2021 16th Annual Conference on Wireless On-demand Network Systems and Services (WONS)

GRETEL: Graph-based Street Coverage Calculation for Vehicle-to-Infrastructure Communication

Michael Niebisch*, Reinhard German*, Anatoli Djanatliev*
*Computer Networks and Communication Systems
Friedrich-Alexander University Erlangen-Nürnberg, Erlangen, Germany
{michael.niebisch, reinhard.german, anatoli.djanatliev}@fau.de

***Abstract*—Connected vehicles will exchange large amounts of data with remote systems. This can include recent traffic information, search results, or software updates to the car. Data communications can, therefore, be expensive as currently all transmissions to and from the vehicles are done via mobile service providers. Wireless Local Area Network (WLAN) offloading to home deployed Access Points (APs) for internet connectivity can be a more affordable option, as the use of the frequency spectrum is free of charge. While the technology is already widely deployed, the outdoor availability on the street is critical for the use in vehicles. To analyze the street coverage we have developed GRETEL, a GRaph-based streET covErage caLculation. GRETEL enables the analysis of Vehicle-to-Infrastructure (V2I) communications by combining location data with signal measurements mapped to the relevant road topology. To test GRETEL's performance, we conducted test drives to measure WLAN beacon frames and identify receivable WLAN APs. We determine that more than 9 % of all APs in our data set are commercially available connection options. With GRETEL, we could determine that the subset of commercially available APs covers about 60 % of the street network. Therefore, we introduced a novel method for street coverage calculations called GRETEL and showed encouraging results for the use of commercially available WLAN APs for V2I communications.**

***Index Terms*—V2I, coverage calculation, road coverage, graph-based calculation, field test**

I. INTRODUCTION

Future vehicles will use large amounts of data for various use cases. While some application data is time-critical, i.e., safety information, other vehicle applications – without user interaction – are more delay-tolerant. Both types of applications need to transfer data while the vehicle is moving, therefore, mobile communication networks are used, which are widely available. The use of said communication technology, however, can be expensive, as providers can charge by the amount of transferred data. In contrast to this, several internet service providers offer connectivity to home deployed WLAN APs for fixed rates. The APs are deployed in private households, with the incentive of free access to other APs for the customer, if they choose to enable the additional access network for other users. The additional, opportunistic use of WLAN APs for delay-tolerant applications can decrease the amount of mobile communication data significantly, as described in [1] and [2]. Nonetheless, the availability of these WLAN APs for vehicles is unpredictable even for a single access point. They can be placed anywhere inside the household, and can therefore be on the opposite building side in relation to the street or otherwise obstructed. Public access point maps of the providers only indicate the number of APs in any given street or area and do not provide coverage information. To generate reliable data for availability on the street for a moving vehicle, measurement drives have to be conducted. Signal measurements indicate the existence of an AP and provide information on the signal quality. As every measurement is only a single data point, all data points of a base station have to be collected and evaluated. For the geospatial evaluation of measurement data, the use of the Minimum Bounding Box (MBB) is common [3]. This method estimates the coverage area but does not relate to geographical conditions or the road network, which is mainly relevant in the vehicular context.

To evaluate the street coverage from vehicular signal measurements, we developed GRETEL, a GRaph-based streET covErage caLculation, utilizing map matching and graph calculations. We, therefore, combine the knowledge of the street layout, with the measurements in the road network, enabling the coverage evaluation. With GRETEL we are able, in contrast to the MBB method, to correctly map overlapping AP coverage in the relevant area. As we use the driven route for evaluation, we can combine multiple drives on the same streets, enriching our data set.

To sum up, our key contributions are:

1) Introduction of GRETEL as a novel method for signal coverage calculation on a street network.
2) Measurement runs capturing WLAN beacons in a vehicular environment.
3) Analysis of WLAN street coverage with GRETEL in comparison to the MBB.

In Section II we will introduce related work, while Section III presents GRETEL for street coverage calculation. Section IV details the measurement setup. Section V reports the received results before Section VI describes the conclusion and future work.

II. RELATED WORK

The use of WLAN access points from moving vehicles has been studied for a long time. Ott and Kutscher in [4] describe the connection in a highway scenario with a straight road, while Gass et al. tested the connection on a desert road in [5], therefore eliminating interference by other senders. Both see viable intermittent connection times, depending on the speed

ISBN 978-3-903176-35-5 © IFIP

of the vehicle. Many results have been obtained from testbeds over ten years ago, like Cabernet [6], CarTel [7], VanLAN [8] or DOME [9] by using either openly accessible APs, or self-deployed networks. However, many internet service providers and manufacturers of APs have since moved to default encryption schemes for privacy and security concerns. While previous works report connections to private APs, we show connection data with commercially accessible networks. As testbeds like DOME use regular transit vehicles, i.e., buses, they are subject to regular routes and do not cover the full area around the APs [9]. There are many challenges for vehicular WLAN deployments which can be seen in [10]. As the foundation to apply the approaches in [10] is always the possibility to connect to an available access point, we will only focus on this step. By capturing all streets in an area, we try to generate the full coverage of the APs. Brinkhoff et al. in [3] describe different approximations for geospatial data, including the Minimum Bounding Box.

