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 km^2 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.

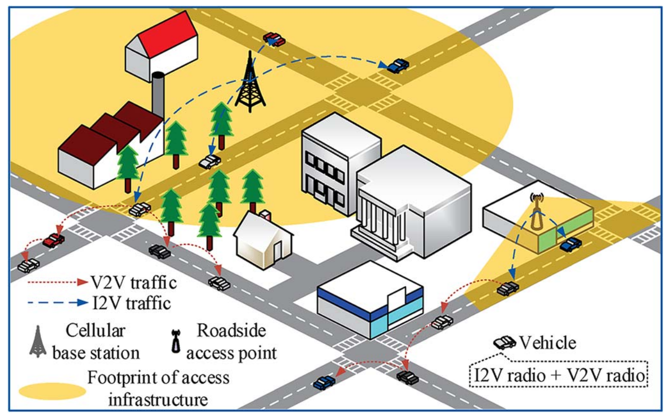

Fig. 1. Downlink traffic delivery in vehicular access networks.

A. Roadmap and Main Results

To better understand the capacity–cost issue in vehicular access networks, in this paper, we consider a scalable urban

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[1]To deemphasize the ad hoc nature of vehicular networks, we redefine the term VANETs, which is traditionally the acronym of vehicular ad hoc networks.

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 km^2 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 $25X$ RAPs[2]; 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

[2] X is used to represent a ratio relationship rather that a specific value.

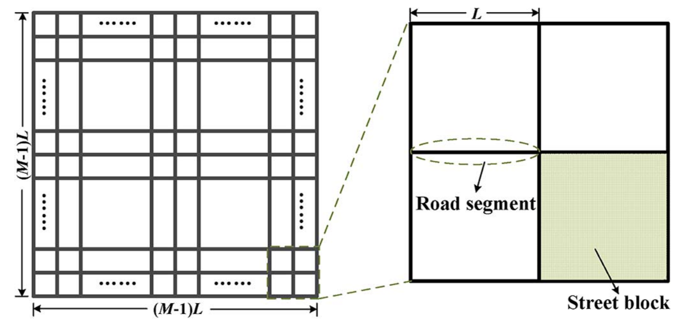

Fig. 2. Grid-like urban street pattern.

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 $\mathbb{G}(M, L)$, 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 $\mathbb{G}$ 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 $\mathbb{G}$ by $\mathcal{G} = 2(M-1)^2$. The scale of the urban grid is therefore

TABLE I
USEFUL NOTATIONS

Symbol	Description
N	The average number of vehicles in the grid
M	The number of parallel roads in the grid
L	The length of road segment
$\mathcal{G}$	The total number of road segments
$\mathbb{G}$	The urban grid
β	Path-loss exponent
ξ	Vehicle density
W	Communication bandwidth
θ	Ratio between the number of MGs and N_M
N_B	The number of deployed BSs
N_M	The number of deployed MNs
N_R	The number of deployed RAPs
R_V	Transmission radius of V2V communications
R_M	Transmission radius of M2M communications
$\tau_{\mathcal{B}}$	The number of tiers in BS service square
$\tau_{\mathcal{C}}$	The number of tiers in the coverage of BS
λ_B	Downlink capacity for deployment of BSs
λ_B^P	Downlink capacity of B2V transmissions
λ_B^A	Downlink capacity of V2V transmissions (BS)
τ_M	The number of tiers in WMB service square
τ_{MR}	The number of tiers in the coverage of MN
τ_W	The number of tiers in the coverage of WMB
λ_M	Downlink capacity for deployment of WMBs
λ_M^M	Downlink capacity of M2M transmissions
λ_M^P	Downlink capacity of M2V transmissions
λ_M^A	Downlink capacity of V2V transmissions (WMB)
L_R	Service region of an RAP
R_C	Transmission radius of RAP
λ_R	Downlink capacity for deployment of RAPs
λ_R^P	Downlink capacity of R2V transmissions
λ_R^A	Downlink capacity of V2V transmissions (RAP)

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.

