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Take it or Leave it: Decentralized Resource Allocation in Mobile Networks

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***Abstract*—Human activity patterns such as communication and cooperation rely in large parts on smartphone-based interaction. Day-to-day available communication means are taken for granted. But in scenarios where communication infrastructure is broken, such as in the aftermath of a disaster, communication establishment becomes crucial. In those post-disaster conditions ubiquitous mobile devices carried by humans can be used to establish basic ad-hoc communication services in order to aid first responders or to organize volunteers. However, these services rely heavily on the runtime of the utilized mobile devices and therefore network failure and communication capability show a strong dependency on the lifetime of mobile devices. In this paper, the potentials of decentralized resource allocation strategies in mobile networks, with harsh post-disaster conditions, are examined. Considering energy resources to prolong functioning of basic post disaster communication services, different resource allocation strategies are proposed. Through an extensive simulation study we show that (i) the proposed strategies for resource allocation lead to significant improvement of the lifetime of the mobile devices (up to 7.8 %) and (ii) the time in which a stable service quality (w.r.t. to the received messages) is provided can be extended by 80 % compared to the baseline.**

I. Introduction

Today an increasing amount of mobile devices – such as smartphones and tablets – have changed the way people interact with each other. A large part of today's communication is done relying on mobile devices such as smartphones with connectivity to cellular infrastructure-based networks [1]. Disasters such as hurricanes or earthquakes increase the demand for communication significantly [2], though at the same time disable the communication infrastructure in large parts [3]. In order to counter this challenge and to provide communication, approaches that establish hybrid, ad-hoc and delay tolerant networks for disaster communication services have been proposed by the research community [4], [5].

The performance and use of these approaches are strongly dependent on (i) the number of participating mobile users and (ii) the available battery capacity, as these render the communication potential in the network. Nodes going offline as they run out of battery decrease the ad-hoc network lifetime and performance of the proposed communication services.

Up to now few approaches or related research have considered an allocation of external power sources, such as car batteries, in order to enhance the network lifetime. If considered, the approaches relied on a centralized allocation, which is infeasible in an infrastructure-less network. Thus a decentralized resource allocation service is proposed in this paper, which is not intended to replace communication establishing approaches such as [4], [5]. Instead it operates concurrently with the communication establishing approaches. The resource allocation service relies on a set of ad-hoc and delay tolerant networking strategies to provide an appropriate distribution of knowledge within the network. This enables the service to enhance the lifetime of mobile devices and provide a stable service quality over a longer period of time. The contributions of this paper are the following:

- The conception, modeling, and investigation of a scenario in which participants of an infrastructure-less network compete for vital resources.
- A decentralized resource allocation service consisting of a set of components aiming at the individual selection of resources and distribution of knowledge about their availability.
- An in-depth simulation-based analysis and evaluation of the proposed services highlighting (i) the impact of different service compositions, (ii) the influence of changing scenario characteristics to assess its robustness, and (iii) a comparison of the proposed and a baseline solution.

This paper is structured as follows: At the outset Section II provides a description of the considered post-disaster infrastructure-less scenario and its characteristics. Section III gives an overview of state-of-the-art communication services and systems that find application in post-disaster scenarios. The detailed explanation of the proposed decentralized resource allocation service is found in Section IV. We highlight how the system copes with scenario characteristics, distributes knowledge about resources, and supports a final decision to take or not to take a resource. Section V addresses the three-parted evaluation. The section also introduces the modeling of the scenario and the evaluation setup. Section VII concludes.

II. Scenario

The scenario used in this paper describes an urban area in post-disaster conditions in which any means of infrastructure supported communications are unavailable. The urban area is populated with mobile users equipped with standard resource-constrained mobile devices as well as randomly placed, non-mobile and limited resources, such as water, food, or energy sources. The mobile devices have (i) communication interfaces such as WiFi and Bluetooth for local communication and (ii) different energy consumption states which may lead to devices going offline. A subset of the devices participate in

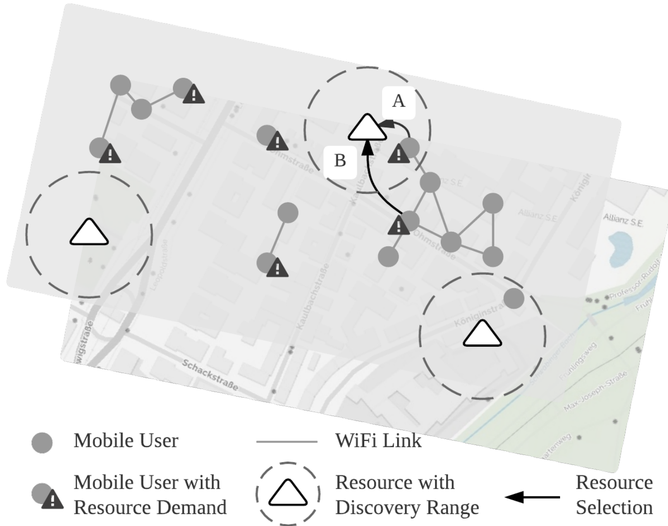


Figure 1. Scenario components in an urban ad-hoc communication network. Resources can be discovered and consumed by mobile users.

a network to provide disaster relief services as described in the next section. One of its goals is to enable fundamental communication services, such as emergency-calls which are key criteria for post-disaster response, utilizing the devices of the mobile users [4], [5]. Those communication services will be explained in Section III. However, the main goal of this disaster relief service is to ensure the continuous provision of communication, thus (i) providing the basis for improved communication quality and (ii) maintaining the possibility for post-disaster communication for as long as possible. Energy as a resource may be used to prolong availability and functionality of the on top communication services. The amount of resources provided by immobile sources randomly appearing over time is limited. Once appeared they can be discovered and consumed. Each resource has a discovery range in which mobile users will detect their presence. To distribute these scarce resources, a decentralized resource allocation service, which is installed on the mobile devices, is used. It is introduced in Section IV.

