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# Scalability Analysis of Context-Aware Multi-RAT Car-to-Cloud Communication

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***Abstract*—Nowadays always-connected vehicles create opportunities for novel services like vehicles serving as highly mobile sensor platforms in the Internet of Things context. Hereby, cars upload and transfer their sensor data readings via a mobile communication network into the cloud. Data is shared in the cloud via vehicle big data marketplaces. As wireless resources are limited and shared by all users, data transfers need to be conducted efficiently. The ongoing growth of generated data inside vehicles and thereby the increasing data upload demand becomes more and more challenging to Mobile Network Operators.**

**Within the scope of the work, an opportunistic Multi-Radio-Access-Technology (Multi-RAT) uploading approach is proposed in order to conduct those data uploads faster and more efficiently. This approach leverages multiple network interfaces and combines them to one unified communication link. Data uploads can be delayed to exploit good channel conditions and avoid uploads when the channel quality is insufficient. The simulative results and evaluations highlight that the proposed method is well-suited for vehicular data uploads. Even though a trade-off in the age of information is created, the throughput is increased. Besides, better performance in spectral efficiency is achieved in comparison to traditional single-link transmissions.**

***Index Terms*—car-to-cloud, vehicle-to-x (V2X), multi-link, multi-RAT, multi-homed, multi-path, MPTCP, MPQUIC**

## I. Introduction

The integration of connectivity into vehicles is continuously growing and cars are becoming an increasingly important part of the Internet of Things (IoT) [1]. Vehicles navigate every corner of the world and at the same time, they observe their environment through built-in sensors. Exploiting these observations creates a large-scale wireless sensor network creating enormous big data potential. The first two vehicle big data marketplaces AutoMat [2] and Otonomo [3] arise to lift this so far unexcavated treasure. With millions of connected cars participating on those platforms in the near future, the efficient car-to-cloud data transfer becomes more and more challenging. To solve this challenge, the underlying paper proposes the usage of one combined Context-Aware Transmission (CAT) and Multi Radio Access Technology (Multi-RAT) approach.

The Multi-RAT-concept combines multiple cellular networks in one combined communication channel. At first glance, it seems as if the load is just distributed onto multiple networks, thus doubling the throughput. In practice, this may occur in places where Mobile Network Operators (MNOs) share antenna sites. In those locations, the Multi-RAT approach helps load balancing between different networks and improves the throughput of all users. In heterogeneous scenarios, where one MNO has good network coverage while another MNO has not, the Multi-RAT approach achieves maximum gains [4]. Different networks complement each other and vehicles benefit, which would otherwise suffer from bad their primary MNO's bad coverage.

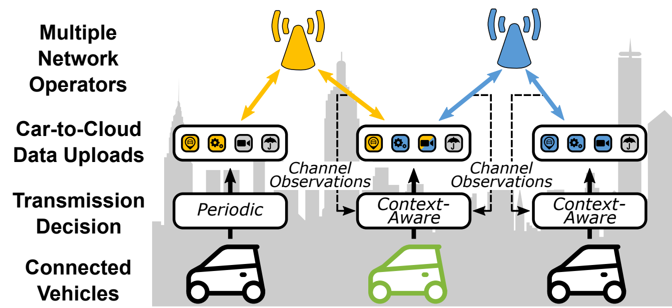


Fig. 1. Large scale analysis of Connected Vehicles, which upload their sensor data into the cloud. Hereby, vehicles may exploit multiple cellular networks at the same time while following context-aware transmission strategies.

On the other hand, the CAT methodology is an opportunistic communication technique for delay-tolerant applications. Uploading data, when experiencing bad channel conditions, requires more resources to send data: applying a more robust modulation and coding scheme reduces throughput, the upload takes longer and due to the worse channel the error probability is higher, thus packet loss may occur. Therefore, CAT [5] may reschedule data uploads from a periodic transmission to exploit good channel conditions.

Within the scope of this paper, the proposed approach is introduced in detail and afterward evaluated in a simulative study. The study uses a realistic network layout based on publicly accessible cell tower data and a microscopic vehicle simulator, which is parameterized using a crowd-sourced road layout map. The results indicate that the proposed approach achieves higher throughputs as well as spectral efficiency as conventional single link data uploads.