Since the reception of WLAN APs is intermittent Balasubramanian et al. in [11] and Mehmeti and Spyropoulos in [2] propose the usage of WLAN to enhance mobile communication systems instead of replacing them. Although the connection is more affordable, the varying data rate and intermittent reception have to be taken into account.

III. GRAPH-BASED STREET COVERAGE CALCULATION

Vehicular measurements of communication technologies combine the movement and localization of the car and the signal measurements of the communication link. Due to the vehicular environment, the discrete measurement points in a single test run have a relation in time and location. However, if multiple runs on the same or nearby streets are taken into account, the relation to the street network is relevant. By utilizing the road network, junctions, parallel streets and other road layouts can be accurately mapped to the signal measurements. For our method we have the following assumptions:

1) The localization of the signal measurement is accurate to distinguish roads.
2) A road map of the measurement run is available.
3) The measured signal level is time-insensitive in the order of the measurement time.
4) Measurement and location updates are frequent, particularly in relation to vehicle speed.

We developed GRETEL with two main goals. First, we want to analyze the coverage area of any single base station in the road network. Second, we are interested in the signal overlap of multiple base stations in the area. In many technologies, multiple base stations can be received in a single location. The overlap can be used for the expansion of base stations as well as for handover strategies. A common way to estimate the coverage area of a base station can be the calculation of the diagonal of the Minimum Bounding Box. While the method has little computational effort, it does not use any relation to the street layout and can easily over or underestimate the reception. In order to evaluate GRETEL, we will later compare our measurements in the analysis with the diagonal of the MBB. The graph-based street coverage calculation is possible by combining multiple steps from the test setup to the calculation of the street coverage. An overview can be seen in Fig.1. We can combine measurement data from multiple test drives and use the signal measurement, as well as the location measurement. By applying map matching, the driven street segments can be identified, to which we can then map our signal measurements. From such a graph, containing the street layout and the measurements, the calculation of the street coverage is possible.

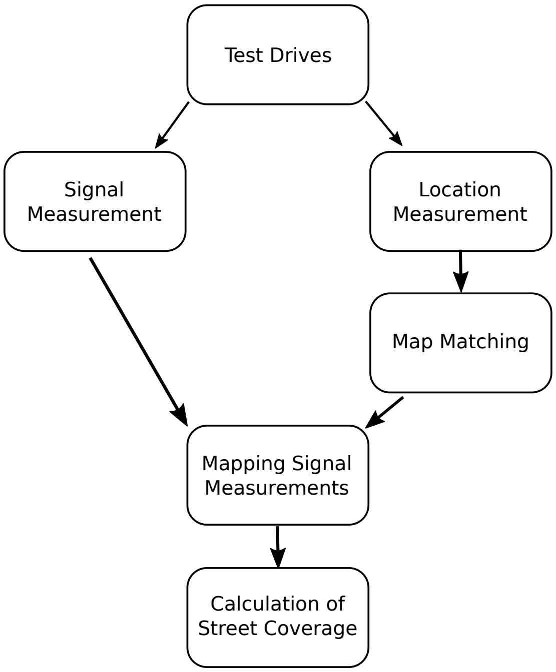

Fig. 1: GRETEL overview

A. Test Drives and Measurements

During the test drives, we collect positioning data from a Global Navigation Satellite Systems (GNSS) receiver and signal measurements for our respective communication link. In some technologies, e.g., WLAN, a signal scan has to be triggered, with the results returned after a period of time. In the case of WLAN, when the command to trigger a scan event is sent, the WLAN card scans all channels. For this, it loops through all channels, while staying on every channel for a period of time. As the beacon scan interval is not globally synchronized, each AP can send its beacon anytime. To capture a possible beacon frame on the channel, the scan stays tuned to every channel frequency for a short while. As there are eleven channels, a full scan on the application layer takes about $1.5\,\mathrm{s}$. When the scan is done, the information of all discovered access points is delivered at once, with an age relating to the scan, while the scan is triggered again.

