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Limiting the Footprint of Monitoring in Dynamic Scenarios through Multi-dimensional Offloading

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Abstract—**Multiple offloading techniques are used in today's communication systems. Most approaches rely on cellular offloading to reduce the burden on the cellular infrastructure, especially in crowded situations. While the load on the cellular infrastructure decreases, network participants that are actively involved in the networking effort by device-to-device communication carry the load of a majority of devices. Though, by focusing on the cellular medium for offloading, the increased number of public available network access points remains mostly unused by most approaches. Incorporating access points for offloading entails numerous advantages, such as a reduced load on the cellular data plan of mobile users. In this work, the potentials of multi-dimensional offloading are assessed using the example of a state-of-the-art adaptive monitoring system that, so far, only employs cellular and device-to-device offloading. We show that the system can benefit from adding additional components and protocols that enable multi-dimensional offloading. Through an extensive simulation study we show that combining different offloading techniques leads to significant improvements regarding the achieved service quality (up to 15-fold) and the responsiveness (up to 5-fold), while reducing the load on the mobile nodes by at least 35% even in scenarios with good cellular connectivity.**

I. INTRODUCTION

The vigorous growth of the amount of mobile devices – such as smartphones and laptops – leads to an increase of mobile data traffic. Throughout the day, traffic load on mobile networks experiences significant fluctuations. These fluctuations are primarily handled by cellular networks, which accordingly face overload situations more frequently [1]. Several solutions have been proposed by the research community to overcome potential network service degradations. First, individual offloading strategies to reduce the burden on e.g. the cellular network or individual mobile consumers [2], [3]. Second, approaches that exploit the locality and the social relations of users for inter-user interaction via technologies such as Bluetooth and Wi-Fi ad hoc [4]. Cellular offloading may pursue two different goals: (i) to reduce the number of cellular connections, and/or (ii) to reduce the amount of cellular traffic. Mechanisms that are able to adapt between local and global communication strategies, show great performance improvements over static approaches [5], [6]. The functionality of adaptive mechanisms depends on accurate state information of individual devices and the network itself. To provide robust and reliable state information in challenging environments, we proposed the adaptive monitoring service CRATER [7] in earlier work. Nevertheless, CRATER, and other adaptive mechanisms [5], [6] are evaluated in scenarios without considering essential social links between nodes [4]. Furthermore, the approaches are currently limited to take advantage of individual offloading techniques. Accordingly, they rely on e.g. device-to-device or cellular offloading techniques to achieve their goals. The importance of other offloading techniques, like using public infrastructure, remains mostly unconsidered. However, with the increasing coverage and accessibility of public infrastructure, such as Wi-Fi access points (APs), [8]–[10] the question arises why they are not considered in the design. Applying *multi-dimensional offloading* to a communication system, i.e. utilizing multiple offloading techniques in parallel, promises improved service quality and entails a great opportunity, but is currently an unsolved challenge.

This work assesses the potential of multi-dimensional offloading in dynamic scenarios on the example of CRATER [7]. Based on an in-depth analysis of the service and current network characteristics several important extension are proposed in the form of CRATER^{io}. First, it includes the support for offloading using public infrastructure entities (IEs). Second, an improved selection scheme to decide between different offloading modes, while ensuring constant monitoring quality under different conditions, is proposed. Third, an economic usage of the given resources to limit the footprint of CRATER^{io} without degrading the achieved service quality is achieved. The resulting performance characteristics and the impact of social links between nodes, are assessed in an extensive simulation study using the Simonstrator platform [11]. Our results reveal that by using multi-dimensional offloading even with poor cellular connectivity (only 2.5% of the mobile nodes), CRATER^{io} delivers monitoring data from at least 75% of the nodes (a 15-fold increase compared to the initial design). Furthermore, at least one-third (35%) of the resulting uploading traffic can be offloaded over public infrastructure, significantly reducing the load on the cellular network. The contributions of this paper are the following:

- A set of system extensions to support multi-dimensional offloading within CRATER^{io}.
- A simulative analysis of the proposed extended adaptive monitoring system in the modeled scenario.
- An in-depth evaluation focusing on three essential aspects: (i) the influence of infrastructure entities on adaptive systems, (ii) the impact of social links between mobile nodes, and (iii) the potential savings and performance gains enabled by applying multi-dimensional offloading.

The remainder of the paper is structured as follows: Section II introduces the targeted scenario. The systematic extensions introduced by CRATER$^{\text{io}}$ are explained in Section III. Including an overview of CRATER, discussing the weaknesses that are addressed in this work. Section IV shows the evaluation. Section V deals with the related work on existing monitoring approaches supporting different offloading concepts and on general offloading approaches in mobile networks. Finally, Section VI concludes this work.

II. SCENARIO

The scenario used in this paper describes a downtown area that is subject to both (i) high dynamics regarding the user density and the cellular connectivity and (ii) social relations between users to model crowd formations in several proportions. The dynamics concerning the density are represented by users joining and leaving at different points in time by e.g. switching on/off either their mobile phones or the respective communication interfaces or by leaving the area. With an increasing user density we assume that the present cellular network begins to operate unreliably once a certain number of connections is exceeded [1]. Public places, such as bars, restaurants or parks, that are part of the scenario, emit a certain degree of attraction to the mobile users resulting in a social force pulling users to that places [12], [13]. A varying strength of the social relations results in more or less crowded places. Beside this, public IEs that are placed at different locations are accessible for mobile offloading purposes.