## II. Related Work

Using heterogeneous networks for efficient vehicular communication is subject to many studies. Lauridsen et al. [6]

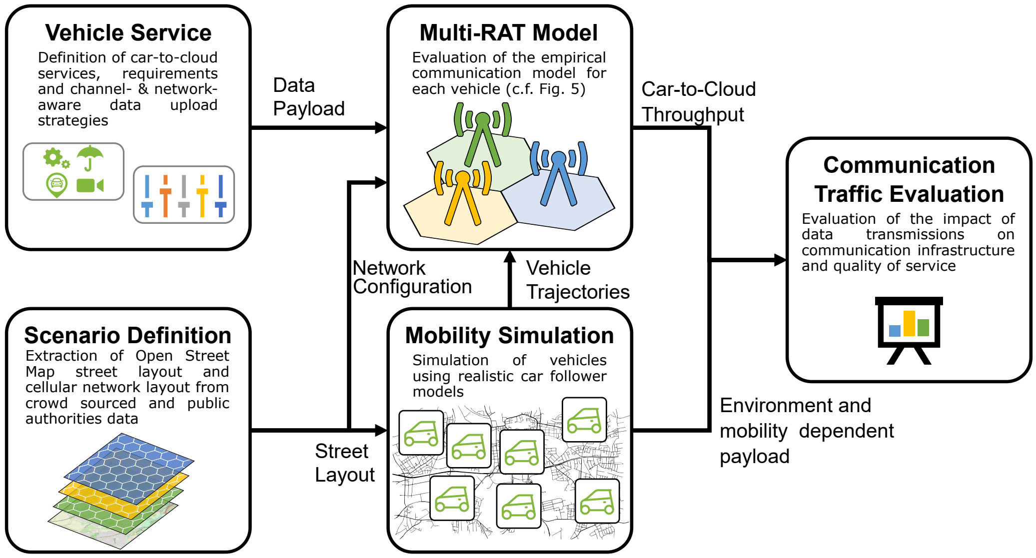


Fig. 2. Methodology of the car-to-cloud communication traffic evaluation

presented in their experimental study the usage of multiple cellular networks to reduce the latency of periodic message transfer. The most prominent protocol for aggregation on the transport layer is Multipath TCP (MPTCP) [7], which has been implemented into the Linux kernel. MPTCP extends the basic Transmission Control Protocol (TCP) protocol, is transparent to the upper layers, and allows seamless handover between networks. The novel UDP-based competitor MultipathQUIC performs similar, but requires adaption of higher layer protocols as it is implemented in the kernel, but the userspace. Therefore, this work simulates the behavior of MPTCP. First empiric evaluations of Multi-RAT car-to-cloud data transfers promise throughput improvements [4]. The opportunistic context-aware scheduling is based on the previous work of the authors. It has proven its applicability in several evaluations [5]. Several extensions and adaptions exist, like the machine-learning-based variant [8]. Just recently, [9] proposed a. Client-side Adaptive Scheduler That minimizes Load and Energy (CASTLE) performs a passive cell load scan. Based on the load, data transfers are rescheduled using a random backoff. Hereby, a similar gain in terms of spectral efficiency can be achieved. However, those studies observe only single or a few vehicles. Large scale studies are missing. Therefore, this work contributes to a large scale analysis, where all network participants behave in an opportunistic approach.

## III. Proposed Solution Approach

The following section introduces transmission schemes for vehicular sensor data uploads. The first single Radio Access Technology (RAT) methods are illustrated and in the following extended for Multi-RAT usage. Within the scope of this work, a naive periodic transmission scheme serves as a ground reference. Here, sensor data is aggregated for a fixed interval, e.g. $\Delta t = 30\ s$. After the interval has expired, data is transmitted without observing and considering the environment, context and communication link quality.