In a vehicular setup, the scan age is important. A vehicle traveling at $30\,\mathrm{km/h}$ covers a distance of $12.5\,\mathrm{m}$ during a $1.5\,\mathrm{s}$ scan interval. A GNSS receiver may update the vehicle location every $100\,\mathrm{ms}$. However, as the scan trigger is not synchronized to GNSS periodicity but rather scans again as soon as a previous scan has been completed, the scan results can be obtained between location updates. We compensate for the location error by calculating the absolute scan time for an AP beacon frame. We then use linear interpolation to calculate the location of the scan. From a test drive, we want to achieve two outcomes: First, all location updates, which result in the full location measurement data set, second, signal measurements with the corresponding location information. Depending on the used technology, i.e., scan frequency or time of a scan, and the frequency of the location updates, appropriate steps have to be taken, to calculate the approximate location of the signal scan.

B. Map Matching

The next step for the calculation of street coverage is map matching the measurement drives to a street network. We have chosen to use the fast map matching (FMM) algorithm by Yang and Gidofalvi in [12], which utilizes OSMnx by Boeing [13]. OSMnx uses OpenStreetMap data to create a network graph. We found FMM to be fast and reliable for many parts of our test area. However, due to the sometimes unreliable labeling of data in OpenStreetMap, we use the full street network for the map matching, also including bike lanes, which are often built next to roads. The emergence of ambiguity led to certain occasions where a GNSS trace was matched to bike lanes or pedestrian crossings. Additionally, this sometimes led to disconnected street networks. We would only expect a minor impact from mismatched street segments, as a bike lane parallel to the street has about the same length. However, for our later analysis we chose to manually correct all deficiencies and create a fully connected graph.

The graph of a road network, like the example in Fig. 2, consists of multiple street nodes. A street node is an imported node from OpenStreetMap, used to resemble the course of the street. Every street node is associated with coordinates and all streets are recreated using linear connections between two street nodes. After applying the map matching algorithms, we get a subgraph of the full street network, containing relevant edges. We define this graph of the road network as:

$$G_r = (V_r, E_r) \tag{1}$$

Here V_r is the set of all nodes in the road network and $E_r \subseteq \{(x,y) \mid (x,y) \in V_r^2 \text{ and } x \neq y\}$ is the set of all edges.

C. Mapping Signal Measurements

After we have determined all relevant street segments from our drives, we can match our scan result to a street. This is done in a first step by utilizing the OSMnx functionality of calculating the closest edge to the scan coordinates. We are doing this only on the subset of driven edges as it increases the precision. In our example aforementioned step is seen in Fig. 2, e.g., we determine that a beacon is closest to the street consisting of the nodes S_1, S_2, S_3, S_4. In the next step, we further determine the two closest nodes of the street segment to the beacon scan location. For this, we calculate the distance of the scan to the line stretching between two nodes. As this line is only relevant between the two nodes, we use the dot product to calculate the distance to the closest node, if the scan is not in between both nodes. This can be seen in Fig. 3. The scan node A_1 is in between street nodes S_3 and S_4. We define a scan node, as a single measurement point from one base station. Dotted lines indicate the boundary between both calculations.