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.) Φ with intensity measure Ξ on $\mathbb{G}(M, L)$. Further, $\Xi(dx) = \xi dx$, where $\xi \in (0, +\infty)$, means that the average number of vehicles on the road of length dx is ξdx. We denote by N the average number of vehicles in the grid. Therefore

$$N = \Xi(\mathbb{G}) = \int_{\mathbb{G}} \Xi(dx) = \mathcal{G} L \xi. \tag{1}$$

Then, $\xi = N/\mathcal{G}L = N/2L(M-1)^2$. We have $M = \Theta(\sqrt{N})$, since ξ should be positive and bounded.[3] In addition, ξL 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].

[3]We use standard order notations in this paper to denote asymptotic results. Given nonnegative functions $f_1(n)$ and $f_2(n)$, $f_1(n) = \Omega(f_2(n))$ means $f_1(n)$ is asymptotically lower bounded by $f_2(n)$, and $f_1(n) = \Theta(f_2(n))$ means $f_1(n)$ is asymptotically tight bounded by $f_2(n)$.

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: $P_{ij} = KP_i/l(d_{ij})$, 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 β 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.,

$$\mathcal{T}_{ij} = W_{ij} \log_2(1 + SINR_{ij}) \tag{2}$$

where W_{ij} 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 $\mathbb{G}(M, L)$. The grid is hence divided into N_B squares of equal area, which is denoted by $\mathcal{B}$, and therefore, $|\mathcal{B}| = (M-1)^2 L^2/N_B$. 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 $\mathbb{G}$. 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 $Tier(2)$,

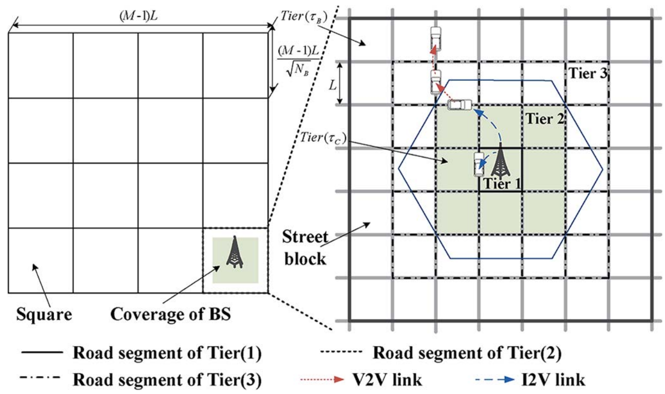

Fig. 3. Grid-like VANETs with deployment of cellular BSs.

and so forth. It can be seen that $Tier(\tau)$ contains $16\tau - 12$ road segments. Let $\tau_{\mathcal{B}}$ denote the number of tiers of each square. Thus

$$\tau_{\mathcal{B}} \leq \left\lceil \frac{1}{2}\sqrt{\frac{|\mathcal{B}|}{L^2}} + 1 \right\rceil = \left\lceil \frac{M-1}{2\sqrt{N_B}} + 1 \right\rceil \tag{3}$$

where $\lceil \cdot \rceil$ is the ceiling function.

For simplicity, the coverage of the BS is considered a square area of $\tau_{\mathcal{C}}$ tiers, although it is often assumed that the cellular BS covers a hexagon region. A similar approximation can be seen in [29]. When $\tau_{\mathcal{C}} \geq \tau_{\mathcal{B}}$, we let $\tau_{\mathcal{C}} = \tau_{\mathcal{B}}$. In this case, the network is fully covered by BSs and, therefore, operates in the infrastructure mode. When $\tau_{\mathcal{C}} < \tau_{\mathcal{B}}$, 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 λ_B^P and λ_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:

