXT '16. New York, NY, USA: ACM, 2016, pp. 35–49. [Online]. Available: http://doi.acm.org/10.1145/2999572.2999607

[106] A. S. da Silva, P. Smith, A. Mauthe, and A. Schaeffer-Filho, "Resilience support in software-defined networking: A survey," *Computer Networks*, vol. 92, Part 1, pp. 189 – 207, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128615003229

[107] H. Aïache, V. Conan, G. Guibé, J. Leguay, C. Le Martret, J. M. Barcelo, L. Cerda, J. Garcia, R. Knopp, N. Nikaein, X. Gonzalez, A. Zeini, O. Apilo, A. Boukalov, J. Karvo, H. Koskinen, L. R. Bergonzi, J. C. Diaz, J. Meessen, C. Blondia, P. Decleyn, E. Van de Velde, and M. Voorhaen, "WIDENS: advanced wireless ad-hoc networks for public safety," in *IST Summit 2005, 14th Mobile & Wireless Communication Summit, June 19-23, 2005, Dresden, Germany*, Dresden, GERMANY, 06 2005. [Online]. Available: http://www.eurecom.fr/publication/1658

[108] M. de Graaf, H. van den Berg, R. J. Boucherie, F. Brouwer, I. de Bruin, H. Elfrink, I. Fernandez-Diaz, S. Heemstra de Groot, R. de Haan, J. de Jongh, S. Nunez, J.-K. van Ommeren, F. Roijers, J. Stemerdink, and E. Tromp, "Easy wireless: broadband ad-hoc networking for emergency services," in *Sixth Annual Mediterranean Ad Hoc Networking Workshop*. Corfu, Greece: Ionian University, Mar. 2007. [Online]. Available: http://doc.utwente.nl/64460/

[109] M. D. Mueck, V. Frascolla, and B. Badic, "Licensed shared access – state-of-the-art and current challenges," in *2014 1st International Workshop on Cognitive Cellular Systems (CCS)*, Sept 2014, pp. 1–5.

[110] I. Gomez-Miguelez, A. Garcia-Saavedra, P. D. Sutton, P. Serrano, C. Cano, and D. J. Leith, "srslte: An open-source platform for LTE evolution and experimentation," *CoRR*, vol. abs/1602.04629, 2016. [Online]. Available: http://arxiv.org/abs/1602.04629

[111] S. S. Kumar, R. Knopp, N. Nikaein, D. Mishra, R. T. Bheemarjuna, A. Franklin A, K. Kuchi, and R. Gupta, "FLEXCRAN: Cloud radio access network prototype using OpenAirInterface," no. EURECOM+5079, Bengaluru, INDIA, 01 2017. [Online]. Available: http://www.eurecom.fr/publication/5079

[112] "IEEE Spectrum - Software-Defined Radio Will Let Communities Build Their Own 4G Networks," http://spectrum.ieee.org/telecom/wireless/softwaredefined-radio-will-let-communities-build-their-own-4g-networks, Nov. 2015, last access: Feb 2018.

[113] "OpenAirInterface - 5G software alliance for democratising wireless innovation," http://www.openairinterface.org/, last access: Feb 2018.

[114] "OpenLTE - An open source 3GPP LTE implementation," https://sourceforge.net/projects/openlte/, last access: Feb 2018.

[115] "OpenBTS - Open Source Cellular Infrastructure," http://openbts.org/, last access: Feb 2018.

[116] E. Hatorangan and T. Juhana, "Mobile phone auto registration to openbts-based cellular network in disaster situation," in *Telecommunication Systems Services and Applications (TSSA), 2014 8th International Conference on*, Oct. 2014, pp. 1–3.

[117] "OpenBSC - Open Source Mobile Communications," https://osmocom.org/projects/openbsc, last access: Feb 2018.

[118] "Asterisk - open source framework for building communications applications," http://www.asterisk.org/, last access: Feb 2018.

[119] "FreeSWITCH - The world's first cross-platform scalable FREE multi-protocol softswitch," https://www.freeswitch.org/, last access: Feb 2018.

[120] "OpenVPN - Open Source VPN," https://openvpn.net/, last access: Feb 2018.

[121] "JXTA - The Language and Platform Independent Protocol for P2P Networking," https://jxta.kenai.com/, last access: May 2017.

[122] "OpenWRT - A GNU/Linux based firmware program for embedded devices such as residential gateways and routers," https://openwrt.org/, last access: Feb 2018.

[123] "Inmarsat BGAN," http://www.inmarsat.com/service/bgan/, last access: Feb 2018.

[124] "Ettus Research - The leader in Software Defined Radio (SDR)," https://www.ettus.com/, last access: Feb 2018.

