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Designing inclusion and continuity for resilient communication during disasters

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ABSTRACT

This paper addresses the challenge of establishing a resilient disaster communication system that transitions seamlessly from a phone-based ad hoc network to any portable infrastructure and back. For this purpose, this paper presents a value-based design of an autonomous and self-organized protocol (SOS-hybrid). This design ensures seamless integration between various communication networks taking local context into account to increase inclusion and continuity of connectivity. SOS-hybrid has two benefits. First, local self-organization can adapt to the local situation in a disaster area. Second, context-awareness can fill in the spatial gaps of coverage associated with top-down approaches. An agent-based modelling approach was used to develop the simulation of the proposed communication network to evaluate the impact of introducing SOS-hybrid in the aftermath of a disaster. SOS-hybrid allows phones to simultaneously provide the benefits of (i) ad hoc mobile networking, allowing hard-to-reach people to connect, and (ii) infrastructure-based communication, allowing phones to more efficiently send messages over long distances. Benefits include two-way communication between community and rescue operators, inclusion and continued connectivity for immobile citizens stuck in isolated out of coverage areas, and seamless transition without loss of messages.

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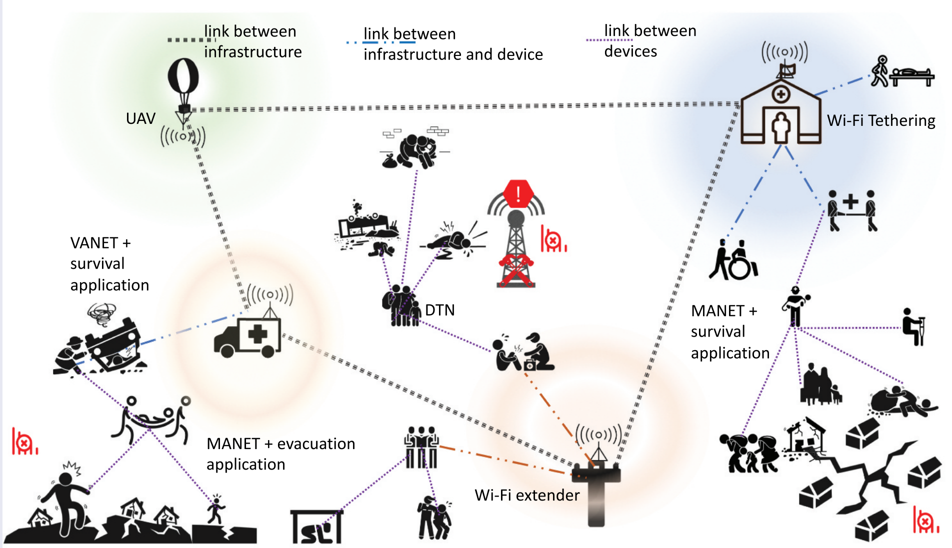
Designing inclusion and continuity in disaster communications



1. Introduction

Communication is vital during disasters. Disaster response requires the involvement of and communication between non-governmental organisations, governments and affected citizens (Clark et al., 2019; Daar et al., 2018). However, damage to backbone telecommunications and electricity grids prevents traditional communication channels such as telephones, radios and televisions from exchanging and broadcasting information. Affected citizens are often no longer able to use their mobile phones to request help or coordinate rescue activities due to lack of connectivity. This paper presents the design of a hybrid communication system (SOS-hybrid) that ensures continued connectivity and

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communication during disasters to address this challenge.

Disasters are now occurring with an average of one disaster per week (Berlemann & Steinhardt, 2017; IFRC, 2015; Yeeles, 2018). Rapid urbanisation, for example, entails that 2/3 of the world population (especially the poor) in the next decade will live in river deltas that are prone to massive calamities such as flooding due to sea-level rise (Cutter & Finch, 2008). To ensure that a broader population has access to communication opportunities, the availability of having affordable and easy to deploy solutions becomes a fundamental requirement for emergency communication systems. This holds in particular for the first 72 hours after a disaster, for which communication most often relies solely on the citizens' mobile phones.

Enabling communication between these phones without infrastructure using Mobile Ad hoc Networks (MANET) has been shown to work. This increases community resilience (Banerjee et al., 2020; Petersen et al., 2020) until rescue arrives. *Resilience* here is defined as citizens being able to recover and adapt to the disrupted situation after a disaster. Notably, this does not necessarily mean the restoration of earlier infrastructures (Koliou et al., 2020). Once rescue teams are on-site, citizens can connect to external WiFi equipment such as Unmanned Aerial Vehicles (UAVs); (Tuna et al., 2014), WiFi access points (Sakano et al., 2016), and high capacity radio relays (Al-Hourani & Kandeepan, 2013) brought on site by the rescue teams. These forms of equipment can provide connectivity over a larger area and provide internet access over the disaster site. Such solutions, however, do not work for citizens who are outside the coverage of these infrastructures. Their rescue depends on the ability to communicate using an on-the-fly ad hoc mobile network that utilises Bluetooth or WiFi capability of mobile phones to transmit messages. Such ad hoc networks are the only possible way for those who are immobile (i.e. secluded) to communicate.

This paper explores the potential of a new approach: a hybrid design, in which two types of solutions – ad hoc mobile MANET solutions and infrastructural WiFi solutions – work together. This paper makes this the primary goal and investigates whether a hybrid design can ensure reliable and continuous message delivery irrespective of the location and mobility of citizens.

2. Related work: implications of the existing communication approaches

Traditionally, ad hoc mobile MANET solutions, i.e., bottom-up approaches, and infrastructural WiFi solutions, i.e., top-down approaches, work independently from each other. A top-down approach directs communication towards the citizens and rescue operators. The equipment used for top-down communication is generally owned by the government, rescue operators and telecommunication providers. This equipment temporarily replaces traditional backbone telecommunication infrastructures during disasters and provide connectivity across a particular range.

In bottom-up approaches, a community can exploit available technologies such as phones to distribute information and use citizens' context-awareness to recover (Howard et al., 2017). One of the benefits of such community-centred communication systems is that people know their community better than the authorities do. People know which houses have small children, elderly people, people in wheelchairs, etc., so they know where assistance is most urgent. People also know which of their neighbours with specific skill sets may help, such as medical doctors, firefighters and builders. Lastly, people know about local resources, such as tools, tractors, boats, medical supplies and food.

This information can be shared with other citizens, utilized immediately after the disaster, and often does not reach authorities due to a lack of two-way communication. If locals are actively involved in rescuing themselves and others, this may greatly improve survival chances.

Both top-down and bottom-up approaches have their drawbacks. Top-down approaches require time to implement. The interplay between regulatory barriers such as socioeconomic status and government policy and technological and geographical limitations determines where broadband and telecommunication infrastructure is set up (Grubesic et al., 2011). Most often, infrastructural coverage for communication and basic facilities does not equally extend to every part of a city or area. This is true for many countries such as Bangladesh (Dwivedi et al., 2007), India (Bagchi, 2005), Nepal and Indonesia (Quibria et al., 2003). A disaster makes these 'islands of inequity' (Alizadeh, 2017; Grubesic, 2015) even more neglected.