### A. Context-aware Data Transmission with CAT

One improved car-to-cloud data transfer scheme for opportunistic communication is the CAT approach [5]. This methodology aims at leveraging connectivity hotspots for transmissions and thereby reduces the impact of Machine-Type Communication (MTC) on human-to-human (H2H) traffic. The method has proven its applicability in several analytic, simulative and empirical studies. CAT is based on observing network quality indicators, which are provided by the underlying User Equipment (UE), e.g. the Signal to Interference plus Noise Ratio (SINR). The transmission start is based on a random process: for each data upload, a transmission probability is calculated, which is based on the current network quality. The better the network quality the higher the transmission probability. The underlying approach founds on the generalized metric representation form, which has been introduced as part of the context-predictive machine-learning CAT variant by Sliwa et al. [8]:

$$\Theta_\Phi(t) = \frac{\Phi(t) - \Phi_{min}}{\Phi_{max} - \Phi_{min}} \tag{1}$$

The observed network quality metric $\Phi(t)$ at time $t$ is aligned into the normalized metric $\Theta(t)$, which ranges between $0$ and $1$. Based on this the transmission probability can be derived as follows:

$$p_\Phi(t) = \begin{cases} 0 & , \quad t \leq t_{min} \\ \Theta_\Phi(t)^\alpha & , t_{min} < t \leq t_{max} \\ 1 & , t_{max} < t \end{cases} \tag{2}$$

The case distinction with $t_{min}$ guarantees that at least a minimum amount of data is aggregated in the vehicle. At the same time, $t_{max}$ ensures a maximum period for aggregation to limit the delay until data arrival at the receiver. The exponent $\alpha$ defines a weight, which allows fine-tuning of the algorithm. Within the scope of this study, only the network quality indicator SINR is taken into account for channel-aware transmissions.

### B. Multi-RAT Selection

When multiple communication links are available different possibilities of distributing the data uploads exist. This section introduces the following strategies:

- **SR**: Use only one single, pre-defined link
- **MR-ALL**: Use every possible link
- **MR-BEST**: Use only the best available link

The most straightforward strategy is Single-RAT (SR) scheduling. Here, all data is uploaded via one single network. The vehicle is not allowed to switch between multiple networks and makes use of its initially defined MNO. In *MR-ALL* full link aggregation is applied. All available networks and MNO are exploited as much as possible to maximize the throughput. This is the most greedy approach and claims most resources. The resulting throughput is the sum of throughput of all links. For the common transport layer protocols MPTCP and Multipath QUIC (MPQUIC) this is the default setting. The underlying study will show later that this method does not perform best in terms of efficiency.

The approach *MR-BEST* makes use only of the best link according to its network quality indicators, e.g. SINR. Only one link is used at a time. Whenever another link becomes better, e.g. due to moving closer to the base station or experiencing fewer interferences, priority is switched and the data is delivered via that link.

### C. Channel-Aware Multi-RAT Transmissions

For launching the upload transmission this study proposes an Multi-RAT adaption of CAT. Here, for each of the $N$ communication links an individual transmission $p_{\Phi,i}$, which is based on the normalized general network quality indicators $\Phi$, is calculated. The Multi-RAT transmission probability $p_{MR}$ is then defined as the maximum of each communication link's transmission probability:

$$p_{MR}(t) = \max_{i \in N} \left( p_{\Phi,i}(t) \right) \quad (3)$$

Fig. 3 illustrates the proposed Multi-RAT CAT schemes in comparison to a periodic transmissions. The upper plot shows the time-series of the radio channel quality indicator SINR for two available MNOs. The lower plot shows a comparison of data uploads for the proposed upload schemes. While the periodic schemes start transmissions every thirty seconds, the CAT schemes observe channel quality and make use of connectivity hotspots.

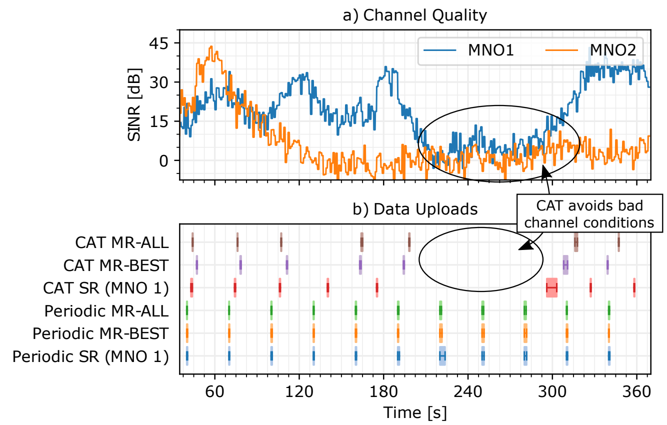


Fig. 3. Comparison of different transmission schemes at the example of one vehicle. Whereas the periodic schemes start transmissions every thirty seconds, the CAT methods try to leverage connectivity hotspots and avoid bad channel conditions. The Single-RAT (SR) uses Mobile Network Operator (MNO) 1.

