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Adaptive Monitoring for Mobile Networks in Challenging Environments

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***Abstract*—The increasing capabilities of mobile communication devices are changing the way people interconnect today. Similar trends in the communication technology domain are leading to the expectation that data and media are available anytime and everywhere. A result is an increasing load on communication networks. In dynamic mobile networks that particularly rely on wireless communication such data requirements paired with environmental conditions like mobility or node density increase the risk of network failure. Consequently, monitoring is crucial in mobile networks to ensure reliable and efficient operation. Current monitoring mechanisms mostly rely on a static architecture and exhibit problems to handle the changes of mobile networks and environmental conditions over time. In this paper, an adaptive monitoring mechanism is presented to overcome these limitations. The mechanism exploits the connectivity and resource characteristics of mobile communication devices to (i) reconfigure its monitoring topology and (ii) adapt to changes of mobile networks and environmental conditions. Through evaluations we show that our proposed solution reduces the achieved relative monitoring error by a factor of six and represents a robust and reliable monitoring mechanism for these challenging environments.**

I. Introduction

Well equipped hand-held communication devices, such as smartphones or tablet PCs paired with a growing availability of wireless broadband access over cellular networks [1] enable the use of applications and services anytime and anywhere. The resulting traffic from this increased and data-intensive utilization is primarily handled by cellular networks. Especially in crowded areas (e.g., tourist attractions or train stations), or during popular events, the resulting traffic exceeds the capacity of cellular networks. This becomes apparent by a degrading network performance and can be observed by the users [2]. To overcome these problems several solutions have been proposed (i) to offload the resulting traffic of data-intensive applications over Wi-Fi ad hoc [3] or (ii) to exploit the locality of interaction as, for instance, in location-based services [4]. The resulting direct communication between devices leads to a decentralization of the rather centralized services and applications, where the client devices have been initially served with content from a respective service/content provider. In return, the decentralized topology prevents from monitoring and collecting relevant information from client devices to (i) determine the current state of the network and device and (ii) to adapt the provided content or the communication accordingly. Bypass [5] is an example for the adaptation between global and local communication strategies depending on the obtained information at the central coordinating service/content provider. The given example demonstrate the necessity for a feedback channel from the single devices to the central coordinating service/content provider. Harnessing the density of mobile devices for the direct data exchange a fraction of nodes does either maintain an intermittent or no feedback channel to reduce the traffic and connections over the cellular network. Consequently, a service/content provider may only collect and analyze the monitored data from a fraction of devices, resulting in an imprecise and incomplete view of the consuming devices.

To counteract this problem and to monitor the network and mobile devices this paper introduces CRATER. The presented approach constitutes an adaptive monitoring solution for dynamic, i.e., challenging environments. In particular it targets crowded places where the number of devices and the resulting traffic reaches the maximum capacity of cellular networks. Depending on the current network state, CRATER facilitates *centralized* as well as *decentralized monitoring* to gather relevant data from the participating devices. It relies on centralized monitoring if all devices obtain a direct connection to a service/content provider over the cellular network. Decentralized monitoring is deployed if direct communication between the mobile devices is used, e.g., Wi-Fi ad hoc or Bluetooth. In this mode of operation CRATER autonomously identifies devices that have (i) a cellular network connection and (ii) sufficient energy resources. These devices serve to collect monitoring data from other nodes without an active cellular connection. Therefore, ad hoc connections are established among nearby nodes to forward the collected data to nodes with a cellular network connection. Subsequently, the collected information is transmitted over the cellular network to a service/content provider facilitating an accurate and complete view over the participating nodes in the considered environment.

CRATER is designed to tackle the challenges that relate to the deployment of mobile ad hoc networks (MANETs) [6], [7]. More precisely, it (i) operates on top of mobile nodes (which leads to a constantly changing communication topology with intermittent connection), (ii) handles the error-prone and wireless communication medium with a limited communication range, and (iii) considers the limited resources of the mobile devices (e.g., energy) as well as the limited capacity of the shared communication medium. Furthermore, due to its adaptive design, CRATER reacts to the varying user density. Using a model of a train station that represents an example for the envisaged challenging environments, the evaluation shows that CRATER accurately monitors the current state of the communication network with a mean relative error below one percent. Furthermore, CRATER is highly robust, operating

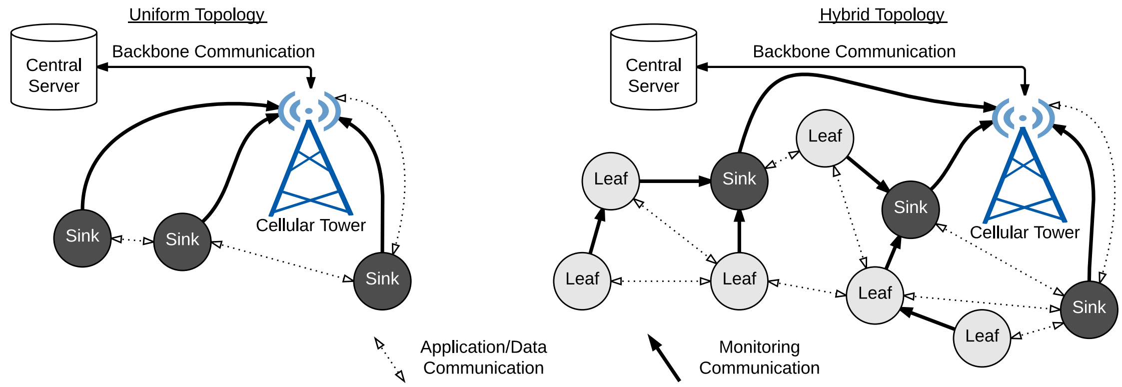


Figure 1: The uniform and hybrid topology structures of CRATER.

in the presence of fast moving users.