$$\lambda_B(N, N_B) = \min\left\{\lambda_B^P, \lambda_B^A\right\}. \tag{4}$$

We first study the downlink throughput λ_B^P for B2V transmissions in the hybrid mode. The total bandwidth W is further divided into αW 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^τ denote the received signal power of vehicle $\mathcal{V}_0$ on a road segment of $Tier(\tau)$ from its own BS in the square $\mathcal{S}_0$, where $\tau \leq \tau_{\mathcal{C}}$. From the propagation model, we have

$$P_r^\tau \geq \frac{KP_B}{\left[\sqrt{2}L\left(\tau - \frac{1}{2}\right)\right]^\beta} \tag{5}$$

where P_B is the transmission power of BSs. The interference suffered by $\mathcal{V}_0$, which is denoted by I_B, comes from the signal power of all the other BSs transmitting on the same channel. We have

$$\begin{aligned} I_B &\leq \sum_{q=1}^{\infty} 8q \cdot \frac{KP_B}{\left[\left(3q - \frac{1}{2}\right)\sqrt{|\mathcal{B}|}\right]^\beta} \\ &= \sum_{q=1}^{\infty} \frac{8qKP_B}{\left[\left(3q - \frac{1}{2}\right)\frac{(M-1)L}{\sqrt{N_B}}\right]^\beta} \\ &\leq \frac{8KP_B N_B^{\frac{\beta}{2}}}{L^\beta (M-1)^\beta}\left[\left(\frac{2}{5}\right)^\beta + \int_1^\infty \frac{1}{(3q-\frac{1}{2})^{\beta-1}}dq\right] \\ &\leq \frac{2^{\beta+1}KP_B N_B^{\frac{\beta}{2}}}{5^\beta L^\beta (M-1)^\beta} \cdot \frac{12\beta+1}{3\beta-6}. \end{aligned}$$

Given that $\mathcal{V}_0$ is on a road segment of $Tier(\tau)$, the SINR of the received signal from the BS at $\mathcal{V}_0$ is given by

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

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 $\mathcal{V}_0$ on a road segment of $Tier(\tau)$, where $\tau \leq \tau_{\mathcal{C}} - 1$, from (2), we have

$$\lambda_B^P = W_\tau \log_2(1 + SINR_\tau) \tag{7}$$

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

$$\lambda_B^P = \frac{W_{\tau_{\mathcal{C}}}\log_2(1+SINR_{\tau_{\mathcal{C}}})}{\left(\sum_{\tau=\tau_{\mathcal{C}}}^{\tau_{\mathcal{B}}} 16\tau - 12\right)/(16\tau_{\mathcal{C}} - 12)}. \tag{8}$$

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

$$\sum_{\tau=1}^{\tau_{\mathcal{C}}-1}\frac{(16\tau-12)\xi L\lambda_B^P}{\log_2(1+SINR_\tau)} + \frac{\left(\sum_{\tau=\tau_{\mathcal{C}}}^{\tau_{\mathcal{B}}} 16\tau - 12\right)\xi L\lambda_B^P}{\log_2(1+SINR_{\tau_{\mathcal{C}}})} = \frac{\alpha W}{9}.$$

Therefore, $\lambda_B^P = (\alpha W/9)/\xi L \mathcal{U}_1$, where

$$\begin{aligned} \mathcal{U}_1 &= \sum_{\tau=1}^{\tau_{\mathcal{C}}-1}\frac{16\tau-12}{\log_2(1+SINR_\tau)} + \frac{\sum_{\tau=\tau_{\mathcal{C}}}^{\tau_{\mathcal{B}}} 16\tau - 12}{\log_2(1+SINR_{\tau_{\mathcal{C}}})} \\ &\leq \frac{\sum_{\tau=1}^{\tau_{\mathcal{B}}} 16\tau - 12}{\log_2(1+SINR_{\tau_{\mathcal{C}}})} \\ &= \frac{4\tau_{\mathcal{B}}(2\tau_{\mathcal{B}}-1)}{\log_2\left(1+\mathcal{U}_2\left[\frac{M-1}{(\tau_{\mathcal{C}}-\frac{1}{2})\sqrt{N_B}}\right]^\beta\right)} \\ &\leq \frac{2\left(\frac{M-1}{\sqrt{N_B}}+4\right)^2}{\log_2\left(1+\mathcal{U}_2\left[\frac{M-1}{(\tau_{\mathcal{C}}-\frac{1}{2})\sqrt{N_B}}\right]^\beta\right)}. \end{aligned}$$