## IV. Methodology and System Model

### A. V2X Service and Data Modeling

In the underlying work, vehicles act as remote sensors as part of a future vehicle big data marketplace. Data is encoded using the Common Vehicle Information Model (CVIM) data format as described in preceding work [10]. The CVIM defines a standardized data model for vehicle big data aggregation. It allows large scale data mining and harmonizes sensor configurations and value readings of different car manufacturers. In the underlying work, vehicle data generation is emulated using a random fake data generator. Each vehicle generates constantly 100 KByte/s of sensor data. The data is accumulated in CVIM data packages until the upload scheduling decision is made. Afterwards, the data packages are flushed into an uploading queue. When the upload to the cloud is finished, the age of the package is calculated. In the following, the age of data means the age of the first (oldest) information, which is inside of one data package.

### B. Street and Mobile Network Environment Model

This work is conducted at the example of the German city Dortmund. Dortmund inhabits with its surrounding suburbs 600.000 people, however, the study focuses on the inner city part, which has a metropolitan character. The environment models used in this work are based on crowed sourced or freely accessible data. The street layout is imported from the Open Street Map (OSM) project [11]. OSM is a community-driven project aiming at providing an open, free-to-use and highly precise map that includes streets, buildings, traffic lights, speed limits and more. The second part of the environment is described by the cell tower layout and available bandwidth per cell tower. Precise location and cell tower data from public and freely accessible datasets were enriched and used. These base station locations were imported from the public databases of the Federal Network Agency for Telecommunications [12] and Katasteramt Dortmund [13]. Frequency and bandwidth information have been added using crowd-sourced information [14], [15].

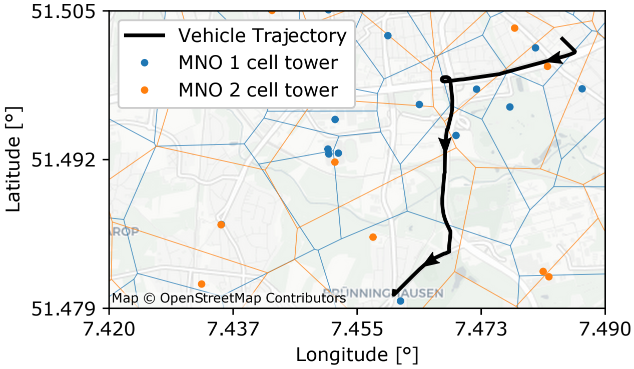


Fig. 4. Illustration of the the resulting trajectory of one example vehicle of the mobility simulation. The figure also shows surrounding base stations and coverage of two Mobile Network Operators (MNOs)

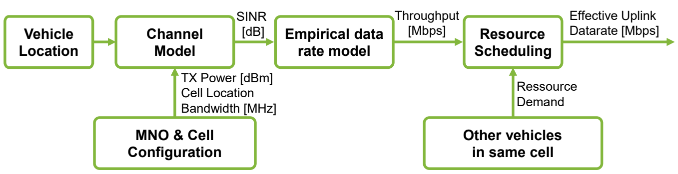


Fig. 5. Schematic illustration of the cellular communication model. Inputs are the positions of all vehicles from the mobility simulation and the environment description. The output is the effective uplink data rate per vehicle.

### C. Vehicle Traffic Simulation

For realistic user mobility, the vehicle traffic is simulated using the open-source software Simulation of Urban Mobility (SUMO) [16]. SUMO is a microscopic traffic simulator where each vehicle is explicitly modeled using a car follower model. It uses the previously described OSM map import for its road layout with vehicle trips. The communication model is linked to the vehicle traffic simulation using the SUMO's Traffic Control Interface (TraCI) programming interface. Figure 4 shows an example trajectory of one vehicle moving in the simulation with surrounding cell tower locations of two MNOs. Within the scope of this evaluation, two scenarios with different population sizes are evaluated. In the first case, representing an unsaturated network, the simulation is run with 500 vehicles. In the second evaluation, the network is crowded with 1800 vehicles. Here, the communication network is crowded and vehicles need to compete for resources.