[125] D. G. Reina, M. Askalani, S. L. Toral, F. Barrero, E. Asimakopoulou, and N. Bessis, "A survey on multihop ad hoc networks for disaster response scenarios," *Int. J. Distrib. Sen. Netw.*, vol. 2015, pp. 3:3–3:3, Jan. 2015. [Online]. Available: http://dx.doi.org/10.1155/2015/647037

[126] P. Bosshart, D. Daly, G. Gibb, M. Izzard, N. McKeown, J. Rexford, C. Schlesinger, D. Talayco, A. Vahdat, G. Varghese, and D. Walker, "P4: Programming protocol-independent packet processors," *SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 3, pp. 87–95, Jul. 2014. [Online]. Available: http://doi.acm.org/10.1145/2656877.2656890

[127] M. Shahbaz, S. Choi, B. Pfaff, C. Kim, N. Feamster, N. McKeown, and J. Rexford, "Pisces: A programmable, protocol-independent software switch," in *Proceedings of the 2016 Conference on ACM SIGCOMM 2016 Conference*, ser. SIGCOMM '16. New York, NY, USA: ACM, 2016, pp. 525–538. [Online]. Available: http://doi.acm.org/10.1145/2934872.2934886

[128] "LimeNET Network-in-a-Box - A software-enabled network in a box based on the LimeSDR board," https://www.crowdsupply.com/lime-micro/limenet, last access: Feb 2018.

[129] J. Costantine, Y. Tawk, S. E. Barbin, and C. G. Christodoulou, "Reconfigurable antennas: Design and applications," *Proceedings of the IEEE*, vol. 103, no. 3, pp. 424–437, March 2015.

[130] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Proceedings of the ACM SIGCOMM 2013 Conference on SIGCOMM*, ser. SIGCOMM '13. New York, NY, USA: ACM, 2013, pp. 375–386. [Online]. Available: http://doi.acm.org/10.1145/2486001.2486033

[131] D. Bharadia and S. Katti, "Full duplex mimo radios," in *11th USENIX Symposium on Networked Systems Design and Implementation (NSDI 14)*. Seattle, WA: USENIX Association, Apr. 2014, pp. 359–372. [Online]. Available: https://www.usenix.org/conference/nsdi14/technical-sessions/bharadia

[132] S. S. Hong, J. Mehlman, and S. Katti, "Picasso: Flexible rf and spectrum slicing," in *Proceedings of the ACM SIGCOMM 2012 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communication*, ser. SIGCOMM '12. New York, NY, USA: ACM, 2012, pp. 37–48. [Online]. Available: http://doi.acm.org/10.1145/2342356.2342362

[133] X. Gelabert, B. Sayrac, and S. B. Jemaa, "A heuristic coordination framework for self-optimizing mechanisms in lte hetnets," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 3, pp. 1320–1334, Mar. 2014.

[134] K. Tsagkaris, G. Poulios, P. Demestichas, A. Tall, Z. Altman, and C. Destré, "An open framework for programmable, self-managed radio access networks," *IEEE Communications Magazine*, vol. 53, no. 7, pp. 154–161, Jul. 2015.

[135] R. R. Oliveira and M. P. Barcellos, "Control plane cooperation design: towards robust programmable wans," in *Proceedings of the 12th International on Conference on Emerging Networking EXperiments and Technologies*, ser. CoNEXT '16, 2016.

[136] X. Foukas, N. Nikaein, M. M. Kassem, M. K. Marina, and K. Kontovasilis, "Flexran: A flexible and programmable platform for software-defined radio access networks," in *Proceedings of the 12th International on Conference on Emerging Networking EXperiments and Technologies*, ser. CoNEXT '16, 2016.

[137] S. S. Savas, M. Tornatore, M. F. Habib, P. Chowdhury, and B. Mukherjee, "Disaster-resilient control plane design and mapping in software-defined networks," in *2015 IEEE 16th International Conference on High Performance Switching and Routing (HPSR)*, Jul. 2015, pp. 1–6.

[138] J. D. Toit, I. Ellefsen, and S. V. Solms, "Bring your own disaster recovery (byodr)," in *2016 IST-Africa Week Conference*, May 2016, pp. 1–12.

[139] A. Patel and M. Vutukuru, "Optvnf: Architecting optimal virtual network functions," in *2017 IEEE International Conference on COMmunication Systems & NETworkS*, Jan. 2017.

[140] Huawei, "5G: A Technology Vision," http://www.huawei.com/ilink/en/download/HW_314849, 2013, last access: Feb 2018.

[141] O. G. Aliu, A. Imran, M. A. Imran, and B. Evans, "A survey of self organisation in future cellular networks," *IEEE Communications Surveys Tutorials*, vol. 15, no. 1, pp. 336–361, First 2013.

