Vehicles Meet Infrastructure: Toward Capacity–Cost Tradeoffs for Vehicular Access Networks

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Abstract—Access infrastructure, such as Wi-Fi access points and cellular base stations (BSs), plays a vital role in providing pervasive Internet services to vehicles. However, the deployment costs of different access infrastructure are highly variable. In this paper, we make an effort to investigate the capacity–cost tradeoffs for vehicular access networks, in which access infrastructure is deployed to provide a downlink data pipe to all vehicles in the network. Three alternatives of wireless access infrastructure are considered, i.e., cellular BSs, wireless mesh backbones (WMBs), and roadside access points (RAPs). We first derive a lower bound of downlink capacity for each type of access infrastructure. We then present a case study based on a perfect city grid of 400 km² with 0.4 million vehicles, in which we examine the capacity–cost tradeoffs of different deployment solutions in terms of capital expenditures (CAPEX) and operational expenditures (OPEX). The rich implications from our results provide fundamental guidance on the choice of cost-effective access infrastructure for the emerging vehicular networking.

Index Terms—Access infrastructure, capacity-cost tradeoffs, downlink capacity, vehicular networks.

I. INTRODUCTION

There has been strong interest and significant progress in the domain of emerging VehiculAr NETworks (VANETS)1 over the last decade. VANETs target the incorporation of telecommunication and informatics technologies into the transportation system and, thereby facilitating a myriad of attractive applications related to vehicles, transportation systems, and passengers [1]–[4]. Since Internet access is an essential part of our daily life, expected anytime and anywhere, providing pervasive Internet access to vehicles can be envisioned not only to cater to the ever-increasing Internet data demand of passengers [5]–[7] but also to enrich safety-related applications, such as online diagnosis [8], and intelligent anti-theft and tracking [9], in which the servers can be on the Internet cloud. A recent automotive executive survey [10] further reveals that Internet access is predicted to become a standard feature of motor vehicles. One practical way to provide Internet connectivity to vehicles is through the use of wireless wide area networks, such as off-the-shelf 3G or 4G cellular networks. Due to the relatively high cost of cellular access, people may prefer to use much cheaper access technologies, such as the “grassroots” Wi-Fi access point. Equipped with a Wi-Fi radio, vehicles can access the Internet on the move along the road. This type of access network is often referred to as drive-thru Internet in the literature [11]. The problem of using Wi-Fi access points is that one has to tolerate intermittent connectivity, as mentioned in a real-world measurement study of the drive-thru Internet [12]. Another possible solution to providing Internet access to vehicles is through the use of a fixed wireless mesh backbone (WMB) [13], which consists of wirelessly connected mesh nodes (MNs) including one gateway to the Internet. The difference between Wi-Fi access point and wireless mesh is that the latter uses wireless mesh-to-mesh links as backhaul, whereas the former fully relies on external wired connectivity. It is expected that such a mesh structure could be a compromise between high cost and poor connectivity. However, since VANETs have yet to become a reality, there remains great uncertainty as to the feasibility of each type of access infrastructure in terms of network performance and deployment cost.

A. Roadmap and Main Results

To better understand the capacity–cost issue in vehicular access networks, in this paper, we consider a scalable urban
area where vehicles access the Internet through deployed infrastructure nodes. We first analyze the downlink capacity of vehicles to show how it scales with the number of infrastructure nodes deployed. The downlink capacity is defined as the maximum average downlink throughput uniformly achieved by all the vehicles from the access infrastructure. To provide pervasive Internet access, two operation modes of the network are considered: infrastructure mode, in which the network is fully covered by infrastructure nodes, i.e., all the vehicles are within the coverage of the infrastructure, and hence, only infrastructure-to-vehicle (I2V) communication is utilized to deliver the downlink traffic; and hybrid mode, in which the network is not fully covered, and the downlink flow is relayed to the vehicles outside the coverage of infrastructure nodes by means of multihop vehicle-to-vehicle (V2V) communications, as shown in Fig. 1. A lower bound of the downlink capacity is derived for the network with deployment of cellular base stations (BSs), WMBs, and roadside access points (RAPs), respectively. To investigate the effect of key factors, such as the deployment scale and the coverage size of infrastructure nodes, we present a case study based on a perfect city grid of 400 km² with 0.4 million vehicles. More importantly, we examine the capacity–cost tradeoffs of different deployments. It is shown that in the hybrid mode, to achieve the same downlink throughput, the network roughly needs $X$ BSs, $6X$ MNs, or $25X$ RAPs²; whereas in the infrastructure mode, if it is desired to improve the downlink throughput by the same amount for each deployment, we roughly need to additionally deploy $X$ BSs, $5X$ MNs, or $1.5X$ RAPs. By explicitly taking capital expenditures (CAPEX) and operational expenditures (OPEX) of access infrastructure into consideration, the deployment of BSs or WMBs is cost-effective to offer a low-speed downlink rate to vehicles; nonetheless, when providing a high-speed Internet access, the deployment of RAPs outperforms the other two alternatives in terms of deployment costs. Such implications could provide valuable guidance on the choice of access infrastructure for the automobile and telecommunication industry. Particularly, as the automotive industry gears up for supporting high-bandwidth applications, noncellular access infrastructure will play an increasingly important role in offering a cost-effective data pipe for vehicles.

B. Literature Review

To the best of our knowledge, this work represents the first theoretical study on capacity–cost tradeoffs when providing pervasive Internet access to vehicles. Reference [14] is the most relevant literature, in which Banerjee et al. first examined the performance–cost tradeoffs for VANETs by considering three infrastructure enhancement alternatives: BSs, meshes, and relays. They demonstrated that if the average packet delay can be reduced by a factor of 2 by adding $X$ BSs, the same reduction needs $2X$ MNs or $5X$ relays. They argued that relays or meshes can be a more cost-effective enhancement due to the high cost of deploying BSs. The objective of their work is to improve network delay by augmenting mobile ad hoc networks with infrastructure, which is different from ours. Moreover, our methodology is also different from that adopted in [14]. Notably, quite a few research works [15]–[17] focus on content downloading in VANETs. Although we consider a downlink scenario as well, our focus is to unveil capacity–cost tradeoffs for deployment of vehicular access networks.

