Small cells, wireless backhaul and renewable energy: a solution for disaster aftermath communications

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ABSTRACT
In this paper we propose a network infrastructure to be deployed in the aftermath of a disaster with the aim of providing communication services to both emergency responders and civilians. The proposed infrastructure is a Network of Small Cells powered by renewable energy that features an all-wireless multi-hop backhaul network together with self-organization capabilities. After describing the main challenges to be investigated in the scenario under consideration, we describe in detail the proposed solution, introducing its main building blocks and architectural entities, and highlighting its benefits in comparison with legacy solutions.

Categories and Subject Descriptors
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1. INTRODUCTION
Communications is one of the most valuable asserts in the aftermath of disasters such as earthquakes, hurricanes, floods and terrorist attacks: on one side, it is vital to allow first responders such as firemen, police and medical assistance to coordinate and act both quickly and efficiently; on the other side it is of fundamental importance for civilians as well as for a broad range of use cases that go from emergency calling to getting in touch with potentially dispersed relatives and friends. The big challenge is that today’s communications are largely based on land network deployments, which unfortunately get easily damaged in the event of a disaster, often to the point that communications are not feasible over the whole disaster area.

In the recent literature, the topic of communications in disaster aftermath scenario has been dealt with from different perspectives. Some publications, among which we highlight [1–5], focus more on the issue of how to perform communications among emergency responders (firemen, police, etc.). From a technology point of view, most of these solutions [1–4] focus on wireless mesh networks based on the IEEE 802.11 standard, which are proposed as a convenient solution to the problem of achieving interconnectivity among the different emergency responder organizations, while avoiding the traditional problem of terminal incompatibility. In [5], Wireless Sensor Networks, such as those based on the IEEE 802.15.4 standard, are also considered, though in this case the focus is on monitoring the area of the disaster to obtain situational awareness and coordinate actions more efficiently.

It is to be noted that, while all the previously mentioned proposal are based on already standardized and commercialized radio technologies (IEEE 802.11 and 802.15.4), the complete system that would be needed by emergency responders is not standardized yet. In particular, the technology being proposed at the networking and application layer differs from each proposal, and is far from being standardized; hence, potential incompatibility problems among emergency responder organizations remain, and the solution to this problem is left to some superior organization (e.g., a dedicated governmental agency) to identify the specific system to be adopted by all organizations, and to commission its production to one manufacturer (with the consequent lock-in problems), or defining a standard (with the corresponding effort, delay and cost) for such system to be manufactured by multiple vendors on a competitive basis.

Furthermore, focusing on emergency responders only neglects a significant part of the problem of communications in disaster aftermath scenarios: how to restore civilian communications. A landmark paper on this topic is [6], which analyzes the issue from a policy point of view: the main conclusions is that for today’s competitive telecommunications market, in order to avoid the high costs and delays of traditional government-funded disaster recovery, governments should require from mobile operators the satisfaction of certain requirements for the recovery of service in disaster aftermath. This in turns translates into the need for operators to have a contingency plan for restoring communications in response to disasters.
The efficiency of such contingency plan has been evident in recent disasters. For example, after the Japan earthquake of May 11, 2011, “By 24 March [...] 90 per cent of the base stations in the Tohoku region – where the quake struck hardest – were back up” [7]. This has been regarded as a good achievement in comparison with previous similar disasters. However, this means 13 days for the original network to be restored: if no alternative communication infrastructure is present, it is still a significant outage. Can we do better?

A simple solution suggested in [6] is to use a satellite communication network as a backup. The same technology is also considered in other publications such as [8,9]. However, this type of communications is very costly, and presents additional issues such as high delay.

The solution that we propose in this paper is the use of a network of small cells powered by renewable energy and interconnected by a wireless backbone. This solution is described in the upcoming section.

