On the Impact of Direct-to-Cell Satellite Communication in Decentralized Disaster Networks

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ABSTRACT

In the future, Low-Earth Orbit satellite constellations will directly provide cellular services from space. Especially for large-scale disasters, where desperately needed communication infrastructure is often severely damaged or destroyed, this may be a significant game-changer for disaster relief efforts. However, limited or partial availability of satellite connectivity may be more probable than full coverage in the next years. This paper proposes and investigates a possible integration of direct-to-cell satellite communication in decentralized disaster networks, facilitating a combination of delay-tolerant networking with limited satellite availability. Simulation results indicate that already a few satellite links positively impact communication performance, increasing network connectivity and message spread in a city-wide disaster scenario with user mobility.

Keywords

Direct-to-Cell, Satellite Communication, Disaster Networks, Delay-/Disruption-Tolerant Networking (DTN)

INTRODUCTION

Sophisticated *Information and Communication Technologies* (ICT) and their infrastructures serve as the backbone of modern societies, granting us, for example, high-speed access to the Internet or instant messenger services. We are accustomed to have terrestrial or cellular ICT networks at our disposal, and a large part of our everyday routine relies and depends on their availability. But recent disasters like Hurricanes in Puerto Rico and Florida or large floods in parts of Germany and the Netherlands emphasized that these ICT infrastructures are vulnerable: the resulting destruction of infrastructure led to a complete communication blackout inside the disaster area and cut it off from the outside. The lack of communication between emergency services, individual rescue teams, and incident management heavily impaired disaster relief. Furthermore, the affected population was unable to call for help or inform emergency services of severe problems (German Federal Agency for Civic Education, 2021; Kreienkamp et al., 2021; Zorrilla, 2017). As a result of climate change and the increase in extreme weather conditions, such devastating, large-scale natural disasters have become more frequent in recent years and are expected to increase further in the future (Gallucci, 2018; Toya & Skidmore, 2018; Université Catholique de Louvain (UCL), 2022).

The absolute importance of communication for disaster relief efforts (Hagar, 2015) is addressed internationally with a wide range of research on resilient ICT infrastructure (Fehling-Kaschek et al., 2020; Hollick et al., 2019) as well as strategies for communication provision in disaster areas without working ICT infrastructure (Chakraborty

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et al., 2018; Mahoro Ntwari et al., 2021; Zobel, 2023). Another possible solution for communication in disaster areas is the use of satellites. However, using satellite services for communication is typically costly. It requires powerful satellites in usually geostationary orbit and for the users specialized equipment like satellite telephones and expensive subscription fees. This makes everyday use or widespread stocking for emergencies unrealistic, and thus, only a small fraction of stakeholders typically use satellite communication.

With the increasing deployment of Low-Earth-Orbit (LEO) satellite constellations in recent years, however, this may be subject to change. The lower orbits and larger networks of LEO satellite constellations result in higher connectivity, higher speeds, and less costly hardware compared to traditional geostationary satellites. Particularly, Starlink gained a lot of attention (and media coverage) due to its provision of internet access over its LEO satellite network, e.g., in the Ukraine war since 2022. But specialized hardware is still required to connect devices like smartphones to use internet services (Xing et al., 2023).

However, recent technological advances will allow for the direct integration of cellular and satellite networks without a middlebox, like a dedicated access point. In general, the inclusion of *Non-Terrestrial Networks* (NTN) is already envisioned as part of future 5G/6G cellular networks (3GPP, 2020). Researchers have shown the feasibility of implementing core functions of normal cellular networks on LEO satellites and realizing a cellular link between satellite and ground devices, referred to as *direct-to-cell* (D2C) communication (Li et al., 2022; Liu et al., 2024).

The practical feasibility has also been demonstrated. Starlink launched new satellites with direct-to-cell capabilities in January of 2024, with the intention to provide text services first, followed by voice, data, and IoT services using standard 4G/LTE protocols from 2025[1]. At the time of this writing, trials for 'text via satellite' have started in the United States, as stated by Starlink and T-Mobile[2]. During the disasters in Florida, USA caused by Hurriances Helene and Milton in September and October 2024, respectively, Starlink's D2C text services were made publicly available within the disaster area[3]. Similarly, Apple states that their iPhone 14 and newer can connect to satellites to access limited services such as emergency calls and text messaging[4].