Bottom-up approaches also have their drawbacks. Generic mobile ad hoc networks drain phone energy reducing communication opportunity and participation for phones with lower battery charges. Taking a systems perspective, Banerjee et al. (2021) shows that forming all possible connections with nearby phones incurs such high battery costs that those who have low initial battery are quickly unable to participate. This is worsened by the possible unavailability of energy infrastructure, which means phones can also not be recharged.

Previous work (Banerjee et al., 2020, 2021), proposes improvements to the bottom-up approach of mobile ad hoc networks that remedy the typical drawbacks of mobile ad hoc networks. The 'Self-Organisation for Survival' (SOS) protocol self-organises to ensure that only phones with sufficient battery charge become central to reroute messages and that low battery charge phones only form necessary connections. This protocol is adaptive so that phones switch roles as the state of their relative battery charge changes over time. SOS enables all citizens with different phones, regardless of their battery charge, to form a communication network and participate in organising self-rescue operations during the immediate aftermath of a disaster. Notably, the SOS protocol is entirely decentralised. All operations are based on local knowledge and distributed.

Even though SOS can provide emergency communication to citizens, regular access to backbone communication infrastructures is often preferable. First, authorities use communication infrastructure to transmit trustworthy information to citizens, structure rescue operations, and communicate instructions for citizens to follow to improve their chance of survival.

Second, most communication infrastructures are more efficient in transferring messages than mobile ad hoc networks, especially over longer distances. Mobile ad hoc networks require many phones to reroute messages sent over longer distances, which incurs a small battery cost every time. The present article aims to combine the benefits of the bottom-up SOS with the benefits of top-down approaches: A hybrid approach.

A stylised resilient hybrid-communication system connectivity is shown in Figure 1, depicting the communication capacity of a community over time. Complete dependence on infrastructure results in discontinued communication, as shown in the graph (yellow line). Restoring communication requires either repairing infrastructure or replacing damaged parts with new equipment. While restoration can take days or even weeks, SOS and SOS-hybrid can fill in and reduce this impact through an autonomous and self-organised mobile ad hoc network. This ensures reduced disruption so that communication services can quickly resume when time is of the essence.

2.1. A hybrid approach: The missing systems perspective in existing research

Hybrid approaches have been proposed before. Researchers in Engineering and Computer Science have designed communication protocols and frameworks that allow multiple types of equipment to work together. Most studies propose frameworks (Madey et al., 2006) that are centrally controlled systems which improve either data latency or bandwidth optimization. These studies (Bhatnagar et al., 2016; Chandran et al., 2020; Ochoa & Santos, 2015; Shibata et al., 2007) propose the use of global knowledge to control and design systems that ensure connectivity. For example, Madey et al. (2006) propose the use of wireless call data triangulated from cellular towers to obtain and understand the movement and calling pattern of a population during an emergency in their WIPER (Wireless Phone-Based Emergency Response System). Bhatnagar et al. (2016) propose an approach to designing a hybrid communication emergency network and use centralized

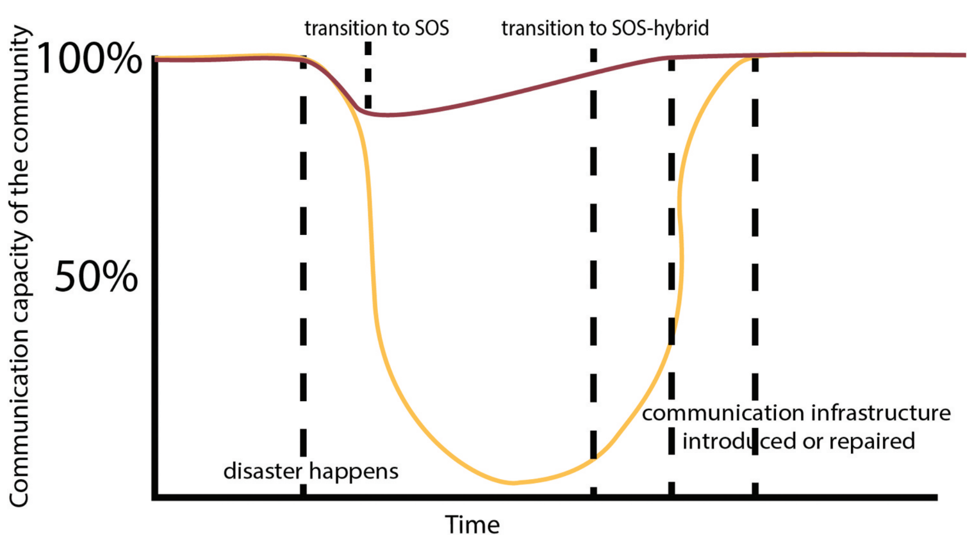

Figure 1. Stylised resilient communication graph. The yellow line represents the development of connectivity over time without the SOS-hybrid protocol. The brown line represents the same with the SOS-hybrid. Events occur at the dashed lines. The first dashed line denotes the beginning of infrastructure failure due to damage caused by disaster, where connectivity starts to drop due to cascading failures. At the last three dashed lines, more and more infrastructures become available again.

control to gather and disseminate data. NerveNet (Inoue et al., 2014) has been designed with central control and utilizes a mesh topology for increasing redundancy. Hybrid systems that rely on centralized control can only work if power grids are not affected by disasters.

Madey et al. (2006) recognize that central control during extreme emergencies such as an earthquake is not possible as most infrastructures tends to be damaged. Additionally, extended power outages reduce the number of phones that can provide such services. A lack of consideration of energy efficiency and an over-reliance on centralized solutions have been common disadvantages in many technologies proposed over the years (Chandran et al., 2020; Legendre et al., 2011; Shibata et al., 2007). A second disadvantage is that many hybrid technologies require expensive equipment. NerveNet was developed in Japan. Many disaster-prone countries, however, are underdeveloped or still developing. Therefore, the proportion of tech-literate population is limited, and there is a limited budget available for maintaining sophisticated hybrid solutions.

The top-down approach provides a stable means of communication for all people within the range of the available infrastructure. The SOS ad hoc mobile network is adaptive, forming and breaking ad hoc connections with phones that come into transmission range and move out of this range again. This adaptivity requires the costly formation of connections but has its own merits. An adaptive network may not provide constant access to all people. However, as people move around, the network may also provide intermittent access to communication for those in remote locations. SOS fills in the spatial gaps, where infrastructure is unavailable.

Figure 2 illustrates a disaster site with various top-down communication equipment. It also shows that mobile and immobile citizens might not be in the coverage area. The citizens outside of the range of traditional equipment can utilize mobile ad hoc networks to communicate with others. A combined solution, in this case, allows a seamless and continued network consisting of both infrastructure-based communication and mobile ad hoc networks. A connection choice depends on what is available (optimum) at any given time.