The remainder of the paper is structured as follows. Section II describes the targeted scenario with the related assumptions. The system design of CRATER is introduced in Section III and subsequently evaluated in Section IV. Afterwards, Section V deals with the related work on decentralized monitoring and data collection in mobile networks. Finally, Section VI concludes the paper.

II. SCENARIO

The scenario used in this paper models a populated place in an urban area that is subject to high dynamics, which we consider being a challenging environment. In our scenario, the dynamics become particularly apparent by the arrival and departure rate of users leading to crowds that alter the current user density, ranging from a sparsely to a densely populated place. Dependent on the user density in the considered area we assume that the present cellular network is able to handle the resulting traffic to a certain degree but operates unreliable, once a threshold is exceeded [2]. The varying user density accompanied by the problems of the communication network require transitions from one operating mode to the other. In the following we present the details of the scenario and outline our assumptions regarding, the considered place, the users, and the utilized communication devices.

The considered place in our scenario is represented by an urban railway station. With the selection of a railway station for our scenario we follow the suggestions from from Badonnel et al. [8]. In their work, they investigated the establishment of a MANET among users to extend the existing communication infrastructure of a railway station. Furthermore, a railway station is populated with pedestrians that walk around with crowds forming during busy times. The crowds are formed through passengers that (i) arrive by foot to catch a train, (ii) arrive by train to leave the railway station, or (iii) arrive by train and try to catch another train. The peaks of people due to the periodical arriving and departure are used to model the varying user density with the resulting overload of the cellular communication network. With respect to the communication infrastructure it is assumed that the railway station is covered with a cellular network that is accessible from anywhere within the station and can serve a maximum number of users. Furthermore, the station might be covered with Wi-Fi access points. However, they may not accessible for everybody but only grant access for a limited number of users. Consequently, the presented version of CRATER does not not consider Wi-Fi access points as additional means to communicate.

The considered users in the scenario have hand-held communication devices, such as smartphones or tablet PCs, and move through the railway station. With their communication devices, users may consume different types of applications and services. In addition to the applications and services a monitoring mechanism is deployed that monitors different attributes to characterize the state of the communication network and devices. The corresponding monitoring entities are assumed to be located on the users' devices to locally monitor relevant attributes. The measured monitoring data is subsequently collected by a central entity which provides the required information to applications and services for adaptation. The mechanism assumes that provider equipment e. g., cell towers, cannot be utilized for deployment of the monitoring solution.

III. CRATER: DESIGN OF AN ADAPTIVE MONITORING SOLUTION

CRATER is an adaptive monitoring mechanism targeted at mobile networks with hand-held communication devices that have different communication interfaces, i.e., for cellular and wireless networks. It is designed as a self-contained service [9], since it does not rely on any other services or applications but operates independently to provide the required monitoring information even if other services or application fail. Consequently, we differentiate between a *data-* and *management-plane*, where the monitoring data is separated from the overall data and transmitted over the management-plane. As a result, the monitoring mechanism still uses the same communication interfaces of a device similar to applications or services. However, it operates on top of its own flexible topology and uses its own tailored routing mechanisms to transmit monitoring data. CRATER consists of two different types of devices, comprising (i) the hand-held devices of end-users, referred to as *nodes* and (ii) a *central server*. The mobile nodes periodically measure a set of predefined monitoring attributes, serving as basis to determine the current state of the network and nodes. The central server establishes and maintains a connection to every node to collect the locally measured monitoring data. Based on this data it determines the current state of the network and nodes, which serves other applications and services as knowledge base.