The capacity of vehicular access networks is a recent research focus and is in active development. Pishro-Nik et al. [18] initiated the study of capacity scaling for VANETs and showed the impact of road geometry in the analysis. Our previous work [19] studied the unicast capacity of vehicles for a social-proximity VANET. In [20], Zhang et al. analyzed the multicast capacity of hybrid VANETs, in which BSs are deployed to support communications between vehicles. In [21], Wang et al. investigated the uplink capacity of hybrid VANETs. However, the uniform downlink capacity of VANETs with deployment of different access infrastructure is not well understood. The downlink capacity of a multihop cellular network with regular placement of normal nodes and BSs was first reported by Law et al. [22]. As a follow-up effort, in [23], Li et al. investigated capacity scaling for multihop cellular networks of randomly placed BSs and normal nodes distributed following a general inhomogeneous Poisson process. What makes our work different from prior research is that we compare different access infrastructure under the same vehicular environment in terms of performance and cost.

The remainder of this paper is organized as follows. Section II introduces the system model. We analyze the downlink capacity for each type of infrastructure deployment in Section III. In Section IV, we present the case study and examine the capacity–cost tradeoffs. Section V concludes this paper.

II. SYSTEM MODEL

A. Urban Street Pattern

The street layout of urban areas is modeled by a perfect grid $G(M, L)$, which consists of a set of $M$ vertical roads intersected with a set of $M$ horizontal roads. Each line segment of length $L$ represents a road segment, as shown in Fig. 2. The grid street pattern is very common in many cities, such as Houston and Portland [24]. Let $G$ be a torus to eliminate the border effects, as a common practice to avoid tedious technicalities [25]. We denote the total number of road segments in $G$ by $G = 2(M - 1)^2$. The scale of the urban grid is therefore

\footnote{X is used to represent a ratio relationship rather than a specific value.}
determined by $M$ and $L$. For example, $M$ is roughly 100, and $L$ is generally from 80 to 200 m for the downtown area of Toronto [26]. A summary of the mathematical notations used in this paper is given in Table I.

### TABLE I

**USEFUL NOTATIONS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>The average number of vehicles in the grid</td>
</tr>
<tr>
<td>$M$</td>
<td>The number of parallel roads in the grid</td>
</tr>
<tr>
<td>$L$</td>
<td>The length of road segment</td>
</tr>
<tr>
<td>$G$</td>
<td>The total number of road segments</td>
</tr>
<tr>
<td>$G_M$</td>
<td>The urban grid</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Path-loss exponent</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Vehicle density</td>
</tr>
<tr>
<td>$W$</td>
<td>Communication bandwidth</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Poisson point process (p.p.)</td>
</tr>
<tr>
<td>$P$</td>
<td>The number of MGs and $N_M$</td>
</tr>
<tr>
<td>$N_B$</td>
<td>The number of deployed BSs</td>
</tr>
<tr>
<td>$N_M$</td>
<td>The number of deployed MNs</td>
</tr>
<tr>
<td>$R$</td>
<td>The transmission radius of V2V communications</td>
</tr>
<tr>
<td>$R_M$</td>
<td>Transmission radius of M2M communications</td>
</tr>
<tr>
<td>$\tau_B$</td>
<td>The number of tiers in BS service square</td>
</tr>
<tr>
<td>$\tau_C$</td>
<td>The number of tiers in the coverage of BS</td>
</tr>
<tr>
<td>$\lambda_B$</td>
<td>Downlink capacity for deployment of BSs</td>
</tr>
<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of B2V transmissions</td>
</tr>
<tr>
<td>$\lambda_B$</td>
<td>Downlink capacity of V2V transmissions (BS)</td>
</tr>
<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of V2V transmissions (M2M)</td>
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<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of M2M transmissions</td>
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<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of V2V transmissions (M2M)</td>
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<tr>
<td>$\lambda_W$</td>
<td>Downlink capacity of WMBs</td>
</tr>
<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of WMBs</td>
</tr>
<tr>
<td>$L$</td>
<td>Service region of an RAP</td>
</tr>
<tr>
<td>$R_C$</td>
<td>Transmissions radius of RAP</td>
</tr>
<tr>
<td>$\lambda_B$</td>
<td>Downlink capacity for deployment of RAPs</td>
</tr>
<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of R2V transmissions</td>
</tr>
<tr>
<td>$\lambda_M$</td>
<td>Downlink capacity of V2V transmissions (R2V)</td>
</tr>
</tbody>
</table>

#### B. Spatial Distribution of Vehicles

Taking a snapshot of the grid in which vehicles are moving, it is considered that vehicles are distributed according to a Poisson point process (p.p.) $\Phi$ with intensity measure $\Xi$ on $G(M, L)$. Further, $\Xi(dx) = \xi dx$, where $\xi \in (0, +\infty)$, means that the average number of vehicles on the road of length $dx$ is $\xi dx$. We denote by $N$ the average number of vehicles in the grid. Therefore

$$N = \Xi(G) = \int_G \Xi(dx) = GL\xi,$$

(1)

Then, $\xi = N/GL = N/2L(M - 1)^2$. We have $M = \Theta(\sqrt{N})$, since $\xi$ should be positive and bounded. In addition, $\xi L$ is typically much larger than 1 for urban areas. The assumption of p.p. for vehicle distribution on the road has been made in many studies such as [18] and [27].

#### C. Propagation and Channel Capacity

For simplicity, the received signal power $P_{ij}$ at receiver $j$ from transmitter $i$ follows the propagation model described as follows: $P_{ij} = K P_i L(d_{ij})$, where $P_i$ is the transmission power of transmitter $i$, $d_{ij}$ is the Euclidean distance between $i$ and $j$, and $K$ is a parameter related to the hardware of communication systems. The path-loss function is given by $l(d_{ij}) = (d_{ij})^\beta$, where $\beta$ is positive and called the path-loss exponent. Typically, we have $\beta = 4$ for urban environments [28]. The phenomenon of channel fluctuations is not considered since a macroscopic description of power attenuation previously shown is sufficient for throughput analysis of a long-term average.

The channel capacity of transmitter $i$ and its receiver $j$ is given by Shannon capacity, i.e.,

$$T_{ij} = W_i \log_2(1 + SINR_{ij}),$$

(2)

where $W_i$ is the spectrum bandwidth for the transmission, and $SINR_{ij}$ is the signal-to-interference-plus-noise ratio (SINR) at receiver $j$. The interference seen by receiver $j$ is the aggregation of the signal power received from all simultaneous transmitters, except its own transmitter $i$. For ease of comparison, the same path-loss exponent and total bandwidth, which is denoted by $W$, are adopted for each type of deployment of access infrastructure.