The inequalities hold according to (3) and (6). We denote $5^{\beta}(3\beta-6)/(12\beta+1)2^{(3/2)\beta+1}$ by $\mathcal{U}_2$. A lower bound of λ_B^P is given by

$$\lambda_B^P \geq \frac{\alpha W/(9\xi L)}{2\left(\frac{M-1}{\sqrt{N_B}}+4\right)^2}\log_2\left(1+\mathcal{U}_2\left[\frac{M-1}{\left(\tau_{\mathcal{C}}-\frac{1}{2}\right)\sqrt{N_B}}\right]^{\beta}\right). \quad (9)$$

We denote $\tau_{\mathcal{C}}=\tau_{\mathcal{B}}^{\kappa}$, $0<\kappa<1$ 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 λ_B^A 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. Φ of vehicles. Following [31], an average medium access probability over all the vehicles of Φ is given by

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

where $\bar{\mathcal{N}}$ is the average number of neighbors of a generic vehicle within the carrier sensing range. We have

$$\bar{\mathcal{N}} \leq \xi L\cdot 2\left\lceil\frac{4R_V}{L}\right\rceil\left(\left\lceil\frac{4R_V}{L}\right\rceil+1\right) \leq 8\xi L\left(\frac{2R_V}{L}+1\right)^2.$$

Therefore

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

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 $\mathcal{V}_0$ from its transmitter is given by $P_r \geq KP_V/R_V^{\beta}$. We denote by $I_{\mathcal{V}_0}$ the aggregate interference power suffered by $\mathcal{V}_0$ in V2V transmissions. A close-form expression of $I_{\mathcal{V}_0}$ is difficult to determine. In the following, we derive an upper bound of $I_{\mathcal{V}_0}$. 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

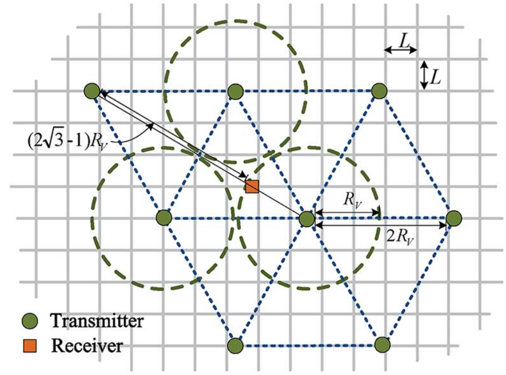

Fig. 4. Triangular lattice of simultaneous transmitting vehicles.

marked and interferers in the first layer is at least R_V and at least $(\sqrt{3}q-1)R_V$ in the qth layer, $q>1$. Hence

$$\begin{aligned} I_{\mathcal{V}_0} &\leq \frac{6KP_V}{R_V^{\beta}}+\sum_{q=2}^{\infty}6q\cdot\frac{KP_V}{\left[(\sqrt{3}q-1)R_V\right]^{\beta}} \\ &\leq \frac{6KP_V}{R_V^{\beta}}\left[1+\int_1^{\infty}\frac{1}{(\sqrt{3}q-1)^{\beta-1}}dq\right] \\ &= \frac{6KP_V}{R_V^{\beta}}\left(1+\frac{1}{\sqrt{3}(\beta-2)(\sqrt{3}-1)^{\beta-2}}\right). \end{aligned}$$

Let $SINR_V$ denote the SINR of the received signal at $\mathcal{V}_0$ from its V2V transmitter. Then, it follows that

$$SINR_V \geq \frac{(\beta-2)(\sqrt{3}-1)^{\beta-2}}{2\sqrt{3}+(\beta-2)(\sqrt{3}-1)^{\beta-2}}=\mathcal{U}_3(\beta). \quad (11)$$

It can be seen that $SINR_V$ is lower bounded by $\mathcal{U}_3(\beta)$, which only depends on β.