[142] P. Ahokangas, S. Moqaddamerad, M. Matinmikko, A. Abouzeid, I. Atkova, J. F. Gomes, and M. Iivari, "Future micro operators business models in 5g," in *6th International conference on Restructuring of the Global Economy (ROGE)*, Jun. 2016, pp. 143–149.

[143] L. B. Michael, M. J. Mihaljevic, S. Haruyama, and R. Kohno, "A framework for secure download for software-defined radio," *IEEE Communications Magazine*, vol. 40, no. 7, pp. 88–96, Jul 2002.

[144] G. Baldini, T. Sturman, A. R. Biswas, R. Leschhorn, G. Godor, and M. Street, "Security aspects in software defined radio and cognitive radio networks: A survey and a way ahead," *IEEE Communications Surveys Tutorials*, vol. 14, no. 2, pp. 355–379, Second 2012.

[145] 3GPP, "Security of Home Node B (HNB) / Home evolved Node B (HeNB)," 3rd Generation Partnership Project (3GPP), TR 33.820, Dec. 2009.

[146] Y. Zou, J. Zhu, X. Wang, and L. Hanzo, "A survey on wireless security: Technical challenges, recent advances, and future trends," *Proceedings of the IEEE*, vol. 104, no. 9, pp. 1727–1765, Sept 2016.

[147] S. Aragon, F. Kuhlmann, and T. Villa, "Sdr-based network impersonation attack in gsm-compatible networks," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, May 2015, pp. 1–5.

[148] U. Meyer and S. Wetzel, “A Man-in-the-middle Attack on UMTS,” in *Proceedings of the 3rd ACM Workshop on Wireless Security*, ser. WiSe ’04. New York, NY, USA: ACM, 2004, pp. 90–97. [Online]. Available: http://doi.acm.org/10.1145/1023646.1023662
[149] E. Dondyk and C. C. Zou, “Denial of convenience attack to smartphones using a fake wi-fi access point,” in *2013 IEEE 10th Consumer Communications and Networking Conference (CCNC)*, Jan 2013, pp. 164–170.
[150] A. Shaik, R. Borgaonkar, N. Asokan, V. Niemi, and J. Seifert, “Practical attacks against privacy and availability in 4g/lte mobile communication systems,” *CoRR*, vol. abs/1510.07563, 2015. [Online]. Available: http://arxiv.org/abs/1510.07563
[151] J. Cao, M. Ma, H. Li, Y. Zhang, and Z. Luo, “A survey on security aspects for lte and lte-a networks,” *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 283–302, First 2014.
[152] M. Zhang and Y. Fang, “Security analysis and enhancements of 3GPP authentication and key agreement protocol,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 2, pp. 734–742, March 2005.
[153] J. Huang and C.-T. Huang, “Design and verification of secure mutual authentication protocols for mobile multihop relay wimax networks against rogue base/relay stations,” *Journal of Electrical and Computer Engineering*, vol. 2016, 2016.
[154] I. Bilogrevic, M. Jadliwala, and J.-P. Hubaux, “Security Issues in Next Generation Mobile Networks: LTE and Femtocells,” 2010.

Matteo Pozza is a PhD student at the Department of Computer Science of the University of Helsinki. His main research area is mobile networks (4G/5G), technologies such as SDN and NFV, and machine learning. He received his Bachelors and Masters degree in computer science from the University of Padua, Italy, in 2014 and 2016 respectively.

Ashwin Rao is a Post-doctoral researcher working under the supervision of Sasu Tarkoma in the NODES research group at the University of Helsinki. He did the PhD in the DIANA (previously Planete) project team at Inria Sophia-Antipolis, and he obtained his masters degree from the School of Information Technology at the Indian Institute of Technology Delhi.

Hannu Flinck is a Research Manager in Architecture and Systems Research group at Nokia Bell Labs Espoo, Finland. He received his M.Sc. degree (1986) and Lic.Tech. degree (1993) in Computer Science and Communication Systems from Aalto University. His research areas have been covering routing and Internet protocols for mobile networks, content delivery, cloud computing and software defined networking. His current research topics include mobile edge computing, network function virtualization, SDN and network slicing particularly in the context of 5G networks on which he has publications in ICC’17 and also one in EuCNC 17. He is active participant to the IRTF/IETF where he has contributed to RFCs and internet drafts.

Sasu Tarkoma (SMIEEE’12) is a Professor of Computer Science at the University of Helsinki, and Head of the Department of Computer Science. He has authored 4 textbooks and has published over 160 scientific articles. His research interests are Internet technology, distributed systems, data analytics, and mobile and ubiquitous computing. He has eight granted US Patents. His research has received several Best Paper awards and mentions, for example at IEEE PerCom, IEEE ICDCS, ACM CCR, and ACM OSR.