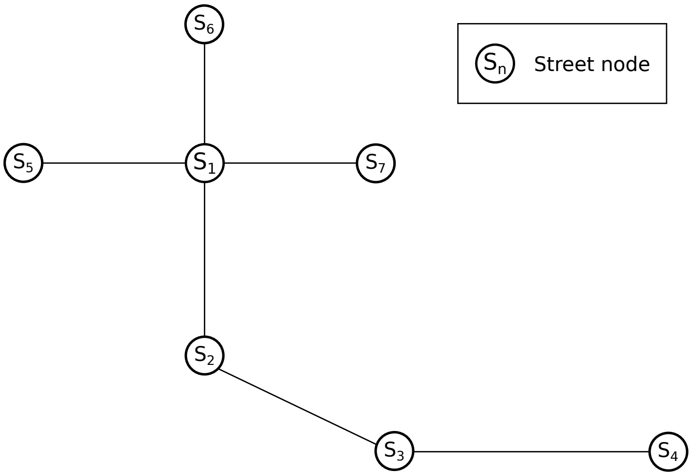

Fig. 2: Graph of street nodes

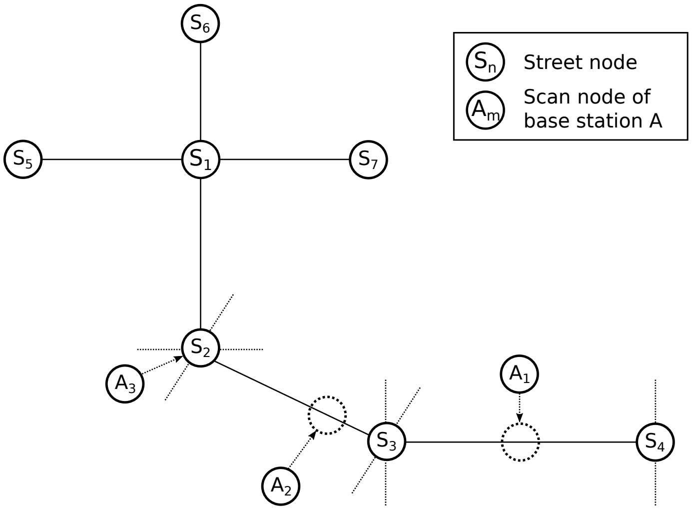

Fig. 3: Mapping of scan nodes into street graph

Before inserting the scan nodes into the street graph, we project the position of the scan node on the line between both street nodes. Projection is important as otherwise, the length of a street coverage would be longer than the street itself, due to the zigzag between all nodes. The perpendicular offset does not alter our results, as we are only interested in the longitudinal distribution of signal scans.

When we cannot determine a meaningful perpendicular projection of our signal node location – as seen for node A_3 in Fig. 3 – we use the coordinates of the closest node – S_2 in this case – and insert the new node on either side.

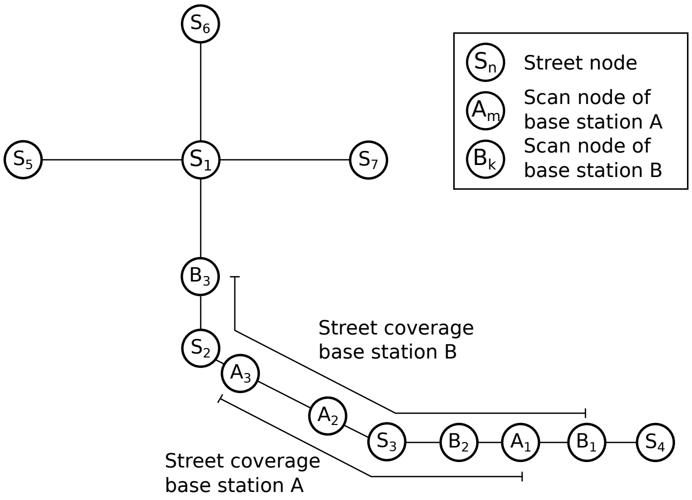

Fig. 4: Full graph of scan and street nodes

As we are later calculating the distance by the location and not the hop count, the exact sequence does not matter. If we define the set of all scan nodes as V_s, then $V = V_r \cup V_s$ and $E \subseteq \{(x, y) \mid (x, y) \in V^2 \text{ and } x \neq y\}$, the resulting graph is:

$$G = (V, E) \tag{2}$$

D. Calculation of Street Coverage

The insertion of all signal scans into the street network enables us to determine the overlap between access points. Multiple drives on the same street segment are compensated by using the projection onto the street. Therefore, we can easily improve our measurements by driving the same route again and inserting the new signal scans into the network graph. In order to calculate the coverage of any given AP, we have to determine the minimum subgraph of the corresponding signal nodes. The problem is similar to the NP-hard Steiner tree problem, which describes a tree of minimum weight, containing a subset of vertices, but allowing additional vertices. For our approach, we can allow loops as the reception around a housing block is valid although the subgraph is not loop-free. In our graph G, we have multiple scan nodes of other APs and street nodes between scan nodes of a single AP. In the simplified network in Fig. 4, we can observe this for both base stations A and B. We can therefore not simply calculate the minimum spanning tree, between nodes from one base station. To solve the problem, we use Dijkstra's algorithm to find the shortest way between all scan tuples of a base station. Let p_{AP} be a path found by Dijkstra's algorithm, defined as:

$$p_{AP} = (x_1, x_2, ..., x_n) \tag{3}$$

with

$$x_i \in V, \text{ for } 1 \leq i \leq n \tag{4}$$

Then let $p_{AP} \in P_{AP}$ if P_{AP} is the set of all paths between scan tuples of an AP, found by Dijkstra's algorithm. When we define the graph of a single AP as:

$$G_{AP} = (V_{AP}, E_{AP}) \tag{5}$$

with:

$$V_{AP} = \{x \mid x \in V \text{ and } x \in p_{AP}\} \tag{6}$$

$$E_{AP} \subseteq \{(x, y) \mid (x, y) \in V_{AP}^2 \text{ and } x \neq y\} \tag{7}$$

As G_r can be constructed from independent measurement drives, it can be disconnected. Therefore, G_{AP} can also be disconnected. For A in Fig. 4 we calculate Dijkstra for A_1A_2, A_1A_3 and A_2A_3 and build the union of all found paths. This can be seen in Tab. I for all tuples and the corresponding union of all shortest paths. As all scan nodes in this simplified example are on a simple connection without any crossings, the union of all shortest paths is also the shortest path between the two farthest beacon nodes. One can easily determine that this approach is also suitable in more complex situations, i.e., scans between S_1S_7 and S_1S_6.