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

$$\begin{aligned} \bar{\eta_1} &= \frac{\left(\sum_{\tau=\tau_{\mathcal{C}}+1}^{\tau_{\mathcal{B}}}16\tau-12\right)\xi L}{(16\tau_{\mathcal{C}}-12)\xi L} \\ &= \frac{(2\tau_{\mathcal{B}}+2\tau_{\mathcal{C}}-1)(\tau_{\mathcal{B}}-\tau_{\mathcal{C}})}{4\tau_{\mathcal{C}}-3} \sim \frac{\tau_{\mathcal{B}}^{2-\kappa}-\tau_{\mathcal{B}}^{\kappa}}{2}. \end{aligned} \quad (12)$$

Recall that $\tau_{\mathcal{C}}=\tau_{\mathcal{B}}^{\kappa}$, $0<\kappa<1$. Therefore, from (10)–(12), downlink capacity λ_B^A can be lower bounded as follows:

$$\begin{aligned} \lambda_B^A &\geq \frac{(1-\alpha)W\log_2(1+SINR_V)P_{ac}}{\bar{\eta_1}} \\ &\geq \frac{(1-\alpha)W\log_2\left(1+\mathcal{U}_3(\beta)\right)}{8\xi L(2R_V/L+1)^2\bar{\eta_1}} \\ &\sim \frac{(1-\alpha)W\log_2\left(1+\mathcal{U}_3(\beta)\right)}{4\xi L(2R_V/L+1)^2\cdot\left(\frac{M-1}{2\sqrt{N_B}}+2\right)^{2-\kappa}}. \end{aligned} \quad (13)$$

Let $(R_V/L)=\tau_{\mathcal{B}}^{\mu}$ establish a relationship between the transmission range of vehicles and the number of tiers of $\mathcal{B}$, where

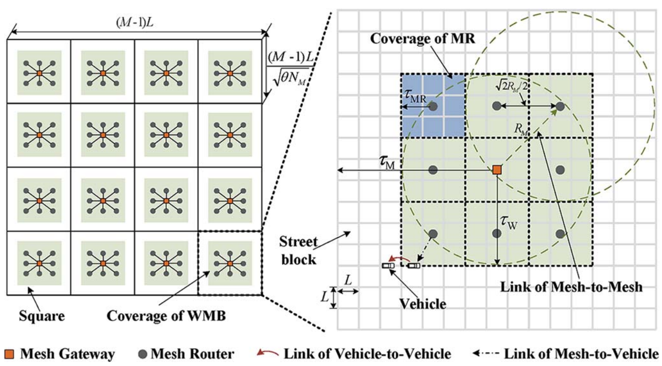

Fig. 5. Grid-like VANETs with deployment of WMBs.

$0 < \mu < 1$. 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 λ_B^A from (13), i.e., $\lambda_B^A = \Omega((N_B/N)^{1-(\kappa/2)+\mu})$. Recall that $N_B = N^{\nu}$, $0 < \nu < 1$. Therefore, $\lambda_B^A = \Omega(N^{(\nu-1)(1-(\kappa/2)+\mu)})$.

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 λ_B. Since $\lambda_B^P = \Omega((N_B/N)\log_2(N/N_B))$ and $\lambda_B^A = \Omega((N_B/N)^{1-(\kappa/2)+\mu})$, 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, θN_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 $(M-1)^2L^2/\theta N_M$. Let τ_M denote the number of tiers of each square. Thus

$$\tau_M \leq \left\lceil \frac{M-1}{2\sqrt{\theta N_M}} + 1 \right\rceil. \tag{14}$$