As illustrated by our scenario, the server may just maintain a direct connection to a fraction of nodes, because the cellular network is overloaded and does not grant access for every node in the network. Consequently, the server is not able to collect the required monitoring data from all nodes, which leads to an incomplete view on the current state of the network and nodes. To enable continuous and complete monitoring in spite of the arising problems in challenging environments CRATER is designed to monitor the network even if only a fraction of nodes is connected to the server. Thus, the monitoring mechanism operates on top of a flexible topology, which is adapted depending on the environmental conditions. As depicted in Figure 1, it has two different topology structures, comprising a *uniform* and a *hybrid* topology structure. In the uniform topology structure all nodes maintain a direct link over the cellular network to the central server, which is able to collect the locally measured monitoring attributes from the nodes. In the hybrid topology structure, as depicted on the right-hand side in Figure 1, only a set of nodes has these direct links. We refer to this nodes as *sinks*. The remaining nodes, which are not able to connect to the server due to the overloaded cellular network, are denoted as *leaves*. As leaves do not have the possibility for a direct upload of their collected monitoring data they must identify and affiliate to nearby sinks. Consequently, leaves and sinks directly exchange information with each other without the need for a prevailing communication infrastructure, using for instance Wi-Fi ad hoc or Bluetooth. As a result, sinks serve two purposes: (i) they collect monitoring data from leaves and (ii) upload the collected as well as own monitoring data over the cellular network to the central server. To obtain collected monitoring data from leaves, which are currently not located in the direct communication range of a sink, CRATER applies concepts from mobile ad hoc networks (MANETs). The leaves simultaneously act as sources and forwarding nodes of a message so that nearby as well as distant leaves are able to transmit their collected monitoring data to sinks. As shown in Figure 1, CRATER facilitates that in both network states, uniform and hybrid, monitoring data can be gathered from all nodes, despite being a sink or a leaf.

Based on the presented design two main challenges arise that stem from the (i) adaptation between two different topology states and (ii) application of concepts from MANETs. With respect to the first challenge CRATER must detect when the cellular network is overloaded to execute a transition from a uniform to a hybrid topology structure. On the contrary, it must detected if resources are released to execute a transition from the hybrid to the uniform network structure. The second challenge arises from the direct information exchange between nodes to collect monitoring data from nodes, which are not directly connected to the central server. Consequently, CRATER must deal with the peculiarities related to MANETs, covering (i) node mobility, (ii) the limited communication range, (iii) the resulting short-lived connections between nodes, and (iv) the resource-constrained devices.

To implement the presented concepts of CRATER as well as to tackle the resulting two major challenges, CRATER consists of three basic components that are deployed on the mobile nodes (cf. Figure 2). These components serve to (i) detect changes in the environment, (ii) react on these changes by switching to the appropriate topology, and (iii) continuously monitor the current network state. The *No-Sink Advertising* component is introduced in Section III-A and used to react on missing connectivity and to identify potential sinks for the collection of monitoring data. For the affiliation of leaves to sinks, CRATER introduces the *Sink Advertising* component, as detailed in Section III-B. Finally, the *Data Routing* component is explained in Section III-C and serves for the collection of locally measured monitoring data from the leaves at sinks.

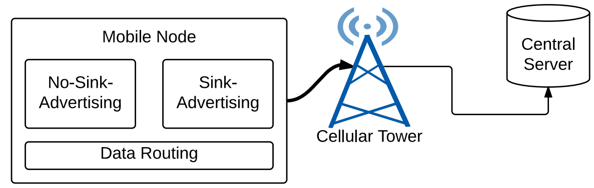


Figure 2: Components of the mobile CRATER nodes and the central server.

A. No-Sink Advertising

The corresponding procedure from the No-Sink Advertising component is executed by leaves, which lost their connection or could not yet connect to the central server over the cellular network. The procedure is performed to trigger a transition of CRATER from the uniform to the hybrid topology structure, if new nodes try to join the network but are not able to as the infrastructure entities may be overloaded. This transition from an uniform to an hybrid structure has to be executed to enable the affiliation of leaves to the sinks and to incorporate and collect their monitoring data. Furthermore, the No-Sink Advertising procedure is performed by leaves to keep CRATER in the hybrid topology structure due to the continuous overload of the cellular network. Consequently, the procedure is responsible to ensure that leaves advertise themselves if they have no direct upload to the server and are not yet connected to at least one sink. During the reminder of this section we detail the corresponding state chart with the related actions of the No-Sink Advertising procedure.

As depicted on the left-hand side in Figure 3, a leaf starts in the idle state. If it is not aware of any sink, either in its communication range or several hops away, the leaf executes transition $a1$, enters the *active* state, and broadcasts a *No-Sink-Messages*. The transmission of No-Sink-Messages for a prospective affiliation with a sink is always executed by leaves to avoid a proactive advertisement by a sink even if it is not required. Leaves may stay in the active state and periodically broadcast No-Sink-Messages as shown by the state transition $a2$. CRATER uses a contention-based sending scheme [10] to prevent the whole network from unnecessary broadcasts, if multiple leaves are in an active state. Contention-based sending or forwarding describes a robust communication scheme where multiple nodes prepare the transmission of the same message, while only a subset of nodes executes the transmission. For the selection of these nodes an *hesitation time* T_{h} is introduced, which consists of a fixed maximum time $T_{\text{h\_max}}$ and a hesitation factor between 0 and 1 to delay the transmission of that message. The factor is called *hesitation factor* h_{f} and may depend on multiple weighted attributes or on a single attribute. Equation (1) shows the basic formula for the hesitation time. On reception of a message nodes calculate T_{h} and delay the forwarding of that message correspondingly. If nodes overhear the forwarded message from another node (due to its smaller T_{h}), they do not forward but discard the message.