### D. Communication Model

The underlying work proposes an analytic base enriched a measurement-based throughput model for simulating the communication environment. Figure 5 shows an illustration of the proposed communication model. It takes as input the positions from all vehicles from the mobility simulation as well as the environment configuration with given cell tower layout and the according cell configuration with transmission power and bandwidths. For each vehicle, it calculates the path loss and attenuation using the Winner-II channel model C2 [17] for the urban macro cells. With the given noise

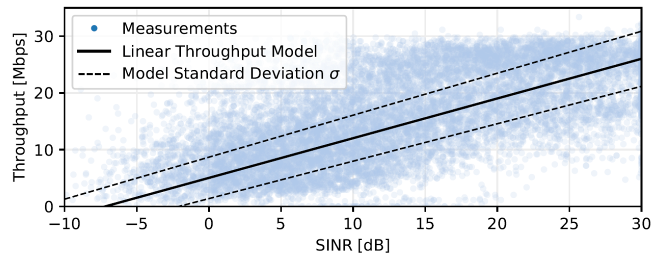


Fig. 6. The empiric throughput model is based on measurement samples, which were taken during a two hour drive-test. The model consist of a linear component for the average throughput as well as a random component, which is defined by the measurements standard deviation $\sigma$.

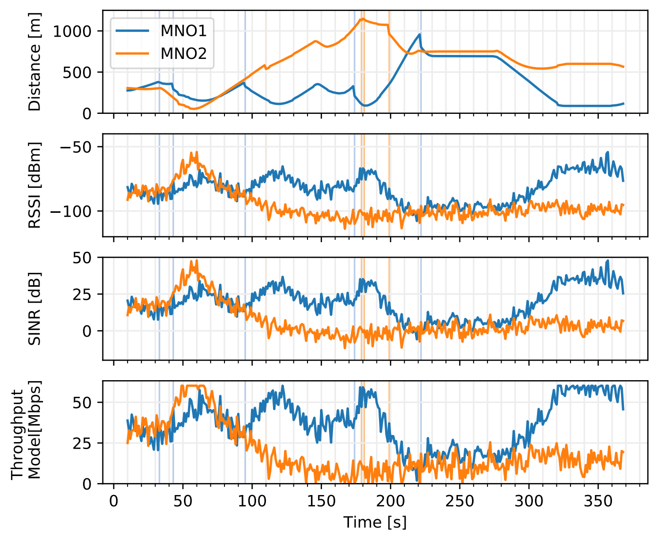


Fig. 7. Example evaluation of the full communication model stack shows the distances to the associated base station, the resulting Received Signal Strength Indicator (RSSI) as well as channel quality in form of the Signal to Interference plus Noise Ratio (SINR). Afterwards the throughput model is applied. In this case, the vehicle is alone in its cell and gets all resources assigned. Vertical colored lines indicate handovers between different cells of one MNO.

floor, transmit power and antenna gains the SINR estimate is calculated. To transform an SINR value into a throughput, an empiric data rate model is used. Here, the application layer throughput has been measured on a real-world two-hour drive test. The correlation between experienced SINR and measured throughput is illustrated in Figure 6. As a simplification linear fitting has been applied to estimate the mean throughput. A random component is added by considering the standard deviation of the mean values. The full communication model stack has been implemented in python.

A full example of the communication model is illustrated in Figure 7. The top row illustrates the distance of the vehicle to the currently attached cell tower. In the row below the received power is calculated in the form of the RSSI. This power level is used to derive the channel quality (SINR). Afterwards the throughput model is applied. This represents the maximum possible throughput without any other vehicles in the same cell. With other vehicles, resources must be shared and available throughput will decrease. Vertical lines indicate handover