The subgraph for an AP G_{AP} enables the calculation of street coverage, as we have all street nodes between the scan nodes to determine the street geography. However, the reception of scan measurements can be intermittent and the route network sparsely connected. That can lead to long distances between scan nodes, i.e., due to geography, the other side of a house can only be reached by driving around the block. To encompass this, we define that concurrent scan nodes must be within $50\,\mathrm{m}$ distance of each other or they will be treated as an own subgraph – if at least two scan nodes are left to connect. We have chosen to use $50\,\mathrm{m}$ for the following reason. A vehicle driving $50\,\mathrm{km/h}$ travels a distance of $20.83\,\mathrm{m}$ in the $1.5\,\mathrm{s}$ of a possible WLAN scan. In the case of missing the signal in one scan between two other scans, the distance between those scans – in the worst case – will be $41.66\,\mathrm{m}$. Even then we would not cut the graph connection, as this is below the $50\,\mathrm{m}$ distance in our method. For the most part of our measurements, the vehicle speed was well below $50\,\mathrm{km/h}$, which would imply missing multiple beacons before we cut the connection. The method will become more precise if a street was covered multiple times by the measurement runs. On a very dense scan measurement, the cutting distance could be lowered significantly and be chosen accordingly. However, WLAN will cut the connection to an AP, after a timeout, depending on the reception of messages from the AP. In the vehicular scenario, the continuous reception then also depends on the speed. To encompass the distance between measurement scans we can simply define (6) as:

$$V_{AP} = \{x \mid x \in V \text{ and } x \in p_{AP} \text{ and } c(p_{AP}) < 50.0\} \tag{8}$$

with $c\colon p_{AP} \to \mathbb{R}$ being the cost function, indicating the length of the path in meter.

During the street coverage calculation of an AP we can also determine the overlapping coverage of all access points. If we define e as an edge in E and if $e \in E_{AP}$, then e saves the information of coverage. After processing all APs, we can easily calculate the number of overlapping APs as well as the corresponding overlap length by the information saved for each edge.

TABLE I: Minimum Subgraph

Tuple	Shortest Path	Union
A_1A_2	$A_1 \rightarrow B_2 \rightarrow S_3 \rightarrow A_2$	$A_1 \rightarrow B_2 \rightarrow S_3 \rightarrow A_2 \rightarrow A_3$
A_1A_3	$A_1 \rightarrow B_2 \rightarrow S_3 \rightarrow A_2 \rightarrow A_3$	
A_2A_3	$A_2 \rightarrow A_3$	
B_1B_2	$B_1 \rightarrow A_1 \rightarrow B_2$	$B_1 \rightarrow A_1 \rightarrow B_2 \rightarrow S_3 \rightarrow A_2 \rightarrow A_3 \rightarrow S_2 \rightarrow B_3$
B_1B_3	$B_1 \rightarrow A_1 \rightarrow B_2 \rightarrow S_3 \rightarrow A_2 \rightarrow A_3 \rightarrow S_2 \rightarrow B_3$	
B_2B_3	$B_2 \rightarrow S_3 \rightarrow A_2 \rightarrow A_3 \rightarrow S_2 \rightarrow B_3$	

IV. WLAN BEACON MEASUREMENT

To evaluate GRETEL and to determine the reception of WLAN APs in a vehicular environment, we conducted several test drives. We recorded WLAN beacon frames in rural and suburban areas. While we only expect to receive home deployed WLAN APs in residential areas, some major roads run along residential areas, which were also covered by test drives. We used commercial hardware for the measurement and mounted two antennas on top of the vehicle. We only measured 2.4 GHz beacon frames, as this frequency band is fully authorized for outdoor use. The used WLAN card was able to support the IEEE 802.11n amendment, the two externally mounted antennas had an amplification of 5 dBi each. For every successfully received beacon frame, we recorded the received signal strength, frequency band, estimated throughput, BSSID, SSID, and the age of the scan. We can calculate the time of reception by using the age of the scan relative to the report time of the full scan report, which includes multiple scan results. From the time of the reception, we can further calculate the location on the street. We systematically conducted test drives, as this avoids a bias from regular driving patterns of selected car users. We tried to cover all streets in an area, i.e., trying to drive around every housing block to measure the full coverage of all access points. Only in some cases, this has been obstructed by the street layout, pedestrian zones, or construction. We further used GRETEL to analyze the street coverage.