3. Conceptual design requirements of the protocol: enhancing SOS to SOS-Hybrid

The primary goal of this paper is to design an easy-to-deploy hybrid communication system that can utilize the benefits of both top-down and bottom-up emergency communication approaches. To incorporate inclusion and continuity, SOS-hybrid extends the design of ”Self-Organization for survival” (SOS) system (Banerjee et al., 2020, 2021). SOS system uses a bottom-up self-organized communication approach to provide affected communities extended and increased access to

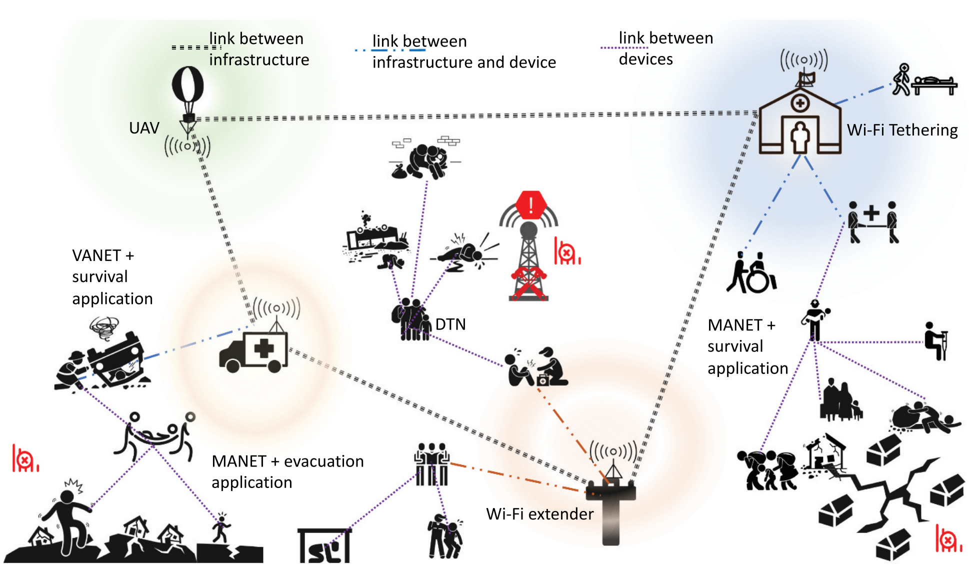

Figure 2. Illustration of a disaster site with various types of communication equipment used for connectivity and their corresponding possible network solutions. Four different bring-on-site types of infrastructure are shown, UAV, VANET, WiFi Extenders, and a relief camp with WiFi access. Each has its own coverage limitations. There are both mobile and immobile citizens and coverage areas corresponding to each type of equipment.

communication via a peer-to-peer communication network designed for fair participation.

SOS (Banerjee et al., 2020) consists of a decentralized context-adaptive topology control protocol that utilizes Bluetooth low energy (BLE) interface of phones to connect with other phones in an area and form MANET. The SOS protocol combines three algorithms and uses preferential attachment based on the energy availability of devices to form a loop-free scale-free adaptive topology for an ad-hoc communication network. SOS aims at overcoming limitations generated by the uneven distribution of battery charge among mobile devices in emergency situations. The fundamental idea underlying SOS is compensating battery charge inequality with a non-homogeneous allocation of communication costs. SOS uses context-aware local self-organisation to deliver participatory fairness, where the topology adapts and no phone has a fixed role as message routing hub. As the battery charge changes over time their role also changes over time. This makes sure that everyone has same amount of communication opportunity. The SOS system has a number of advantages. First, it is adaptive to the environment. This means it is applicable in scenarios that may vary in the density and mobility of devices, and in the availability of energy sources. Second, it is energy-efficient through changes in topology. This means it can be flexibly combined with several routing protocols. Third, the protocol requires no changes on the hardware level as it uses BLE interface of phones. This means it can be implemented on all current phones, also in the global south, without any recalls or investments in hardware changes.[1] This research presented in this paper differs from previous work as the design includes a protocol that accounts for switching between bottom-up and top-down communication approaches and delivers inclusive and continues communication services. The hybrid protocol utilizes local knowledge and context-awareness to find the most optimum network to connect depending on availability. This approach ensures that messages are delivered for both mobile and immobile citizens continuously and reliably for a more extended period if at all possible. The design of the protocol adopts a socio-technical systems perspective for requirement specification. The system itself includes many entities, including the environment for which it is designed. Emergent behavior arises when all entities in the system: (mobile and immobile) citizens, physical infrastructure, and mobile phones (with or without access to energy resources) interact. Existing literature proposes solutions that focus on individual device level performance and do not account for the emergent behavior of the system as a whole. Below, the scope of the research and design limitations are first introduced. Next are the requirements of this design, some of which are already met by SOS, and some of which are novel to this paper. The design approach itself is described as are the design choices. Last, the design itself is presented: a new protocol called SOS-Hybrid.

3.1. Research scope and design limitations

SOS-hybrid is an advanced version of the preliminary design of SOS. The initial version of SOS has been proposed in previous work (Banerjee et al., 2020, 2021) where it has been demonstrated that the relative advantage of SOS depends on the density of an area. In a densely populated area, more phones are in the range of each other, thus allowing more chances of transferring messages. Therefore the successful deployment of SOS-hybrid depends on the density of phones in an area. Additionally, each person must have the SOS-hybrid application installed on their phones to seamlessly transition back and forth between various communication networks.

3.2. Value-based system requirements: designing for continuity and inclusion

The design of the protocol is based on six main value-based system requirements: continuity, inclusion, participatory fairness, reliability, automatic and adaptive services, and distribution of tasks.

3.2.1. Continuous connectivity for all, despite 'islands of inequity'

The first requirement that SOS-Hybrid is designed to meet is spatial justice. The requirement is to ensure that, regardless of where the government or rescue operators decide to put emergency communication equipment, as many people as possible should access these resources even if they are outside the coverage area of the equipment that rescue workers have brought. Impoverished, highly populated areas, so-called 'islands of inequity' (Grubesic, 2010), need to be able to be reached by disaster response teams.

Furthermore, those in impoverished areas especially need to be empowered to help themselves, because, if a system achieves resilience only through empowering the affluent citizens, the system may promote rather than reduce already existing injustices (Comes et al., 2019). Hybrid solutions need to provide this functionality: to provide communication to these areas that may fall outside the range of current emergency communication infrastructures.

3.2.2. No new equipment

The second requirement is that no new equipment is needed or changes at the hardware level of phones. Other hybrid solutions that appear in the literature introduce new equipment (Miranda et al., 2016), allow for WiFi tethering (Raj et al., 2014), high-range radio relays (Soldani & Dixit, 2008), low power wide area network technology (Ali et al., 2017), or UAVs (Tuna et al., 2014) and sometimes requires changes to be made to the hardware level of mobile phones as part of the solution.

