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Route-based Radio Coverage Analysis of Cellular Network Deployments for V2N Communication

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Abstract—Cellular vehicle-to-network (V2N) communication will be the backbone of the connected vehicles of future. One of the key requirements of the connected vehicles is a near universal coverage on the streets. Traditional radio network planning for cellular coverage is done with raster format whereby all pixels in a network area have equal weighting. Whereas, for V2N communication the target is to primarily ensure continuous network coverage on the streets. In this work, a route-based methodology which is pertinent for V2N coverage analysis is presented. This method adds another key parameter into consideration, namely, the base stations (BS) deployment schema. Existing cellular networks, whereby, small base stations (BSs) are deployed at the macro BS cell-edge, at traffic hotspots or to compensate for coverage holes, may not be sufficient for V2N coverage especially at millimeter wave (mmWave) carrier frequencies. Herein, we perform the coverage analysis for an existing small BS deployment as well as for an ultra-dense deployment at 2 GHz, 5 GHz and 28 GHz carriers. The statistics for signal-to-noise-plus-interference ratio (SINR) and achieved rate are aggregated by a large number of realistic vehicular routes from Google Directions application programming interface (API).

Index Terms—5G mobile communication, cellular V2X, millimeter wave propagation, performance analysis

I. INTRODUCTION

Intelligent transport systems (ITS) are aiming to provide safe and efficient transportation services for all modes of passenger and freight transport. An important enabler for ITS is the vehicle-to-everything (V2X) communication that refers to wireless communication between a transceiver mounted on a vehicle and transceivers in the surrounding environment. As an umbrella term, V2X encompasses a range of connectivity scenarios that generally include short-range vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and long-range vehicle-to-network (V2N) connectivity scenarios [1].

The specific nature of V2X requirements has led to different lines of radio access technology development. In particular, the

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two most prominent access technologies currently considered by the automotive industry are IEEE 802.11p and cellular V2X (C-V2X). The former is an amendment to the IEEE 802.11 WiFi PHY/MAC layer specifications to enable inter-vehicular communications by defining new functions for dynamic environment, controlled by the IEEE 802.11 MAC [2].

In contrast to IEEE 802.11p which is based on distributed control of ad-hoc networks, C-V2X refers to the mobile network based vehicular communication with centralized control. The mobile network standards, such as, fourth-generation (4G) long-term evolution (LTE) and, more recently, the fifth generation (5G) new radio (NR) bring many advantages when compared to ad-hoc networks. In mobile networks, the base station (BS) service areas can be large and the centralized mobile network infrastructure provides continuous and ubiquitous coverage for baseline mobile services, as well as, improvements in quality-of-service (QoS) and robust security. The 5G automotive association (5GAA) is driving for allocation of ITS spectrum on 5.9 GHz to boost C-V2X development [1], [2].

Recently, 5G millimeter wave (mmWave) communication has attracted a growing interest in both industry and research communities. The mmWave access is a promising technology component for meeting the demand of high data rate and low latency requirements of 5G. In this field the technology research has been progressing fast and there are excellent contributions published on coverage and channel characteristics of mmWave frequencies [3], [4]. Most importantly, there are large chunks of bandwidths available on frequencies above 10 GHz and the increase of carrier frequency will decrease antenna dimensions enabling effective beamforming using compact antenna arrays that can also be conveniently placed on vehicles [5].

The fundamental challenge of mmWave communication is the heavy signal propagation loss. It is known from many studies that mmWave signals are strongly attenuated by walls making the provisioning of outdoor-to-indoor coverage difficult [6]. Accordingly, a wide area stand-alone mmWave mobile network seems not to be a feasible option due to the high deployment and operational costs associated with the ultra-dense networks needed to provide full coverage. Implementing 5G mmWave radio would be easier through co-deployment

with existing small BS designs that already provide a multi-radio platform including 3G and 4G radios [7]. However, in order to achieve a universal coverage of mmWave carrier, densification of the network with small BSs is needed.