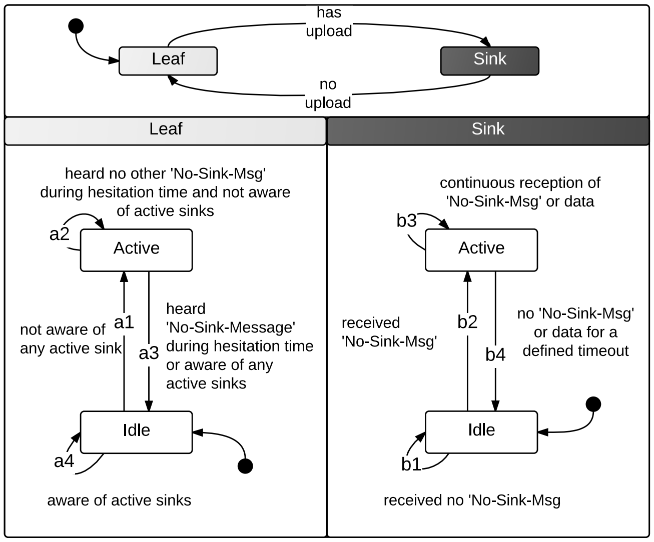


Figure 3: State chart of the advertising mechanisms in CRATER: No-Sink Advertising and Sink Advertising combined with the periodic upload check functionality.

Consequently, the resulting traffic is reduced, because only a few nodes forward messages in the network.

$$T_{\mathrm{h}} = h_{\mathrm{f}} \cdot T_{\mathrm{h\_max}} \quad \text{with} \quad 0 \leq h_{\mathrm{f}} \leq 1 \tag{1}$$

Thus, leaves only broadcast a No-Sink-Message when they did not overhear any other No-Sink-Message during their hesitation time and are still not aware of any sink. The hesitation factor h_{f} for a No-Sink-Message is computed by the normalized battery capacity as shown in (2). Consequently, leaves with higher energy resources will broadcast earlier. In cast that a leaf (i) overhears a No-Sink-Message or (ii) becomes aware of an active sink, transition $a3$ is executed and the node enters the idle state again. Otherwise, it remains in the active state and keeps broadcasting No-Sink-Messages. Assuming the leaf became aware of a sink or still overhears No-Sink-Messages, it stays in idle state, which is shown by transition $a4$. Otherwise, it executes transition $a1$ and enters the active state.

$$h_{\mathrm{f}} = \frac{bat_{\mathrm{cur\_cap}}}{bat_{\mathrm{max\_cap}}} \tag{2}$$

To prevent nodes from remaining leaves and staying either in the idle or active state, nodes periodically check if they may become sinks. This check is performed by the *Sink Advertising* mechanism, as described in the following section.

B. Sink Advertising

The *Sink Advertising* component provides two important procedures for the successful deployment of CRATER. The first procedure is responsible to determine if a node is either leaf or sink. This determination is periodically checked by trying to connect to the central server over the cellular network in case that no connection could be established so far. In Figure 3, the corresponding state chart is depicted on top of the figure. According to the resulting state, nodes become either leaves or sinks. Based on this procedure, CRATER ensures that a transition from the hybrid to the uniform topology structure is executed if the cellular network has sufficient capacity to serve all nodes. The second procedure of the Sink Advertising component targets the advertising of sinks so that leaves can affiliate to an advertised sink. As indicated before, sinks are important nodes, because they collect the monitoring data from affiliated leaves and have a direct connection to the central server to upload the collected data. Consequently, the Sink Advertising component must ensure that leaves (i) are aware of sinks, (ii) affiliate to one sink, and (iii) successfully transmit the collected data. In general, CRATER uses a multiple-sinks approach, because single-sink mechanisms show a degrading performance with an increased risk of failure. To distinguish between multiple sinks, every sink obtains a unique *sinkID*. The ID is used (i) to determine the affiliation from a leaf to a sink and (ii) to forward the monitoring data to the correct sink. CRATER adapts bio-inspired routing schemes from wireless sensor networks to establish and maintain the paths between leaves and sinks. To reduce the negative influence of node mobility on stored paths, it relies on loose paths where leaves decide themselves if they are suitable to perform forwarding. As a result, a gradient value, similar to pheromones or steepness indicators [11], [12], is introduced that decreases with an increasing distance to a sink. The collected monitoring data travels along an increasing gradient to reach the respective sink. In the following, we present the state chart for the advertisement of sinks, which is depicted on the right-hand side of Figure 3. Afterwards, we describe the structure of a *sink table* that is used to manage the information about sinks and detail the corresponding *Sink-Advertising-Messages*.