2. THE PROPOSED SOLUTION

We propose a solution to be used for both emergency responders and civilians in a disaster aftermath situation. This solution is depicted in Figure 1. As represented in the figure, we distinguish between (i) the disaster area and (ii) the out-of-disaster area. The disaster area is the zone where the pre-existing communications infrastructure has been destroyed, and therefore the zone to be covered with the new infrastructure for emergency and civilian communications. The out-of-disaster area is the zone not affected by the disaster. From an architectural point of view, it is assumed that part of the network infrastructure (in particular a fully-functional core network) of the considered Mobile Network Operator (MNO) is in the out-of-disaster area, and hence is still operational. Our proposal consists of deploying a new mobile radio access network in the area of the disaster, which should serve the following purposes:

- to provide mobile communication services (data, voice calls, push-to-talk) to emergency responders;
- to restore mobile communication services for use by civilians.

For both these purposes, we consider the use of 3GPP mobile communications technologies, such as UMTS/HSPA and LTE. This choice is obvious for civilian use, given the high current penetration of UMTS/HSPA, and the expected high adoption of LTE. As for the use by first responders, we argue that these technologies are much better suited than legacy dedicated technologies. The reasons are the following. First, the most traditional type of communication performed by first responders, i.e., push-to-talk voice communications, is readily supported by 3GPP, in the form of the Push-to-Talk over Cellular (PoC) technology. Second, unlike many legacy first-responder communications technologies, 3GPP technologies also provide means for IP-based data connectivity, which
has already proven to be very useful to first responders. Third, the use of already standardized technologies such as UMTS/HSPA and LTE relieves governmental institutions from having to define new dedicated standards with the aim of achieving interoperability among the communication platforms of the different emergency responder institutions (police, firemen, etc.). Fourth, dedicated technologies are more expensive, due to the fact that components and devices are manufactured in limited numbers, while 3GPP-based devices can be cheaper due to their mass market and the corresponding economies of scale.

Clearly, the fact that the same network infrastructure is used both for first-responders communications and for civilian communications implies that proper policies are in place to give the needed priority to first responders communications. The exact definitions of these policies should be negotiated between governmental institutions and mobile network operators as part of the contingency plans to be adopted in the event of a disaster.

Fast deployment is probably the most important requirement in infrastructures deployed for disaster recovery. As a consequence, cable-less deployments are preferable to those requiring the layout of cables for both communications and power supply. Our proposal is to use an all-wireless Network of Small Cells (NoS) deployed with a loose and approximate planning in the disaster area. Small Cells (SCs) are base stations with a small form factor (similar to that of a WiFi access point). This type of devices is preferred over traditional macro and micro base stations for a number of reasons. First, the small form factor is easier to deploy in a loosely planned fashion, in response to the identification of communication needs (e.g., “we need connectivity over here”). Second, SCs have lower power requirements, which opens up the possibility of powering them with renewable energy, which, as we will argue later, is extremely beneficial. Third, the deployment of a dense network of self-organizing small cells is a very practical way of rolling out a high capacity network, and in fact this type of technology has already gained significant consideration for non-disaster scenarios.

We propose that SCs are interconnected by means of wireless backhaul links based on existing technologies (e.g., IEEE 802.11, IEEE 802.16): all these interconnections form a wireless mesh network which is the backbone of the NoS. Moreover, each SC is powered by a renewable energy supply (e.g., a photovoltaic system), so as to achieve a self-sustainable and completely cable-less network. We note that energetic self-sustainability is highly valuable in a disaster aftermath scenario, since the electric grid gets also often damaged or destroyed in the event of a disaster.

All the nodes of the NoS have the same functionalities, except the two edge nodes called Local NoS Gateways (LNGWs), which connect the NoS with the core network in the out-of-disaster area. The connectivity between the LNGWs and the core network of the MNO can be realized using cables deployed on purpose, if feasible, or high capacity wireless links. The dimensioning of such links is to be analyzed on a case by case basis, considering different factors like the available infrastructure after the disaster, the monetary cost of the equipment to be installed, the cost of the connection and the required link capacity.