People walk over paths and streets in the scenario. Thus, obstacles like houses are taken into account. Mobile users are equipped with communication devices, such as smartphones or tablets. The devices have communication interfaces for local communication via Wi-Fi and for cellular communication. Crowds occur at different strengths at the social places, depending on their degree of attraction. Regarding communication possibilities, it is assumed that the whole downtown area is covered by a cellular network. Public Wi-Fi access points at different places can be used by the users to reduce the load on their individual data plans. Beside multiple applications and services that the users may consume with their devices, each device deploys CRATER$^{\text{io}}$. This enables local measurement and collection of data in the network.

III. CRATER$^{\text{io}}$: MULTI-DIMENSIONAL OFFLOADING FOR MOBILE NETWORK MONITORING

In the following, the main contributions of CRATER$^{\text{io}}$ to support multi-dimensional offloading are presented, beginning with a short introduction of the initial system CRATER [7]. CRATER embodies an adaptive monitoring solution for mobile environments. It operates independent of other applications and services and collects information on the current state of the network including information on the participating nodes. By adapting the topology to environmental changes, such as node mobility and density, the system provides an accurate network state. To provide seamless network state observation two different topologies are used (cf. Figure 1). The participating nodes periodically report the requested monitoring information to the *cloud component*, which can be abstracted to a centralized entity in the core network. Mobile nodes are allocated two distinct roles by the cloud component, depending on the environmental conditions: the *sink* and the *leaf* role. *Sinks* directly upload monitoring information via their cellular connection to the cloud component. *Leaves* do not use their own cellular communication interface to upload information. Instead, by using local ad hoc connectivity, such as Bluetooth, Wi-Fi ad hoc, or LTE Direct, they affiliate to adjacent sinks. While the performance of the cellular network does not degrade, i.e. is able to handle a large number of parallel cellular connections, all nodes directly upload their monitoring information, operating as sinks. This operational mode is referred to as *uniform* topology as visible in Figure 1. If the load on the cellular network, i.e. the number of cellular connections, exceeds the manageable load and is overloaded, CRATER switches to the *hybrid* topology. Here, only a fraction of the nodes is assigned the sink role, while others remain leaves (cf. Figure 1). Sinks continue to upload their monitoring information via the cellular network, while leaves drop their cellular connection to free additional capacities in the cellular network. Therefore, to guarantee consistent monitoring performance, leaves affiliate to sinks in their proximity that relay their monitoring data to the cloud component.

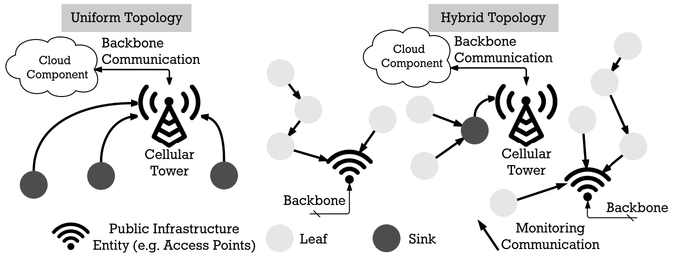

Figure 1: The two topology states of CRATER$^{\text{io}}$. Mobile nodes distinguished into sinks and leaves and additional infrastructure entities for multi-dimensional offloading.

Thus, in the hybrid topology sinks must upload their own monitoring information as well as the data of the affiliated leaves. Leaves do not just act as source for monitoring information, they also forward data from nearby other leaves to the respective sink using a bio-inspired routing scheme for device-to-device offloading, if necessary . To ensure robustness of the ad hoc routing, leaves aim to choose the most stable sink to send their information – the sink that is the least likely to recede into distance shortly. For that purpose the system consists of mechanisms for (i) topology establishment and maintenance and (ii) routing of monitoring information between leaves and sinks. For topology establishing and maintenance the system mainly relies on the *No Sink Advertising* and the *Sink Advertising* mechanisms. Depending on the individual role of a node, either is used. Once a node is assigned the leaf role it is essential that it gets aware of adjacent sinks to affiliate to one, if the node is not aware of any. To advertise this need,

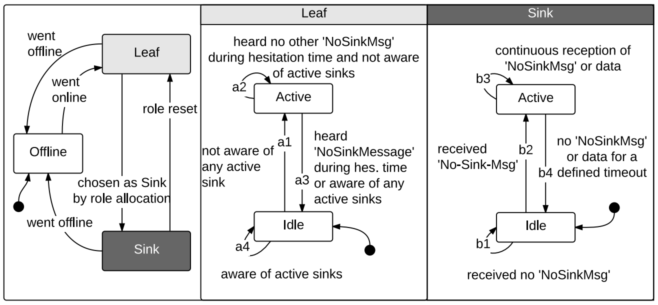

Figure 2: State chart of the topology establishing and maintenance mechanisms in Crater^{io}.

leaves send *NoSinkMessages*. During that active advertising a leaf is in its *active* state as shown in Figure 2 which shows the state chart of a single node. Depending on their current role nodes react differently to incoming messages.

On reception of a *NoSinkMessage*, after a short hesitation time, sinks respond with a *SinkAdvertisingMessage*, stating their presence. The hesitation time is applied to prevent multiple sinks from unnecessary flooding, using a contention based advertising scheme [7]. A sink sending *SinkAdvertisingMessages* switches to its active state (cf. Figure 2). Leaves overhearing active sinks store the results in an individual sink table. The system returns to the uniform topology once the load on the cellular network reduces and all nodes are assigned the sink role again. For an in-depth description of Crater and in a more detailed description of the component, the interested reader is referred to [7].