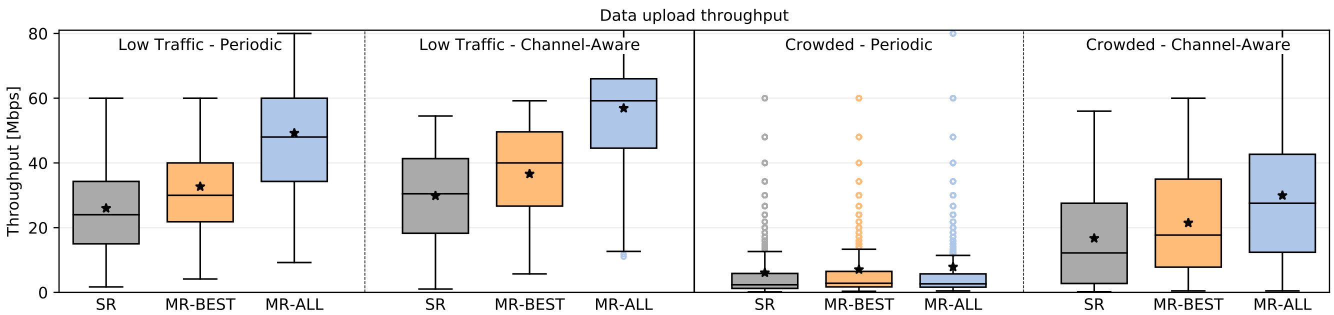


Fig. 8. Resulting application layer throughput of vehicle data package uploads for the scenario with "normal" vehicular traffic with uncongested cells and the crowded scenario. Context-Aware Transmissions (CATs) achieve higher throughput than periodic schemes. Multi Radio Access Technology (Multi-RAT) transmissions with full link aggregation MR-ALL results in highest throughput.

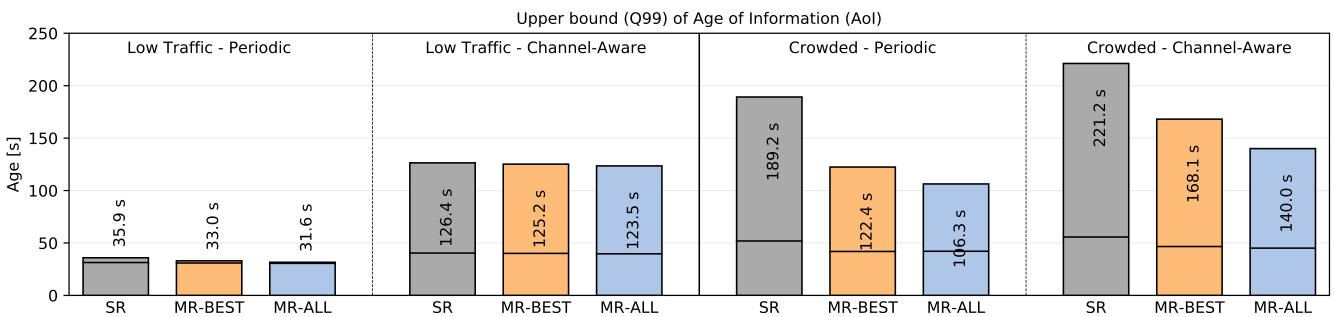


Fig. 9. Upper bound (99% quantile) of the Age of Information (AoI) for one scenario with "normal" vehicular traffic and uncongested cells and one crowded scenario with congested cells. Single-RAT (SR) performance is generally worst, while MR-ALL achieves lowest AoI. For Context-Aware Transmission (CAT), age of information is higher due to delayed upload. The AoI-gap between non-CAT and CAT decreases for the crowded scenario. The horizontal lines indicate median values.

between different cells. The vehicle is always assigned to the cell with the highest received power. Handovers between two cells are performed with a 3 dB margin.

## V. Experiment Evaluation

The following subsection evaluates and discusses the results of the simulative evaluation of Multi-RAT car-to-cloud data transfers. Figure 8 presents the resulting throughput. The resulting figure is split into four parts. The two leftmost represent the normal scenario with 500 vehicles. The network operates "normally" and is not congested. Vehicles do not need to compete for resources. The two rightmost parts of the figure represent the crowded scenario with a large number of vehicles competing. For each scenario, the left half represents periodic upload schemes, the right half the CAT. The MR-ALL generally achieves the highest throughput in all cases. This is due to the fact, all networks are exploited as much as possible. Therefore, the individual throughput of single networks is summed up. The Multi-RAT best link (MR-BEST) uses only the best available link with respect to channel quality. The throughput is therefore increased in comparison to plain SR performance. The data upload itself, described as air time, is faster.