Figure 1 shows the components of the scenario. Some of the mobile users depicted have demand for resources. Users with demand can move to resources they discovered in order to collect them (cf. notion A in Figure 1). The decentralized resource allocation service ensures that devices of users that discovered a resource share availability information with other surrounding devices. This information enables mobile users out of reach of the resources to also try to collect them if they are still available (cf. notion B in Figure 1). According to [6] mobile users collaborate (shown by their unity and prosocial behavior) in the aftermath of a disaster instead of panicking and acting selfishly.

In the scenario, mobile users are naturally limited to walk along open areas, paths, and streets, resulting in some parts being visited less frequently than others. A multitude of so called *attraction points* lead to natural movement patterns of users between different places on the map [7]. Those attraction points represent open spaces, such as parks, where people tend to gather in emergency situations. To model the explorative behavior of users they either move towards these attraction points or choose a random location representing people searching for relatives, first-aiders, or resources.

III. Communication Services for Post-Disaster Networks

In case of a disaster, communication is key in coping with the aftermath of the situation and supporting relief efforts. Typically in such situations special online services are established in order to contact family and friends, call for help, or share situational information and resources. In addition to these infrastructure-based services, there are a variety of post disaster communication services in place that can operate independently from existing communication infrastructure [4]. Especially for disaster response scenarios a comprehensive overview of communication types and applications is given in [8]. Based on this, we provide an introduction to the area of communication services for post-disaster networks in this section. We give an overview of the types of services used for self-organized communication between civilians and rescuers in disaster scenarios.

The first group of disaster related services focuses on providing civilians with relevant information and warnings. The US Federal Emergency Management Agency (FEMA) or the German Office of Civil Protection and Disaster Assistance have produced mobile apps to inform civilians about disaster preparedness and disaster response, including virtual maps with useful information [9], [10].

The second group of disaster services focuses on civilians in need when critical infrastructure, such as cellular networks, are broken. Several applications allow victims to broadcast distress signals via their smartphones [11]. Similar systems try to forward SOS-messages to nodes that are in direct neighborhood of a person in need. Such systems do not only focus on professional rescue-workers, but empower the affected communities themselves to provide additional, spontaneous, self-organized rescue teams [12].

The last group of services enables simple text based communication to allow civilians to communicate and cooperate in post-disaster situations. Specialized chat services similar to applications like Twitter and WhatsApp, can function without requiring any infrastructure [13]. A separate problem to the utility of special services in post-disaster ad-hoc networks, is the distribution of the service app itself. If service apps for disaster communications are not pre-installed, there are ways to deploy apps in disrupted infrastructures offline [14].

IV. Approach: Decentralized Resource Allocation Service

There are two problems to be addressed in the proposed scenario. First, mobile users with their devices, called nodes, have to know about the availability of required resources in order to collect them. The location and arrival time of new resources cannot be predicted and is not known by mobile nodes a priori. Thus, resources can only be discovered by nodes moving around. To share this information with nodes in need of resources, the discovering node generates resource advertisements, containing the geographic coordinates and the last known amount of resources available. A service continuously running on the participant's phone distributes these advertisements using the methods described in Section IV-B.

Second, a node has to decide if it is worthwhile to obtain resources it learned about, when that should be done and which resource to pick. Due to scarcity, it may not always be the best decision to pursue all available resources, since others may already have taken them before the node arrives, resulting in wasted time and undesired detours. We introduce a service that autonomously decides when a node should start or stop walking to a resource, which consists of three components.

The *demand evaluator* determines whether a node is currently requiring resources, and if so, initiates the resource selection process. For example, demand could be expressed by explicit user input when considering physical resources, or derived from the battery charge state.

Next, for each node, a *cost mapper* computes the individual costs for known resources, considering different node and resource attributes. Those attributes are for example the resource amount and type, the distance from the node to the respective resource, and the estimated cost to obtain the selected resource. If the trip would consume more resources than available, a value of INVALID is returned. Amongst others, possible cost-mapper are e.g. the minimum distance or the maximum gain regarding to a non INVALID resource.

The *selection strategy* uses this cost-mapping to create a linear order of all known resources of a specific type and chooses the best option. Usually this is the resource with the least non-INVALID costs. If a resource could be found, the user is alerted and guided to the resource through directions on screen. We propose different selection strategies in Section IV-C.

The service constantly monitors incoming advertisements to evaluate whether better options are available, or if the target resources have been depleted in the meantime, and adjusts the selection accordingly.

A. Scenario Characteristics

While the resource allocation problem can be applied to any kind of resource that must be collected in person, we only consider the problem of charging a node's battery in this paper. All nodes are present in the beginning of the scenario. They start with varying amounts of resources and have a maximum battery capacity e_{max} up to which they can recharge themselves at immobile *Resource Distributor Beacons* (RDBs). These RDBs could for example be battery packs dropped from a plane, or car batteries provided by civilians. We use a fixed total amount of resources available, which are deployed in the area over time as explained in Section V-A and first must be discovered by the nodes.

A node can be in one of three resource consumption states. They begin in ROAMING state in which they follow their personal movement policy. In this state, the node's current energy level e_c is reduced by E_r per second. If e_c is zero, the node stops moving and communicating then changes to OFFLINE state, from which it cannot recover. If a node wants to recharge at an RDB, it enters HEADING state consuming E_h resources instead. We require $E_h > E_r$ to reflect the additional energy usage by the phone's screen and GPS component required for navigating the user towards the target. As a consequence, heading for an already depleted resource results in, not only wasting the user's time but also the device's valuable energy.

Nodes return to ROAMING state either after arriving at the RDB or if the selection strategy decides that pursuing the target is no longer worthwhile. For simplicity charging is assumed to be instant. Nodes try to maximize their own profit by transferring as much energy as possible from an RDB, up to their maximum capacity e_{max}. RDBs carry a unique *beacon ID* and maintain a *Beacon Sequence Number* (BSN), which is increased every time their amount of energy changes. The BSN is used by the nodes to determine the actuality of availability information as described below. Nodes are able to obtain exact information on the amount of resources available at an RDB and its current BSN upon discovery.