Crater is restricted to the utilization of cellular and device-to-device offloading techniques. The system uses all potential resources of the nodes and the cellular network to maximize the gain achieved using device-to-device and cellular offloading in the hybrid topology. However, as recent studies reveal [8]–[10], [14], the usage of mobile offloading using public infrastructure entities, such as Wi-Fi access points in bars, cafes, and parks, provides the opportunity to further reduce the load on the cellular network and the mobile nodes. The importance of resource-saving networking is indisputable, especially for adaptive systems, such as [5], [6], that utilize the user's resources under certain environmental conditions to guarantee for a constant high performance. Furthermore, the burden on the network and on shared mediums, like cellular or Wi-Fi, must be minimized by sensible utilization of the available resources. The clear objective of the initial design of Crater is achieving higher performance by adapting the behavior of the system to environmental changes. By maximizing the achieved performance of the system, the burden on the individual entities and the cellular infrastructure is very high. Reducing the load on individuals, e.g. sinks, is very important to guarantee wide acceptance and long lifetime of a system. Especially, for monitoring systems that aim to deliver accurate results at very low cost, the reduction of the footprint of the system is essential [15].

To reduce the burden on both (i) the cellular network, which is currently stressed to its limit, and (ii) the mobile nodes that carry out different roles when necessary, Crater^{io} must provide additional techniques. These must enable economic usage of resources even under harsh conditions, but keep the achieved performance at a constant high level. Those harsh conditions are characterized by e.g. a very limited cellular network connectivity, high node mobility, and short-timed appearances of nodes. Relying exclusively on the cellular network can result in a substantial challenge once the cellular connectivity is, for example, (i) strictly limited, (ii) at a very low quality due to environmental conditions, or (iii) individual user's are not willing to spend their own limited data plan for the traffic of others [16]. Combined with the requirement to deliver high quality monitoring results under a wide spectrum of scenarios and with low burden on the individuals, additional concepts must be used to collect relevant monitoring data. The load on sinks that maintain whole areas to guarantee the effective collection of monitoring data can be reduced when some of the leaves affiliate to public infrastructure entities as visible in Figure 1.

This work proposes Crater^{io}, an extension to [7]. The system supports mobile offloading via infrastructure entities (IEs), thereby enabling multi-dimensional offloading over (i) the cellular network, (ii) the mobile ad hoc network for device-to-device offloading, and (iii) the herein presented solution for offloading data to infrastructure entities. This includes the two following main concepts/components: (i) an *assignment strategy* for leaves to distinguish between IEs and mobile sinks and (ii) a monitoring *component for infrastructure entities* that facilitates regional data collection. The assignment strategy, however, does not only favor IEs once they appear. It needs to consider that a sink that is in near proximity to a leaf for a long time, thus being very stable from the leaf's perspective, may be a better choice for uploading the monitoring information instead of a static non-mobile infrastructure entity that is in range for a short period of time. This so-called *short-termed appearance*, is handled by the system by giving credit to long-sighted sinks in the form of taking the time a sink has been in proximity to a leaf into account. Thus, only when a leaf is not aware of a sink being in adjacency for a longer time period, it is likely to switch its best sink and send the monitoring information to an adjacent infrastructure entity. The process of favoring stable connections, which may lead to a favoring of sinks with a lower *sink quality*[1] compared to adjacent infrastructure entities works as follows. Think of a leaf and a sink moving in a similar direction towards an infrastructure entity. Assuming the IE is overheard by the leaf in a short period of time when the leaf passes by. While the IE may has a better sink quality compared to the mobile sink the proposed assignment strategy ensures that in such brief detection periods the leaf still favors the more stable connection to the mobile sink. This stable connection is characterized by the time the

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[1] Sink Quality: a weighted metric including attributes like the remaining battery capacity and the load on a sink according to [7]

leaf knows either the sink or the static infrastructure entity. The CRATER$^{\text{io}}$ component for IEs ensures the advertising similar to the active advertising by sinks. Furthermore, it collects the incoming monitoring data and uploads it to the cloud component for further analysis.

In this way, CRATER$^{\text{io}}$ is able to support mobile offloading via public infrastructure entities in a sensible way. The proposed assignment strategy ensures the stability of the topology, while IEs can be used by the leaves to upload their data in a multi-hop topology without burdening sinks longer.

IV. PERFORMANCE EVALUATION

The evaluation of the proposed system CRATER$^{\text{io}}$ in the introduced scenario (cf. Section II) addresses three main aspects. First, evaluating the influence of incorporating infrastructure entities for multi-dimensional offloading in the monitoring effort of CRATER$^{\text{io}}$ on its performance metrics. Second, assessing the impact of social relations between mobile entities on system performance metrics. Third, outline the savings by meaningful usage of the given resources using multi-dimensional offloading. The influence of IEs is examined in two different scenario configurations by varying (i) the number of accessible IEs and (ii) their placement. The number and the placement of infrastructure entities are important for a realistic scenario as both parameters lead to a fluctuating coverage, as seen in [9], [10]. Assessing the impact of social relations, which is a main factor for group formation [4], is essential for CRATER$^{\text{io}}$ in scenarios with and without IEs. Grouping of nodes results in variations in the density of areas, which must be handled by sinks accordingly. Variations of the attraction factors of the public places (cf. Section II) lead to changes in the grouping strength. Reduced utilization of the given resources is essential for long network lifetime and ensures scalability in situations that require it at the same time. Thus, instead of choosing a number of sinks limited by the cellular network load/connections, we argue that a reduced number of sinks suffices to deliver good performance without too much degradation in service quality, while decreasing the load on the nodes and the cellular network significantly. This trade off between using the different offloading schemes and the resulting performance is evaluated in a scenario with fluctuating usage of the cellular network in the third part of the evaluation.