3. SELF-ORGANIZATION CAPABILITIES
It is crucial that the small cells to be deployed feature self-organization capabilities to allow a loosely planned deployment with minimum intervention by system engineers. These self-organization capabilities need to cover different aspects. First, at the radio access level, the different cells must coordinate among themselves for spectrum access in order to provide for an efficient utilization of the available spectrum resources in the disaster area. This is crucial since, for example, resorting to traditional frequency planning approaches would be too time and resource consuming and, in the aftermath of a disaster, would cause unacceptable delays in the roll out of the radio access network in the affected area. Different techniques will be adopted depending on the type of radio technology being used: for WCDMA the focus will be on power control and scrambling code management, whereas for LTE it will be on interference coordination leveraging on interference information exchanged among eNBs over the X2 interface.

Second, given that we are considering the use of a wireless multi-hop backhaul network to connect the small cells among themselves and with the operator’s core network, it is vital that self-organization capabilities are also employed to manage the wireless backhaul itself, as we will discuss in detail in Section 4.3.

Compared to the traditional deployment of (isolated) small cells, a NoS allows a more cost-effective deployment by building a network between nearby small cells, hence allowing multiple small cells to share the same connection to the core network of the MNO. In a generic scenario, this presents several advantages. First, it reduces deployment and operation costs for the Mobile Network Operator (MNO). Second, it offloads signaling traffic from the core network of the MNO. Third, when combined with local IP access (LIPA) and SIPTO, it also helps offloading data traffic from the core network of the MNO. However, the feature of a NoS that is likely to be more appreciated in disaster aftermath scenarios is fast deployment. In fact, by removing the need for previous site and frequency planning prior to network roll out, and by avoiding the time consuming layout of cables, a NoS can be deployed very quickly in response to a disaster.

4. ARCHITECTURE OF THE NOS
The proposed architecture for the communications infrastructure is based on the concept of networks of femtocells coined in the context of EU project BeFEMTO [10], which is directly applicable to networks of small cells. In fact, femtocells could be seen as a particular instantiation of small cells. We focus on all-wireless Networks of Small cells (NoS) due to their fast deployment and self-organized operation, as argued above, and more specifically, we focus on their architectural implications to the Evolved Packet System (EPS). The proposed approach leverages on the advantages of mesh networking deployments and geographic and backpressure routing so as to produce a scalable solution by reducing over-the-air control overhead for building an operational network.

Figure 1 illustrates the concept of all-wireless NoS integrated...
4.1 Challenges of networks of small cells

The integration of data networking concepts, such as a large-scale geographic and backpressure-based all-wireless NoS, in a 3GPP context has some architectural implications. This high-level architectural design affects in all relevant procedures of the operation of the network, but the adaptation of such procedures to the new architecture is constrained by what has already been standardized by 3GPP. In practice, this translates into the need to not introduce modifications neither to user equipment (UE) nor to 3GPP procedures, yet being able to efficiently serve UEs inside the NoS. Small cells have been thoroughly standardized in EPS, but, up to our knowledge, no concept such as NoS is being considered.

Particularly relevant are those procedures related to mobility management (including handoff and location management). In a large-scale NoS, a high number of UEs will be changing from one small cell to another one in relatively short periods of time. Consequently, local mobility management has to solve the scalability problem in terms of signaling towards the Mobility Management Entity (MME) at the core network of the MNO. The bandwidth of the links from the LNGWs to the core is very costly, and therefore the signaling traffic must be kept local as much as possible. Another scalability problem to solve is the large-scale all-wireless nature of the network under consideration. In this case, the goal is to minimize over-the-air signaling traffic.

Due to the constraints posed by 3GPP specifications, the high-level design principles of the architecture are those of the EPS, still some adaptation is needed for the correct integration of NoSs. In this paper, we advocate the adequacy of concepts previously developed in the context of data networking over wireless mesh networks (e.g., geographic routing) to solve some of the issues that appear in large-scale all-wireless NoSs while leaving 3GPP procedures unchanged. The following subsection explains how we achieve this goal.

4.2 Overview of the architecture

Bearing in mind the above scalability challenges, two main components were envisioned, namely, a geographic network overlay that exploits geographic information for key network layer procedures (e.g., routing and mobility management) and Local NoS Gateways (LNGW) acting as interface between the NoS and the core network of the MNO.