Despite its feasibility, direct-to-cell communication is still in its infancy. Aside from theoretical specifications or corporate advertisements, actual capabilities or details of working implementations are currently unknown and will probably be subject to change. The widespread and highly functional availability of D2C communication for everyone in a disaster area would address many problems that the affected population and emergency services face today and could support disaster relief efforts enormously. However, until then, limited or partial availability of satellite-cellular connections is more probable, and it is unclear how they could be integrated into existing solutions for post-disaster communication networks.

To address this issue, this paper proposes a viable integration of D2C satellite communication into a decentralized *Delay-Tolerant Network* (DTN) for post-disaster communication. This combined communication system is implemented in an event-based simulator to specifically investigate the impact of D2C capabilities on message spread in a city-scale disaster network. Using a lower-end estimate for the number of available satellite connections and the data throughput, we show that message spread significantly increases. However, a considerable influence of node mobility, which is normal in DTNs, still persists and cannot be removed entirely. Our results emphasize the benefits even partially available low-bandwidth satellite links with ground-based networked devices can bring to decentralized disaster networks.

The remainder is structured as follows. First, the envisaged disaster network and the integration of direct-to-cell capabilities are presented. Afterwards, we introduce the simulation environment and the simulated disaster scenarios. This is followed by a presentation and discussion of our evaluation results before concluding the paper.

SATELLITE-TO-CELL IN DECENTRALIZED DISASTER NETWORKS

When disasters rupture and destroy ICT infrastructure, our everyday means of communication are severely hindered or rendered completely unusable. But communication is desperately needed for effective disaster relief — not only for emergency services, which usually bring their own communication equipment, but also for the affected population (Hagar, 2015; Toya & Skidmore, 2018). Delay-Tolerant Networks (DTNs) have proven to provide basic means of communication by spanning a decentralized multi-hop network utilizing civilians' smartphones (Lieser et al., 2017). However, such networks are typically heavily clustered in large disaster situations as a result of civilian mobility and the short-range links between devices (Álvarez et al., 2018; Zobel et al., 2021). Communication within a cluster — i.e., a group of interconnected devices, e.g., within a shelter or around other Points-of-Interest — is

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[1] https://api.starlink.com/public-files/DIRECT_TO_CELL_FIRST_TEXT_UPDATE.pdf

[2] https://www.reuters.com/business/media-telecom/apples-iphones-support-starlink-direct-to-cell-coverage-us-2025-01-29/