When planning a small BSs extension for a 4G network one of the main goals is to improve the in-building signal-to-interference-plus-noise ratio (SINR) in macro cell edges. This leads to deployments where small BSs are located at building walls and lamp posts. Such deployments support also the coverage provision on streets very well. Namely, while outdoor to indoor signals suffer from wall penetration, the outdoor signals propagate in street canyon and line of sight (LoS) frequently occurs between the transmitter and the receiver. A deployment that is dense enough for outdoor to indoor coverage may actually be too dense for street coverage provision in low carrier frequencies and the system easily becomes interference limited in outdoor locations. However, if we make use of mmWave frequencies in small BSs, then the dense deployment turns out to be beneficial. Therefore, it is important to analyse different deployment scenarios from a V2N applications point of view.

Another important aspect to consider is the methodology used for the coverage analysis. Conventional radio network planning methods make use of the raster format where all the pixels in a 2D or 3D evaluation area are taken into account while calculating the network performance measures. This approach, however, is not suitable for the V2N application where vehicular users move in a nearly one dimensional road network. The routes travelled by vehicles can be treated as lines and thus a route-based evaluation methodology is expected to provide a simple, useful and relevant tool to study the QoS along vehicle routes.

A. Contributions

Based on the discussion in the introduction, the aim of this paper is two-folded: 1) We analyse the performance of different deployment scenarios from a V2N perspective, 2) We develop a route-based performance evaluation methodology for V2N studies.

To be more precise, as a starting point we have used the Vienna heterogeneous network (HetNet) deployment applied in [8], where small BS sites are located on macro cell edges. On those areas, the small BSs deployment is sufficiently dense to provide a continuous connectivity at 2 GHz frequency. However, this deployment may not be sufficient for the mmWave connectivity. Therefore, we densify the network and analyse the resulting ultra-dense deployment scenario.

We consider 2.6 GHz, 5 GHz and 28 GHz carrier frequencies, and the radio channel characteristics have been modelled by using the WinProp ray tracing software [9]. We note that the use of 28 GHz has been previously discussed e.g. in [3], where concerns on the applicability of this carrier frequency for outdoor deployments have been expressed. Thus, our aim is to contribute to this discussion from V2N coverage perspective. Since we focus on the V2N connectivity in the streets, we have developed a new methodology, whereby, the simulation



Fig. 1. Ultra-dense network deployment in Vienna city based on HetNet layout of [8]. Macro BSs and small BSs are denoted by red markers and by yellow markers, respectively.

statistics is created from a large number of different routes that we have created by using the Google Directions API.

It is also good to acknowledge that vehicular communication is prone to high handover rates. Street coverage over several blocks is likely to include coverage holes especially in street crossings. In such locations, a radio link may suffer a sporadic failure. This is particularly evident in the mmWave band. Indeed, both handover and re-connections procedures imply interruption times that adversely impact on the throughput and latency. The methodology of the present study is suitable for the evaluation and optimization of the V2X radio access network when services are targeted to the road users.

According to our best knowledge, there are no prior studies where feasibility of mmWave carrier in existing 3G/4G outdoor as well as ultra-dense small BSs networks has been investigated from V2N connectivity perspective in a realistic scenario.

Summary of contributions:

- We provide a system level analysis of the V2N mmWave street connectivity when applying the 4G/5G HetNet deployments targeting macro cell-edge and, on the other hand, the ultra-dense small BS deployments targeting street coverage. We provide a street coverage performance evaluation framework for 5G in different cellular deployment scenarios.
- We present a new simulation methodology, whereby, a large number of realistic vehicular routes are created using Google Directions API and a ray-tracing signal statistics is aggregated in an urban city. This approach allows tailoring of the network performance analysis specifically for vehicular users.

II. NETWORK SCENARIO AND PERFORMANCE EVALUATION METHODOLOGY

A. Network deployment and BS parameters

The deployment of [8] provides a heterogeneous network (HetNet) with systematic and dense small BSs coverage extension. The network has been built on a digital map of city of Vienna such that macro BSs provide an umbrella coverage and small BSs are used to ensure high quality-of-service in areas

TABLE I
ASSUMED BS CAPABILITIES

Parameter	Value	
	Macro BS	Small BS
TX power	46 dBm	30 dBm
Operation band	2.6 GHz	2.6 GHz
Bandwidth	20 MHz	20 MHz
Antenna gain	18 dBi	5 dBi
Antenna height	30 m	10 m
MIMO	2×2	2×2

where macro BS coverage is weak. There are 17 tri-sectored macro BSs and 221 small BSs in the considered network area of 2.5 km in length and 2.5 km in width. The ultra-dense small BSs deployment in Fig. 1 is an extension for the HetNet of [8], obtained by systematically adding small BSs especially close to the macro BS sites. The total number of small BSs in the ultra-dense deployment scenario becomes 366.