A threshold is used to determine whether a node currently has demand for a resource. In this work, we consider the cost mapper *MinDistance*, which assigns each RDB a cost of $-1/d$, with d being the line of sight distance between node and RDB. With the nodes velocity v it determines the set of INVALID RDBs by checking whether the node would deplete all its energy en route as seen in Equation 1.

$$e_c \leq E_h \cdot (d/v) \tag{1}$$

Or if the additional energy consumption of HEADING outweighs the available amount for recharge as seen in Equation 2.

$$r'_e(r'_e \leq (d/v) \cdot (E_h - E_r)) \tag{2}$$

B. Advertisement of Resource Availability

A node discovering an RDB generates a resource advertisement as a tuple *Adv(src, dst, beacon ID, BSN, r, TTL, l, t)*, where *src* and *dst* are the origin and intended receiver of the advertisement, initially set to the beacon ID and *null*; *r* is the amount of resources available; *TTL* is a maximum hop count for flooding; *l* the RDB's location; and *t* the time at which the advertisement has been created. Advertisements created by a node or received from others are placed in the node's advertisement store. For each beacon ID, only the most recent advertisement is saved, i.e., the one with the highest BSN. Advertisements are automatically removed from the store after $t + t'$, t' being the node's memory span, to reduce the amount of outdated information.

To share advertisements among nodes different dissemination strategies and their combinations are used. Within the *Immediate Flooding* (IF) approach each time a node's store is updated with newer information, it creates and sends a copy of the advertisement with an increased hop count. A node does not flood a message if the maximum hop count is reached or if it has seen a more up to date information of the RDB.

Since the low density network faces frequent disconnectivity, only a few nodes can be reached by IF [15]. Thus, we employ a variant of the epidemic routing protocol SPIN-1 [16] as a *Store-and-Forward* (S&F) approach. The protocol uses a three-way handshake to exchange availability information. Every x seconds, where x is randomly drawn from an interval to reduce contention, a node broadcasts a list of all known beacon IDs and their respective BSNs. Nodes overhearing this message compare the list to the set of advertisements from their own store. They collect all announcements received from other nodes within a short period of time (1s). For each missing or newer advertisement, a unicast request containing only the beacon ID is sent to a random known provider of the information, who replies with the complete advertisement. If the request remains unanswered, the next provider is selected.

If all discovered RDBs are advertised to all nodes without restriction, some nodes will start heading for them without the chance of receiving any resources, as closer nodes already deplete the RDB, wasting additional energy. We call this problem *Over-Competition*. To reduce the number of instances of futile HEADING, we propose an extension to the dissemination process called *Advertisement Fading*. Here nodes in HEADING subtract their demand, i.e., $e_{max} - e_c$, from the resource amount of an advertisement of their target before sending it out. Whereas before advertisements represented the last known state at an RDB, they now also give an estimate about how many resources are left if all members of the hop sequence would collect them instantaneously, based on the assumption that each hop increases the distance to the RDB. Still, the receiver is only informed about the demand of nodes in this particular sequence, not knowing of other nodes also closer to the RDB. Also, the advertisement placed in its store is only a snapshot of the network path from the RDB to the receiver at this particular point in time. Due to their unpredictable personal movement policy, nodes may pass their former predecessor and become those closest to the RDB, while still believing to have no chance in obtaining resources. To mitigate this problem, we increase the BSN of an RDB every five seconds so advertisements are forwarded and updated more often to reflect the current situation.

C. Resource Selection Strategies

The *Greedy Selection* strategy always chooses the RDB from the advertisement store with the least cost. We compare it to a baseline called *En Passant* where nodes do not exchange advertisements with each other and only take resources if they have demand and are currently within the discovery range of an RDB. This approach minimizes HEADING time since nodes will not travel large distances to reach RDBs they heard about from other nodes, and also reduces over-competition. However, *En Passant* may lead to nodes in need of resources not knowing any RDBs in their vicinity.

Additionally, a centralized *Reservation Oracle* aware of the location and amount of all resources in the area is used for comparison. Nodes reserve resources at the *Oracle* in a first-come, first-serve manner. Like *Greedy Selection*, the *Oracle* chooses the least-cost RDB; however, it takes all existing reservations into account and thus prevents Over-Competition. Performance-wise the *Oracle* is not the upper bound, as the assignment of nodes is performed only once immediately when nodes experience demand. This may result in larger HEADING times as nodes do not benefit from newly generated resources in their vicinity once assigned to a resource.

V. EVALUATION

The evaluation of the decentralized resource allocation service consists of three parts: The impact of different service parameter settings such as heading thresholds, TTL or announcement intervals is evaluated in a default scenario, which imposes harsh conditions on the individual strategies in order to find a working setting for subsequent evaluation parts (cf. Section V-B). In the second part of the evaluation, we use the optimal system parameters to assess the robustness of the systems against scenario changes (cf. Section V-C). In doing so the operating modes of the proposed solutions can be examined in more detail. The third part of the evaluation compares the proposed advertisement dissemination and resource selection strategies in view of our main goal of extending the network's lifetime (cf. Section V-D).

Below we describe (i) the modeling of the scenario, the used evaluation parameters, and the evaluation metrics, (ii) as well as the three fold evaluation, in more detail.