[3] https://www.space.com/spacex-starlink-free-2024-hurricane-helene-milton

[4] https://support.apple.com/en-us/105097

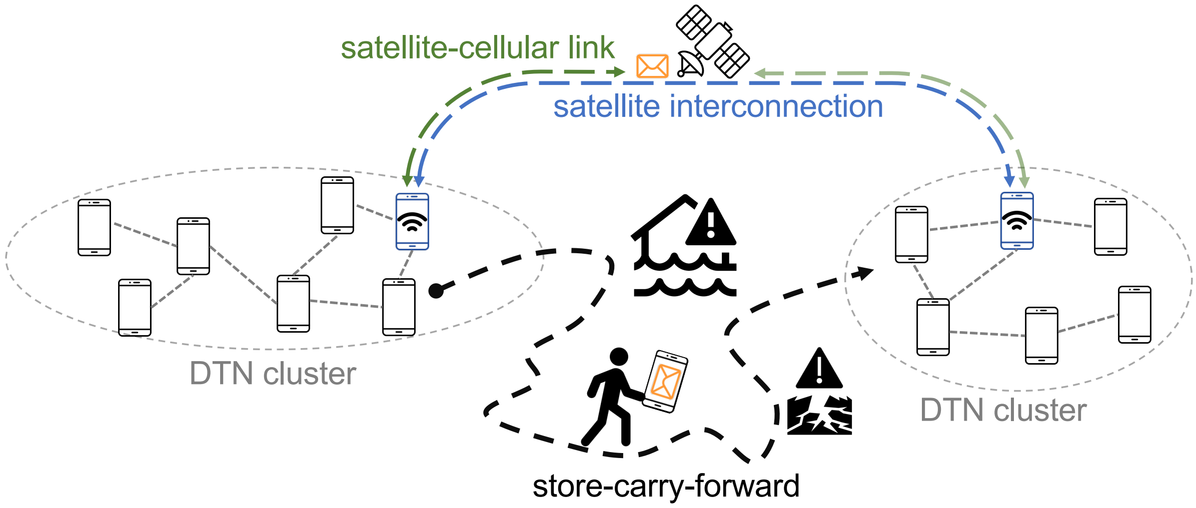

Figure 1. Two DTN clusters are separated physically by impassable terrain, such as flooded and destroyed areas, and communication-wise by a lack of linking communication infrastructure. DTN *store-carry-forward* message distribution is possible but slow, unreliable, and potentially dangerous. A *satellite interconnection*, set up via individual *satellite-cellular links*, would significantly increase connectivity and message distribution in the disaster network.

fast and reliable. In contrast, communication between separate clusters is accomplished by *store-carry-forward* message distribution to overcome the gaps between them. As shown in Figure 1, this means that devices need to move and carry messages between clusters physically. When relying solely on people's movement in the disaster area, this process is unreliable, slow, and potentially dangerous — if clusters can be reached at all, especially when considering, e.g., flooded streets or blocked by debris in the disaster area. Previous work has shown that inter-cluster communication performance can be increased, for example, by adding long-range communication links such as LoRa to the network (Baumgärtner et al., 2020) or using Unmanned Aerial Vehicles (UAVs) as fast and terrain-independent data carriers (Lieser et al., 2019; Zobel, 2023).

However, direct-to-cell (D2C) communication now enables an additional and novel possibility to exchange messages within a disaster area. In contrast to low data rate transmissions and long commutes between network clusters (Baumgärtner et al., 2020; Zobel & Steinmetz, 2024), a suitable satellite interconnection between devices in different clusters could significantly increase communication performance due to faster and more reliable message distribution. When assuming not all devices to be connected via satellite-cellular (SC) links or their limited availability over time, the DTN approach is still necessary for the interconnectivity of satellite-connected devices and the rest of the disaster network. In that case, node mobility will still considerably impact message spread and delivery delay due to store-carry-forward. Since the DTN paradigm comprises the use of heterogeneous networks by design, integrating SC links does not require changes in the DTN protocol stack, only an appropriate *Convergence Layer Adapter* (CLA) must be added to DTN nodes with satellite access (Burleigh et al., 2022). However, the specifics of such a CLA are heavily dependent on the used protocol stacks in the satellite network and are not in the scope of this paper.

Clearly, the number of satellite-connected devices significantly impacts communication: with more SC links, connectivity in the network will increase. Nevertheless, communication performance also depends on the distribution of SC nodes. The largest impact is expected when each network cluster has at least one SC link, providing full network connectivity, improving message spread, and reducing delivery delay. On the other hand, multiple SC devices in a few clusters will negate these benefits. In the worst case, all devices are in one cluster. However, neither the number nor the distribution of satellite-connected devices can be anticipated or determined a priori. Furthermore, this distribution may change over time due to node mobility in the network.

The properties of the satellite interconnection are an additional significant impact factor, mainly categorized in this work through availability and throughput. The availability of a satellite-cellular link can be restricted to certain regions in the disaster area, e.g., due to satellite visibility and orbits, or to certain time intervals, e.g., due to limiting overpass windows. This directly influences the availability of satellite interconnections depending on the network properties. If the satellite network only allows forwarding or routing with end-to-end connectivity, an SC link must be present for both sender and receiver at the same time. If, however, the satellite network itself uses

Table 1. Simulation Environmental Settings.