### III. ANALYSIS OF DOWNLINK CAPACITY

Here, we derive a lower bound of downlink capacity for each type of infrastructure deployment, i.e., BSs, WMBs, and RAPs. Asymptotic results are also given, indicating how the downlink capacity scales with the number of deployed infrastructure nodes. The derivation is mostly based on geometric considerations about interference patterns under certain bandwidth planning. Note that the coverage of the infrastructure node is treated independently from the transmission power in the analysis. It is not necessary to explicitly show the relationship between these two parameters, since the results of our analysis only depend on the coverage of the infrastructure node. Moreover, it is noteworthy that the difference, in our work, between WMB and RAP is that WMBs use wireless mesh-to-mesh links as backhaul, whereas RAPs fully rely on external wired connectivity.

#### A. Network With Deployment of BSs

We denote by $N_B$ the number of BSs deployed in grid $G(M, L)$. The grid is hence divided into $N_B$ squares of equal area, which is denoted by $B$, and therefore, $|B| = (M - 1)^2 L^2 / N_B$. Each square is associated with one BS, which is placed in the central street block of the square, as shown in Fig. 3. It is required that $N_B < (M - 1)^2$, i.e., the number of deployed BSs should be less than the total number of street blocks of $G$. Further, each square is composed of multiple tiers that are co-centered at the BS. Tier(1) of the square is the street block where the BS is located and contains four road segments. The adjacent street blocks surrounding Tier(1) form Tier(2),
and so forth. It can be seen that \( \text{Tier}(\tau) \) contains \( 16\tau - 12 \) road segments. Let \( \tau_B \) denote the number of tiers of each square. Thus

\[
\tau_B \leq \left[ \frac{1}{2} \sqrt{\frac{B}{L^2}} + 1 \right] = \left[ \frac{M - 1}{2\sqrt{N_B}} + 1 \right] \tag{3}
\]

where \([\cdot]\) is the ceiling function.

For simplicity, the coverage of the BS is considered a square area of \( \tau_C \) tiers, although it is often assumed that the cellular BS covers a hexagon region. A similar approximation can be seen in [29]. When \( \tau_C \geq \tau_B \), we let \( \tau_C = \tau_B \). In this case, the network is fully covered by BSs and, therefore, operates in the infrastructure mode. When \( \tau_C < \tau_B \), the network is partially covered by BSs and operates in the hybrid mode, i.e., BS-to-vehicle (B2V) transmissions and vehicle-to-vehicle (V2V) transmissions coexist. We denote the downlink capacity for the deployment of BSs by \( \lambda_B(N, N_B) \). Further, we denote by \( \lambda_B^P \) and \( \lambda_B^A \) the downlink capacity of B2V and V2V transmissions, respectively. The downlink capacity of the network in the hybrid mode is determined as follows:

\[
\lambda_B(N, N_B) = \min \{ \lambda_B^P, \lambda_B^A \}. \tag{4}
\]

We first study the downlink throughput \( \lambda_B^P \) for B2V transmissions in the hybrid mode. The total bandwidth \( W \) is further divided into \( \alpha W \) and \( (1 - \alpha) W \) for B2V and V2V transmissions, respectively. To mitigate the interference from neighboring squares in B2V transmissions, a simple spectrum reuse scheme is adopted such that a square and its eight neighboring squares use different channels for B2V transmissions, each of which is of bandwidth \( \alpha W/9 \).

Let \( P^*_r \) denote the received signal power of vehicle \( V_0 \) on a road segment of \( \text{Tier}(\tau) \) from its own BS in the square \( S_0 \), where \( \tau \leq \tau_C \). From the propagation model, we have

\[
P^*_r \geq \frac{K P_B}{\sqrt{2L(\tau - \frac{1}{2})}} \tag{5}
\]

where \( P_B \) is the transmission power of BSs. The interference suffered by \( V_0 \), which is denoted by \( I_B \), comes from the signal power of all the other BSs transmitting on the same channel. We have

\[
I_B \leq \sum_{q=1}^{\infty} 8q \cdot \frac{K P_B}{(3q - \frac{1}{2}) \sqrt{|B|}}^\beta
\]

\[
= \sum_{q=1}^{\infty} 8qK P_B \left( \frac{M(q - 1) L}{\sqrt{N_B}} \right)^\beta
\]

\[
\leq 8KP_B N_B^\beta \left( \frac{2}{5} \right)^\beta + \frac{\infty}{(3q - \frac{1}{2})^{3-\beta-1}} dq
\]

\[
\leq \frac{2^{\beta+1}KP_B N_B^\beta}{5^{\beta}(M - 1)^\beta} \cdot \frac{12\beta + 1}{3\beta - 6}.
\]

Given that \( V_0 \) is on a road segment of \( \text{Tier}(\tau) \), the SINR of the received signal from the BS at \( V_0 \) is given by

\[
\text{SINR}_r \geq \frac{5^\beta(3\beta - 6)}{(12\beta + 1)2^{\beta+1}} \left( \frac{M - 1}{(\tau - \frac{1}{2}) \sqrt{N_B}} \right)^\beta. \tag{6}
\]

Throughout the analysis, we neglect noise as was done in previous works such as [22] and [23], since we focus on an interference-dominated vehicular environment.

For \( V_0 \) on a road segment of \( \text{Tier}(\tau) \), where \( \tau \leq \tau_C - 1 \), from (2), we have

\[
\lambda_B^P = W_r \log_2(1 + \text{SINR}_r) \tag{7}
\]

where \( W_r \) out of \( \alpha W/9 \) is the bandwidth allocated to a single vehicle on a road segment of \( \text{Tier}(\tau) \). Since vehicles on road segments of \( \text{Tier}(\tau_C - 1) \) need to relay the downlink traffic to vehicles outside of coverage of the BS (see Fig. 3), we have

\[
\lambda_B^P = \frac{W_{\tau_C} \log_2(1 + \text{SINR}_{\tau_C})}{(\sum_{q=1}^{\tau_C-1} 16\tau - 12) / (16\tau_C - 12)} \tag{8}
\]

From (7) and (8), we can obtain

\[
\sum_{q=1}^{\tau_C-1} (16\tau - 12) \xi L A_B^P \log_2(1 + \text{SINR}_r) + \frac{(\sum_{q=1}^{\tau_C-1} 16\tau - 12) \xi L A_B^P \log_2(1 + \text{SINR}_{\tau_C})}{\log_2(1 + \text{SINR}_{\tau_C})} = \frac{\alpha W}{9},
\]