V. MEASUREMENT RESULTS

Our data set currently includes 104.9 km of road network, measurements from about 17900 unique access points, and more than 192000 beacon frames. We can further identify 1667 APs from two internet service providers – which we will refer to as accessible access points – that offer access to their networks. The ratio of accessible APs to all APs in our data set is about 9.2 %.

A. Signal Strength

A first indication of the availability of WLAN APs is the reception of beacon frames. Beacons can be either sent periodically by the AP or on-demand if a station is actively searching for access points. If a beacon is received, it indicates the existence of an AP in communication distance. Therefore, all beacon frames already have a receive level, for which the decoding of the message is possible. Further, the signal strength is regularly indicated in dBm. Fig. 5 shows the signal levels of the received beacons in our data set. There are few beacons received with signal levels smaller than -90 dBm, as they are rarely decoded. We can see, that more than half of the receivable beacon frames have a smaller receive level than -80 dBm. Additionally, we can observe, that the signal level of the accessible APs set has about the same ratio of signal levels as the full data set.

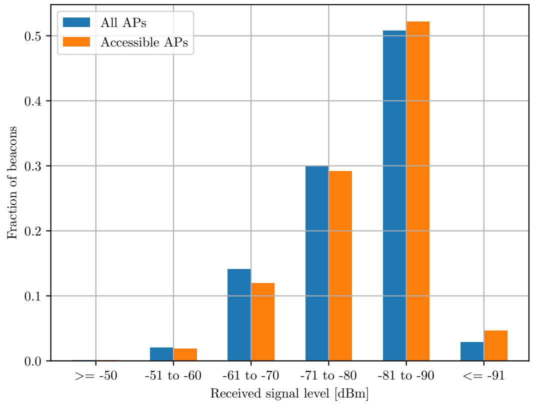

Fig. 5: Signal level for received beacon frames

To evaluate the receive level further, we use Fig. 6. There, we can find the improvement of the signal level depending on the lowest quality beacon received for an access point. Generally, the signal level improves significantly for most APs. For all APs with beacon frames lower than -90 dBm we even find an improvement of more than 30 dB. Thus the reception of a beacon with a small signal level should not lead to the exclusion of the AP. We can explain the bias on smaller signal levels in Fig. 5 with the movement on the street. As the vehicle first has to move into the range of the AP, pass the closest point to it, and leave again, beacon frames are recorded on approach and departure of the communication range. Small improvements for high-quality APs can be explained by considering the fact, that there is only a small room for improvement of the signal level. Additionally, these situations can occur when the vehicle speed is high and the reception of the AP is obscured. We can conclude from Fig. 6, that most of the access points achieve high signal levels, despite low signal level measurements.

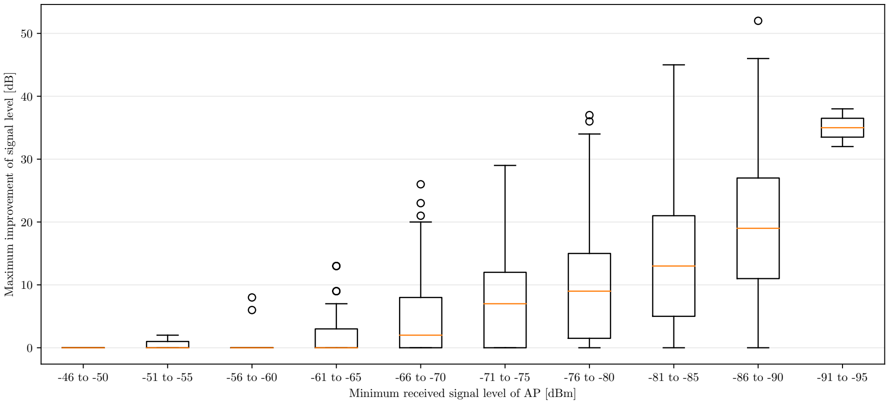

Fig. 6: Signal level improvement of accessible APs

B. Street Coverage

Wireless APs only have a limited range. Additionally, the signal propagation is influenced by the surrounding area, e.g., buildings, obstacles, or other APs. In our proposed setup, the user has no option to influence the placement of the AP in relation to the street. As placement is an important factor, we measure the range of a given AP by calculating the length of the covered street network.

This is done using GRETEL, which builds a graph network of beacon and street nodes and can therefore calculate the street coverage of a single AP, as well as the overlap of multiple APs. In Fig. 7 we can see the resulting complement of the cumulative distribution function (CDF) for the coverage of the access points. $50\,\%$ of APs have a street coverage of more than $80\,\mathrm{m}$. About $4\,\%$ cover more than $400\,\mathrm{m}$. These long distances are possible for some APs, that are very favorably positioned towards the street, and thus more road network is covered.