Scenario	Map	Inner City, Post-Disaster
	Size	3000 m x 3000 m
	Mobility Model	Civilian Disaster Mobility [a] 10 random seeds for mobility
	Points of Interest	disaster-related (3 constant, 6 temporary)
	Duration	8 h
Disaster Network	Nodes	200
	Satellite-Cellular Links	[0, 2, 3, 4, 5]
	DTN PHY	WiFi, 54 Mbit/s, 50 m range
	SC link PHY	9.6 kbit/s [b], continuous connectivity
	Message Size	64 Byte
	Message Creation	every 20-40 seconds, random node
	Randomization	10 random seeds for SC link and node selection

[a] cf. Zobel et al., 2021 [b] cf. (3GPP, 2025)

delay-tolerant networking, it can store messages for later forwarding so that simultaneous satellite links are not needed to interconnect clusters. The throughput of the satellite interconnection describes the amount of data that can be exchanged over it. In both cases, links are further specified by whether they are bi-directional or uni-directional and whether they are symmetric or asymmetric.

Of course, availability and throughput depend highly on several factors, such as the envisaged satellite network, the distribution and technical capabilities of the devices on the ground, the weather, etc. This work focuses on symmetric, bi-directional satellite links with a realistically achievable throughput suitable for the most important emergency services (3GPP, 2025; Álvarez et al., 2018; Lieser et al., 2017). We assume the satellite interconnection to allow message distribution between all (simultaneously) satellite-connected DTN nodes. The fully realistic depiction of SC links, including, e.g., speed or weather dependence, orbit calculations, or efficient link utilization, is not within the scope of this paper (cf. Li et al., 2022 or Kondrateva et al., 2018, for example). Furthermore, we restrict communication to the disaster area, despite the ultimate future idea of direct-to-cell being to allow access to all Internet services directly. Our assumptions and restrictions allow us to specifically address the impact of satellite-cellular communication on the disaster network's performance while reducing cross-influences.

SIMULATION SETUP

Simulations are performed with the *Python Opportunistic Network Simulator* (PONS)[5], extended by satellite interlink capabilities. The Hypergossip (Khelil et al., 2007) protocol is added for DTN routing, including fully simulated neighborhood detection and message exchange. The evaluation scenario consists of a 3x3 km^2 inner-city scenario of a medium-sized European city. We vary node mobility and the number of SC links, as listed in Table 1, simulated for 8 hours each. 200 nodes, each representing a person carrying a smart mobile device, constitute the disaster network. They mostly reside around Points of Interest (PoI), between which they can move on the streets in small groups, as defined by the Civilian Disaster Mobility (Zobel et al., 2021) model. The resulting mobility from the model is randomized using ten different random seeds, which define the placement of nodes around the PoIs at the start of the simulation and the movement around and between the PoIs during the simulation.

The scenario consists of nine PoIs, taken from the city's map. Three PoIs are shelters from the city's official disaster plan and remain constant throughout the simulation. Six PoIs are local community places that are only visited by nodes within specific time frames in the simulation. Figure 2 shows one exemplary mobility distribution for the aggregated[6] node positions using one out of ten mobility seeds. The highest concentration is present around points of interest, with highly varying intensity on pedestrian routes between these locations.

Most importantly, we simulate device-to-device connectivity between DTN nodes as WiFi connections with a maximum range of 50 m (Lieser et al., 2019; Zobel & Steinmetz, 2024). At the start of the simulation, two

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[5] v0.1.5; available on GitHub: https://github.com/gh0st42/PONS

[6] Aggregation samples all node positions every second in a 30 m x 30 m grid.

Figure 2. Aggregated node locations in the disaster scenario for one exemplary of the ten mobility distributions. Locations are sampled every second and aggregated in a 30 m x 30 m grid. Points of interest are discernible by the high concentration of measurements. Pedestrian routes show varying usage intensity. Mind the logarithmic scale.

to five nodes are selected based on another random seed for the disaster network, respectively, and provided with satellite-cellular links. This randomized selection is intended to result in different distributions of the few satellite-capable devices that, as discussed later, may heavily influence the communication performance under highly unequal or changing distributions throughout the simulation runs. The DTN without SC links (i.e., 0) is used as a comparison baseline. The SC links are assumed to provide a maximum throughput of 9.6 kbit/s, similar to the minimal requirements for 5G NTN Narrowband IoT connectivity (3GPP, 2025), with permanent availability between all satellite-connected devices. Every 20 to 40 seconds during the simulation, one randomly selected node creates a message in the disaster network.