After becoming a sink, the node starts in the *idle* state of the corresponding state chart. As long as a sink does not receive a No-Sink-Message, it remains in the idle state, as depicted by transition $b1$. The reception of a No-Sink-Message indicates that at least one leaf is trying to affiliate to a sink. As indicated by transition $b2$ the sink enters the *active* state, where it periodically advertises itself by broadcasting *Sink-Advertising-Messages*. A sink remains active as long as it receives either successive No-Sink-Messages or data from leaves, which prove that its active presence is still required (state transition $b3$). Otherwise, transition $b4$ is executed and the sinks becomes idle, stopping the proactive Sink Advertising. To reduce the overhead and the probability of collisions, a contention-based sending scheme similar to the one for the No-Sink Advertising is used. Advertising messages are only broadcasted when no other nearby sink advertises itself during the delayed transmission of the message. The hesitation factor is computed on the weighted battery status similar to (2). On reception of a Sink-Advertising-Message during the delayed transmission of the own Sink-Advertising-Message sinks execute transition $b4$ and go back to the idle state. Received Sink-Advertising-Messages are stored in the local sink table of sinks and leaves. Sink tables are maintained by both sinks and leaves to manage information about advertised sinks. The sink table consists of (i) the sinkID, (ii) the received gradient, (iii) the number of updates received by that sink, and (iv) a timestamp for the last update. The timestamp is used to modify the current value of the gradient for the corresponding sink. With an older timestamp, the value of the gradient is reduced to account for the mobility of nodes. Older entries for a sink are potentially less reliable due to the constantly changing topology as well as the arrival of new sinks and the disappearance of old ones. Furthermore, the number of updates from a sink is an indicator for stable sink-leaf connections. This column of the sink table represents the main criterion for the selection of the own sink. In CRATER leaves select stable sinks, where multiple consecutive Sink-Advertising-Messages have been received in the past. Based on this decision CRATER prevents leaves from selecting sinks that just pass by leading to a frequent selection of new sinks instead of a few but constant sinks. If multiple sinks exhibit the same value for the number of updates, sinks with a higher gradient are preferred.

A Sink-Advertising-Message, which is initiated by an active sink, contains (i) a *messageID* for the unique identification, (ii) the sinkID to identify the corresponding sink, (iii) the hop count that represents the aforementioned gradient and is decreased with every hop to build a relative topology around sinks, (iv) the time-to-live (TTL) to adjust the spatial size of the region the sink may be responsible for, and (v) the sink quality, which corresponds to the battery status and is calculated as in (2). On reception of a Sink-Advertising-Message, leaves just forward the message if different conditions are met. A received message is only considered to be forwarded if (i) the TTL permits a further hop and (ii) the message with the related messageID has not been processed before. After both criteria have been met the message is forwarded if either (i) the sink table is empty, (ii) the received sinkID corresponds to the currently best sinkID according to the sink table, or (iii) the received gradient is greater or equal to the own best sink in the sink table. If at least one of these criteria is fulfilled, the node forwards the message using the same contention-based forwarding scheme as the sink.

C. Data Routing

To conclude the section about the system design, we describe the methods to route the collected monitoring data from leaves to sinks. These methods are used if CRATER is in the hybrid topology, where leaves are aware of at least one sink. The forwarding of data from leaves to sinks is mainly based on the concept that only local information is used to determine the path towards a sink. Consequently, the next hop is determined without a route discovery mechanism. Instead, as introduced in the beginning of this section, CRATER adapts bio-inspired routing schemes. Nodes decide based on their current value of the gradient if messages should be forwarded.

Whenever a leaf starts to send monitoring data to its respective best sink it broadcasts a *Data-Message* containing the data as payload. If another Data-Message is received during a given time window, which must be forwarded, the leaf uses this message to piggyback its data. A Data-Message includes field for the unique sinkID and the gradient. The sinkID is used for the identification of the correct sink. If a leaf receives a Data-Message with a sinkID that differs from the ID of the affiliated sink the message is dropped. The gradient is used to head the message into the right direction, since message are routed towards the highest gradient value. If the gradient of the message is equal or smaller than the stored gradient in the sink table, the message is dropped as well. Both sinkID and gradient fields limit the number of potential forwarders. To forward the messages after both criteria have

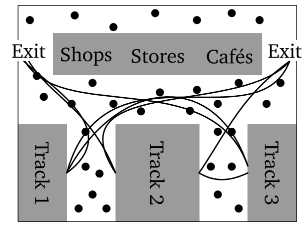


Figure 4: Modeling of the railway station with obstacles

been met, the contention-based forwarding scheme from the Sink-Advertising mechanism is used. The hesitation factor is based on the current gradient and the battery as shown in Equation (3). This computation favors leaves that have the highest gradient and a high battery capacity left.

$$h_{\mathrm{f}} = w_{\mathrm{bat}} \cdot \frac{bat_{\mathrm{cur\_cap}}}{bat_{\mathrm{max\_cap}}} + w_{\mathrm{grad}} \cdot \frac{grad_{\mathrm{own\_grad}}}{grad_{\mathrm{max\_grad}}} \tag{3}$$

On reception of Data-Messages sinks and leaves buffer and process the collected monitoring data according to the type of the data, as discussed below. A leaf subsequently forwards the data towards its sink, whereas a sink uploads the monitoring data to the central server. CRATER distinguishes three different types of data: *normal uncompressed data*, *duplicate sensitive aggregates* and *duplicate insensitive aggregates*. Especially for uncompressed data and duplicate sensitive aggregates the rate of received and undetected duplicates at intermediate leaves as well as sinks should be small. The normal uncompressed data describes simple raw data points. The aggregated data in CRATER is according to its sensitivity to duplicates, following the classification of Madden et al. [13]. Duplicate insensitive aggregates may comprise minimum or maximum, whereas duplicate sensitive aggregates cover sums, averages, or counts, which are affected by duplicate processing at nodes.