A. Modeling of the Scenario and Evaluation Setup

We simulated the resource distribution service using the event-based Simonstrator Framework [17] which comprises the IEEE 802.11g standard from the ns-3 simulator [18] to model the WiFi ad-hoc communication. The basic simulation parameters are shown in Table I with default values underlined. We used a communication and discovery range of 100 m, a

Table I
SCENARIO AND SIMULATION SETUP

Simulated Area $[m \times m]$	2000×2000
Max. WiFi Comm. Range $[m]$	100
WiFi Standard	802.11g
Movement Speed $[m/s]$	$1.5 - 2.5$
Movement	13 attraction points with a 20 % exploration factor
Density $[\text{nodes}/km^2]$	25
Max. Battery Capacity	14 400 ru (Resource Units)
Start Energy	Normal distributed, $\mu = 67\,\%$
RDB Generation Interval [*min*]	$\underline{2}$, 5, 10
Energy Amount per RDB [*ru*]	$[1, \underline{2}, 5, 10, 100] \times$ max. Bat. Cap.
Overall Energy [*ru*]	#Nodes $\times 2 \times$ max. Bat. Cap.
Roaming; Heading Cost $[\text{ru}/s]$	1.0; 3.11
Heading Threshold	
– Reservation Oracle	$.1, .2, .3, \underline{.4}, .5, .6, .7, .8, .9$
– En Passant	$.1, .2, .3, .4, .5, .6, \underline{.7}, .8, .9$
– Greedy Selection (IF)	$.1, .2, .3, \underline{.4}, .5, .6, .7, .8, .9$
– Greedy Selection (IF+S&F)	$.1, \underline{.2}, .3, .4, .5, .6, .7, .8, .9$
S&F Announcement Timer [*s*]	$\underline{5\text{-}10}$, 10-20, 20-40, 40-60
Memory Span [*min*]	40
TTL	$1, 2, 3, 4, 5, 6, \underline{7}, 8, 9$

total simulation time of 20 h, and placed 100 nodes randomly on a map. The area of 2x2 km^2 uses real street data from OpenStreetMap[1] of a residential district in the city of Darmstadt, Germany. The nodes' personal movement policy is based on attraction points. Nodes move with a speed between 1.5 and 2.5 m/s and randomly select one of the 13 locations marked as `amenity=park` in OpenStreetMap as their next target. Since resources are placed at random places on the map, which may not lie on a node's route, nodes may also select a random point instead of an attraction point with an *exploration factor* of 0.2 as explained in Section II. They pause 15-20 min before selecting the next target.

Nodes have a maximum battery capacity of 14 400 resource units (ru). Together with a consumption rate of $E_r = 1\,\text{ru}/\text{s}$, this allows nodes to communicate for 4 h in ROAMING state with a full charge. The estimated consumption in ROAMING state is based on a power usage study of an HTC Dream smartphone conducted by Zhang et al. [19]. Nodes utilize the CPUs for 50 %, and to constantly transmit messages via WiFi in both states, while cellular communications are disabled due to the lack of functioning mobile base stations. Then the formula for the power consumption in [19] becomes $\beta_{uh} \cdot \mathit{util} + \beta_{\text{CPU}} + \beta_{\text{WiFi}} + \delta_{\text{state=H}}(\beta_{br} \cdot \mathit{brightness} + \beta_{\text{GPS}})$ where $\beta_{uh} = 4.34\,\text{mW}/\text{s}$ is the consumption rate of the CPUs, $\mathit{util} = 50$ the CPU's utilization factor, $\beta_{\text{CPU}} = 121.46\,\text{mW}/\text{s}$ the system's base energy usage, $\beta_{\text{WiFi}} = 10\,\text{mW}$ the energy usage in WiFi high power mode assuming the antenna being only active 10-15 ms every second, $\beta_{br} \cdot \mathit{brightness} = 2.4\,mW \cdot 128$ the screen's consumption with brightness set to 50 %, and $\delta_{\text{state=H}} = 1$ if the node is HEADING, and 0 otherwise. This results in a consumption of 348.46 mW/s in ROAMING and 1085.21 mW/s in HEADING state, or $E_h = 3.11\,\text{ru}/\text{s}$. The nodes' start energy is distributed with a mean μ of 67 % (9648 ru), which is a typical average battery charge of a user's smartphone [20].

[1] http://openstreetmap.org

New resources are generated over time at uniformly distributed random places on the map. Each t_{gen} minutes, k resources are placed with an amount of r resources units each. Different energy amount per RDB and generation intervals are used. However, the amount of resources placed until the end of the simulation always totaled to 200 % of a node's battery capacity times the number of nodes (288 000 ru).

The simulations are repeated with 10 different seeds. Time-based metrics, measured with an one minute interval, are (i) the total number of nodes alive, (ii) the total number of resources on the field, and (iii) the Over-Competition expressed as the number of HEADING nodes which would not receive any resources if all HEADING nodes would be served immediately in order of their distance to their target RDB. Additionally, (iv) the exchange of messages by the disaster service network is simulated as follows: every minute a new virtual source S_n and receiver R_n are generated at random places on the map. Each source generates and repeatedly broadcasts a single message m_n. As in epidemic routing [21], any node within communication range of S_n gets "infected" with m_n, as well as nodes within communication range of other nodes infected with m_n. If a node carrying m_n reaches R_n, the message is said to be delivered at this point in time. After successful delivery, or 1 h after creation of source and receiver, S_n, R_n, and all m_n are removed from the network. We report the ratio of delivered messages within a sliding window of 1 h over time. Note that the exchange of these messages is purely virtual and does not involve actual transmissions between source, receiver, or nodes.

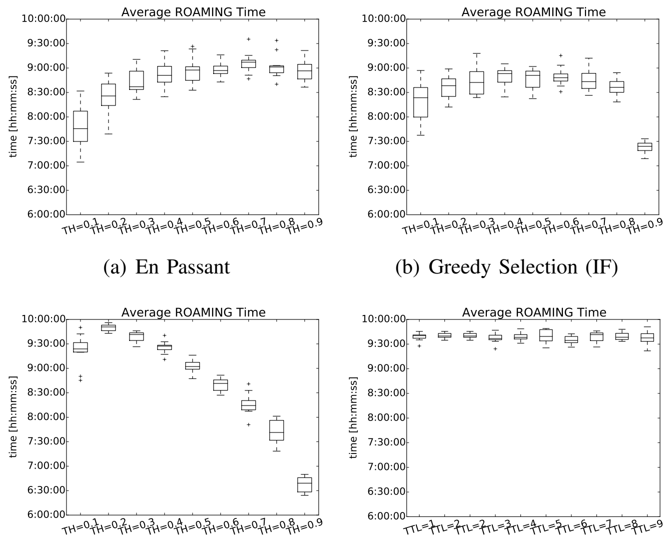
The following node-based metrics are considered: (i) the total time spent in ROAMING state/the percent of time spent in HEADING state; (ii) the mean number of messages per second sent by nodes; (iii) first/half/last nodes dead metrics [22].