In the following we detail (i) the modeling of the scenario and the used evaluation parameters, (ii) the influence of IEs within multi-dimensional offloading in CRATER$^{\text{io}}$, (iii) the impact of social relations between mobile entities in systems that rely on device-to-device offloading, and (iv) the savings by meaningful usage of the accessible resources.

A. Modeling of the Scenario and Evaluation Setup

In our previous work [7] the focus of the scenario was on the dynamic of the environment, but with good cellular network connectivity. However, as discussed before, mobile offloading onto public fixed infrastructure, such as access points, grows in importance for todays networking [8]–[10], [14] as cellular networks are subject to performance degradations [1]. For that purpose we model the performance degradations of the cellular network and the decreasing willingness of users to send data via the cellular network, motivated by e.g. a limited data plan, by limiting the number of the used sinks. This limits the number of cellular connections at the same time as sinks are the only nodes using the cellular network. In doing so, two effects can be examined: (i) how the performance of CRATER$^{\text{io}}$ is affected by poor cellular connectivity and (ii) how already a low number of sensibly placed IEs can improve the system performance and reduce the load on the mobile nodes in adaptive systems supporting multi-dimensional offloading.

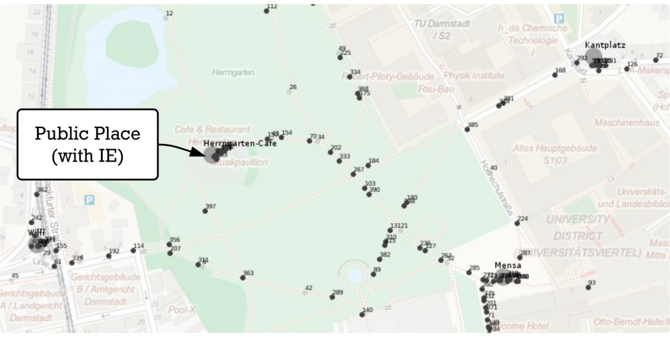

Figure 3: Modeling of the OpenStreetMap-based scenario including social interesting public places, and additional public infrastructure entities (IEs) like access points.

Furthermore, by refining the scenario used in this work, important social relations between users [4] are modeled. The scenario, which is based on OpenStreetMap (OSM) data, comprises a number of attraction points that represent public places such as bars, cafes, parks, or a university campus, as visible in Figure 3. The attraction points emit a social force, called *attraction factor*, for mobile nodes, which, depending on the strength, results in more or less formations of crowds. It varies between 0 and 1 for a low and high social force. Based on this, different characteristics of the public places can be modeled. In the scenario, the mobile nodes are only able to move across the paths and roads provided by the OSM data, as any other places like houses or lakes represent obstacles that users cannot pass. Additionally, different amounts of infrastructure entities, operating in Wi-Fi ad hoc mode to ensure connectivity with the mobile nodes, are placed on the map using multiple placement strategies. Table I shows the summarized simulation setup. It also highlights the three placement strategies which are explained in detail in Section IV-B. The ratio of infrastructure entities covering the attraction points is varied between 0 and 1 in $^{1}/_{3}$ steps as visible in Table I.

The evaluation is performed using the Simonstrator platform [11]. The Simonstrator comprises the IEEE 802.11g standard from the ns-3 simulator [17] to model the Wi-Fi ad hoc communication between the nodes. Two hours of operation are simulated, while the first 20 minutes are not considered for measurements, resulting in 100 minutes of measurement time. The initial 20 minutes are used to reach a steady state in the

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Table I: Scenario and simulation setup

Simulated Area	$1500\,m \times 1500\,m$
Max. Wi-Fi Comm. Range	$88\,m$
Infrastructure Entity Comm. Range	$88\,m$
Movement Speed $[^m/_s]$	$1.5 - 2.5$
Density $[^{\text{nodes}}/_{km^2}]$	$13.3 - 177.7$
Number of Attraction Points	10
Max. Base Station Connections [%]	2.5, 5, 7.5, 10, 12.5, 20, 30, 50
Infrastructure Entities Placement	Rnd, Grid, Social
Coverage Ratio of Infra. Entities	0, 0.33, 0.66, 1
Attraction Factor	0.0, 0.2, 0.4, 0.6, 0.8

scenario. The simulations are repeated with ten different seeds. Bar charts show the average with the 95% confidence interval. The distribution of results is shown in box plots and cdf's. 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 outlines the different settings for the three main parts of the evaluation. The movement speed is uniformly distributed in the given interval. 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 according to [18]. The number of attraction points is limited and fixed to ten in this scenario, representing the main public places in this map section. To enforce the adaptivity of CRATER$^{\text{io}}$, a churn model that achieves a fluctuating density by joining and leaving nodes during the simulation is used. In doing so, the node density changes multiple times from sparse to dense and vice-versa, triggering CRATER$^{\text{io}}$ to adapt between both topologies. The underlined variations represent the default values that are used when other parameters are altered.

In the evaluation, the following metrics are considered and used to assess the results. The **completeness** of a monitoring system, which describes the percentage of how many of the potentially possible monitoring information D_{pos} is collected by the system (D_{real}) at the nodes in a given interval T_i. This metric is used to assess the performance of the monitoring system, ranges between 0% and 100%, and is calculated as shown in Equation 1.

$$\text{completeness}(T_i) = \frac{D_{\text{real}}}{D_{\text{pos}}} \times 100 \text{ in time interval } T_i \qquad (1)$$

In our simulations, the time interval T_i is set to one minute. Another important metric is the **ratio of the offloading traffic**, which describes the ratio of how much of the overall upload traffic to the cloud component in CRATER$^{\text{io}}$ is offloaded via mobile offloading ($Tr_{\text{up-mobile}}$) and cellular offloading ($Tr_{\text{up-cel}}$) techniques respectively. It ranges between $[0, 1]$ and is calculated according to Equation 2.