Such solutions bring three disadvantages. First, they are often too expensive for citizens, especially as disaster-prone areas are often poorer than average. Second, not all governments have the budget or the foresight to invest in new equipment to help disaster mitigation. Third, the skilled professionals required to operate these systems are not always available.

3.2.3. Reliable message delivery for all

The third requirement is that all messages sent are to be received by the intended receiver within a reasonable period. Every message can make a difference in a person's survival in a disaster situation. It is helpful to separate the different parts of this requirement:

- No message should be lost indefinitely.
- All messages that people want to be sent should be sent, regardless of their situation.
- All messages that need to be received should be received, regardless of the sender's or the receiver's situation.

3.2.4. Automatic and adaptive services

The fourth requirement is that the system is autonomous and can automatically adapt to changing circumstances of a disaster (Gilrein et al., 2021. The technical system should operate independently and automatically, without operators intervention. Citizens should not need to think about establishing a network or choosing the type of connection required to send a message. These operations should occur in the background seamlessly and automatically. This requirement ensures that the system is usable for a population with little technical education and know-how.

3.2.5. Distributed architecture

The fifth requirement is a distributed and decentralised system. Systems that rely on centrally organised communication are vulnerable to disruptions caused by disasters. There is always a central point of failure. Distributed systems are more resilient to adapt to changing conditions. Centrally organised systems are often designed and optimised for a specific topology and disaster scenario. However, because no two disaster scenarios are the same, there is a risk of performing suboptimally when the context is different from what was anticipated or when the context changes over time.

3.2.6. Participatory fairness

The sixth requirement, namely participatory fairness, was the primary requirement of the previous work published on SOS (Banerjee et al., 2020, 2021). Participatory fairness refers to equal opportunities for the participation of all citizens using their phones. As discussed in the introduction section, many ad hoc mobile communication solutions do not consider inequity in battery charges. They require significant battery power to form connections to neighbouring phones. SOS allows phones to switch roles, depending on battery availability.

High-battery phones carry the burden of forming connections and acting as nodes to relay messages. When they become depleted or the neighbouring phones have higher battery power they switch roles. The adaptive context-aware role switching allows low-battery phones to participate for a longer time period and higher-battery phones to remain connected. As participatory fairness is discussed at length in previous work, and is not the primary focus of this paper. However, participatory fairness as a value is still an important requirement in the protocol design.

4. Approach: context-awareness and self-organization

Context-awareness and self-organisation as an approach can fulfil the central values formulated above in the requirements section. This paper proposes a context-adaptive protocol to enable autonomous self-organising and self-healing to ensure continued connectivity for communication in sudden-onset disasters. The protocol is based on the MAPE cycle proposed by Kephart and Chess (2003): a cycle of **M**onitoring contextual changes, **A**nalyzing possible connections, **P**lanning the network and then **E**xecuting the connection and message transmission, as described in this section.

When a phone is not connected to any infrastructure and wants to send a message, it starts monitoring its context (i.e. its environment). It monitors if there is an alternative working infrastructure in the vicinity to connect. If not, it monitors if there are other phones nearby.

The protocol requires each phone or device to store an information tuple with contextual information. The contextual information stored on each phone consists of its unique identifier, an infrastructure-id that represents the infrastructure to which it is (possibly) connected, a subtree identifier and its residual battery charge. The phone also maintains a list of possible connections with other phones in the vicinity. Initially, a disconnected phone has an empty list of connections. When the phone transitions to SOS or hybrid mode, it starts making connections, and this list grows. If the phone connects to infrastructure, it updates the information tuple: An infrastructure-connected phone maintains the identification of the infrastructure in its information tuple. Otherwise, the infrastructure identification number field in the information tuple remains null.

When this field is null, it triggers an event-driven reconfiguration process requiring the phone to find alternative ways to form a communication network. Phones either connect to other disconnected phones to form their own SOS ad hoc network, or connect with another phone with an infrastructure connection to be part of a hybrid network.

By analysing its context, each phone decides which connection to choose. The goal of the protocol is to facilitate a smooth transition between infrastructures and ad hoc mobile networks that travel back and forth between different communication choices.

Choices range from:

- getting connected to newly available infrastructure, i.e, infrastructure mode,
- connecting to other phones to form a mobile ad-hoc network, i.e, SOS mode,
- become part of a hybrid network by being indirectly connected to infrastructure through another phone.

Figure 3 depicts a flowchart representation of this process concerning the different types of connections.

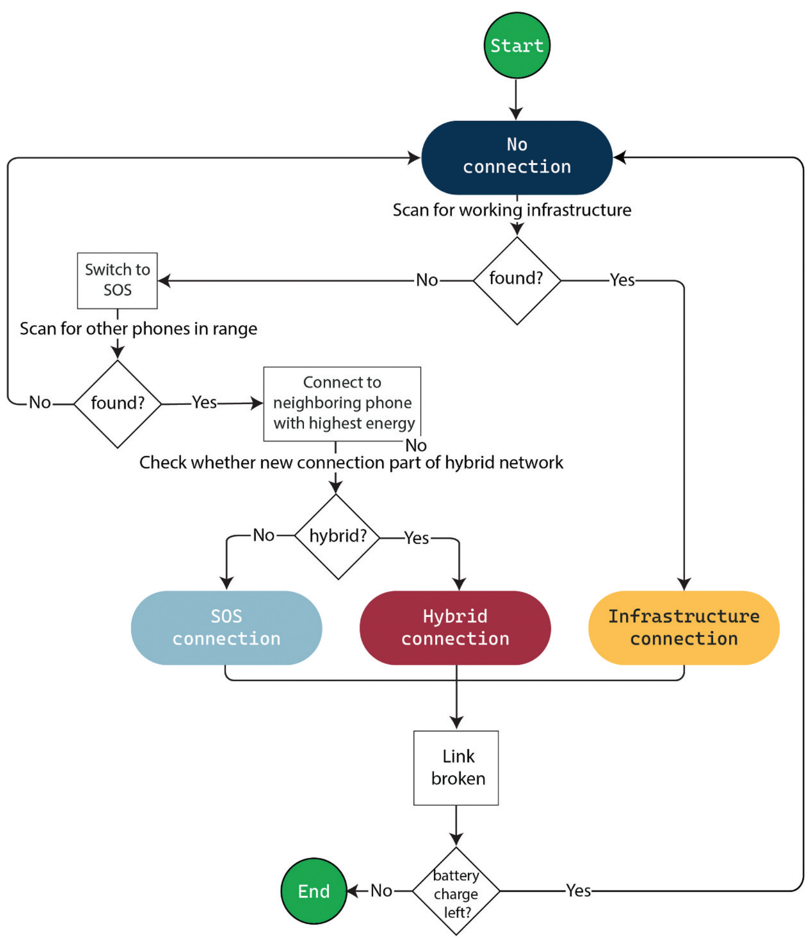

Figure 3. Flowchart representing the connection procedure. The connection procedure is followed by all phones. The goal of the protocol is a smooth transition that travels back and forth between different fragmented solutions or connections. Choices include getting connected to a newly available infrastructure or a mobile ad hoc network. Each phone chooses between three types of connections. First, infrastructure mode, where a phone finds a working tower or any other equipment that allows a phone to get connected to the outside world (in yellow). Second, SOS mode, where phones outside of the range of infrastructure form a bottom-up self-organized mobile ad hoc network following the SOS protocol (in sky blue). Third, hybrid mode, where a phone is connected to infrastructure and has neighbouring phones that are indirectly connected to an infrastructure (in red). The process ends once the battery charge of a phone is exhausted.