Therefore, \( \lambda_B^P = (\alpha W/9) / \zeta \Lambda_{U_1} \), where

\[
U_1 = \sum_{\tau=1}^{\tau_C-1} \frac{16\tau - 12}{\log_2(1 + \text{SINR}_r)} + \frac{\sum_{q=1}^{\tau_C-1} 16\tau - 12}{\log_2(1 + \text{SINR}_{\tau_C})} \leq \frac{4\tau_B(2\tau_B - 1)}{\log_2 \left( 1 + U_2 \left( \frac{M - 1}{(\tau_C - \frac{1}{2}) \sqrt{N_B}} \right)^\beta \right)}
\]

\[
\leq \frac{2 \left( \frac{M - 1}{(\tau_C - \frac{1}{2}) \sqrt{N_B}} + 4 \right)^2}{\log_2 \left( 1 + U_2 \left( \frac{M - 1}{(\tau_C - \frac{1}{2}) \sqrt{N_B}} \right)^\beta \right)}.
\]
The inequalities hold according to (3) and (6). We denote $5^\beta (3\beta - 6)/(12\beta + 1)2^{(3/2)\beta + 1}$ by $U_2$. A lower bound of $\lambda_B^P$ is given by

$$\lambda_B^P \geq \frac{aW/(9\xi L)}{2(\frac{M-1}{\sqrt{N^\eta}}+4)^2} \log_2 \left( 1 + U_2 \left[ \frac{M - 1}{(\tau_c - 1/2)\sqrt{NB}} \right]^\beta \right). \quad (9)$$

We denote $\tau_c = \tau_B^0$, $0 < \kappa < 1$ and $N_B = N^\nu$, $0 < \nu < 1$. Asymptotically, it is clear that $\lambda_B^P \Omega(N_B/N \log_2(N/N_B)) = \Omega(N^{\nu - 1} \log_2 N)$. Note that $\lambda_B^P = \Omega(N_B/N) = \Omega(N^{\nu - 1})$ when $\kappa = 1$, i.e., the network operates in the infrastructure mode.

Next, we study downlink capacity $\lambda_B^P$ for V2V transmissions. Let $P_V$ and $R_V \geq L$ be the transmission power and transmission radius of V2V communications, respectively. The carrier sensing multiple access (CSMA) with a carrier sensing radius of $2R_V$ is adopted by vehicles to access the channel of bandwidth $(1 - \alpha)W$. Since simultaneous transmitters cannot be within a distance of $2R_V$, according to the stipulation of CSMA, the distribution of transmitting vehicles in the area outside the coverage of BSs follows a Matérn-like hard core (MHC) p.p. [30]. Such MHC p.p. is a dependent marked p.p. of original Poisson p.p. $\Phi$ of vehicles. Following [31], an average medium access probability over all the vehicles of $\Phi$ is given by

$$P_{ac} = (1 - e^{-N})/N$$

where $N$ is the average number of neighbors of a generic vehicle within the carrier sensing range. We have

$$N \leq \xi L \cdot 2 \left[ \frac{4R_V}{L} \left( \frac{4R_V}{L} \right) + 1 \right]$$

$$\leq 8\xi L \left( \frac{2R_V}{L} + 1 \right)^2.$$

Therefore

$$P_{ac} \geq 1 - \exp \left( -8\xi L (2R_V/L + 1)^2 \right) \frac{1}{8\xi L (2R_V/L + 1)^2}. \quad (10)$$

Since $\exp(-8\xi L (2R_V/L + 1)^2)$ decays to 0 very fast, we can ignore this exponential term in (10).

For V2V transmissions, the received signal power at destination $V_0$ from its transmitter is given by $P_r \geq KP_V/R_V^\alpha$. We denote by $I_{V_0}$ the aggregate interference power suffered by $V_0$ in V2V transmissions. A close-form expression of $I_{V_0}$ is difficult to determine. In the following, we derive an upper bound of $I_{V_0}$. Since we consider a high-density urban environment, simultaneous V2V transmitters under the CSMA scheme with carrier sensing radius $2R_V$ cannot be denser than a triangular lattice [32]. As shown in Fig. 4, the six nearest interferers in the first layer are at distance $2R_V$. The next 12 interferers form the second layer, and so on. The distance between the receiver marked and interferers in the first layer is at least $R_V$ and at least $(\sqrt{3}q - 1)R_V$ in the $q$th layer. Hence

$$I_{V_0} \leq \frac{6KP_V}{R_V^\alpha} + \sum_{q=2}^{\infty} 6q \cdot \frac{KP_V}{(\sqrt{3}q - 1)R_V^\alpha}$$

$$\leq \frac{6KP_V}{R_V^\alpha} \left[ 1 + \sum_{q=2}^{\infty} \frac{1}{(\sqrt{3}q - 1)^{\alpha-1}dq} \right]$$

$$= \frac{6KP_V}{R_V^\alpha} \left[ 1 + \frac{1}{\sqrt{3}(\beta - 2)(\sqrt{3} - 1)^{\beta - 2}} \right].$$

Let $\text{SINR}_V$ denote the SINR of the received signal at $V_0$ from its V2V transmitter. Then, it follows that

$$\text{SINR}_V \geq \frac{(\beta - 2)(\sqrt{3} - 1)^{\beta - 2}}{2\sqrt{3} + (\beta - 2)(\sqrt{3} - 1)^{\beta - 2}} = U_3(\beta). \quad (11)$$

It can be seen that $\text{SINR}_V$ is lower bounded by $U_3(\beta)$, which only depends on $\beta$.

Note that vehicles on road segments of $\text{Tier}(\tau_c)$ need to relay the downlink traffic to vehicles from $\text{Tier}(\tau_c + 1)$ to $\text{Tier}(\tau_B)$. On the average, every vehicle on road segments of $\text{Tier}(\tau_c)$ is required to relay the traffic for $\eta_1$ vehicles. We have

$$\eta_1 = \frac{\sum_{\tau=\tau_c+1}^{\tau_B} \tau L}{(16\tau_c - 12)\xi L}$$

$$= \frac{2\tau_B + 2\tau_c - 1)(\tau_B - \tau_c)}{4\tau_c - 3} \sim \frac{\tau_B^2 - \tau_c^2}{2}. \quad (12)$$

Recall that $\tau_c = \tau_B^0$, $0 < \kappa < 1$. Therefore, from (10)–(12), downlink capacity $\lambda_B^A$ can be lower bounded as follows:

$$\lambda_B^A \geq \frac{1 - \alpha)W}{8\xi L (2R_V/L + 1)^2} \log_2 \left( 1 + \frac{\text{SINR}_V P_{ac}}{\eta_1} \right)$$

$$\geq \frac{(1 - \alpha)W}{8\xi L (2R_V/L + 1)^2} \log_2 \left( 1 + \frac{U_3(\beta)}{\eta_1} \right)$$

$$\sim \frac{(1 - \alpha)W}{4\xi L (2R_V/L + 1)^2} \left( \frac{M-1}{2\sqrt{N^\eta}} + 2 \right)^{2-\kappa}. \quad (13)$$

Let $(R_V/L) = \tau_B^0$ establish a relationship between the transmission range of vehicles and the number of tiers of $B$, where
0 \leq \mu < 1$. Moreover, it is required that $\mu < \kappa$, since the transmission range of vehicles should be smaller than that of BSs. Then, we can obtain an asymptotic lower bound of $\lambda_B^2$ from (13), i.e., $\lambda_B^2 = \Omega((N_B / N) \lambda^{1-(\kappa/2)+\mu})$. Recall that $N_B = N^\nu$, $0 < \nu < 1$. Therefore, $\lambda_B^2 = \Omega((N^{\nu-1-(\kappa/2)+\mu})$.