In Fig. 8 we can see the complement CDF of the number of simultaneously receivable APs. In $60\,\%$ of the street network, at least one access point is receivable. In more than $20\,\%$ of locations, more than three access points can be received. Our empirical data approximates the reception probability of a minimum n accessible APs on any given street position by:

$$p(n) = (0.6)^n \tag{9}$$

quite well.

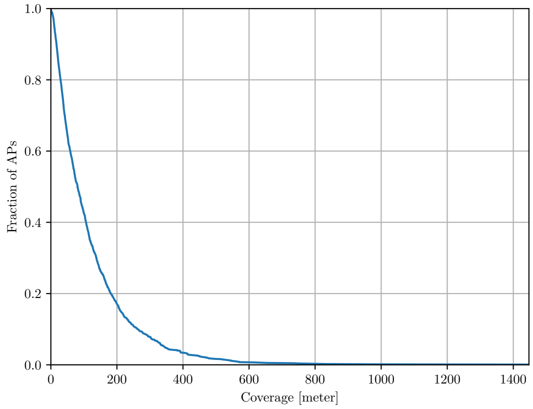

Fig. 7: Complement CDF of accessible AP coverage

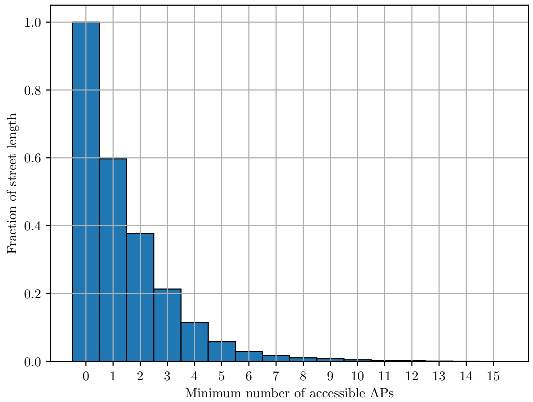

Fig. 8: Complement CDF of accessible APs on street

C. Comparison of GRETEL and Minimum Bounding Box

To approximate the street coverage of an access point, there is also the option to calculate the diagonal of the minimum bounding box of all beacon frame locations. This is a common calculation for geospatial data, as only the maxima and minima of the coordinate axis have to be found. Although GRETEL is a more complex system for the street coverage calculation, it is more precise and also enables us to calculate the overlap of coverage areas. This is not possible in the simplified calculations of the bounding box. We can compare the bounding box approximation with GRETEL for the street coverage of APs in Fig. 9 as we also calculated the corresponding values for our data set. The diagonal dotted line indicates the equivalent value for both methods. A measurement above this line indicates a greater bounding box distance than GRETEL. About three

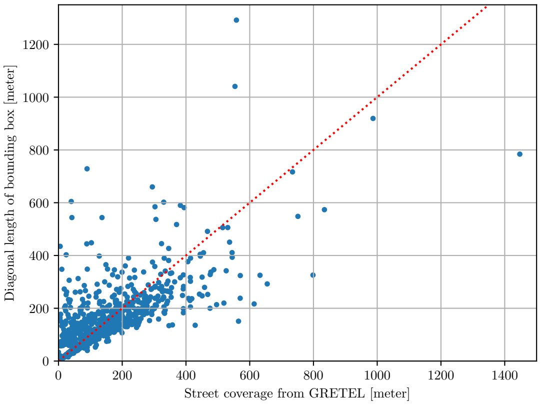

Fig. 9: Street coverage by GRETEL versus approximating bounding box

quarter of all measurements are below the diagonal. This is easily explainable, as the diagonal of the bounding box is shorter than any other path through the bounding box that contains both diagonal corners. We analyzed our data set for all outliers from the diagonal.

In general, there are two reasons for this behavior. In cases with a greater street coverage distance by GRETEL than the bounding box distance, i.e., below the diagonal, many streets inside the bounding box are suitable for reception, leading to a larger street coverage. For points above the diagonal, GRETEL calculates shorter communication distances than the bounding box. This is often due to our approach of disconnected coverage segments if the distance between scans on the street is too large. Both of these effects are in favor of GRETEL. If a larger segment of the street network is inside the coverage of an AP, we can easily determine the length of coverage. If there are multiple intermittent segments of coverage, GRETEL does not overestimate the reception of the AP. In contrast to the bounding box algorithm, GRETEL is capable of analyzing the overlap of AP coverage and, thus, derives more information from the measurement data.