B. Influence of Strategy Parameter Settings

For this part of the evaluation we used a default scenario setting (underlined parameters in top half of Table I) to analyze the influence of strategy parameter changes. We evaluated the proposed strategies *En Passant* and *Greedy Selection* using *Immediate Flooding* (IF) only, as well as a combination of *Immediate Flooding* and the *Store-and-Forward* dissemination strategy (IF+S&F).

The impact of *Advertisement Fading* and the *Reservation Oracle* strategy are not analyzed in this part of the evaluation, as we consider the former an extension of the *Greedy Selection* strategy, and the latter acts as an upper bound for the performance in Section V-D.

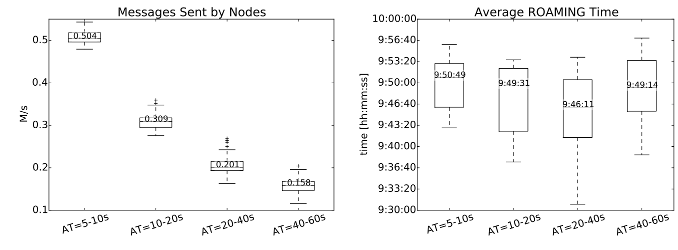
Figures 2(a-c) shows the impact of the chosen demand threshold on the nodes' ROAMING time for the three variants. In the following figures boxplots show the median which is represented by a solid line inside the box, while the lower and upper quartile are represented by the boxes. Whiskers show the upper (lower) data point within 1.5 of the interquartile range. Outliers are represented by crosses.



(a) En Passant (b) Greedy Selection (IF)

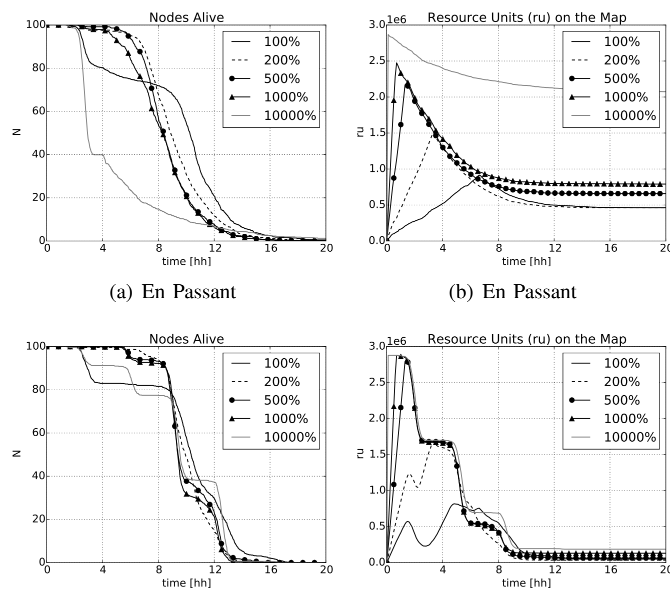
(c) Greedy Selection (IF+S&F) (d) Greedy Selection (IF+S&F)

Figure 2. Mean total ROAMING time for different demand thresholds (a-c) and different TTL (d).



(a) (b)

Figure 3. Impact of the frequency of S&F announcement timer (AT).



(a) En Passant (b) En Passant

(c) Greedy Selection (IF+S&F) (d) Greedy Selection (IF+S&F)

Figure 4. Nodes alive and resources on field for different RDB resource amounts (in % of a node's maximum battery capacity).

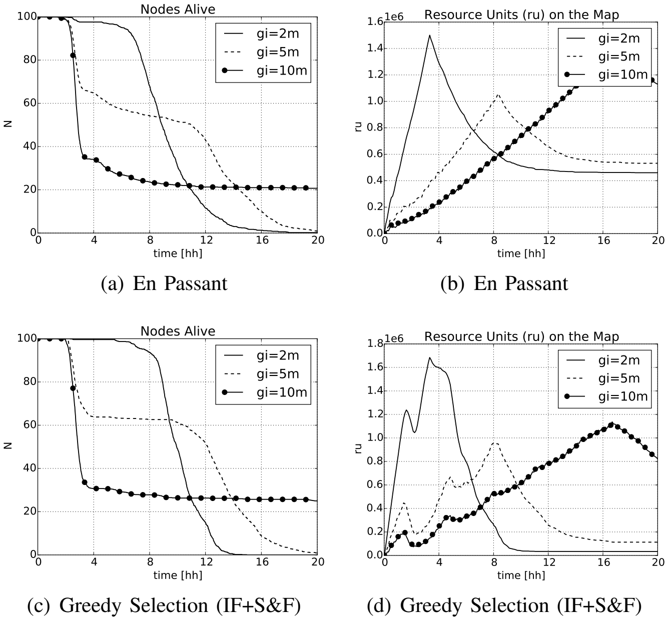
Since in the *En Passant* strategy nodes forget the location of RDBs as soon as they leave the discovery range, nodes may not be able to recharge at all once they hit a low threshold, resulting in an overall shorter mean lifetime (and subsequently ROAMING time). With a threshold of 10 % half of the nodes are offline after 6 h 59 min, while this mark is reached almost 2 h later with a threshold of 70 % (8 h 51 min), which is the optimum w.r.t. the ROAMING time. Here, nodes profit from taking resources at every opportunity. As nodes will not travel distances beyond 100 m, *En Passant* is the strategy with the shortest fraction of node lifetime spent HEADING. *Greedy Selection* (IF) shows similar characteristics to *En Passant*, which is not surprising as though advertisements are now remembered by nodes and shared with others, they do not travel very far due to the high disconnectivity observed in a delay-tolerant network. The ROAMING time of nodes with IF+S&F decreases with higher thresholds. Nodes can take their time before recharging, as the exchange of advertisements with other nodes passing enables them to select the best resource from a larger number of options. Thus, low thresholds such as the optimal 20 %, are sufficient; 20 % battery capacity are still enough to keep a node alive for 48 min in ROAMING state. With increasing threshold values nodes try to recharge themselves more frequently, which results in higher competition. A threshold of 90 % leads to nodes almost always heading for a newly generated resource they learned about, even if they are further away then their competitors and have no chance of obtaining resources. The message TTL has no significant effect on the lifetime of nodes as shown in Figure 2(d).