$$R_{\text{up-ratio, cel}||\text{mobile}} = \frac{Tr_{\text{up-cel}}}{Tr_{\text{up-overall}}}; \quad \frac{Tr_{\text{up-mobile}}}{Tr_{\text{up-overall}}} \qquad (2)$$

The next two metrics are CRATER$^{\text{io}}$-specific as they are used to assess the load on the individual nodes due to the role assignment and the responsiveness of the system. Both the **leaf active ratio** and the **sink active ratio** ($R_{\text{si}||\text{le,active}}$) describe how long a mobile node (n) spends its own resources actively for the overall monitoring effort by e.g. advertising the need for affiliation in the role as leaf or for topology maintenance in the case of being a sink. They are calculated as visible in Equation 3.

$$R_{n,\text{si}||\text{le,active}} = \frac{T_{n,\text{si}||\text{le,active}}}{T_{n,\text{si}||\text{le}}} \text{ with } T_{n,\text{si}||\text{le}} > 0 \qquad (3)$$

The metric to estimate the **ratio leaves are not aware of any sink** ($R_{\text{no sink}}$ for n nodes), thus being online without knowing any sink, provides estimations on the connectivity CRATER$^{\text{io}}$ is able to achieve. Equation 4 shows this ratio.

$$R_{\text{no sink}} = \frac{\sum_{i=1}^{n} \frac{T_{i,\text{no sink}}}{T_{i,\text{leaf}}}}{n} \text{ with } T_{i,\text{leaf}} > 0 \qquad (4)$$

B. *Influence of Infrastructure Entities*

The performance of systems relying on cellular offloading techniques to reduce the amount of traffic and/or the number of cellular connections over the cellular network is depending on the efficiency of the offloading approach and obviously the amount of cellular connections that are used. However, it is intended that CRATER$^{\text{io}}$ uses as few cellular connections as possible. By reducing the usage of cellular connection within the system, the performance of CRATER$^{\text{io}}$ even under the harshest network conditions, regarding cellular connectivity can be examined. While the robustness against mobility and network density has been shown in [7] this part of the evaluation focuses on connectivity fluctuations in mobile networks. With fewer cellular connections, thus less potential sinks, the responsibility of each sink rises significantly when the environmental changes require the hybrid topology of CRATER$^{\text{io}}$. By varying the percentage of the potential cellular connections, i.e. the percentage of sinks, between $2.5\,\%$ and $50\,\%$ (cf. Table I) the performance under different connectivity situations is evaluated. Without multi-dimensional offloading potential the system is able to provide monitoring results from at least 80% in median of the nodes when the cellular connectivity does not decrease below 12.5% as visible by the boxes without (io) annotation showing the completeness in Figure 4(a). However, the resulting quality fluctuations show that the results achieved by the initial system version may not be meaningful enough to base decisions on the data.

Below 12.5% cellular connectivity the resulting completeness drops significantly for the initial version without multi-dimensional offloading potential as visible by the boxes without the (io) annotation in Figure 4(b). Using CRATER$^{\text{io}}$, supporting multi-dimensional offloading, the achieved completeness is only slightly affected by a strong decrease in the cellular network connectivity, hence the number of the used sinks. Furthermore, the results gain considerable in their informative value as (i) the achieved completeness increases and (ii) the result fluctuations shown by the size and the outliers of the box plots are reduced remarkably for all connectivity variations. As without any usage of infrastructure

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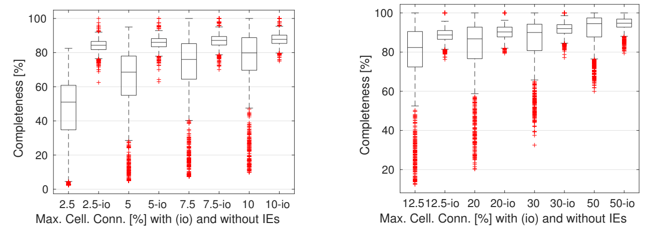


(a) Impact on the completeness for 2.5-10% cellular connectivity

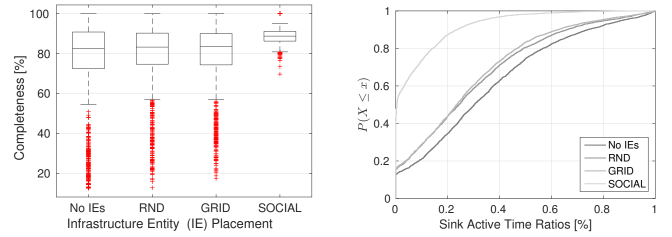
(b) Impact on the completeness for 12.5-50% cellular connectivity

Figure 4: The importance of multi-dimensional offloading and of cellular connectivity on the system performance

experiences a sharp drop in system performance is visible for 12.5% cellular connectivity and below, the 12.5% are chosen as default value (cf. Table I) for the cellular connectivity in the following scenarios.

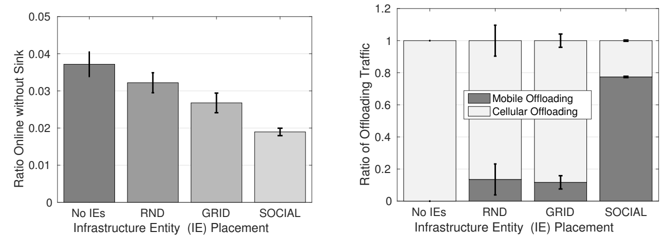
Once infrastructure entities are supported for mobile offloading in CRATER^{io}, as proposed in this work in form of multi-dimensional offloading support including the selection scheme between different offloading techniques, multiple significant improvements are visible. For the following evaluation part the percentage of cellular connections, i.e. the percentage of the sinks, and the social factor are set to their respective default values, while the placement as well as the number of infrastructure entities are varied according to the simulation settings visible in Table I.