4.2.1 Geographic network underlay

A key building block of our architecture for the NoS is a sublayer (referred to as Geo Sublayer in figure 2) inserted in the stack just below the IP layer that is capable of handling geographic information and of executing network layer functionality, such as routing or mobility management, based on this information. In fact, IP packets are transported as payload of geopackets (i.e., packets that are forwarded based on the geographic information they carry in their header). The rationale behind exploiting geographic information is to benefit from the scalability of geographic routing protocols. This scalability is attained by only exchanging information with neighboring nodes, which allows taking forwarding decisions based only on the local position and that of the neighboring nodes. Additionally, as explained in section 4.3 in detail, our proposed routing protocol also leverages the scalability advantages of backpressure routing, while efficiently distributing the load amongst all small cells as needed, hence fully exploiting the available resources (in particular, the bandwidth in the wireless backhaul) in a self-organized way as they are deployed. The combination of these two routing approaches results in less radio resources being consumed, which makes these schemes interesting in resource-constrained deployments, such as those found in disaster areas. Furthermore, this geographic underlay network is transparent to both IP and 3GPP messaging, hence not implying any modification to their specifications, and, thus, to their regular operation.

4.2.2 Local Network of Small Cell Gateway (LNGW)

Additionally, scalability towards the core network is attained by introducing a new network node (referred to as Local NoS Gateway, or LNGW) acting as interface between the NoS and the core. LNGWs implement a logical function called Proxy S-GW (P-SGW) that performs S1-U bearer termination and mapping between the NoS and the EPC, as well as user-plane data routing from/to the NoS and the EPC.

There could be multiple LNGWs in a NoS, mainly depending on the dimensions of the network or area to cover after the disaster, the traffic patterns to serve, and the availability of stable spots where a link (wired or wireless) could be established towards the core. These nodes will act as traffic aggregation points of the NoS for both signaling and user data towards the core network of the MNO. In this sense, they have functionality similar to that of a HeNB GW for femtocells in the sense that the network entities of the core network (MME and S-GW) and small cells send regular S1 messages, as if they were communicating to each other, but in fact, these messages are being intercepted by the LNGW, which triggers the corresponding geographic procedures internal to the NoS without modifying the messages. However, a substantial difference is that the LNGW is deployed in the local network and not on the core network side. This has some security implications since the IPsec tunnel should be broken at the LNGW. However, this issue is out of the scope of this paper.

4.2.3 Other relevant building blocks

The correct operation of the geographic underlay also requires maintaining an associated Local Location Management service (LLM). As we anticipated, in a large-scale NoS...
a high number of UEs will be changing from one small cell to another in relatively short periods of time. User location mechanisms in 3GPP networks rely on mobile subscriber identifiers, such as the Serving Temporary Mobile Subscriber Identity (S-TMSI). Since our scenario assumes that a small cell can obtain the geographic coordinates of the intended destination within the NoS, an LLM scheme is needed in order to map a given 3GPP mobile subscriber identifier to the geographic coordinates of the small cell where that UE is currently camped on.

As the concept of NoS has not been standardized in 3GPP Technical Specifications (TS), there is no existing 3GPP mechanism that allows small cells to exchange user-plane data directly between them, i.e., without having to traverse a S-GW or a P-SGW [11]. In our scenario, IP packets are routed over the NoS in a completely transparent way to existing 3GPP control- and user-plane procedures. In order to do so, small cells in the network implement Local IP Access (LIPA) mechanisms that are able to identify IP packets addressed to local UEs. Once detected, these packets are handed over to an underlay network that carries out routing and local location management. This underlay network is built by inserting a new layer between legacy IP and L2 layers (see figure 2), which keeps on working in the same way, as interfaces are respected. We note that this functionality is critical in a disaster aftermath scenario, where the communications among first responders is expected to generate a huge amount of local traffic.

The reader should also notice that the implications described above are only local to the NoS and completely transparent to both the EPC and the UEs. This is shown in Figure 2 where the protocol stack (user and data planes) of the SC and the LNGW are represented. One can see that the side of the protocol stack exposed to the UE by the SC is exactly that standardized by 3GPP. The same happens at the LNGW. As a final remark, we note that intermediate SCs, i.e., those helping other SCs to make their bearers reach the appropriate 3GPP entities, just work at the transport layer (using 3GPP terminology), and hence are transparent to 3GPP control and user plane traffic. Therefore, at intermediate SCs, only L1, L2, and the Geo Sublayer are involved in the forwarding of geopackets.