In the forthcoming performance analysis we apply parameters of Table I in the macro BS and small BS configuration. Let us briefly reflect these values against the state of the art. As previously discussed, the 1 W (30 dBm) transmission power is feasible for outdoor small BSs and 40 W transmission power is typical for macro BSs. The applied carrier frequencies in the performance evaluation are 2.6 GHz, 5 GHz and 28 GHz. The 2.6 GHz frequency is currently used in many 4G LTE deployments and license assisted access (LAA) provides an attractive 5G deployment option at 5 GHz [10]. The antenna gain in macro BS is set to 18 dBi, that is a typical value when using conventional panel antennas. In small BSs, antenna gains can vary with carrier frequency. Here 5 dBi is a feasible assumption for 2.6 GHz. In higher frequencies, e.g. in 28 GHz, it is usual to assume clearly higher antenna gains than in 2-5 GHz operation frequencies. This is justified since antenna dimensions depend on the operating frequency and high gain planar array can be more easily built on higher frequencies to execute active beam steering. Yet, we have adopted a conservative approach and assumed 5 dBi antenna gain on both 5 GHz and 28 GHz carriers.

B. Creation of route statistics

Integration of Google Maps with the radio environment simulated by WinProp provides an innovative and convenient tool for the street coverage analysis. This simulation environment allows us to study the outdoor street coverage by creating statistics of realistic user routes obtained by dropping pairs of locations in a city and then using Google Directions API [11], see Fig. 2. Moreover, the explicit modelling of adjacent 3D building structures along vehicle routes allows the simulation environment to also take into account the radio propagation effects, such as, street canyon effects, road intersections and shadowing on street corners that have significant impact on street level coverage. Within a route, the signal strength on different frequencies is then measured using 5-10 m steps in the ray tracing signal map.

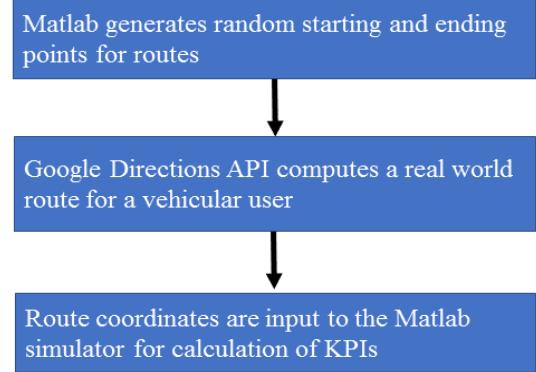


Fig. 2. Methodology for creating the route statistics.

The signal statistics are aggregated only for the pixels that are included in the real world vehicular routes. The routes can be generated based on different criteria e.g. shortest travel distance, fastest travel time, avoiding highways etc. Many of the routes overlap on certain part which may consist of the most popular roads of the city area. Thus pixels in the overlapping regions appear multiple times in the aggregated SINR and rate statistics, resulting in weighted aggregation which is proportional to the real world use of the route.

C. Computation of the signal-to-interference-plus-noise ratio

The SINR at a given coordinate point can be computed as $\Gamma = \gamma_0 / (1 + \sum_{k \neq 0} \gamma_k)$, where γ_0 is the SNR of the signal received from the serving BS and values $\{\gamma_k\}_{k \neq 0}$ represent the SNRs of the interfering signals. We note that serving BS is the one that provides the highest SINR. In the decibel scale, SNR is of the form $\gamma_0^{\text{dB}} = P_u^{\text{tx}} - P_u^N - CL$, where P_u^{tx} is the fraction of the total transmission power $P_{\text{tot}}^{\text{tx}}$ on the bandwidth W_u , i.e. $P_u^{\text{tx}} = P_{\text{tot}}^{\text{tx}} - 10 \cdot \log_{10}(W_{\text{tot}}/W_u)$. The term P_u^N is the noise power on the applied bandwidth, i.e. $P_u^N = -173.9 \text{ dBm} + 10 \cdot \log_{10}(W_u)$ and CL is the Coupling Loss that includes the channel propagation loss and the antenna gains in both ends.