D. CRATER *Central Entity*

The central entity in the CRATER design is fairly simple. It is used as central gathering point of all data, which is uploaded from the sinks. With the received information from the sinks in the network the central entity computes the global view on the network and nodes. In the current design of CRATER the central entity is not responsible for any other task except acting as the central data sink. It does not maintain any topology structures in the network or affects the selection of sinks.

IV. EVALUATION

The evaluation of the proposed adaptive monitoring mechanism CRATER targets two main goals: (i) examine the robustness of the monitoring mechanism and (ii) compare the adaptive monitoring mechanism with a static centralized monitoring mechanism. In terms of the static centralized solution, mobile devices can only connect to the central server over the cellular network. The robustness of CRATER is examined in two different scenario by varying (i) the movement speed of the mobile nodes and (ii) the number of nodes, thus the density. Both scenarios have been chosen, as they represent typical challenges from MANETs that must be tackled. In the following, we detail (i) the modeling of the scenario and the used evaluation parameters, (ii) the evaluation of the robustness of CRATER, and the (iii) comparison between CRATER and the static centralized monitoring mechanism.

Table I: Scenario and simulation setup

Simulated Area	$2000\,m \times 2000\,m$
Max. Wi-Fi Comm. Range	$129\,m$
Max. Base Station Connections	585
Network Density $[\text{nodes}/km^2]$	$36.3, 92.2, 181.5, \underline{273.7}, 363, 544.5$
Movement Speed $[m/s]$	$\underline{1\text{-}2}$, 2-4, 4-8

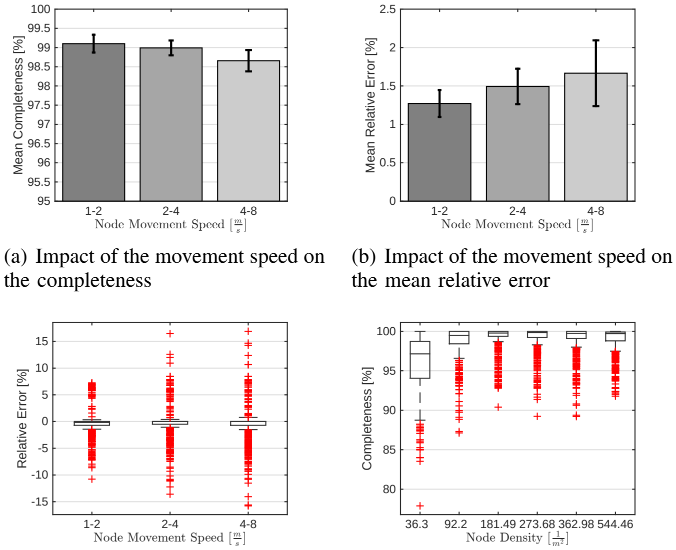
A. Modeling of the Scenario and Evaluation Setup

The modeled environment in the scenario corresponds to a railway station, as proposed by [8]. As depicted in Figure 4, we model a part from a railway station that comprises tracks and shopping facilities and is populated with user that move according to different movement models. The different movement models are used to model (i) continuously present users in the railway station and (ii) the arrival or departure of users by incoming or outgoing trains. In Figure 4 the continuously present users are represented by the black dots. They move through the station according to the Steady-state Random Waypoint Mobility model [14]. The arrival and departure of groups of users is indicated by the solid lines, which sketch the potential paths through the station. Along these paths groups of nodes arrive, move along the paths, and subsequently leave the railway station either by train or by one of the exits. For the simulative evaluation comprising the model of the environment and the user mobility, we rely on PeerfactSim.KOM [15] that comprises a model from ns-3 [16] of the IEEE 802.11g standard to simulate the Wi-Fi ad hoc communication between the devices. Three hours of operation are simulated where the first hour is used to reach a steady state of the simulated scenario, while measurements are taken during the remaining two hours. Five different seeds are used for repeating the experiments. Bar charts show the average with the 95% confidence interval. For a better understanding of the distribution of results box plots are utilized. Boxes represent the lower and upper quartile and the median is depicted by the solid line inside the box. Whiskers show the upper (lower) data point within 1.5 of the interquartile range. Outliers are represented by crosses.

Table I summarizes the simulation setup. Furthermore, it outlines the different settings of the movement speed as well as node densities. The underlined configurations represent the default configurations. The movement speed of nodes is uniformly distributed in the given intervals. The density in the network is varied by changing the number of nodes while keeping the simulated area constant.