### 4.3 Wireless Multi-hop Backhaul

As we argued in Section 2, the use of a wireless multi-hop backhaul network is a key aspect of our proposal for disaster aftermath communications. In order to allow the NoS to be deployed and become operational quickly, the multi-hop wireless backhaul must self-configure and self-organize itself without manual intervention, and ideally, without centralized servers. To realize this distributed approach, the NoS requires a carefully designed solution for the routing of S1 packets (see Figure 1) within the wireless backhaul.

This section discusses on the main challenges for the design of such a routing solutions, and presents our proposed solution as well, briefly explains its implications on the 3GPP architecture.

#### 4.3.1 Requirements for Routing in the NoS

Given the unreliability of the environment (SCs with depleted energy, unreliable links, etc.), distributed solutions are more appropriate, as their self-configuring and self-healing capabilities provide more robustness. This is in contrast with centralized solution which have single points of failure and normally require human intervention for reconfiguration. Therefore, a routing solution for disaster aftermath should be distributed. Furthermore, the solution should be scalable; in practice this translates into being as stateless as possible. That is, the routing protocol should not require storing a lot of network information at nodes (i.e., SCs). The reason is that NoSs may potentially have a large number of nodes and serve a large number of users. Therefore, solutions that require having a complete picture of the whole network for route calculation would not be appropriate. This requirement is even stronger in all-wireless NoSs, since such an information would be obtained by transmitting high volumes of control traffic over the air. In conclusion, disaster aftermath networks should ideally require no route computation prior to sending a data packet. In this way, a routing protocol could be deployed in an unreliable all-wireless NoS without generating high volumes of control overhead. Furthermore, since there would be no stateful routes to maintain in the network, there would be no need for extra processing at nodes, hence becoming more energy efficient.

#### 4.3.2 Proposed Routing Protocol for the NoS

The novelty of the proposed routing protocol resides in that it allows communication between a small cell and the S-GW (through any LNGW), or even, any pair of small cells in the NoS by exploiting two different routing approaches, namely backpressure and geographic routing. Specifically, the knowledge that nodes require for taking routing decisions is: 1) the geographical coordinates of the destination (which are carried in each data packet), 2) the queue backlogs of 1-hop neighbors (which is exchanged in hello packets), and 3) geographic coordinates of 1-hop neighbors (also in hello packets). In this way, and only with this information, nodes take forwarding decisions on a per-packet basis.
hence, there is no concept of route. To explain the behavior of the protocol at a high level, the information on queue backlog is used for load balancing purposes (i.e., packets are sent to those nodes that are less loaded), and the geographic information is used to steer packets towards the intended destination. The combination of both approaches provides both scalability and a good balance between using all the available resources in the NoS and making the packet reach the destination in a timely fashion.

The routing protocol proposed matches the main requirements mentioned above:

- Scalability: the routing protocol is able to serve a high number of SCs. Additionally, it is able to react properly to increases in traffic load.
- Quasi-Stateless: the information stored at each small cell increases linearly with the number of 1-hop neighbors (i.e., with the density of SCs), but does not depend on the total size of the network, which can therefore be very large. Moreover, there is no end-to-end route computation needed to steer packets towards the intended destination.
- Distributed: by exploiting local (1-hop) information only, the routing protocol does not need a central entity for its operation.
- Dynamicity: the routing protocol takes forwarding decisions on a per-packet basis. Therefore, the routing protocol has unconstrained dynamics in the sense that the path followed by different data packets belonging to the same flow may not be the same.

Detailed information on the operation of the protocol, the theoretical framework with which the resulting distributed routing protocol is built, and evaluation results of the routing protocol can be found in [12].

5. RENEWABLE ENERGY

As we discussed in Section 1, the use of renewable energy is very promising for a NoS to be employed in a disaster aftermath scenario, because it allows the small cells to be entirely cableless. In this section, we will discuss about the technical implementation of this solution.