According to (9) and (13), we can obtain a feasible downlink throughput $\lambda_B(N, N_B)$ when related network parameters are given. Next, we show an asymptotic lower bound of $\lambda_B$. Since $\lambda_B^2 = \Omega((N_B / N) \log_2 (N / N_B))$ and $\lambda_B^2 = \Omega((N_B / N)^{1-(\kappa/2)+\mu})$, we have

1) when $\mu < \kappa/2$, $\lambda_B(N, N_B) = \Omega((N_B / N) \log_2 (N / N_B))$;

2) when $\kappa/2 \leq \mu < \kappa$, $\lambda_B(N, N_B) = \Omega((N_B / N)^{1-(\kappa/2)+\mu})$.

Therefore, the downlink throughput of the network mainly depends on the number of deployed BSs, the coverage of the BS, and the transmission radius of the vehicle. For the case in which the transmission range of vehicles is relatively small, compared with the coverage of BSs, the downlink throughput of B2V transmissions is lower than that of V2V transmissions and, hence, determines the network throughput; with a relatively large vehicular transmission range, V2V communications limit the network throughput since the medium access probability of vehicles is quite small and, therefore, degrades the per-vehicle throughput in V2V transmissions.

B. Network With Deployment of WMBs

The network with deployment of WMBs is shown in Fig. 5. There are $N_M$ MNs in the network, $\theta N_M$ of which are functioned as mesh gateways (MGs) connecting to the Internet through the wireline, where $0 < \theta < 1$. Similar to BSs, MGs are regularly placed in the grid, each of which is deployed at the center of a square of area $(M - 1)^2 L^2 / \theta N_M$. Let $\tau_M$ denote the number of tiers of each square. Thus

$$\tau_M \leq \left\lfloor \frac{M - 1}{2 \sqrt{\theta N_M}} + 1 \right\rfloor. \quad (14)$$

In each square, there are $(1 - \theta)N_M / \theta N_M$ mesh routers (MRs) deployed, each of which can be reached wirelessly by the MG through one hop or multiple hops. Hence, $1 - \theta / \theta$ MRs and one MG constitute a WMB in each square. Let $R_M$ denote the transmission radius of mesh-to-mesh (M2M) communications. We consider a regular lattice deployment of MRs with nearest nodal distance of $(\sqrt{2}/2)R_M$, as shown in Fig. 5, so that the Internet traffic is delivered from the MG to MRs of the first layer through one hop and to MRs of other layers through multiple hops. Moreover, each MN covers an area of $(\sqrt{2}/2)R_M \times (\sqrt{2}/2)R_M$ with $\tau_{MR}$ tiers, where

$$\tau_{MR} \leq \left\lceil \frac{\sqrt{2}R_M}{(4L) + 1} \right\rceil. \quad (15)$$

Vehicles within the coverage of the MN receive the downlink traffic through mesh-to-vehicle (M2V) communications. We denote by $Q$ and $\tau_W$ the number of layers of MRs and the number of tiers of the coverage region of each WMB, respectively. It follows that $\sum_{q=1}^{\nu} Q_q = 1 - \theta / \theta$. Hence, $Q \leq 1/2(1 - \theta)/\theta + 1$. We have

$$\tau_W \leq \left\lceil \frac{\sqrt{2}R_M}{{3 + (1 - \theta)/\theta}} \right\rceil. \quad (16)$$

When $\tau_W > \tau_M$, let $\tau_W = \tau_M$. The network is completely covered by WMBs if $\tau_W = \tau_M$; otherwise, it is not completely covered. In the case where $\tau_W < \tau_M$, vehicles outside the coverage of the WMB receive the downlink traffic through V2V transmissions and require the assistance of vehicles on road segments of Tier($\tau_W$). We denote the downlink capacity for the deployment of WMBs by $\lambda_M(N, N_M)$. Further, we denote by $\lambda^M_M$, $\lambda^P_M$, and $\lambda^A_M$ the downlink capacity of M2M, M2V, and V2V transmissions in the hybrid mode, respectively.

We first study $\lambda^M_M$ for delivering Internet traffic from the MG to MRs. All the MNs adopt the same transmission power $P_M$ for M2M transmissions. The total bandwidth $W$ is divided into $W_1$, $W_2$, and $W_3$ for M2M, M2V, and V2V transmissions, respectively. It holds that $W = W_1 + W_2 + W_3$. It is considered that M2M communications are under the coordination of the CSMA scheme with carrier sensing radius $2R_M$. We denote by $I_M$ the interference suffered by a receiver in M2M transmissions. Similar to the calculation of the upper bound of $I_{\nu_{\ell}}$, $I_M$ can be upper bounded as follows:

$$I_M \leq \frac{6 K P_M}{R_M^3} \left(1 + \frac{1}{3 \sqrt{(\beta - 2)(\sqrt{3} - 1)^{\beta - 2}} \right).$$

Therefore, the SINR of the M2M transmission is given by $SINR_M \geq \eta_3(\beta)$. Note that on average, every MG is required to deliver the downlink traffic for $1 - \theta / \theta$ MRs. Given a carrier sensing radius of $2R_M$, an average medium access probability over all MNs, which is denoted by $P'_{ac}$, is at least $P'_{ac} = 1/\sum_{q=1}^{\nu} Q_q$. In particular, $P'_{ac} = 1$ for $Q = 1$ and $P'_{ac} \geq 1/9$ for $Q = 2$. Therefore, $\lambda^M_M$ can be lower bounded as follows:

$$\lambda^M_M \geq \frac{W_1 \log_2 (1 + SINR_M) P'_{ac}}{(1 - \theta) / \theta} \geq \frac{W_1 \log_2 (1 + \eta_3(\beta)) P'_{ac}}{(1 - \theta) / \theta}. \quad (17)$$