To assess **the impact of the placement of infrastructure entities** the system is evaluated with three placement strategies: (i) a *random*, (ii) a *grid-based*, and (iii) a placement at the selected attraction points of the scenario, referred to as *social* placement. All strategies are compared with the performance of the system in its initial version, thus without mobile offloading capabilities (no usage of infrastructure entities) and 12.5% of cellular connectivity. The results show that the achieved improvements depend on a sensible placement of the infrastructure entities. The completeness is slightly improved for the random and grid placement, however for the social placement the completeness improves significantly as visible in Figure 5(a). Accordingly, with only 12.5% of cellular connectivity, i.e. every eighth node is a sink, CRATER^{io} is able to deliver a minimum of 80% the monitoring data from the mobile nodes by supporting multi-dimensional offloading (a 25% point increase compared to the initial system). The time sinks are active, thus the burden on the sinks, is reduced substantially for the social placement of infrastructure entities as depicted in Figure 5(b) showing the active ratios of sinks for the different placement strategies. For the initial version without infrastructure entities support and both the random and grid placed infrastructure entities only $12\% - 17\%$ of the mobile sinks remain inactive. With the social placement up to 50% of the sinks are able to remain inactive over the whole simulation time as visible in Figure 5(b) by simultaneously increasing the achieved service quality (cf. Figure 5(a)). While, 90% of the sinks are active for a maximum of 60% and



(a) Impact of IE placement on the completeness

(b) Impact of IE placement on the sink active ratio



(c) Impact of IE placement on the no-sink ratio

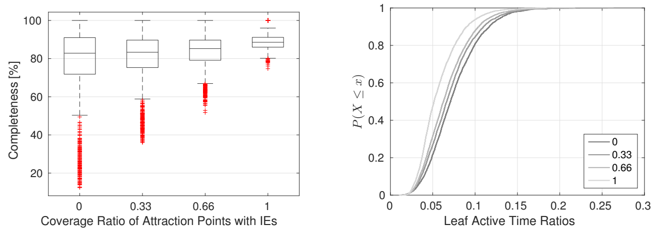
(d) Impact of IE placement on the offloading ratios

Figure 5: Evaluation of the impact of the placement of infrastructure entities (IEs)

75% for the initial version and the random and grid placed infrastructure, the social placement can reduce the burden on the mobile sinks, regarding the active sink time, by a factor of three, achieving an active time of at most 25% for 90% of the sinks and improving the performance at the same time.

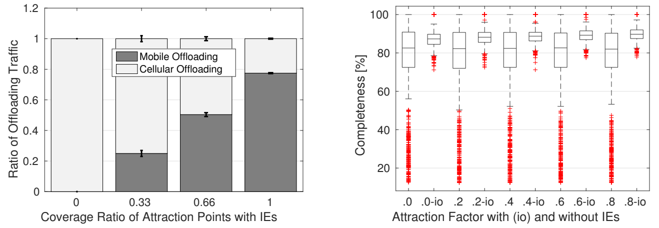
Beside the significant gains in the achieved completeness, CRATER^{io} can improve the time leaves are not aware of any sink (fixed or mobile) by half from 3.6% to 1.8% for the placement at social attraction points, as seen in Figure 5(c). The narrow confidence intervals underpin the performance and the robustness CRATER^{io} is able to achieve by supporting multi-dimensional offloading of monitoring data. The achieved goal of reducing the load on the individual mobile nodes that take the sink role becomes visible in Figure 5(d). For the random and grid placement of infrastructure entities a relative small amount of around 10% of the overall uploading traffic can be offloaded with mobile offloading techniques in average. However, in the case of the social placement, where infrastructure entities are placed directly at social interesting points, such as bars and parks, over 75% can be offloaded with mobile offloading according to Figure 5(d). Summarized, by sensible placement of infrastructure entities a 25% point increase in the completeness can be achieved in scenarios with low cellular connectivity (12.5%), leading to a reliable collection of monitoring data from at least 80% of the mobile nodes. Beside that the load on the mobile nodes (especially sinks) can be reduced significantly, as up to 75% of the uploading traffic can be offloaded via infrastructure entities.

Taking a look at the impact of **the number of infrastructure entities** that can be used for mobile offloading Figure 6 reveals that already a very low number of additional infrastructure entities can result in significant improvements of the



(a) Impact of the coverage of IEs on the completeness

(b) Impact of the coverage of IEs on leaf active ratios



(c) Impact of the coverage of IEs on the offloading ratios

(d) Impact of the attraction factor on the completeness

Figure 6: The impact of the coverage ratio of infrastructure entities (IEs) of attraction points and the attraction factor

system characteristics. Hence, four different coverage ratios of infrastructure entities at the social attractive points are chosen. Accordingly, the coverage ratios are varied between 0, 1/3, 2/3 and 1 as shown in Table I . The completeness of the system is improved for all configurations where multi-dimensional offloading is supported, however using fixed mobile offloading stations at each social attractive point greatly improves the completeness compared to additional infrastructure entities at 1/3 or 2/3 of the social attractive points (cf. Figure 6(a)). Already 90% of the leaves spend approximately less than 8% of their time being leaf searching for sinks in their proximity (cf. Figure 6(b)), which is a 40% decrease compared to the scenario with no additional infrastructure entities. Similar to the results for the placement variations it is clearly visible that infrastructure entities at 1/3 of the attractive points do already take more than 20% of the uploaded traffic (cf. Figure 6(c)). It becomes apparent that the ratio of the mobile offloaded traffic versus the cellular offloaded traffic shows a positive linear dependency to the number of additional infrastructure entities.