Furthermore, for the evaluation of data rates, we assume 20 MHz bandwidth for macro BS and small BS on 2.6 GHz. In higher carrier frequencies we expect that larger chunks of frequency bands are available and accordingly, we assume 100 MHz in 5 GHz which is possible through carrier aggregation [12] and 500 MHz in 28 GHz. The achieved data rate is computed by applying the mapping

$$R_u = \begin{cases} R_{\max}, & \Gamma > \Gamma_{\max}, \\ A \cdot W_u \cdot \log_2(1 + \Gamma/B), & \Gamma_{\min} < \Gamma \leq \Gamma_{\max} \\ 0, & \Gamma < \Gamma_{\min} \end{cases} \quad (1)$$

where R_{\max} is the maximum rate that is related to the highest modulation and coding scheme in the link adaptation. This is achieved if the SINR exceeds the threshold Γ_{\max} . The parameters A, B are used to fit this ‘Shannon approximation’ with the link adaptation curves. Due to 2 × 2 MIMO we have used values $A = 0.66$, $B = 1.1$ according to [13].

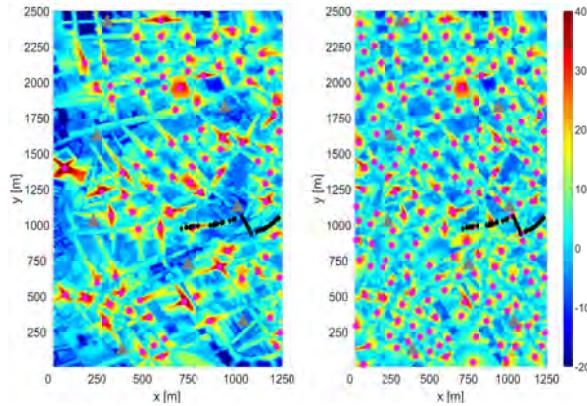


Fig. 3. The SINR map for the network area at 2.6 GHz carrier frequency. Test route is shown with black markers. On the left we have the macro cell-edge based small BS deployment and on the right we have the ultra-dense small BS deployment.

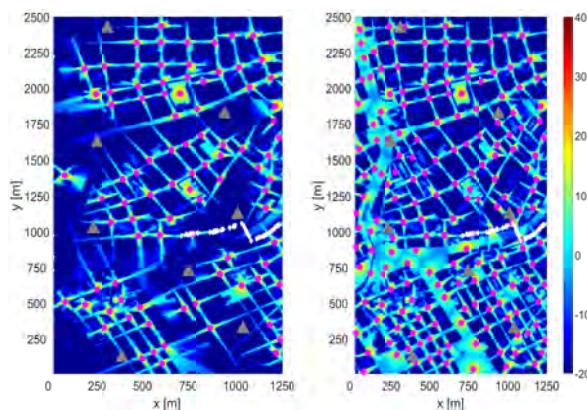


Fig. 4. The SINR map for the network area at 28 GHz carrier frequency. Test route is shown with white markers. On the left we have the macro cell-edge based small BS deployment and on the right we have the ultra-dense small BS deployment.

Finally, Γ_{\min} refers to the lowest SINR required to enable the connection, in our case -7 dB. We note that the parameters A , B and Γ_{\max} depend on the radio link technology. Some further parameter values can be found e.g. from [14].

III. PERFORMANCE EVALUATION

A. Network coverage illustrations

Fig. 3 illustrates the small BS coverage in terms of SINR at 2.6 GHz. In the left-hand side sub-figure, the weak coverage areas (dark blue) are related to the macro BS locations where small BSs do not occur in the original HetNet deployment. Even with areas devoid of small BSs, figure hints that street coverage is very good at 2.6 GHz. The ultra-dense deployment scenario shown in the right-hand side figure illustrates that street coverage at 2.6 GHz becomes nearly universal.