The impact of the frequency at which knowledge about advertisements is announced by nodes with S&F, which is responsible for the majority of the protocol overhead is visible in Figure 3(a). Doubling the announcement timer interval from 5-10 s to 10-20 s reduces the amount of messages sent by 39 %. One would assume that sending fewer announcements would lead to less knowledge distribution of available resources. However, the announcement interval shows no significant impact on the average time in ROAMING state (cf. Figure 3(b)) with differences at most 4 min. While the reduction of protocol overhead is important, a slight increase of 0.2 M/s compared to the announcement timer interval of 10-20 s is reasonable as its leads to better advertisement dissemination in sparse populations.

C. Robustness against Scenario Characteristic Fluctuations

Next, we investigate the impact of the resource amount per generated RDB, the RDB generation interval, and the exploration factor of the individual movement of the nodes.

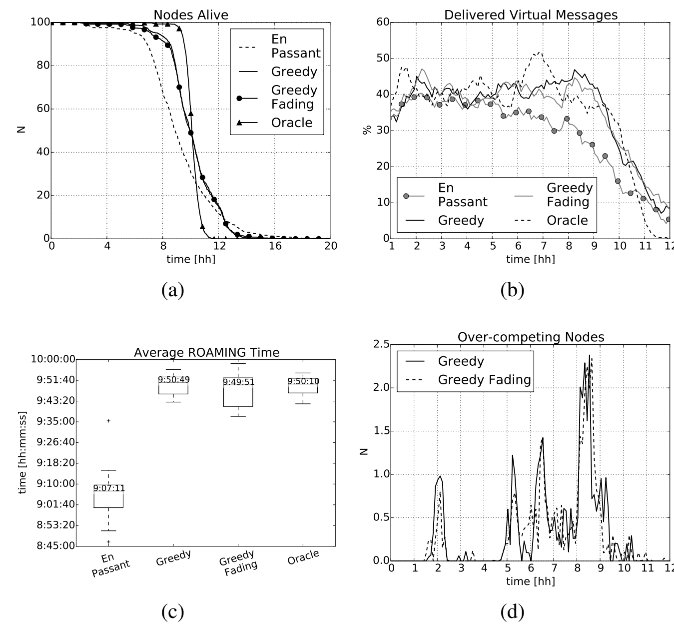
Figure 4 shows the number of nodes alive over time compared to the number of resources on the field for five different resource amounts per RDB. The generation interval is set to one RDB each 2 min; thus, increasing the RDB size results in an overall faster availability of the total amount of resources. With a size of 100 % (w.r.t. to a node's maximum



(a) En Passant (b) En Passant

(c) Greedy Selection (IF+S&F) (d) Greedy Selection (IF+S&F)

Figure 5. Evaluation of the impact of RDB generation interval (gi).



(a) (b)

(c) (d)

Figure 6. Evaluation of the four selection strategies.

capacity), all resources have been placed at approx. 6.66 h, while a size of 10 000 % results in only two RDBs after 4 min, each providing one half of the total resource amount. With the small number of two RDBs, nodes seldom discover them while wandering about. In this setup, *En Passant* performs poorly with less than 40 % of the nodes alive after 4 h. The majority of nodes does not encounter them at all, leading to the large decline at about 2 h 41 min, which is the maximum lifetime of a node with the mean start resource amount. In contrast, advertisement dissemination helps nodes which did not pass an RDB to gain knowledge of their availability.

Visibly as sudden drops in Figure 4(c), some nodes never hear of resources once they reach the demand threshold of 40 % for the first time and run out of battery. After 8 h, 75 % of the resources have been distributed, and with less nodes alive the availability of the last remaining RDB is propagated slower or forgotten.

As the probability of discovering an RDB is equal for all nodes and decreasing with the number of RDBs, resources are taken with consistent speed when using *En Passant*. If knowledge is shared, almost all resources are collected at the end of the simulation. For 100 % and 200 %, Figure 4(d) shows that temporarily the amount of available resources declines before all resources have been placed, namely at the point in time when the majority of nodes hits the demand threshold for the first time. Both strategies benefit from a large number of RDBs with small resources as this makes discovery more likely. However, with 100 % battery capacity per RDB, resources are not made available quickly enough for all nodes to have a chance to recharge. This is supported by the results for increasing the RDB generation interval in Figure 5, where a large number of nodes go offline before the time marker of 4 h. Increasing the number of RDBs placed per generation event while adjusting the generation interval so that an equal amount of resources is available as if single RDBs had been placed in the same time frame. In comparison to the respective generation intervals, the average ROAMING time was reduced by 22 min (2 min interval) to 1 h 43 min (10 min interval). This is due to the fact that an earlier deployment of multiple smaller resources increases their chance of discovery compared to a burst like deployment with larger intervals.

We evaluated the exploration factor of the movement to assess the robustness of the proposed solution. *En Passant* profits from higher exploration factors as more randomness increases the resource discovery rate. *Greedy Selection* is more robust to changes in node movement as the mobile nodes share resource information, leading to a better overall knowledge.