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 τ_{MR} tiers, where

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

Vehicles within the coverage of the MN receive the downlink traffic through mesh-to-vehicle (M2V) communications. We denote by Q and τ_W the number of layers of MRs and the number of tiers of the coverage region of each WMB, respectively. It follows that $\sum_{q=1}^{Q-1} 8q \leq (1-\theta)/\theta$. Hence, $Q \leq 1/2\sqrt{(1-\theta)/\theta} + 1$. We have

$$\tau_W \leq \left\lceil \frac{\sqrt{2}R_M(3 + \sqrt{(1-\theta)/\theta})}{4L} \right\rceil. \tag{16}$$

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 λ_M^M, λ_M^P, and λ_M^A the downlink capacity of M2M, M2V, and V2V transmissions in the hybrid mode, respectively.

We first study λ_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_{V_0}, I_M can be upper bounded as follows:

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

Therefore, the SINR of the M2M transmission is given by $SINR_M \geq \mathcal{U}_3(\beta)$. 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 $P'_{ac} = 1/\sum_{q=1}^{2} 8q$. In particular, $P'_{ac} = 1$ for $Q = 1$ and $P'_{ac} \geq 1/9$ for $Q = 2$. Therefore, λ_M^M can be lower bounded as follows:

$$\begin{aligned} \lambda_M^M &\geq \frac{W_1 \log_2(1 + SINR_M)P'_{ac}}{(1-\theta)/\theta} \\ &\geq \frac{W_1 \log_2\left(1 + \mathcal{U}_3(\beta)\right)P'_{ac}}{(1-\theta)/\theta}. \end{aligned} \tag{17}$$

Next, we study λ_M^P 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

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

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

$$SINR'_{\tau} \geq \frac{5^{\beta}(3\beta-6)}{(12\beta+1)2^{2\beta+1}}\left[\frac{R_M}{\left(\tau-\frac{1}{2}\right)L}\right]^{\beta} \tag{18}$$

where $SINR'_{\tau}$ 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_{τ} 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 needs 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 λ_M^P. For vehicles of $Tier(\tau)$, where $\tau \leq \tau_{MR}-1$, we have

$$\lambda_M^P = W_{\tau}\log_2\left(1+SINR'_{\tau}\right). \tag{19}$$

Let $\bar{\eta_2}$ denote the average number of vehicles that need a vehicle of $Tier(\tau_W)$ to relay the downlink traffic. Then

$$\bar{\eta_2} = \frac{\sum_{\tau=\tau_W+1}^{\tau_M} 16\tau-12}{16\tau_W-12} \leq \frac{\tau_M^2-\tau_W^2}{\tau_W-1}. \tag{20}$$

Therefore

$$\lambda_M^P = \frac{W_{\tau_{MR}}\log_2\left(1+SINR'_{\tau_{MR}}\right)}{1+\bar{\eta_2}}. \tag{21}$$

From (19)–(21), it follows that $\lambda_M^P = (W_2/9)/\xi L\mathcal{U}_4$, where

$$\mathcal{U}_4 = \sum_{\tau=1}^{\tau_{MR}-1} \frac{(16\tau-12)}{\log_2\left(1+SINR'_{\tau}\right)} + \frac{(16\tau_{MR}-12)(1+\bar{\eta_2})}{\log_2\left(1+SINR'_{\tau_{MR}}\right)} \leq \frac{4\tau_{MR}(2\tau_{MR}-1)+\bar{\eta_2}(16\tau_{MR}-12)}{\log_2\left(1+SINR'_{\tau_{MR}}\right)}.$$

We denote the numerator of the last fraction by $\mathcal{U}_5$, which is an upper bound of the average number of vehicles for which an MN provides Internet access. From (14)–(16), we can obtain a lower bound of λ_M^P, i.e.,

$$\lambda_M^P \geq \frac{W_2\log_2\left(1+SINR'_{\tau_{MR}}\right)}{9\xi L\mathcal{U}_5} \sim \frac{W_2}{9\xi L\mathcal{U}_5}\log_2\left(1+\frac{5^{\beta}(3\beta-6)}{(12\beta+1)2^{\frac{1}{2}\beta+1}}\right). \tag{22}$$