The simulation for each number of SC links is run with the ten random seeds for mobility and the ten random seeds for the disaster network, thus, evaluated 100 times each. This results in 500 simulation runs or 4000 hours of simulated time.

EVALUATION RESULTS

The goal of this analysis is to obtain insights into the impact of satellite-cellular links on communication in a disaster network. To this end, we measured the *Message Spread*, i.e., the dissemination of messages over the entire DTN, within a time window (message lifetime) of 1 hour after each message's creation. A value of 0 denotes that a message has not been seen by anyone other than the creating node, while 1 defines perfect dissemination to all nodes within the disaster network. Message spread provides a general measure for communication performance and inter-cluster connectivity within the DTN, as distanced clusters can, without further measures, only be reached utilizing node mobility via *store-carry-forward*.

Figure 3 provides the resulting distribution for the message spread from three selected simulations ($s1, s2, s3$). All three use the same underlying node mobility over the entire simulation time; however, the network's random seed changes, resulting in differences in the random choice of satellite-capable nodes and message creation. Overall, message spread generally increases for all simulated scenarios by introducing satellite-cellular links into the network. Comparable results can be seen for all mobility and network random combinations. However, clearly, the distribution of satellite-capable nodes and the general node mobility are still significant influence factors. The shown results are selected to feature three general behavioral trends induced by node mobility and the distribution of SC nodes, as seen throughout the results.

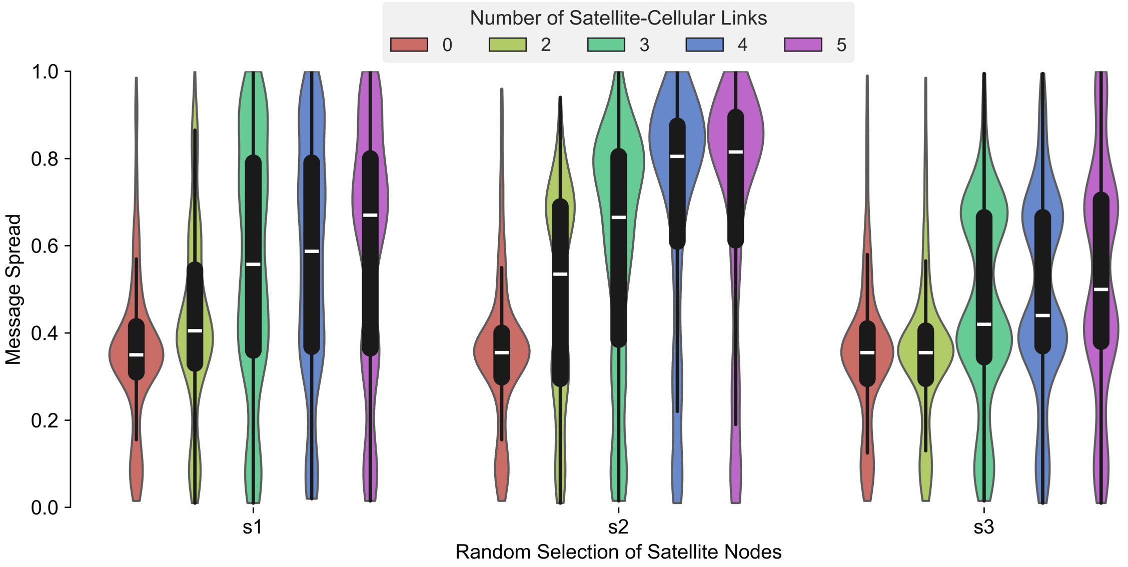


Figure 3. Distribution of network-wide message spread with different numbers of satellite-cellular links. The selected runs are chosen exemplary to showcase different trends induced by node distribution and mobility seen throughout the results. All three use the same mobility of nodes but different random selections for the satellite-capable nodes. With some exceptions, a trend for an increase in message spread with more satellite-cellular links is visible.