D. Comparison of Selection Strategies

A comparison of the performance of the four selection strategies is shown in Figure 6. The results for *Greedy Selection* with only IF are omitted as IF+S&F outperforms them. As the first hours after the disaster are most important [23] a higher node density in the first hours is preferred for communication compared to a solution with a long-living but sparse populated network. The *Reservation Oracle* is able to maintain a high number of online nodes for the longest time. However, due to its non-optimality mentioned above, it is surpassed by *Greedy Selection* with regards to the average ROAMING time. Thanks to sharing the location of RDBs, *Greedy Selection* improves over *En Passant* in this aspect by more than one hour to 9 h 52 min instead of 8 h 50 min until half of the nodes are offline (cf. Figure 6(a)).

The successful delivery of virtual messages supports this finding. *Greedy Selection* is able to deliver more than 40 % in most of the 1 h sliding windows before the 9 h mark, while *En Passant* delivers less than 25 % virtual messages at the same point in time (cf. Figure 6(b)). Moreover, *En Passant* experiences a significant drop in the successfully delivered virtual messages after the 5 h mark while *Greedy Selection* is able to maintain a constantly higher delivery rate. Also, *Greedy Selection* improves the average ROAMING time over *En Passant* by 7.8 % (cf. Figure 6(c)). Surprisingly, *Advertisement Fading* does not lead to better results. While the limitation of advertisements does reduce the number of Over-Competing nodes in the first 5 h (cf. Figure 6(d)), it has no significant effect on the average ROAMING time or the shape of the nodes alive curve.

VI. RELATED WORK

To the best of our knowledge, there is no previous work on distributing vital resources among nodes in a decentralized fashion. However, there are several similar problems.

Stavrakakis and Kokolaki [24] examined the equilibria of a scenario where players choose between a set of limited, low-cost resources and an unlimited resource with high costs. They found that providing players with knowledge, e.g., the number of competitors, may result in a higher social cost than in the case without additional information.

A competition for limited resources emerges in the search of free parking space. Ayala et al. [25] formulated this problem as a finite assignment game where each driver selects a parking spot. If more than one car is assigned to the same spot, the closest one wins at the cost of the traveled distance, while the others pay an additional cost for the fruitless attempt. In contrast to the resource distribution service presented in this paper, the authors of [25] assumed that each instance of the parking place assignment game is independent from all others. The additional energy consumption in HEADING state, as considered in this work, leads to a higher demand by that node in instances played later on. In [26], the availability of parking spots is only disclosed by nodes to their neighbors if the spot is deemed relevant to them, which is not the case if the spot would likely have already been taken once the neighbor arrives. Age and distance are used as features to learn the relevancy of availability reports. Delot et al. [27] employ a decentralized protocol for the reservation of free parking spots with a node acting as a coordinator. A node acts as a coordinator and chooses a winner among interested vehicles, based on each competitor's distance to the spot, their time spent in search of a free place as well as other factors. While the energy provided by charging stations for electric vehicles is unlimited in practice, their scarcity and vehicles blocking them while charging make them a competed resource in the same vein as parking spots [28]. Unlike the herein considered scenario, however, the location of all charging stations are known and the availability of the stations is predictable – which are non applicable assumptions for this work. In [29], reservation requests are routed among the charging stations on the vehicle's path to find the station with minimum waiting time. Like [27], Schürmann et al. [28] choose a coordinator vehicle to allocate a station that just became free.

The problem of nodes running out of energy is usually addressed by reducing consumption, for example by using energy-aware routing schemes [30], [31]. Zamora et al. [32] showed how aggregating SOS messages on the phones of immobilized victims of a disaster can reduce the overall energy consumption of SOS beacons. A reverse situation of the resource distribution problem is studied with the problem of recharging static wireless sensor nodes. Here the goal is to keep as many nodes as possible alive to maintain a stable network and, thus, to cover a maximum possible area. Vehicles [33] can be used to recharge the sensors with little remaining battery life.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced and analyzed a novel scenario of distributing scarce resources among nodes in a post-disaster scenario. We focused on the distribution of electrical resources to prolong the lifetime and maintain the performance of a messaging network, however our solution can be applied to any type of resources that must be collected in person.

To achieve the targeted distribution of resources a modular, decentralized resource allocation service is proposed in this work. The service automatically exchanges resource availability information in a decentralized fashion to perform resource allocation decisions. By using different resource allocation strategies the service is able to increase the average lifetime of nodes by up to 7.8 % compared to a baseline without communication. On top of that the timespan the network was able to deliver at least 40% of the communication service messages was extended from 5 h to 9 h, resulting in a more stable communication service quality. Moreover, the proposed resource allocation service is robust to changes of node mobility and the number of resources and their respective capacity.

We are currently investigating collaborative approaches for multiple resource types, e.g., not taking as much as possible from a certain resources which could reduce the number of nodes heading to resources futilely. Furthermore, the idea of local arbitrators seems fitting for our purpose. We want to examine the potential of decentralized local arbitrators in hierarchical allocation of resources.

A field study simulating a disaster scenario with 150 participants is planned to obtain results for (i) realistic human movement patterns and (ii) realistic disaster communication.

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[2]Networked Infrastructureless Cooperation for Emergency Response
[3]Smartphone-based Communication Networks for Emergency Response
[4]Multi-Mechanisms Adaptation for the Future Internet

References

[1] Cisco, "Cisco visual networking index: Global mobile data traffic forecast update, 2016–2021," Cisco, White Paper, 2017. [Online]. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[2] F. Ranghieri and M. Ishiwatari, *Learning from Megadisasters: Lessons from the Great East Japan Earthquake*. World Bank Publications, 2014.

[3] M. Kobayashi, "Experience of Infrastructure Damage Caused by the Great East Japan Earthquake and Countermeasures against Future Disasters," *IEEE Communications Magazine*, vol. 52, no. 3, 2014.