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 λ_M^A, since V2V communications are considered almost the same in both BS and WMB deployments. Therefore

$$\lambda_M^A \geq \frac{W_3\log_2(1+SINR_V)P_{ac}}{\bar{\eta_2}} \geq \frac{W_3\log_2\left(1+\mathcal{U}_3(\beta)\right)(\tau_W-1)}{8\xi L(2R_V/L+1)^2\left(\tau_M^2-\tau_W^2\right)}. \tag{23}$$

Asymptotically, we have

$$\lambda_M^A = \Omega\left(\frac{N_M(R_M/L)}{N(R_V/L)^2}\right).$$

Let $(R_M/L) = \tau_M^{\sigma_1}$ establish a relationship between the transmission range of MNs and the area of the mesh square, where $0<\sigma_1<1$. Similarly, $R_V/L = \tau_M^{\sigma_2}$, 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:

$$\lambda_M(N,N_M) = \min\left(\frac{\lambda_M^M}{\mathcal{U}_5}, \min\left(\lambda_M^P,\lambda_M^A\right)\right). \tag{24}$$

Since $\lambda_M^M/\mathcal{U}_5 = \Omega(N^{\gamma-1})$, we obtain the following asymptotic bound of λ_M^M 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 $(M-1)^2L^2/N_M$. Therefore, $R_M \geq \sqrt{2}(M-1)L/\sqrt{N_M}$. Thus, we have

$$\lambda_M^P \geq \frac{(W-W_1)\log_2\left(1+SINR'_{\tau_{MR}}\right)}{9N/N_M} \sim \frac{(W-W_1)N_M}{9N}\log_2\left(1+\frac{5^{\beta}(3\beta-6)}{(12\beta+1)2^{\frac{1}{2}\beta+1}}\right).$$

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

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 $L_R = 2(M-1)^2L/N_R$. 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

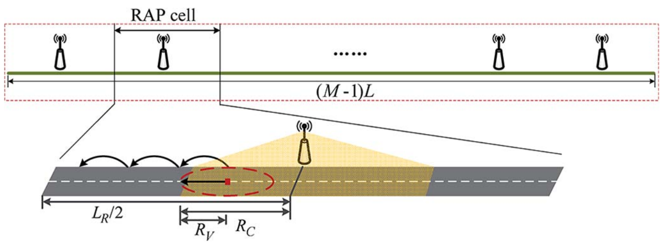

Fig. 6. Grid-like VANETs with deployment of RAPs.

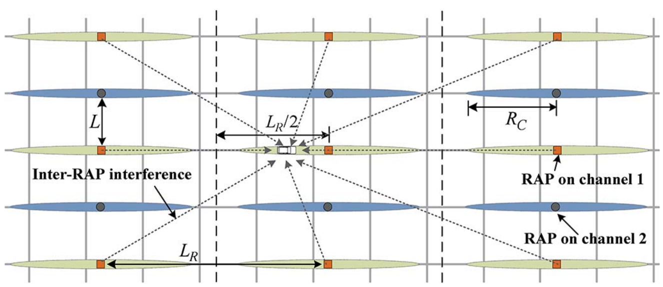

Fig. 7. Illustration of inter-RAP interference for horizontal roads.

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 λ_R^P and λ_R^A, respectively. Similarly, in the hybrid mode