Since connecting to infrastructure is expensive, it does not look for more connections if a phone is already connected via another phone to infrastructure, limiting its scanning and connection energy loss. Suppose a message has to be sent and no routes are present. In that case, the protocol either looks for more phones to connect or asks its connected neighbours to update their connections by monitoring their context. Once monitoring is complete, the protocol determines a plan of action. This plan is based on choices derived from analysis of the context. If a phone finds other phones from a different subnetwork with a high battery charge, it connects to the other phone. All phones in the disaster area follow this procedure, leading to a self-organized mobile network in the absence of infrastructures.

Once WiFi equipment is introduced, phones in the range of coverage connect to the infrastructure the WiFi equipment provides. Phones that are not in the range of coverage but were previously connected peers become part of the hybrid network. Before sending a message, a route needs to be found: An enquiry is sent to all neighbours, and they respond positively if a route is available. The phone sends the message to the next connection if a route is available. If no route is available, the phone asks its locally connected neighbours to find more connections. Upon the request to find more connections each neighbour updates their connection list by checking if they are in range of working infrastructures and other phones. As citizens are mobile, and WiFi equipment may not always be available, new connections may emerge (and older connections dropped). The connection pattern or topology of the network changes. If, despite this last effort no route is found, the message is saved as a pending message until it can be sent. The protocol specifies that the phone tries to send messages each following cycle.

5. Methods

This paper demonstrates that context-awareness and self-organisation for transitioning can be used to seamlessly integrate various approaches for emergency communication. The focus of the study has been on the design of a hybrid communication system that supports inclusion and continuity through reliable delivery of messages for all. An abstraction layer was necessary to support the interplay between connectivity of citizens, reliability of message delivery, continuity of connection and communication in terms of variable coverage and infrastructure availability.

This required a mixed methodology design based on simulation and modelling following the MAPE cycle. The proposed protocol is designed to support community resilience during disasters. The simulation using agent-based modelling was used to compare the proposed hybrid network system to an infrastructure-only communication system. Agent-based modelling is often used to study complex systems and social simulation because of its ability to program heterogeneity in a social context, local interactions, and autonomous agents (Crooks et al., 2008). The hybrid network solution proposed in this paper is purposefully not compared to existing work that focuses on either centralised control or additional hardware, as these solutions do not satisfy the requirements proposed in this study.

The comparison of the basic SOS protocol with existing work that uses mesh topology as their topology has been performed previously (Banerjee et al., 2021). To the authors' knowledge, there are no other hybrid approaches that combine both centralised control and decentralised, self-organisation approaches, which are based on environmental context.

5.1. Populating the model and simulating behaviour

To examine the performance of both hybrid and infrastructure-only communication networks through comparative analysis, a hybrid topology and an infrastructure-only topology was simulated in two separate agent-based models. To this purpose, a two-dimensional torus-shaped world is populated randomly with two kinds of phones, mobile and immobile. 25% of the population of phones are defined as immobile, and the remaining 75% move around independently and randomly. In addition to phones, four backbone communication infrastructures have been included in the simulation in four different locations in the world. Each has a different transmission range and thus a different coverage area. These infrastructures do not work initially but are activated one at a time. Every twelve hours, when infrastructure becomes active, phones in the coverage area of this infrastructure become connected to it. When all infrastructures are active, they provide coverage for 75% of the entire area.

In the infrastructure-only mode, phones in the range of infrastructure form a direct connection with the infrastructure and turn yellow as shown in Figure 4. If there is more than one infrastructure in range, a phone chooses the one to which it is closest. Each phone connects to only one infrastructure, and if they are out of range due to mobility, the connection is lost, and they turn dark blue. In hybrid mode, i.e., in which SOS and infrastructure may both be available, a phone first attempts to connect to an active infrastructure, but in