Next, we study $\lambda^P_M$ for Internet traffic delivering from the MN to vehicles within its coverage. Similarly, to mitigate the interference from neighboring MNs in M2V transmissions, an MN and its neighbors (at most eight) use different channels for M2V transmissions, each of which has bandwidth $W_2/9$. Let
\( P_{MV} \) denote the transmission power for M2V communications. The interference suffered by vehicles in M2V communications, which is denoted by \( I_{MV} \), is given by

\[
I_{MV} \leq \sum_{q=1}^{\infty} \frac{8qKP_{MV}}{(3q - 1)^{\frac{2}{\beta}} R_M} \leq \frac{2^{\frac{2}{\beta}+1}KP_{MV} \cdot 12\beta + 1}{5^3 R_M^{\frac{3}{\beta}} \cdot 3^\beta - 6}.
\]

We denote by \( P_{MV}^* \) the received power of a vehicle on the road segment of Tier(\( \tau \)) from its own MN, where \( \tau \leq \tau_{MR} \). Since \( P_{MV}^* \geq KP_{MV}/(\sqrt{2}(L(\tau - (1/2)))^\beta \), we have

\[
\text{SINR}_\tau^* \geq \frac{5^{\beta}(3\beta - 6)}{(12\beta + 1)^{2^{\beta+1}}} \left[ \frac{R_M}{(\tau - \frac{1}{2})L} \right]^{\beta}
\]

where \( \text{SINR}_\tau^* \) is the SINR of the received signal from the MN for vehicles on road segments of Tier(\( \tau \)).

Similar to the deployment of BSs, \( W_c \) out of \( W_2/9 \) is the bandwidth allocated to a single vehicle on the road segment of Tier(\( \tau \)) for each coverage of MNs. Since vehicles on road segments of Tier(\( \tau_W \)) of the WMB are required to relay the downlink traffic, additional bandwidth need to be allocated to vehicles on the road segments of Tier(\( \tau_{MR} \)) for MNs located in the outmost layer \( Q \) of the WMB, as shown in Fig. 5. In the following, we consider an MN on the boundary of the WMB and derive a lower bound of \( \lambda_M^P \). For vehicles of Tier(\( \tau \)), where \( \tau \leq \tau_{MR} \), we have

\[
\lambda_m^P = W_c \log_2 (1 + \text{SINR}_\tau^*).
\]

Let \( \bar{\eta}_2 \) denote the average number of vehicles that need a vehicle of Tier(\( \tau_W \)) to relay the downlink traffic. Then

\[
\bar{\eta}_2 = \frac{\sum_{\tau=1}^{\tau_{MR}} 16\tau - 12}{16\tau_W - 12} \leq \frac{\tau_M^2 - \tau_W^2}{\tau_W - 1}.
\]

Therefore

\[
\lambda_m^P = \frac{W_{\tau_{MR}} \log_2 (1 + \text{SINR}_{\tau_{MR}}^*)}{1 + \bar{\eta}_2}.
\]

From (19)–(21), it follows that \( \lambda_m^P = (W_2/9)/\xi L \bar{\eta}_3 \), where

\[
\bar{\eta}_3 = \sum_{\tau=1}^{\tau_{MR} - 1} \frac{(16\tau - 12)}{\log_2 (1 + \text{SINR}_{\tau_{MR}}^*)} + \frac{(16\tau_{MR} - 12)(1 + \bar{\eta}_2)}{\log_2 (1 + \text{SINR}_{\tau_{MR}}^*)}
\]

\[
\leq \frac{4\tau_{MR}(2\tau_{MR} - 1) + \bar{\eta}_2(16\tau_{MR} - 12)}{\log_2 (1 + \text{SINR}_{\tau_{MR}}^*)}.
\]

We denote the numerator of the last fraction by \( \bar{\eta}_3 \), which is an upper bound of the average number of vehicles for which an MN provides Internet access. From (14)–(16), we obtain a lower bound of \( \lambda_M^P \), i.e.,

\[
\lambda_M^P \geq \frac{W_2 \log_2 (1 + \text{SINR}_{\tau_{MR}}^*)}{9\xi \bar{\eta}_3}
\]

\[
\sim \frac{W_2}{9\xi \bar{\eta}_3} \log_2 \left( 1 + \frac{5^{\beta}(3\beta - 6)}{(12\beta + 1)^{2^{\beta+1}}} \right).
\]

Moreover, let \( N_M = N^\gamma \), where \( 0 < \gamma < 1 \). Asymptotically, we have \( \lambda_m^P = \Omega(N_M/N) = \Omega(N^{\gamma-1}) \).

We follow the calculation process of (13) to derive \( \lambda_M^A \), since V2V communications are considered almost the same in both BS and WMB deployments. Therefore

\[
\lambda_M^A \geq \frac{W_3 \log_2 (1 + \text{SINR}_{RV}) P_{ac}}{N_M (R_M/L)}
\]

\[
\geq \frac{W_3 \log_2 (1 + \bar{\eta}_4 (\beta) (\tau_W - 1))}{2^\gamma L^2 (R_M/L)^2}.
\]

Asymptotically, we have

\[
\lambda_M^A = \Omega \left( N_M (R_M/L) \right).
\]

Let \( R_M/L = \tau_W^\gamma \) establish a relationship between the transmission range of MNs and the area of the mesh square, where \( 0 < \sigma_1 < 1 \). Similarly, \( R_M/L = \tau_M^\gamma \), where \( 0 < \sigma_2 < 1 \) and \( \sigma_2 < \sigma_1 \). Hence, \( \lambda_M^A = \Omega(N^{\gamma-1}(1+\sigma_2/(1/2)\sigma_1)) \). From (17), (22), and (23), we can obtain a lower bound of \( \lambda_M(N, N_M) \) as follows:

\[
\lambda_M(N, N_M) = \min \left( \frac{\lambda_M}{U_6}, \min(\lambda_M^P, \lambda_M^A) \right).
\]

Since \( \lambda_M^P/U_6 = \Omega(N^{\gamma-1}) \), we obtain the following asymptotic bound of \( \lambda_M^P \) in the hybrid mode:

1) when \( \sigma_2 < (1/2)\sigma_1 \),
\[
\lambda_M(N, N_M) = \Omega \left( \frac{N_M}{N} \right)
\]

2) when \( (1/2)\sigma_1 \leq \sigma_2 < \sigma_1 \),
\[
\lambda_M(N, N_M) = \Omega \left( \left( \frac{N_M}{N} \right)^{1-\frac{1}{2}\sigma_1 + \sigma_2} \right)
\]

When the network is fully covered by deployed WMBs, each MN covers an area of \( (M - 1)^2 L^2/N_M \). Therefore, \( R_M \geq \sqrt{2}(M - 1)L/\sqrt{N_M} \). Thus, we have

\[
\lambda_M^P \geq \frac{(W - W_1) \log_2 (1 + \text{SINR}_{\tau_{MR}}^*)}{9N/N_M}
\]

\[
\sim \frac{(W - W_1)N_M L \log_2 \left( 1 + \frac{5^\beta(3\beta - 6)}{(12\beta + 1)^{2^{\beta+1}}} \right)}{9N}.
\]

It can be seen that \( \lambda_M(N, N_M) = \min(\lambda_M^P/(N_M/N), \lambda_M^P) \) in the infrastructure mode. Asymptotically, \( \lambda_M(N, N_M) = \Omega(N^{\gamma-1}) \).