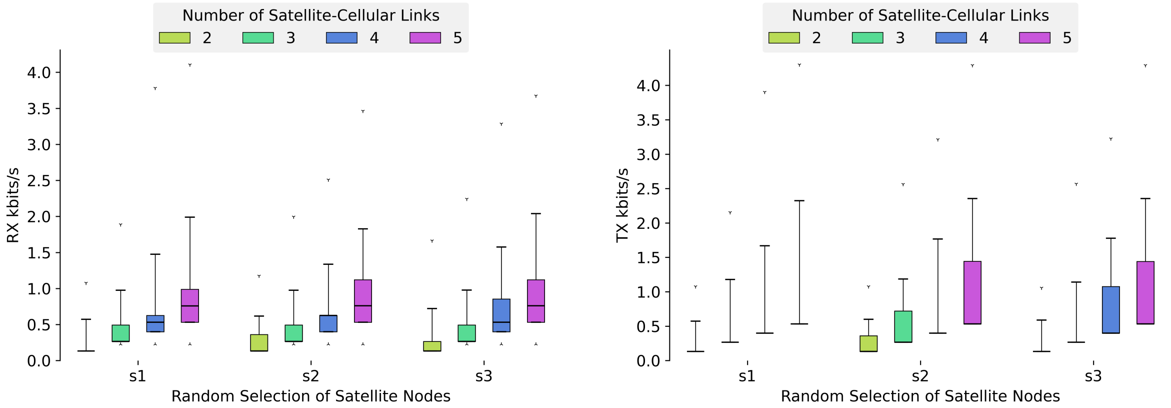
Comparing the baseline (0 SC links) between simulations, only minor deviations are visible for message spread in the pure DTN. This emphasizes the small influence of the differences in random message creation, in contrast to the large impact of node mobility. With a median spread around 35%, the lifetime of 1 hour is clearly insufficient for message dissemination throughout the network. Nevertheless, some messages may spread further due to fortunate circumstances in node mobility. For example, around 9% of messages in simulation $s1$ achieve a spread higher than 0.57, and the top 1.1% of messages even achieve a spread higher than 0.9. In contrast, the lowest 9% of messages do not surpass a spread of 0.1, which underlines the isolation of some parts of the disaster network.

Group $s1$ shows a clear increase in message spread, but the distribution — formerly heavily concentrated around the median — is wider with more SC links. Nevertheless, several messages are not spread far, similar to the simulation without satellite support. This same result is seen for nearly all simulations since there are fewer SC links than network clusters. On the other hand, a quarter of all messages is spread to more than 80% of the network with 3, 4, and 5 SC links, respectively. The upper quartile is not increasing considerably with more SC links, which indicates that some larger parts of the network are not well-connected with other parts that have at least one satellite-capable node in them.

Group $s2$ exhibits a much larger increase in message spread with more SC links compared to Group $s1$. This indicates that there are fewer isolated parts of the network in comparison, indicating a more even distribution of satellite-capable nodes among the larger network clusters. With 4 and 5 SC links, over half of the messages spread to at least 80% of the network. Additionally, there is a much more distinct concentration in the upper quartiles above the median compared to $s1$. Nevertheless, with around 10% of messages not exceeding a message spread of 0.2 at all, some network clusters are still not connected sufficiently.

Group $s3$ reveals two interesting results. First, introducing two SC links does not significantly influence the message spread. There is only a 0.1% increase in the mean spread, while the median stays the same as without satellite links. This indicates that the two satellite-capable nodes are either within the same cluster or in clusters very close to each other. Secondly, a clear separation in the message spread distribution can be seen with three and more SC links; one below the median and one around the third quartile. Clearly, there are two larger, distinct parts of the network forming, one being well-connected over SC links, while the other is not.