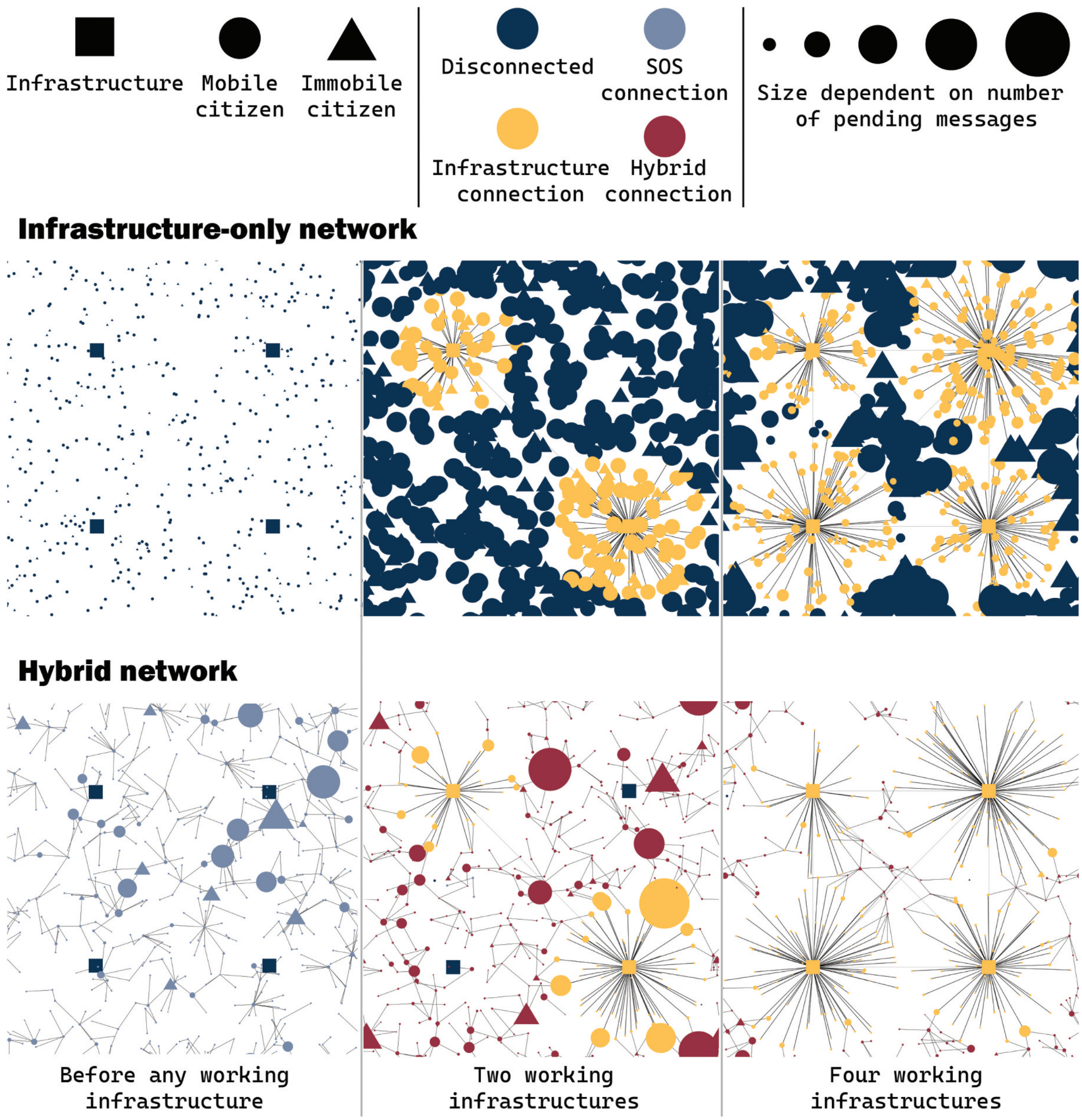

Figure 4. Screenshots of the infrastructure-only and hybrid networks simulations are presented for three instances. Mobile citizens are circles; triangles represent immobile citizens. Infrastructure equipment is square. In the top rows, the infrastructure-only network is displayed. In the bottom row, the hybrid network simulation is displayed. In each row, screenshots corresponding to three different moments are displayed. First, when no infrastructure is available, the hybrid network relies solely on the SOS ad hoc mobile network (in sky blue). In the second screenshot, two infrastructures are active. For infrastructure-only, phones in the coverage area of the two infrastructures are connected (in yellow). For the hybrid network, phones in the range of infrastructure are directly connected (in yellow), other phones are indirectly linked to the infrastructure in hybrid mode (in red), and a few are in SOS mode (in sky-blue). In the last screenshot, all four infrastructures are active.

its absence connects to another phone in range, in a mobile ad hoc network.

Phones connected in SOS networks are shown all grey. When infrastructure becomes active, and is in range, they connect to the infrastructure and turn yellow. Neighbours are informed of the new connection, and they turn red, indicating that they are indirectly connected to infrastructure. Suppose a distant neighbour comes close to another working infrastructure. In that case, this neighbour connects to the infrastructure and leaves the hybrid network. All phones lose energy while connecting, sending and receiving data. Two phones can connect when they are in each other's transmission range, and once connected, they can communicate via this link. In the absence of a direct link, intermediate phones can relay messages for the sender and the receiver. Mobile phones that come in a range of immobile phones in hybrid mode connect and relay their messages.

In infrastructure-only mode, if immobile phones are outside the coverage area of the infrastructure, they keep storing pending messages. The amount of information stored by a phone increases as per the pending messages. When a phone sends messages, the amount of information stored decreases. In the model, the buffer's size is used to continually monitor the delivery of messages. The screenshots of the simulation are shown in Figure 4. The simulation runs until only 10% of the phones (or less) have battery charge left.

5.2. Experimental setup

Experiments are designed to evaluate the delivery of messages for mobile and immobile people in relation to the coverage area. Additionally study reliable delivery of messages during the period of the first 72 hours after a disaster. The influence of different types of connections and the number of pending messages when no connections could be made are analysed. To visualise the impact of these factors, mobile citizens are depicted by circles, and immobile citizens are represented by triangles in the agent-based model depicted in Figure 4.

Infrastructure equipment is square. Each phone grows in size when the number of pending messages grows and shrinks when they are delivered. Active infrastructure is square and yellow. Once mobile phones start connecting, they also turn yellow. In the absence of infrastructure, phones form SOS connections, denoted in sky-blue. To study the impact of coverage, each infrastructure becomes active and covers an area covering 75% of the area.

In each of the simulations, connectivity and/or message delivery is compared for the hybrid network proposed and the infrastructure-only network over time. The simulation environment is a torus-shaped world of 100×100 units with 500 people carrying phones. Of 500 phones, 125 phones are owned by immobile people. The transmission range of each phone is ten units. The four infrastructures with different transmission ranges, one of which starts working after every 12 hours. After 48 hours, all four infrastructures are working.

For those simulations where message delivery is studied, messages are sent continuously: Each phone sends one message every 15 minutes, or five messages are sent in a single burst at the beginning of the simulation. The latter simulation is not a realistic scenario. However, it allows for evaluating how long it takes for messages to be delivered and how many of the five messages reach the correct location. Battery charge in phones was normally distributed at initialisation.

Different metrics are examined that are aimed at avoiding the pitfall of examining the resilience of the system as a whole while forgetting to assess whether functionality for individual citizens is achieved (Doorn et al., 2019). Therefore, metrics are computed for different groups of citizens, or the percentage of citizens who achieve a certain functionality is calculated.

6. Results

6.1. Hybrid network is more inclusive compared to infrastructure-only network

In Figure 4 the last three screenshots of the bottom rows are the hybrid network, and the first row screenshots are the infrastructure-only network. The hybrid network has more red phones than yellow phones, signifying that a significant number of people can access the infrastructure despite a limited coverage area. The last two screenshots of the top row show that in the infrastructure-only network, as more infrastructure becomes active, phones in range become yellow, and their size shrinks.

However, immobile people (triangles) outside of the coverage remain blue (disconnected), and their size keeps growing, signifying that they can never send or receive messages. In contrast, the hybrid network allows immobile people outside of coverage to communicate through phones connected in the SOS network with the infrastructure within range.

6.2. Hybrid network has continuous messages delivery, infrastructure-only has intermittent burst delivery

In Figure 5 panel C shows the message delivery of 500 phones sending 1 message each. In total 500 messages are being sent over both the hybrid network and the infrastructure-only network. Again, 25% of phones are immobile. In Figure 5 panel C, it is clear that for hybrid network message delivery is continuous. Even if immobile phones are not in range of active infrastructure, their messages are relayed through the mobile ad hoc network keeping the overall message delivery at 90%.