**C. Network With Deployment of RAPs**

The coverage of the RAP is 1-D along the road, as shown in Fig. 6. There are \( N_R \) RAPs regularly deployed in the network, and each RAP provides Internet access service to vehicles on the road of length \( L_R \), which is called the RAP cell. It can be seen that \( L_R = 2(M - 1)^2 L/N_R \). The coverage radius of RAP is denoted by \( R_C \). When \( R_C > (1/2)L_R \), let \( R_C = (1/2)L_R \). The network is fully covered by RAPs if \( R_C = (1/2)L_R \). To
provide pervasive Internet access, the network operates in the hybrid mode when $R_V < R_C < (1/2)L_R$. Vehicles within the coverage of the RAP receive the downlink traffic through RAP-to-vehicle (R2V) communications; vehicles at distance $(R_C - R_V, R_C]$ from the RAP are required to relay the downlink traffic for vehicles outside the coverage of the RAP, given the transmission radius of V2V communications $R_V$. The downlink capacity for the deployment of RAPs is denoted by $\lambda_R(N, N_R)$. Furthermore, the downlink capacity of R2V and V2V transmissions is denoted by $\lambda_R^P$ and $\lambda_R^A$, respectively. Similarly, in the hybrid mode

$$\lambda_R(N, N_R) = \min \{ \lambda_R^P, \lambda_R^A \}. \quad (25)$$

We first study the downlink throughput $\lambda_R^P$ in the hybrid mode. To mitigate inter-RAP interference, a spectrum reuse scheme is adopted: 1) RAPs deployed along the same road operate on one common channel; 2) RAPs on any two adjacent parallel roads use different channels; and 3) RAPs on horizontal roads and vertical roads use different channels. To this end, four different communication channels, each of which has bandwidth $(1/4)\phi W$, are allocated. The remaining bandwidth of $(1 - \phi)W$ is allocated for V2V communications. Interference $I_d$ suffered by a vehicle at distance $d$ from the RAP, where $d \leq R_C$, in R2V communications is due to the signal power of all the other RAPs operating on the same channel, as shown in the Fig. 7. We have

$$I_d \leq 2K P_R \left[ \frac{1}{(L_R - d)\beta} + \frac{1}{(qL_R - d)\beta d^\beta} \right] + \frac{2^{1-\beta} K P_R}{(\beta - 1) L_R} \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \frac{1}{(ij)^{\beta}}$$

$$\leq 2K P_R \left[ \frac{\beta L_R - d}{L_R(L_R - d)\beta} + \frac{\beta}{(2L)^\beta} \right] + \frac{2^{1-\beta} K P_R}{(\beta - 2)^2 (L_R)^\beta}$$

where $P_R$ is the transmission power of RAPs. The SINR of the received signal from the RAP is hence given as follows:

$$\text{SINR}_d \geq \frac{\beta L_R - d}{L_R(L_R - d)\beta} + \frac{\beta}{(2L)^\beta} \geq \frac{1}{\eta_3} = U_0(d).$$

For vehicle $V_d$ at distance $d$ from the RAP, where $d \leq R_C$, it follows that

$$\lambda_R^P = W_d \log_2(1 + \text{SINR}_d)$$

where $W_d$ out of $(1/4)\phi W$ is the bandwidth allocated to $V_d$. As previously mentioned, vehicles at distance $(R_C - R_V, R_C]$ from the RAP need to relay the downlink traffic to the vehicles at distance $(R_C, (1/2)L_R]$, which yields an average relaying traffic load of $\eta_3 = ((1/2)L_R - R_C) / R_V$. Hence, for vehicles at distance $d \leq (R_C - R_V, R_C]$ from the RAP

$$\lambda_R^A = \frac{W_d \log_2(1 + \text{SINR}_d)}{1 + \eta_3}.$$

Given the constraint of the total bandwidth, we have

$$\lambda_R^P \geq \frac{1}{8} \phi W / \xi + \frac{2\phi W / \xi + \frac{1}{8} \phi W / \xi}{\log_2(1 + \text{SINR}_R)} \geq \frac{1}{8} \phi W / \xi + \frac{R_C - R_V}{\log_2(1 + \text{SINR}_R)}. \quad (26)$$

Further, let $R_C = ((1/2)L_R)^{\rho_1}$ and $R_V = ((1/2)L_R)^{\rho_2}$, where $0 < \rho_2 < \rho_1 < 1$. Denoting $N_R = N^{\varphi}$, where $0 < \varphi < 1$, it can be obtained that $\lambda_R^P = \Omega(N_R / N \log_2 N_R / N_R)$, where $(N^{\varphi - 1} \log_2 N)$ asymptotically when $\rho_1 < 1/2$, $\lambda_R^A = \Omega(N_R / N) = \Omega(N^{\varphi - 1})$ when $\rho_1 = 1/2$, and $\lambda_R^P = \Omega(N_R / N \log_2(1 + (N_R / N)^{\beta(\rho_1 - 1/2)}) = \Omega(N^{(\varphi-1)(1+\beta(\rho_1 - 1/2))})$ when $\rho_1 > 1/2$.

The derivation of $\lambda_R^P$ is straightforward, since V2V communications are considered almost the same in all scenarios. Therefore

$$\lambda_R^A \geq \frac{(1 - \phi)W \log_2(1 + \text{SINR}_R)P_{ac}}{\eta_3} \geq \frac{(1 - \phi)W \log_2(1 + U_0(\beta)R_V)}{8 \xi L (2R_V + L)^2} \frac{1}{(2L_R - R_C)}. \quad (27)$$

Asymptotically, $\lambda_R^A = \Omega((N_R / N)^{1+\rho_2}) = \Omega(N^{(\varphi-1)(1+\rho_2)})$. 