In the next step, the AoI as a second major key-performance indicator is analyzed. Figure 9 illustrates the upper bounds incorporated by the 99% quantile for the AoI for the previously described scenarios. The horizontal lines within the bars represent the average (median) AoI. The periodic schemes perform better. This is due to the regular data upload. In the normal scenario, 99 % of all packages can be submitted within 35.9 s for the periodic case. For Multi-RAT, a slight speedup of 4.3 s can be achieved using MR-ALL. The CAT data uploads complete all on the same level of approximately 125 s. The increase of duration in data uploads is to due delaying the data uploads in order to exploit connectivity hotspots and avoid transmissions in areas with bad connectivity. For the crowded scenario, vehicles compete for resources and the throughput is generally lower. Therefore, transmissions take longer and the AoI increases. Making use of Multi-RAT data uploads is highly beneficial. For periodic uploads, the maximum AoI is reduced by 62.9 s when using MR-ALL in comparison to SR. For MR-ALL CAT the AoI decrease is even better with an improvement of 81.2 s.

Due to the CAT approach, the data uploads are scheduled to exploit good channel conditions. This result is illustrated in Figure 10. It shows the channel condition in terms of average SINR during data uploads. SR and MR-ALL lay nearly on the same level. The MR-BEST approach achieves better results. All methods have a better SINR when scheduling CAT and not periodic. The same relationship can be seen in the evaluation of spectral efficiency in Figure 11. Efficiency is calculated as the total amount of data transferred by vehicles divided by the

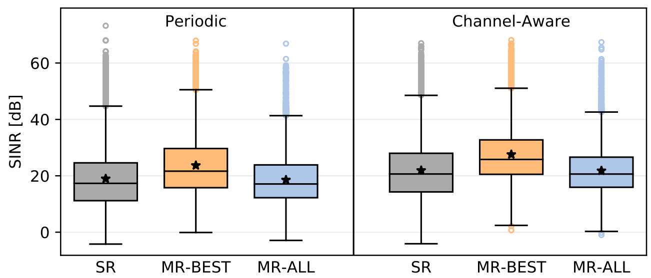


Fig. 10. The average Signal to Interference plus Noise Ratio (SINR) as major channel quality indicator during data uploads is increased due to the Context-Aware Transmission (CAT) approach.

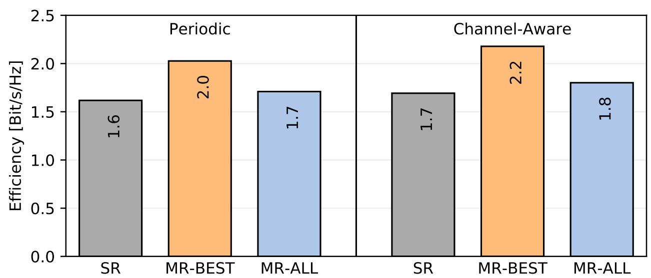


Fig. 11. Spectral Efficiency of the vehicular upload schemes. Transferring data only via the best available link MR-BEST results in best efficiency. Single-RAT (SR) and exploiting all links MR-ALL is worse as data is transmitted during non-beneficial channel conditions.

total resources (bandwidth and time) used. MR-BEST achieves the overall best result, both for periodic and CAT uploads as it only uses the best available MNO. Interestingly, MR-ALL is slightly better than plain SL uploads, even though transmitting data over two networks. But as the majority of data is sent via the better link, the approach results in a slight, but on average increased, spectral efficiency.

## VI. Conclusion

Within the scope of this work, the implication of Multi-RAT automotive sensor uploads for vehicle big data marketplaces has been investigated. Next to the Multi-RAT strategies of exploiting all available networks as much as possible (MR-ALL) and using on the best available network (MR-BEST) different data scheduling have been evaluated. Periodic scheduling starts transmissions in regular intervals, e.g. 30 s, CAT launches data uploads based on the experienced channel quality. Evaluations showed that the Multi-RAT approach increases throughput and minimizes AoI. In terms of efficiency using only the best MR-BEST available communication network results in the highest spectral efficiency. In future work, the authors want to include 5G New Radio, C-V2X and IEEE 802.11p roadside communication into the heterogeneous Multi-RAT.

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