VI. Conclusion and Future Work

We have introduced GRETEL, a graph-based street coverage calculation, enabling us to analyze the street coverage of signal measurements and the overlap of different base stations. Our novel approach considers the road network and the driven route for the coverage calculation, resulting in a more precise analysis in comparison to the minimum bounding box approach. To evaluate GRETEL and develop an idea of WLAN AP coverage on the road network, we present real-life vehicle measurements of WLAN beacon frames from various access points. However, as most of the APs are privately owned they are not an option for V2I connections. Due to privacy and security concerns often the default option in APs is to protect the access. Therefore, we show measurements of two providers of accessible access points that are distributed in private residences. This subsequent subset of APs has about the same properties as the full set of access points. About $9.2\,\%$ of all identified APs are accessible. By using GRETEL, we could determine the median street coverage of an AP as about $80\,\mathrm{m}$, while about $60\,\%$ of streets are covered by at least one accessible access point. Further, more than $20\,\%$ of the street network are covered by at least three APs. We could observe the accuracy of GRETEL for calculation of street coverage, compared to the diagonal of the bounding box. In our future work, we want to model the observed availability by GRETEL in simulation to predict the transferable amount of data. We further want to evaluate the capabilities of heterogeneous communication networks in [11] and [2] by using accessible WLAN APs. Additionally, the WLAN beacon coverage has to be compared with the communication distances when the vehicle establishes a connection with the available APs.

References

[1] K. Lee, J. Lee, Y. Yi, I. Rhee, and S. Chong, “Mobile Data Offloading: How Much Can WiFi Deliver?” *IEEE/ACM Transactions on Networking*, vol. 21, no. 2, pp. 536–550, Apr. 2013, conference Name: IEEE/ACM Transactions on Networking.

[2] F. Mehmeti and T. Spyropoulos, “Performance Analysis of Mobile Data Offloading in Heterogeneous Networks,” *IEEE Transactions on Mobile Computing*, vol. 16, no. 2, pp. 482–497, Feb. 2017, conference Name: IEEE Transactions on Mobile Computing.

[3] T. Brinkhoff, H. . Kriegel, and R. Schneider, “Comparison of approximations of complex objects used for approximation-based query processing in spatial database systems,” in *Proceedings of IEEE 9th International Conference on Data Engineering*, 1993, pp. 40–49.

[4] J. Ott and D. Kutscher, “Drive-thru Internet: IEEE 802.11b for ”automobile” users,” in *IEEE INFOCOM 2004*, vol. 1, Mar. 2004, p. 373, iSSN: 0743-166X.

[5] R. Gass, J. Scott, and C. Diot, “Measurements of In-Motion 802.11 Networking,” in *In Proc. Ieee Wmcsa*, 2006, pp. 69–74.

[6] J. Eriksson, H. Balakrishnan, and S. Madden, “Cabernet: Vehicular content delivery using wifi,” in *Proceedings of the 14th ACM International Conference on Mobile Computing and Networking*, ser. MobiCom ’08. New York, NY, USA: Association for Computing Machinery, 2008, p. 199210.

[7] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. Miu, E. Shih, H. Balakrishnan, and S. Madden, “Cartel: a distributed mobile sensor computing system,” in *In 4th ACM SenSys*, Oct. 2006, pp. 125–138.

[8] R. Mahajan, J. Zahorjan, and B. Zill, “Understanding WiFi-based connectivity from moving vehicles,” Jan. 2007, pp. 321–326.

[9] H. Soroush, N. Banerjee, M. D. Corner, B. N. Levine, and B. Lynn, “DOME: A Diverse Outdoor Mobile Testbed,” in *In Proc. ACM Intl. Workshop on Hot Topics of Planet-Scale Mobility Measurements (HotPlanet*, May 2009.

[10] N. Cheng, N. Lu, N. Zhang, X. Shen, and J. Mark, “Vehicular wifi offloading: Challenges and solutions,” *Vehicular Communications*, vol. 1, p. 1321, 01 2014.

[11] A. Balasubramanian, R. Mahajan, and A. Venkataramani, “Augmenting mobile 3G using WiFi,” Jan. 2017. [Online]. Available: https://www.microsoft.com/en-us/research/publication/augmenting-mobile-3g-using-wifi/

[12] C. Yang and G. Gidofalvi, “Fast map matching, an algorithm integrating hidden markov model with precomputation,” *International Journal of Geographical Information Science*, vol. 32, no. 3, pp. 547–570, 2018. [Online]. Available: https://doi.org/10.1080/13658816.2017.1400548

[13] G. Boeing, “Osmnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks,” *Computers, Environment and Urban Systems*, vol. 65, pp. 126 – 139, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0198971516303970