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**Fig. 6.** Grid-like VANETs with deployment of RAPs.

**Fig. 7.** Illustration of inter-RAP interference for horizontal roads.
TABLE II
VALUES OF PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>M</td>
<td>201</td>
<td>L</td>
<td>100 m</td>
</tr>
<tr>
<td>ξ</td>
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<td>N</td>
<td>4 \times 10^5</td>
</tr>
<tr>
<td>W</td>
<td>10 MHz</td>
<td>β</td>
<td>4</td>
</tr>
<tr>
<td>R_C</td>
<td>100 m</td>
<td>θ</td>
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</tr>
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</table>

According to (26) and (27), \( \lambda_R(N,N_R) \) can be attained from (25) when values of all the impact factors are determined. In addition, the asymptotic bound of \( \lambda_R(N,N_R) \) is given by

1. When \( \rho_1 \leq 1/2 \)

\[
\lambda_R(N,N_R) = \Omega \left( (N_R/N)^{1+\rho_2} \right)
\]

2. When \( 1/2 < \rho_1 < 1 \)

\[
\lambda_M(N,N_M) = \Omega \left( (N_R/N)^{\max[1+\rho_2,1+\beta(\rho_1-1/2)]} \right).
\]

In particular, when the network is completely covered by RAPs, \( \lambda_R(N,N_R) = R_N \geq W N_R \log_2(1 + U_0(R_C))/4N \). The asymptotic result of \( \lambda_R(N,N_R) \) in the infrastructure mode is the same as that of \( \lambda_R^P \) in the hybrid mode.

IV. CASE STUDY

Here, we present a case study of downlink capacity of vehicles based on the results in Section III. The goal is to evaluate the impact of key factors, i.e., the number of infrastructure nodes deployed and the coverage of infrastructure nodes, on capacity performance and compare the three types of infrastructure in terms of deployment cost. The values of parameters for this study are given in Table II.

A. Impact of Coverage of Infrastructure Nodes

We consider a perfect city grid of 20 km \( \times \) 20 km with an average vehicle density of 0.05 vehicles per meter (veh/m). The total bandwidth of 10 MHz is assumed for all types of infrastructure deployment. Moreover, bandwidth allocation is done to maximize the downlink throughput for each case. The downlink capacity is plotted with respect to the number of infrastructure nodes deployed, as shown in Fig. 8. With more and more infrastructure nodes deployed, the network transits from a partially covered status to a fully covered status, and accordingly, the downlink throughput gradually increases. The impact of the coverage size of infrastructure nodes on downlink throughput is investigated. Three different sizes of BS footprint are considered in Fig. 8(a). It can be seen that for each BS coverage, the achievable downlink throughput increases faster than a linear increase with \( N_B \) in the hybrid mode. The reason for this is that the relaying traffic load of relay vehicles decreases very fast when the network gradually becomes fully covered, and therefore, the capacity of V2V communications increases. When the network is fully covered by BSs, the downlink throughput increases almost linearly with \( N_B \). Moreover, it is very intuitive that the network needs more BSs to be fully covered with a smaller size of BS coverage. Similar insights for the other two deployments can be obtained in Fig. 8(b) and (c).

B. Comparison of Deployment Scales

Fig. 9 shows the different trends of downlink throughput when the network is not fully covered by any type of infrastructure. From the average slope of each curve, an important observation can be attained that the network roughly needs \( X \) BSs, \( 6X \) MNs, or \( 25X \) RAPs to achieve a certain downlink throughput in the hybrid mode. A whole picture of the comparison is shown in Fig. 10. Regardless of the operation mode (hybrid or infrastructure), on the average, the network requires \( X \) BSs, \( 5X \) MNs, or \( 15X \) RAPs to achieve a downlink throughput of less than 15 kb/s with our settings. Moreover, it is observed that more MNs are needed than RAPs to achieve the same throughput after Point A shown in Fig. 10. The reason for this is that in the infrastructure mode, the relaying traffic load from the MG to MRs limits the downlink throughput, and there is almost no benefit from better coverage of MNs since the network is fully covered by either RAPs or MNs. As shown in Fig. 11, the downlink throughput severely decreases with a very small value of \( \theta \), which reflects the backhaul capability of wireless mesh networks. Another result in Fig. 10 is that we roughly need to additionally deploy \( X \) BSs, \( 5X \) MNs, or \( 1.5X \) RAPs to improve the downlink throughput by the same amount, given that the network operates in the infrastructure mode.

C. Capacity–Cost Tradeoffs

Deployment cost plays an important role in choosing the cost-effective access infrastructure. CAPEX and OPEX are a major part of the deployment cost [33]. According to the cost models in [33], the estimated deployment cost of each type of access infrastructure is given in Table III. It can be seen that when the network operates in the hybrid mode (low-capacity regime), the deployment of BSs or WMBs is cost-effective for a five-year operation period. (The cost is roughly 120X K€ to deploy \( X \) BSs or 6X MNs.) On the other hand, when the network operates in the infrastructure mode (high-capacity regime), the deployment of RAPs outperforms the other two alternatives in terms of deployment costs for a given downlink throughput requirement. For example, to provide a downlink throughput of 40 kb/s to all the vehicles, we need to pay roughly 530 M€ for the deployment of 4200 BSs or 210 M€ for the deployment of \( 2.1 \times 10^4 \) RAPs for a five-year period. In Fig. 10, the choice of the cost-effective access infrastructure can be made as per the data demand of vehicles. It can be seen that noncellular infrastructure such as RAPs is a good choice for offering a cost-effective high-speed data pipe for vehicles.

V. CONCLUSION

In this paper, we have investigated the capacity–cost tradeoffs of different communication infrastructure for vehicular access networks. The involved alternatives of access infrastructure include BSs, WMBs, and RAPs, which are respectively...
deployed to provide downlink Internet data flow to all the vehicles uniformly in the network. The downlink capacity of vehicles for each kind of deployment has been lower-bounded under the same set of benchmark models by considering a perfect city grid with vehicles distributed on the roads following a Poisson p.p. In addition, asymptotic results, i.e., in the scaling sense, have been given for large-scale deployment. A case study has been presented to examine the capacity–cost tradeoffs of different solutions in terms of both CAPEX and OPEX. Offering fundamental guidance, the results in this paper imply that it is necessary to choose a cost-effective access infrastructure according to the data demand of vehicles. Our future work will focus on validation via a comprehensive simulation experiment and further digging up the implication on network design and operation.

REFERENCES


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