B. Robustness

In mobile scenarios the movement speed is an important factor as it may reduce the system performance significantly. Reasons for that are short-lived links, unstable topology structures, and fluctuating link qualities. Hence, the robustness of CRATER is evaluated under three different movement speed intervals 1-2, 2-4, and 4-8 m/s. Those intervals have been chosen as comfortable walking speed averages at around 1.4 m/s for people above their thirties, whereas 2.5 m/s is possible for younger people [17], [18]. However, as running people must also be considered, a movement speed up to to 8 m/s is also considered. For the evaluation of CRATER's performance the relative error as well as the completeness of the monitoring data are examined. For the relative error, the duplicate sensitive monitoring attribute *node count* has been chosen.



(a) Impact of the movement speed on the completeness

(b) Impact of the movement speed on the mean relative error

(c) Impact of the movement speed on the distribution of the relative error

(d) Impact of the node density on the completeness

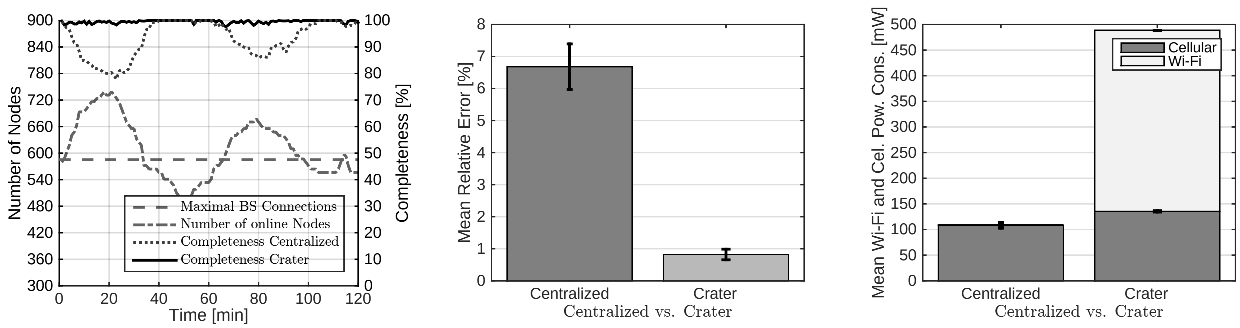
Figure 5: Evaluation of the robustness of CRATER for a varying movement speed and node density

On average CRATER is able to deliver the monitoring data from at least 98.5% of the nodes irrespective of the movement speed interval. Changing the movement speed does not affect the performance of CRATER significantly as visible in Figure 5(a). The narrow confidence intervals underpin the performance and the robustness CRATER achieves. This is achieved while keeping the relative error very low at the same time. On average the relative error is lower than 2.5% and is not significantly affected by variations of the movement speed as shown in Figure 5(b). Taking a look at the distribution of the relative error, it becomes apparent that CRATER basically underestimates the system state (cf. Figure 5(c)), because the boxes stay below zero. An overestimation due to duplicate processing of data applies only for a fraction of the results. The quartile and whisker range remain lower than two percent, thus, underpinning the very accurate monitoring results even under highly dynamic conditions.

Taking a look at the performance of CRATER for different node densities, Figure 5(d) unveils that CRATER exhibits a degrading performance in sparsely populated scenarios. This performance degradation is attributable to natural limitations, because the distance between nodes and the communication range impede the establishment of the hybrid topology. However, the probability that networks are overloaded in sparsely populated areas is less, reducing the need to operate on the hybrid topology. As depicted in Figure 5(d) CRATER only suffers from the intermittent connection between nodes in very sparsely populated scenarios, however, still exhibiting a completeness of over 85%.

C. Static Monitoring vs. CRATER

To estimate the benefit of using adaptive monitoring mechanisms such as CRATER a comparison against a static approach is conducted. The static monitoring approach is only able to



(a) Comparison of the achieved completeness over time for one run

(b) Comparison of the achieved mean relative error

(c) Comparison of the power consumption for the monitoring data exchange

Figure 6: Comparison between CRATER and the static centralized monitoring mechanism

serve mobile nodes with direct cellular upload. Figure 6(a) shows the comparison of both mechanisms during one run to highlight the differences between both approaches over time. The plot shows the current number of present nodes and the maximum amount of connections that can be established over the cellular network. The results outline that both topology states of CRATER, uniform and hybrid, are used over time. The static approach reaches 100% of completeness whenever the number of nodes is lower than the maximal number of cellular connections. Once the number of nodes exceeds that threshold the static monitoring approach cannot deliver accurate results any more. In contrast, CRATER is able to achieve a constantly high completeness, meaning more than 95% of the nodes are included in the monitoring results despite of the environmental conditions. Furthermore, in normal situations, where no overload of the base stations is present, the performance of CRATER is as good as the of the static approach. As shown in Figure 6(b) CRATER achieves significantly more accurate results with a mean relative error below 1%.