Nowadays the use of renewable energy is becoming more and more popular, not only because of environmental issues, but also in several cases thanks to its lower costs. A variety of ambient sources such as solar, thermal, acoustic noise and mechanical vibrations can be exploited as energy suppliers. Among them, solar energy seems to be the most promising solution for its level of diffusion (approx. 23 MW in 2009 [13]) and the significant amount of harvestable energy that it can offer (about 10 mW/cm² during daylight [14]). Usually, this energy is harvested by means of photovoltaic (PV) power generators, i.e., arrays of solar panels made of photovoltaic material (semiconductors able to convert solar radiations into current electricity).

When using PV panels, a key issue is to dimension the PV system based on the power dissipation of the devices to be supplied; this includes the size of the PV panel as well as of the battery that is required to cope with the periods in which solar energy is not available (e.g., at night). Such a problem has been analyzed in the literature for the case of macro Base Stations (BSs) [15,16]; however, due to the high power consumption of this type of BS, the big size and high cost of the required solar panel and batteries caused a scarce success of this solution in the market. On the other hand, small cells have more limited transmission power and computational capabilities than macro BSs; as a consequence, their power amplifiers are smaller, and cooling systems are not needed, thus reducing their total power consumption. Let us take a commercial 3G UMTS/HSPA femtocell as a possible example of a small cell: its average power consumption is about 0.330 kWh/day [17]. Based on the current PV technology, a PV panel of about 60 W and 1 m² size is needed, which is reasonably compact, and has a cost of less than 300 EUR, which is reasonably low. Based on these considerations, we can conclude that, with the current technology, it is now possible to deploy a cost-effective and practical NoS powered by solar energy.

Of course, powering the NoS relying on solar energy, and on renewable energy in general, poses new technical challenges. As a first approximation, we can say that the usage of renewable energy sources introduces a new set of variable in the management of the NoS that represents the energy available at each small BS. In fact, the major problem introduced by the renewable energy is the variable and unpredictable amount of the energy that can be harvested. In fact, solar power can only be harvested during the day, and it is affected by variable phenomena such as clouds, rain, season changes, and so on. Therefore, the system has to be able to dynamically reconfigure itself in order to respond to the energy source dynamics. With this respect, the self-organization capabilities of the network, already discussed in Section 3, are expected to play a key role, for example by having the BSs dynamically switch on and off in a coordinated fashion in order to optimize their power consumption and guarantee network survivability – i.e., to guarantee that there are always enough BSs available with enough energy left to satisfactorily serve the traffic demand.

In addition, as already argued again in Section 3, interference management is a key issue in a loosely planned or unplanned NoS deployment, and it is expected that smart dynamic resource allocation algorithms will tackle this issue by leveraging on information shared among the BSs about the mutual interference. When renewable energy is also used, we suggest that the interference management should be optimized jointly with the BS activation pattern. For example, if two BSs are generating a similar amount of interference, it makes sense for an interference management algorithm to turn off the one that has the lowest residual energy, in order to prolong its lifetime. Similarly, traditional Call Admission Control and Mobility Management strategies account only for the radio aspects of communications. With the advent of small BSs powered by renewable energy, these strategies need to be properly revisited. As a simple example, if a BS is switched on and off according to some duty cycle, the Mobility Management entity must assure that, before allowing a specific BS to turn off, all its users have been handed over to a neighbor BS; at the same time, the Call Admission
Control entity should forbid the attachment of users to the BS that is being turned off.

6. CONCLUSIONS
In this paper we described how a wireless communication network can be deployed quickly and efficiently in the aftermath of a disaster by leveraging on i) small cell devices, ii) a self-organizing wireless multi-hop backhaul network, and iii) renewable energy sources such as, in particular, photovoltaic panels. We discussed in detail the technical challenges that are relevant to each of these particular aspects. Among the interesting future research lines that could be followed based on this work, we highlight the design and investigation of practical self-organization solutions that can manage jointly communication and energy resources, and at the same time the realization of prototype systems that can stand as a proof-of-concept of our proposed architecture.

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8. REFERENCES