Further, Fig. 4 shows the SINR map at 28 GHz carrier frequency. Therein it is noted that while coverage exists in many streets there are still places even close to small BSs

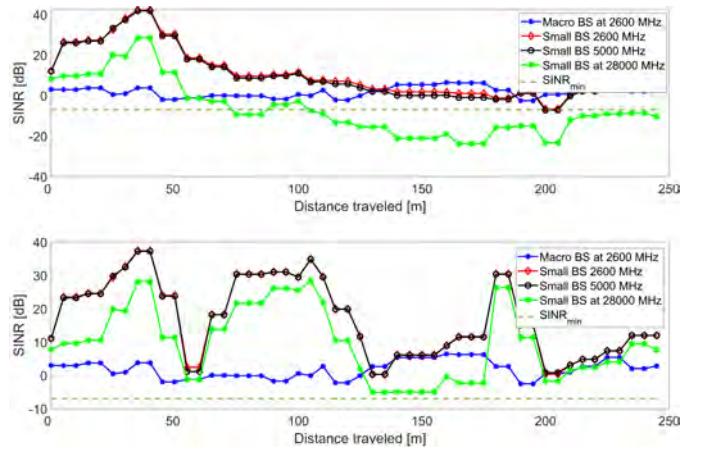


Fig. 5. The received SINR on the test route for the macro cell-edge based small BS deployment (top figure) and ultra-dense small BS deployment (bottom figure).

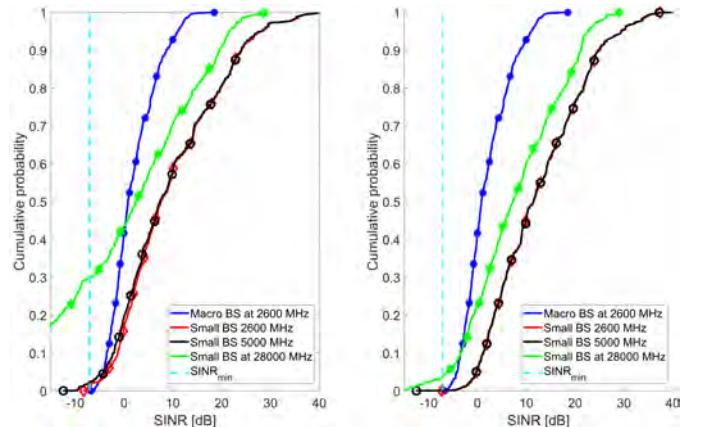


Fig. 6. The CDF of SINR over 100 randomly selected test routes for the macro cell-edge based small BS deployment (left figure) and ultra-dense small BS deployment (right figure).

where coverage is either very weak or even non-existent. Since macro BSs operate at 2.6 GHz, the locations close to macro BS (left-side figure) are completely out of coverage.

B. Street coverage

Fig. 5 shows the received SINR on the first 250 m section of a selected test route. As expected, for the macro cell-edge based small BS deployment scenario (top sub-figure) the SINR on 28 GHz carrier, in large part of the route, suffers from sharp fluctuations and falls below the connection threshold Γ_{\min} . However, the received SINR of small BSs at 2.6 GHz and 5 GHz carriers is relatively higher and SINR curves at these two carriers are overlapping almost all the time. The relatively small difference between the SINRs observed at 2.6 GHz and 5 GHz carriers is due to the fact that difference of propagation losses are almost fully compensated by the corresponding co-channel interference at these carriers. On the 28 GHz carrier co-channel interference does not play an important role but coverage is degraded due to the heavy propagation loss and blocking. Here, macro BSs at 2.6 GHz acts as the fallback

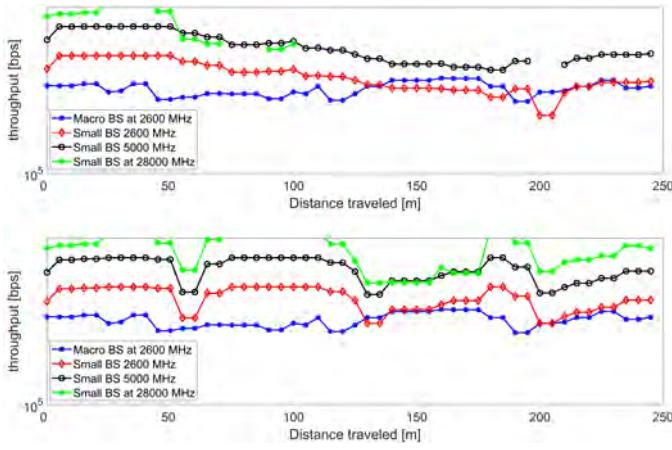


Fig. 7. The user throughput on the test route for macro cell-edge based small BS deployment (top figure) and ultra-dense small BS deployment (bottom figure). User applies 10% of the band.

option for the UE when there is no small BS coverage. On the contrary, the ultra-dense small BS deployment (bottom sub-figure) guarantees full coverage for the test route.