However, the higher performance and the more accurate results are not for free. The additional cost added by CRATER become apparent in Figure 6(c), which represents the mean power consumption, using a component-based energy consumption model for smartphones [19]. Since the static approach does not rely on Wi-Fi, only cellular communication burdens the battery, leading to a mean power consumption of approximately 108mW. In comparison CRATER needs approximately 485mW on average, due to (i) an increased cellular traffic and (ii) the Wi-Fi ac hoc communication to incorporate all nodes in the network. While the additional cellular traffic accounts for less than 30mW of the mean power consumption compared to the static approach, the main impact arises from the utilization of Wi-Fi ad hoc. The reason for the high mean power consumption does not arise from an extensive data exchange but from the idle state of the ad hoc mode, which accounts for 353mW. The additional burden, added by the Wi-Fi ad hoc communication, accounts for 0.35mW on average.

V. RELATED WORK

Taking a look at network monitoring, centralized and decentralized approaches exist. As most centralized approaches, such as [20], [21], are deployed in wired networks, those approaches are not suitable for a comparison with CRATER that addresses wireless networks, i.e, MANETs. The dynamic conditions in MANETs, such as node density and movement speed, have a significant impact on the performance of the monitoring mechanism. Accordingly, the reminder of the related work focuses on (i) decentralized monitoring mechanisms and (ii) bio-inspired routing approaches. The routing approaches are examined, because they constitute an essential ingredient for data routing in the hybrid topology of CRATER.

An approach to reduce the overhead of flooding is shown by DAMON [9]. DAMON relies on a distributed monitoring architecture for multi-hop mobile networks that uses an agent-sink topology for data collection. The used agents control the flooding of the network, which leads to less overhead and reduces the possibility of collisions. But, sinks are static and pre-defined by the network operator, an impossible task in heterogeneous dynamic networks. Considering a detailed local and a sparse global network view, as presented by Nanda and Kotz [22], is helpful to gain a more precise monitoring result. Nonetheless, the used hierarchy, consisting of static mesh nodes and mobile nodes, cannot be maintained in a dynamic MANET environment. Beside that Mesh-Mon is evaluated in a small scale scenario with less than 25 nodes, not appropriate for heterogeneous network scenarios as presented in this work. Load balancing is an important factor in resource constrained environments such as the envisaged scenario. HMAN by Battat and Kheddouci [23] establishes a three-tiered topology based on weights of nodes. Those weights incorporate factors, such as energy consummation, the distance to other nodes, and the storage capacity left. However, HMAN is dependent on the used routing protocol to manage and maintain the topology. Not separating the data and management communication may reduce the overhead but can render the monitoring, a core network service, useless in for example overloaded situations. BlockTree [24] describes a fully decentralized monitoring approach for MANETs, which establishes a hierarchy build by location-aware nodes. BlockTree is capable to provide location-aware monitoring information. Flat approaches, such as Mobi-G [25], show improved performance in sparsely populated areas, as a topology has not to be established and maintained. However, both approaches require detailed information about the nodes' location, which are provided by additional services, such as GPS, rendering such approaches useless in indoor scenarios or when the localization is not as accurate as needed.

Dealing with bio-inspired routing approaches, the danger of single-point-of-failure configurations is presented by Kiri et al. [11]. In such multi-cluster topologies identification and separation of the individual clusters is essential. While a sink failure is handled in the approach, only a pre-defined set of sinks is available, which gives the approach a maximum lifetime. The benefit of using bio-inspired pheromone values for the routing process is demonstrated by Zhu et al. in [12]. Using pheromone values allows an adaption on resources and environmental changes is performed. But, using a single sink configuration can render the approach useless especially in networks with resource constrained devices.

VI. CONCLUSION

In this paper, the novel adaptive monitoring mechanism CRATER for challenging environments is introduced. CRATER exploits the connectivity and resource characteristics of the mobile hand-held devices to facilitate continuous monitoring of the network and nodes. By reconfiguration of the monitoring topology structure the system is able to adapt to a wide range of environmental and network-specific changes, providing a significantly increased performance despite these changes. At the same time, the system is robust against MANET specific challenges like node movement speed and node density. Comparing the system with a non-adaptive monitoring mechanism unveils the potential of CRATER, because it provides complete and accurate results. Nevertheless, the increased performance comes at increased cost. The power consumption of the nodes is significantly higher in contrast to the static approach, because more data is transmitted in the network and two communication interfaces of the device are used.

The presented system is currently concentrated on gathering data from mobile nodes in the network to gain a global network state. Pre-evaluating subsets of the monitored data on, e. g., sinks to gain a local and regional knowledge may facilitate local or regional adaptations to improve performance or reduce cost. For instance, the periodic transmission of CRATER's different message types may be adapted according to the number of affiliated leaves to a sink. Furthermore, using No-Sink-Messages and Sink-Advertising-Messages deliver monitoring information during the topology structuring phase may improve the response time of the monitoring mechanism and provide a more recent view on the network state. Incorporating infrastructure devices like Wi-Fi access points can improve the systems performance as such devices constitute fixed sinks with less energy constraints compared to mobile user devices and a direct server connection. Examining the use of different communication technologies for the direct communication, e.g., Wi-Fi ad hoc and Bluetooth, is part of our future work, because it may offer further possibilities to reduce cost or increase the performance. A prototypical evaluation is planned using the Simonstrator framework [26].

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