C. Impact of Social Relations

The considered scenario includes essential social relations between nodes and public places [4]. Depending on the attraction factor, that indicates how appealing each place is, nodes tend to form groups of different size and lifetime at those attracting places. Accordingly, the impact of group formation for different length of times must be evaluated within CRATER^{io}. For this the attraction factor is varied between 0.0 and 1.0 according to Table I. We evaluate both configurations with and without multi-dimensional offloading to asses the robustness against social relations, i.e. group formation, under different scenario configurations. Figure 6(d) shows both configurations with (*indicated by io*) and without infrastructure entities for multi-dimensional offloading evaluated under the different attraction factor variations. It reveals that the performance is robust against social relations for configurations without the usage of infrastructure entities. However, due to the proximity to the attraction points and the infrastructure entities the configuration with infrastructure entities (io annotation in Figure 6(d)) shows slight dependencies between the attraction factor and the achieved performance. The higher the attraction factor, the better the resulting completeness as nodes stay longer at the respective attraction points. This is a logical consequence to the sensible placement of the infrastructure entities. Nevertheless, the achieved completeness is improved significantly with multi-dimensional offloading, irrespectively of the minor impact of the attraction factor.

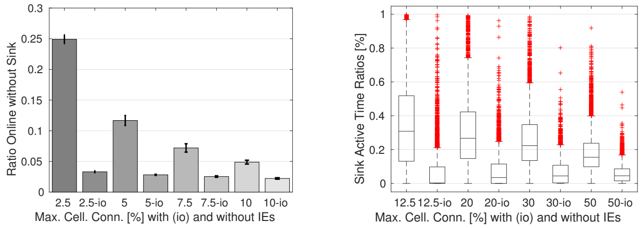
D. Meaningful Usage of Resources

Saving usage of resources is essential in environments, such as mobile networks, where devices are for example battery powered. Especially when the resources of the individual mobile users are exploited for the overall effort, such as monitoring the network state in the case of CRATER^{io}. In the hybrid topology, the saving utilization of the resources can determine the lifetime of a service and the network. It is essential that CRATER^{io} delivers monitoring data from as many nodes as possible even in scenarios with poor cellular connectivity, thus very few sinks. Accordingly, a trade-off between the completeness and the load on the individual nodes rises, as many nodes are connected to a few sinks. While the system is able to deliver accurate and reliable results by using resources of the mobile nodes for the collection of monitoring data [7], the load on the individual sinks depends on the size of the area they operate and maintain. By using multi-dimensional offloading, as proposed in this work, the load on the individual sinks can be reduced significantly. This comes into full effect once very few cellular connections, i.e. very few sinks, are used by systems like CRATER^{io}. While the performance without multi-dimensional offloading degrades by around 12.5% of cellular connectivity (cf. Figures 4(a) and 4(b) in Section IV-B), the performance using multi-dimensional offloading remains comparatively constant, with only minor degradations in service quality.

Figure 7 shows the potential with (indicated by io) and without multi-dimensional offloading in CRATER^{io} for different variations of the cellular connectivity, i.e. the percentage of sinks. The results show that with additional infrastructure for mobile offloading good monitoring results of at least 75% of the nodes can be guaranteed even under very poor cellular connectivity situations of only 2.5%. Thus, data from 30-times more nodes than possible sinks can be collected by using multi-dimensional offloading (cf. Figure 4(a)). In the other case the achieved results vary significantly in sparse connected environments, confirming the need for multi-dimensional offloading in the case of monitoring in mobile networks to guarantee wide applicability under various conditions. While the performance drop is linear for CRATER^{io}, the results of the system without multi-dimensional offloading experience a sharp drop as visible in Figures 4(a) and 4(b). Without multi-dimensional offloading, the system loses in informative value as the completeness ranges between 5% and 80% for the case of 2.5% cellular connectivity (cf. Figure 4(a)).

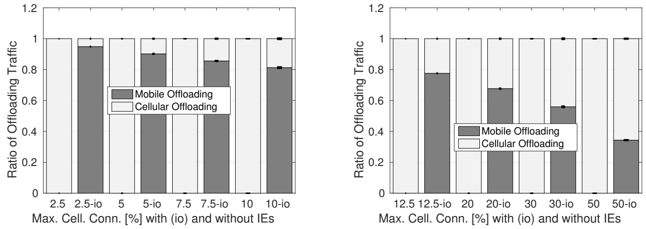
Furthermore, as visible in Figure 7(a) the time leaves are not aware of any uploading possibility can be reduced by the factor of five leading to an average time ratio leaves are not aware of any sink below 5%. In comparison to 25% for the case without multi-dimensional offloading the responsiveness is increased significantly with CRATER^{io}. The load on individual sinks is also increasing as shown in Figure 7(b) as the sink active ratio is reduced by at least 50% in median with multi-dimensional offloading. Concerning the traffic ratios of cellular offloaded and mobile offloaded traffic it becomes apparent that in scenarios with a very poor cellular connectivity most of the traffic is offloaded via the infrastructure entities (cf. Figure 7(c)) to guarantee the constant good performance shown in Figure 4(a). Nevertheless, Figure 7(d) shows that even in scenarios with very good cellular connectivity, where e.g. 50% of the nodes are able to connect via the cellular network still 35% of the traffic can be offloaded via the infrastructure entities. Which means even with good cellular connectivity, i.e. a higher number of sinks, one third of the monitoring traffic that would burden mobile sinks can be offloaded using multi-dimensional offloading techniques within CRATER^{io}.