For infrastructure-only mode, delivery of messages is very dependent on the coverage area and availability of infrastructures. Therefore, a large number of pending messages are not necessarily delivered as some phones move in and out of the coverage area. Whenever they are (re-)connected, messages are delivered in a burst resulting in the peaks. For mobile phones, this still

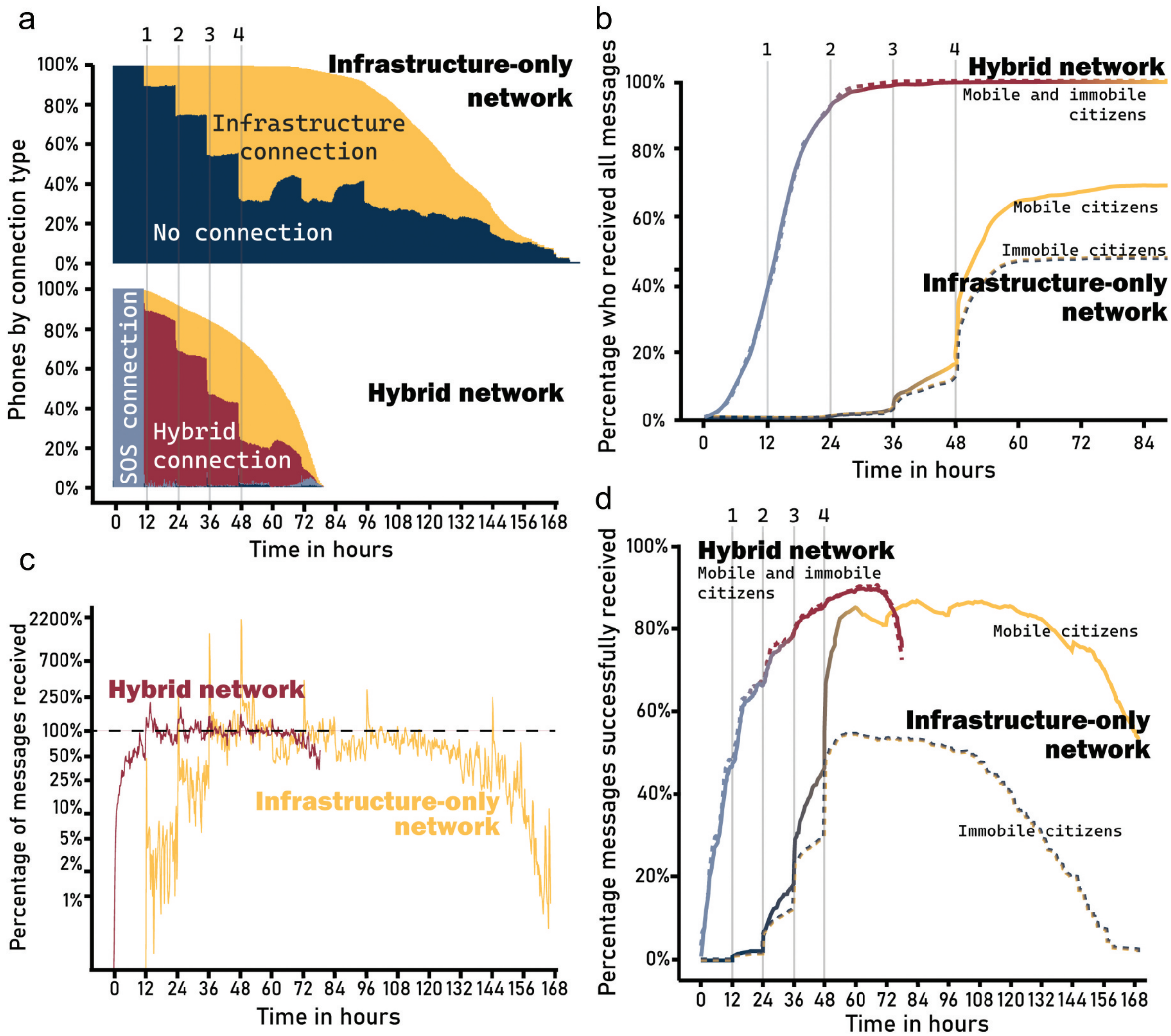

Figure 5. Development of different aspects of the network over time. In each of the panels, the x-axis displays the time in hours. Panel A displays the percentage of phones that belong to one of four categories (on the y-axis). Panel B displays the percentage of phones that have received all of their messages for a specific scenario in which all phones send just five messages at the start of the simulation. This is not a realistic scenario but allows for quantification of the time it takes for messages to reach their destination. The y-axis depicts the percentage of phones that have received all of their messages. The x-axis is truncated to zoom in on whether the messages sent at the start are delivered in time.

provides a way to have messages delivered despite the delay. However, message delivery is not possible for immobile phones if they are outside coverage.

6.3. No difference in the delivery of messages for mobile and immobile people for the hybrid network

In Figure 5, panel B, the yellow line representing infrastructure-based message delivery for mobile phones starts working as soon as the first infrastructure becomes available. However, it takes all infrastructure to be available to deliver all messages for 80% of the phones, i.e., 400 phones that are mobile can walk around and get connected to various infrastructures. Of all immobile phones, only 50% have full delivery of messages once the infrastructure near them becomes available. Approximately 60–65 phones can send and receive all messages. However, around 7% −10% of phones can never communicate as the coverage area of the infrastructure is only 75% of the entire area. This means many phones can neither send nor receive any messages at all. So, suppose an immobile phone is in coverage. In that case, this does not necessarily mean that it will receive all of the messages that have been sent from other locations. If a sender is also immobile and outside coverage, these two phones cannot send or receive messages.

Panel C presents the results for a scenario in which all received messages are tallied to estimate the distribution of message delivery over time. For the infrastructure-only situation, the delivery of messages is very uneven, with as many as 11,000 messages being delivered in a single moment and many moments where very few messages are being delivered. To visualize the data from the infrastructure-only data with all its peaks and troughs alongside the more stable data from the hybrid network, the y-axis is displayed on a log2 scale.

Panel D depicts the percentage of messages that have been delivered to their intended receiver for a scenario in which all phones are continuously sending messages. Hence, the number of existing messages keeps growing. At the left of the x-axis, data is removed from participants that do not have messages intended for them yet, to avoid divide-by-0 errors.

However, there is no difference in the delivery of messages for mobile and immobile people in the hybrid network. Within the first few hours, many phones have received all of the messages that have been sent even before infrastructure has become available. This is because the presented hybrid network utilizes the SOS protocol and only transitions to infrastructure when available. SOS ensures that, before the infrastructure comes up, even low battery phones can stay connected. With the ad hoc mobile connection, immobile people can connect with nearby phones.

This ensures that, despite energy, mobility and coverage differences, all phones have equal participation and continuous message delivery, irrespective of infrastructure presence or absence if other phones are within range.

6.4. Hybrid network provides full connectivity for the 72 hours, Infrastructure-only network runs longer than the hybrid SOS network

In Figure 5 Panel A, the connectivity of the hybrid network is compared to the infrastructure-only network. The hybrid network runs only for the first 72 hours. In the hybrid network, each phone fulfils tasks that are not required for the infrastructure-only network, i.e., forming connections to other phones and relaying messages. These tasks are costly in terms of battery. By default, the infrastructure-only network runs longer than the hybrid network.