The results discussed in Figure 3 showcase the residual influence of node mobility and the distribution of SC nodes on the message spread in the disaster network. As seen for group $s2$, this influence can be reduced significantly with more SC links in some instances. Nevertheless, a more detailed analysis of the distribution remains open for future work. Additionally, it is unclear if there is a certain amount (<100%) of SC links with which their distribution and mobility become negligible.



(a) Received bits per second. **(b) Transmitted bits per second.**

Figure 4. Aggregated overhead and data throughput per node over different numbers of satellite-cellular links. The same random selections for satellite-capable nodes as in Figure 3 are compared.

To further classify our initial results, Figure 4 depicts the aggregated SC link throughput per second, including both overhead and DTN messages. The same result groups ($s1, s2, s3$) as in Figure 3 are shown. Most importantly, the satellite links' maximum capacity of 9.6 kbit/s is not exceeded: the maximum measured was below 4.5 kbit/s, and 97.5% of measurements are below 2.5 kbit/s in transmit with 5 SC links. The overall spread in the required link bandwidth is relatively small, as expected, increasing with more SC links due to the increasing number of possible communication partners. The larger differences between the lower percentiles compared to the 97.5^{th} percentile and the maximum, respectively, hint at a few large bursts of DTN messages being distributed over the SC links, probably when a previously unknown bundle of messages enters the cluster of the sender. In general, it seems that the chosen satellite link capacity could support larger networks with more data traffic, which should be explored in future work. Furthermore, the differences in the groups ($s1, s2, s3$) for the data throughput are less discrete than those for message spread. For the next steps, it is necessary to extend the simulation to allow the comparison of individual node links for a more detailed understanding of possible influences of node mobility on data throughput and under more realistic link properties.

In summary, our evaluation provides the first insights into a combined satellite-cellular delay-tolerant disaster network. We highlighted the positive impact on network connectivity with only a few small-throughput satellite links that could more than double the average message spread in the disaster network but can also significantly increase SC link load. On the other hand, the negative influence of uncontrollable node mobility and distribution persists in our results. Nonetheless, we also discussed open issues for an extended study, such as a more detailed analysis of the influence of node mobility, the distribution of satellite-capable nodes, and data throughput requirements.

CONCLUSION

The recent progress in direct-to-cell (D2C) satellite communication and their foreseen incorporation in future 5G/6G cellular networks (3GPP, 2020) promises significant potential. Overcoming the need for dedicated middleboxes to connect end-user devices like smartphones with satellites could alleviate many challenges that disaster relief currently faces during and after large-scale disaster events. Nevertheless, the technology is still in its infancy — actual capabilities or details of working implementations are currently unknown and will probably be subject to change. Furthermore, it could take at least several years for the widespread availability of D2C with the envisioned communication properties.

In this paper, we discussed a possible integration of D2C communication into a decentralized, delay-tolerant disaster network, using a lower-end estimate for the number of available connections and data throughput. Our simulation results indicate the considerable benefit of D2C on network connectivity, even with only a few satellite-capable smartphones and a small throughput. Nonetheless, a small number of SC links cannot entirely remove the large influence of node mobility on message dissemination, although normal for such probabilistic systems as decentralized disaster networks.

Based on these initial results, future work needs to include further data types like video and speech and more intensive communication patterns to evaluate the boundaries of D2C communication. This may also include differentiation and prioritization of emergency service communication or emergency calls over, e.g., private chats.

Additionally, this work assumed the satellite interconnection as a continuously available one-hop connection, which may be unrealistic, especially for LEO satellite constellations over large-scale disaster areas. Future work may encompass more sophisticated, specifically tailored routing protocols for a combination of routing in ground-based disaster networks and in satellite constellations, respectively. Furthermore, as links may be subject to attenuation, jitter, or disconnections, more realistic simulations for link connectivity and usability are required.

Overall, our results show that large-scale disaster areas without a working communication infrastructure would hugely benefit from satellite-cellular links. Providing desperately needed communication capabilities for emergency services and the affected population alike, direct-to-cell may be the game changer for future disaster relief efforts.

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