[4] A. Al-Akkad, C. Raffelsberger, A. Boden, L. Ramirez *et al.*, "Tweeting 'when online is off'? Opportunistically creating Mobile ad-hoc Networks in Response to Disrupted Infrastructure," in *ISCRAM*, 2014.

[5] N. Suzuki, J. Zamora, S. Kashihara, and S. Yamaguchi, "SOSCast: Location Estimation of Immobilized Persons through SOS Message Propagation," in *INCoS*, 2012.

[6] E. A. Heide, "Common Misconceptions about Disasters: Panic, the "Disaster Syndrome," and Looting," *The First 72 Hours: A Community Approach to Disaster Preparedness*, vol. 337, 2004.

[7] I. Rhee, M. Shin, S. Hong, K. Lee, S. J. Kim, and S. Chong, "On the Levy-walk Nature of Human Mobility," *IEEE/ACM Trans. Netw.*, vol. 19, no. 3, pp. 630–643, 2011.

[8] P. Lieser, F. Alvarez, P. Gardner-Stephen, M. Hollick, and D. Böhnstedt, "Architecture for Responsive Emergency Communications Networks," in *Global Humanitarian Technology Conference (GHTC) (accepted for publication)*. IEEE, 2017.

[9] US Federal Emergency Management Agency (FEMA). [Online]. Available: http://www.fema.gov/mobile-app

[10] K. Brouwers, *Guide for Emergency Preparedness and Correct Action in Emergency Situations*, German Federal Office of Civil Protection and Disaster Assistance (BBK), 2015.

[11] A. Al-Akkad, L. Ramirez, A. Boden, D. Randall, and A. Zimmermann, "Help Beacons: Design and Evaluation of an Ad-hoc Lightweight s.O.S. System for Smartphones," in *ACM CHI*, 2014.

[12] O. Mokryn, D. Karmi, A. Elkayam *et al.*, "Help Me: Opportunistic Smart Rescue Application and System," in *IEEE/IFIP Med-Hoc-Net*, 2012.

[13] T. Hossmann, F. Legendre, P. Carta, P. Gunningberg, and C. Rohner, "Twitter in Disaster Mode: Opportunistic Communication and Distribution of Sensor Data in Emergencies," in *ExtremeCom*, 2011.

[14] A. Al-Akkad and C. Raffelsberger, "How Do I Get This App? A Discourse on Distributing Mobile Applications Despite Disrupted Infrastructure," in *ISCRAM*, 2014.

[15] M.-C. Chuah and P. Yang, "Performance Evaluation of Node Density-based Adaptive Routing Scheme for Disruption Tolerant Networks," *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 3, no. 3, pp. 174–184, 2008.

[16] W. R. Heinzelmann, J. Kulik, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," in *ACM/IEEE MobiCom*, 1999.

[17] B. Richerzhagen, D. Stingl, J. Rückert, and R. Steinmetz, "Simonstrator: Simulation and Prototyping Platform for Distributed Mobile Applications," in *SIMUTOOLS*, 2015.

[18] T. R. Henderson, S. Roy, S. Floyd, and G. F. Riley, "ns-3 Project Goals," in *ACM WNS2*, 2006.

[19] L. Zhang, B. Tiwana, Z. Qian *et al.*, "Accurate Online Power Estimation and Automatic Battery Behavior Based Power Model Generation for Smartphones," in *ACM/IEEE CODES and ISSS*, 2010.

[20] D. Ferreira, A. K. Dey, and V. Kostakos, "Understanding Human-Smartphone Concerns: A Study of Battery Life," in *IEEE PerCom*, 2011.

[21] A. Vahdat and D. Becker, "Epidemic Routing for Partially-Connected Ad Hoc Networks," Duke University, Tech. Rep. CS-200006, 2000.

[22] M. J. Handy, M. Haase, and D. Timmermann, "Low Energy Adaptive Clustering Hierachy with Deterministic Cluster Head Selection," in *IEEE WiMob*, 2002, pp. 368–372.

[23] M. O'Leary, *The First 72 Hours: A Community Approach to Disaster Preparedness*. iUniverse, 2004.

[24] I. Stavrakakis and E. Kokolaki, "Managing Competition for (Public) Resources in Human-centric Networked Environments," in *International Conference on Computing, Networking and Communications*, 2015.

[25] D. Ayala, O. Wolfson, B. Xu, B. Dasgupta, and J. Lin, "Parking Slot Assignment Games," in *ACM SIGSPATIAL GIS*, 2011.

[26] P. Szczurek, B. Xu, O. Wolfson, J. Lin, and N. Rishe, "Learning the Relevance of Parking Information in VANETs," in *ACM VANET*, 2010.

[27] T. Delot, N. Cenerario, S. Ilarri, and S. Lecomte, "A Cooperative Reservation Protocol for Parking Spaces in Vehicular Ad Hoc Networks," in *ACM MobiCASE*, 2009.

[28] D. Schürmann, J. Timpner, and L. Wolf, "Cooperative Charging in Residential Areas," in *IEEE ITS*, 2016.

[29] H. Qin and W. Zhang, "Charging Scheduling with Minimal Waiting in a Network of Electric Vehicles and Charging Stations," in *ACM VANET*, 2011.

[30] C.-K. Toh, H. Cobb, and D. A. Scott, "Performance Evaluation of Battery-life-Aware Routing Schemes for Wireless Ad Hoc Networks," in *IEEE ICC*, 2001.

[31] A. Safwat, H. Hassanein, and H. Mouftah, "Power-Aware Fair Infrastructure Formation for Wireless Mobile Ad Hoc Communications," in *IEEE GLOBECOM*, 2001.

[32] J. Zamora, N. Suzuki *et al.*, "Battery-saving Message Collection Method for Disrupted Communication Service Areas," in *IEEE CCNC*, 2014.

[33] C. Wang, J. Li, F. Ye *et al.*, "Multi-Vehicle Coordination for Wireless Energy Replenishment in Sensor Networks," in *IEEE IPDPS*, 2013.