The CDFs of SINR for all carriers over 100 randomly generated routes are displayed in Fig. 6 and SINRs curves follow the same trend as for the test route. The macro cell-edge based (left-hand side sub-figure) and ultra dense deployment (right-hand side sub-figure) of small BSs in street crossings has led to heavy interference at 2.6 GHz and 5 GHz carriers resulting in SINR distributions which are overlapping almost completely. The small BSs achieve almost full street coverage with 2.6 GHz and 5 GHz carriers. However, at 28 GHz frequency carrier outage is about 30% for macro cell-edge based small BS deployment. This essentially implies that availability of higher bandwidth from 28 GHz carrier is not guaranteed for significant portions of the UE routes resulting in a very heterogeneous quality due to the frequent switching to lower band carriers. The ultra-dense deployment of small BSs improves the coverage at 28 GHz by reducing the outage to about 2%. It is worth noting here that even with such high level of densification it is not feasible to achieve a universal coverage at a mmWave carrier.

In Fig. 7 we have the throughput on the test route for different carriers assuming that 10% of the total frequency bandwidth can be allocated to the UE. The data rates provided by small BSs at 5 GHz and 28 GHz are clearly higher than at 2.6 GHz where the lack of bandwidth and interference limit the performance. Furthermore, the throughput CDFs of Fig. 8 indicates that 28 GHz carrier may provide relatively high achievable throughput. However, the outage probability is also high for 28 GHz, making the use of that carrier challenging from system perspective. The heterogeneous nature of the quality at 28 GHz is also evident from the lower slope in the CDF curve. In 5 GHz carrier outage is comparable to that of 2.6 GHz. Though, significant improvement is achieved for 28 GHz carrier in terms of coverage with ultra-dense small BS deployment scenario, it is still not possible to guarantee such

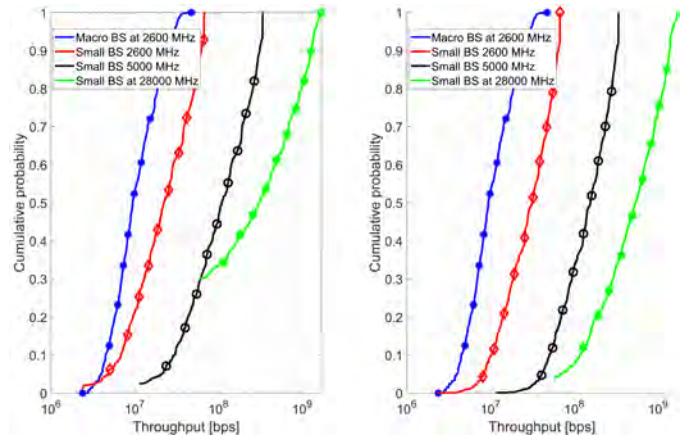


Fig. 8. The CDF of the user throughput over 100 randomly selected test routes for macro cell-edge based small BS deployment (left figure) and ultra-dense small BS deployment (right figure). User applies 10% of the band.

high data rates due to the remaining coverage holes.

IV. CONCLUSIONS

A novel route-based methodology for cellular V2N street coverage analysis was presented. Realistic vehicular routes were created using the Google Directions API and the coverage related ray-tracing signal statistics were aggregated over a large number of street routes. The methodology was tested in two deployment scenarios: first, a previously known HetNet deployment was used where small BSs are located on the macro BS cell-edges. Then, the ultra-dense deployment scenario was assumed where small BSs are densely placed throughout the network area. The SINR and the achieved throughput at 2.6 GHz, 5 GHz and 28 GHz frequency carriers were used as the key performance indicators.

It was observed that in both HetNet-based deployment and the ultra-dense small BS deployment the co-channel interference is limiting the system performance on 2.6 GHz and 5 GHz carrier frequencies. On the other hand, in the HetNet-based deployment the outage at 28 GHz carrier can be around 30%. Thus, the mmWave carrier can be only used in small BSs to create local hotspots if small BS locations from 4G HetNet are used. Furthermore, the analysis of the ultra-dense small BS deployment indicates as well that continuous street coverage at 28 GHz frequency carrier may not be a realistic option even though very large number of small BSs are deployed. Therefore, sub-6 GHz carriers are expected to play a pivotal role in providing the fall-back option for the V2N communication in case of mmWave coverage gaps.

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