However as shown in Figure 5, this also means that for an extended period, when timely delivery of messages is crucial, there is no communication at all. Also, despite the network providing almost 75% coverage, immobile people with phones remain disconnected and are not included in the network.

The last experiment is the extension of the previous experiment in which every phone sends one message continuously. The x-axis in Figure 5 Panel D represents time in hours, and the y-axis represents the percentage of messages received in relation to the total number of messages that could be received. This is never 100% because messages are continuously being sent, so there are always new messages that have not been delivered yet. As in the previous image, the dotted lines represent immobile phones, and continuous lines represent mobile phones. Red represents message delivery over an infrastructure-only network, and blue represents message delivery over the hybrid network.

In Figure 5 panel D message delivery over the hybrid network is continuous and inclusive for both mobile and immobile phones. From the very beginning, message delivery shoots up and nears 80% before infrastructure becomes available. As soon as the infrastructure starts to function, message delivery reaches a plateau at around 95% of all messages for all phones delivered.

There is no message delivery for the infrastructure-only network unless the infrastructure is active and functional.

Additionally, a clear difference between mobile and immobile phones is visible once infrastructure becomes available. For mobile phones, as the number of infrastructures increases, the coverage area increases and hence it reaches 95% delivery for 375 phones. However, for 125 immobile phones, some are inside the coverage area and some outside, which results in only 40% of messages being delivered to the intended receiver. This is the highest that immobile phones can achieve despite all infrastructures working.

However, the infrastructure-only network runs longer. The hybrid network runs shorter than the infrastructure-only network as the transition between different connectivity patterns, sending, receiving and relaying messages for other phones and maintaining the network through self-organization is energy-intensive, and battery power is limited.

7. Discussion

This paper presents a new perspective on inclusion: ensuring coverage is available to all. Coverage is a standard indicator to maximize to achieve a maximum number of people with access to mobile communication, which makes sense from a utilitarian perspective. However, when it is accepted that coverage will not be 100% for all people all the time, but perhaps only 90% on average, one needs to consider how to allocate lack of coverage.

In this sense, coverage is a resource that needs to be fairly distributed. Lack of coverage and communication opportunities should not always fall on the shoulders of the immobile (i.e. secluded), or those with low battery.

Many algorithms introduce unintended biases towards particular segments of society. If these biases are unavoidable, different algorithms' bias should affect different segments, rather than always disadvantaging the same group (Danks & London, 2017; Garcia, 2016; Kirkpatrick, 2016).

Continuity was formulated as a requirement for communication. Technically, whether continuity is vital depends on the type of communication. It may be acceptable for some forms of communication if messages are not delivered for some time and then delivered in batches. This delivery pattern was observed in this paper when SOS was not available. This may be acceptable if messages are not time critical but rather form of logging of reports, e.g., about the number of casualties. For other forms of communication, where time critical information exchange such as location of people trapped under rubble needing immediate rescue is required, SOS-hybrid approach is essential for faster delivery times and more continuous communication.

The results were not all positive for SOS-hybrid. The connecting and relaying costs that come with ad hoc mobile networking meant that the SOS-hybrid solution's longevity was much reduced compared to waiting for infrastructure. This shows that, if the goal is to preserve the battery in setting where recharging is impossible, the SOS-hybrid protocol is unsuitable. However, SOS-hybrid maybe is favourable if the goal is to send time-critical information right after a disaster, but there is a fundamental decision to make: For some disasters, the emergency may be significantly prolonged with little opportunity for emergency action. In this case, preserving the battery and waiting for infrastructure may be the best strategy. SOS-hybrid may be preferred for other disasters, where the crisis is immediate, and time-critical information requesting help or offering help needs to be exchanged immediately.

8. Conclusion and future work

The results demonstrate that, with the large number of communication solutions available for disasters, there are clear benefits of combining these isolated solutions. There is a growing body of literature (Baudoin et al., 2016) that recognises the importance of transitioning from top-down or military-style 'command & control' approaches to more 'community-centric' or 'people-centred' participatory approaches, to ensure effective communication of risks and requirements among all actors (Scolobig et al., 2015).

Rescue operations are impeded by disasters affecting communication, energy and transportation infrastructure (Guidotti et al., 2016). This paper extends Banerjee et al. (2020), (2021)) by showing how an ad hoc mobile network can synergise with emergency infrastructure solutions to fill in contextual and temporal gaps in infrastructure availability.

These gaps are not necessarily a result of disasters and may have existed already prior to it, in which case, the ad-hoc solution transforms rather than restores communication to reduce prior inequalities (Nagenborg, 2019). This value-based design is extended to include marginalised victims. It ensures continuity of seamless communication during disasters to deliver a resilient solution for all.

To fulfil these value-based requirements, SOS-hybrid is presented in this paper. SOS-hybrid is a protocol that enables transitioning between infrastructure-based communication and ad-hoc mobile communication. A hybrid protocol is described that achieves this while being fully distributed: There is no central authority deciding which of the systems is used by a particular phone.

In agent-based modelling simulations, the efficiency of message delivery is compared for scenarios with and without SOS. Scenarios are evaluated in which infrastructure covers various portions of the simulated world, with mobile and immobile phones. Results show that SOS-hybrid can fill the temporal gaps when infrastructure becomes temporarily unavailable. In a real disaster, messages will have different priorities and hence there should be a mechanism by which the protocol based on the message content registers the priority of each message. SOS-hybrid does not look at the message content or label any message based on priority. Including these mechanisms in an extended design could ensure that emergency response teams reach affected people who need immediate attention quicker.

A natural progression of this work is to perform controlled trials to verify the suitability and practical implications of the use of SOS-Hybrid (Heikkinen et al., 2012) and to analyse the impact on communication between different actors involved in disaster recovery. Therefore, research using a real-life study is an essential next step in confirming and investigating other technical limitations such as interoperability issues, security issues, and geological limitations such as line of sight issues.

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The issue of inclusion and continuity are essential for a resilient society. As climate change will continue to increase, the severity and frequency of disasters with the accompanying civilian deaths and displacements (Yeeles, 2018). It thus becomes imperative to design communication systems that enable citizen autonomy to seek rescue during disasters. The design of an autonomous and self-organised protocol that ensures seamless integration between various communication networks based on the respective context can maximise the participation people using their phones, which allows reliable and continuous message delivery, is the first step in this direction.

These findings have significant implications for understanding how the benefits of ad hoc mobile networking allowing hard-to-reach people to connect and the benefits of infrastructure-based communication allowing phones to more efficiently send messages over long distances can be achieved simultaneously.

Note

1. The implementation details of SOS protocol and evaluation are available in previously published work. Readers are referred to Banerjee et al. (2020), (Banerjee et al., 2021) for details.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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