The results indicate that multi-dimensional offloading does not only entail benefits in scenarios with very poor cellular connectivity. Rather, they show that even in situations with good cellular connectivity the usage of additional infrastructure entities for mobile offloading can improve the performance and save resources of the individual resource constrained devices. Especially for adaptive monitoring systems, such as CRATER^{io}, the conservative usage of resources of the mobile devices is crucial. The used number of sinks within CRATER^{io} can be reduced significantly, while the system is able to guarantee for good service quality and reduced resource consumption at the same time. Thus, the system must use a suitable number of sinks even if that entails minor service degradations (cf. Figures 4(a) and 4(b)). The achievable savings regarding the load on the cellular network and more important the mobile nodes do outweigh the minor loss in service quality in most cases.



(a) Impact of multi-dimensional offloading on the ratio leaves are not aware of active sinks

(b) Impact of multi-dimensional offloading on the active ratio of sinks for good cellular connectivity



(c) Impact of multi-dimensional offloading on the traffic ratios for 2.5-10% cellular connectivity

(d) Impact of multi-dimensional offloading on the traffic ratios for 12.5-50% cellular connectivity

Figure 7: Evaluation of the impact of the percentage of cellular connections on the performance of the system with (*annotated with io*) and without multi-dimensional offloading

V. RELATED WORK

Kemp et al. present an approach for resource saving application monitoring by offloading of computational task in [19]. While the potential savings by offloading of computational tasks are shown, the approach is highly dependent on cellular connectivity of each individual user and uses no comparable offloading techniques as presented in this work. DAMON [20] uses an agent-sink topology with device-to-device offloading for distributed data collection in multi-hop networks. In doing so less overhead and fewer potential collisions are achieved. However, the usage of pre-defined and static sinks limits the applicability of the approach for wider scenario usage. Other monitoring approaches for mobile networks, such as [21], [22], show the benefit of device-to-device offloading in hierarchical structures. However, these approaches are limited to ad hoc communication without using cellular or infrastructure upload to provide a global network state of multiple physically isolated areas. Furthermore, at a higher level in the hierarchy, the load on the individual devices rises significantly and is not reduced using a multi-dimensional offloading approach as proposed with CRATER^{io} in this work. Bao et al. [2] propose a framework that exploits clustered devices to reduce the load on the cellular network. Similar to CRATER^{io} the system shows the benefit of device-to-device offloading, however, the authors do not consider the inclusion of public infrastructure entities into the system effort to benefit from multiple offloading techniques at the same time as shown in this work. The feasibility of mobile offloading in urban scenarios, similar to the scenario considered in this work, is assessed in [9]. The authors propose that public infrastructure entities may be used to reduce the load on the cellular network. However, they do not validate the claim in a system to examine the usability and achievable gain. Furthermore, they do not address the selection of different offloading schemes in one system, as it is done in this work. Lou et al. [23] describe an approach to gain the maximum throughput for individual users by taking advantage of neighbors with better cellular connectivity. The requested traffic is then downloaded via an one-hop link from the adjacent neighbor. However, the authors do not consider techniques to decrease the load on the forwarding proxy nodes as CRATER^{io} is doing in its collection process. Furthermore, the approach is still depending on good cellular coverage as

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proxy nodes are only able to provide for data in their one-hop neighborhood. The work done by Han et al. [10] describes a step towards multi-dimensional offloading as the authors argue that the need for both cellular and mobile offloading possibilities is very high, especially in urban networks, due to the increasing coverage of public Wi-Fi infrastructure. The achievable gain by using multi-dimensional offloading is assessed in our work with the example of the adaptive monitoring system CRATER$^{\text{io}}$. The authors of [24] argue that a delayed mobile offloading is very cost-effective concerning the consumed resources, but needs the users patience to accept the delayed upload. By combining device-to-device and mobile offloading CRATER$^{\text{io}}$ provides high coverage in the network under various dynamic environmental conditions. Other discussed solutions from [25] do not capture the whole potential of multi-dimensional offloading as it is done in this work on the example of CRATER$^{\text{io}}$ as they restrict their contribution to individual aspects of the offloading procedure

VI. CONCLUSIONS

This paper assesses the importance and the impact of multi-dimensional offloading. Supporting multiple different offloading techniques is essential in today's networks, where due to the heterogeneity of the networks at least two communication means are omnipresent most of the time [8]–[10], [14]. We validate this importance using the example of an extended adaptive monitoring system, named CRATER$^{\text{io}}$. It is an extension of a state-of-the-art adaptive monitoring system [7]. CRATER$^{\text{io}}$ unites multiple offloading techniques in one system and addresses rising challenges, such as prioritization and selection of individual offloading techniques. We show that CRATER$^{\text{io}}$ can efficiently handle a wide range of scenarios, while improving the service quality and the responsiveness at the same time. Furthermore, the footprint of the monitoring system is reduced significantly as the load on (i) the individual resource-constrained mobile devices, and (ii) the cellular network is reduced using multi-dimensional offloading.

As shown in this work, a significantly reduced number of sinks and the usage of multi-dimensional offloading techniques deliver comparable performance results, (with only minor degradations) and imply considerable less cost regarding the resource and communication medium consumption. To minimize the cost, we plan to use optimization techniques, such as heuristics, to assess the optimal number and selection of sinks in CRATER$^{\text{io}}$, depending on the current network conditions. The practical evaluation of CRATER$^{\text{io}}$ in a testbed with Android devices using different means for communication, such as Bluetooth and Wi-Fi ad hoc, and the extensions proposed in this work is currently ongoing work.

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