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

We first study the downlink throughput λ_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 $d \le R_C$, 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

$$\begin{aligned} I_d \le & \sum_{q=1}^{\infty}\left[\frac{KP_R}{(qL_R-d)^\beta}+\frac{KP_R}{(qL_R+d)^\beta}\right] \\ & + \sum_{q=1}^{\infty}\frac{2KP_R}{(2qL)^\beta} + \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\frac{4KP_R}{\left(i^2(2L)^2+j^2L_R^2\right)^{\frac{\beta}{2}}} \\ \le & 2KP_R\left[\frac{1}{(L_R-d)^\beta}+\int_1^\infty \frac{1}{(qL_R-d)^\beta}dq\right] \\ & + \frac{2^{1-\beta}\beta KP_R}{(\beta-1)L^\beta} + \frac{2^{2-\beta}KP_R}{(LL_R)^{\frac{\beta}{2}}}\sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\frac{1}{(ij)^{\frac{\beta}{2}}} \\ \le & \frac{2KP_R}{\beta-1}\left(\frac{\beta L_R-d}{L_R(L_R-d)^\beta}+\frac{\beta}{(2L)^\beta}\right) \\ & + \frac{2^{2-\beta}\beta^2KP_R}{(\beta-2)^2(LL_R)^{\frac{\beta}{2}}} \end{aligned}$$

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

$$SINR_d \ge \frac{(\beta-1)/(2d^\beta)}{\frac{\beta L_R-d}{L_R(L_R-d)^\beta}+\frac{\beta}{(2L)^\beta}+\frac{2^{1-\beta}(\beta-1)\beta^2}{(\beta-2)^2(LL_R)^{\frac{\beta}{2}}}} = \mathcal{U}_6(d).$$

For vehicle $\mathcal{V}_d$ at distance d from the RAP, where $d \le R_C$, it follows that

$$\lambda_R^P = W_d \log_2(1+SINR_d)$$

where W_d out of $(1/4)\phi W$ is the bandwidth allocated to $\mathcal{V}_d$. 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 $\bar{\eta_3} = ((1/2)L_R - R_C)/R_V$. Hence, for vehicles at distance $d \in (R_C - R_V, R_C]$ from the RAP

$$\lambda_R^P = \frac{W_d\log_2(1+SINR_d)}{1+\bar{\eta_3}}.$$

Given the constraint of the total bandwidth, we have

$$\begin{aligned}\lambda_R^P \ge & \frac{\frac{1}{4}\phi W}{\frac{2\xi(R_C-R_V)}{\log_2(1+SINR_{R_C-R_V})}+\frac{2\xi(1+\bar{\eta_3})R_V}{\log_2(1+SINR_{R_C})}} \\ \ge & \frac{\frac{1}{8}\phi W/\xi}{\frac{R_C-R_V}{\log_2(1+\mathcal{U}_6(R_C-R_V))}+\frac{R_V+\frac{1}{2}L_R-R_C}{\log_2(1+\mathcal{U}_6(R_C))}}. \end{aligned} \tag{26}$$

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 $\lambda_R^P = \Omega(N_R/N \log_2(N/N_R)) = \Omega(N^{\varphi-1}\log_2 N)$ asymptotically when $\rho_1 < 1/2$, $\lambda_R^P = \Omega(N_R/N) = \Omega(N^{\varphi-1})$ 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 λ_R^A is straightforward, since V2V communications are considered almost the same in all scenarios. Therefore

$$\begin{aligned}\lambda_R^A \ge & \frac{(1-\phi)W\log_2(1+SINR_V)P_{ac}}{\bar{\eta_3}} \\ \ge & \frac{(1-\phi)W\log_2\left(1+\mathcal{U}_3(\beta)\right)R_V}{8\xi L(2R_V/L+1)^2\left(\frac{1}{2}L_R-R_C\right)}. \end{aligned} \tag{27}$$

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

TABLE II
VALUES OF PARAMETERS

Parameter	Value	Parameter	Value
M	201	L	100 m
ξ	0.05 veh/m	N	4×10^5
W	10 MHz	β	4
R_V	100 m	θ	0.25

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 $1/2 < \rho_1 < 1$

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

In particular, when the network is completely covered by RAPs, $\lambda_R(N, N_R) = \lambda_R^P \geq W N_R \log_2(1 + \mathcal{U}_6(R_C))/(4N)$. The asymptotic result of $\lambda_R(N, N_R)$ in the infrastructure mode is the same as that of λ_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 × 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 θ, 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 2.1×10^4 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

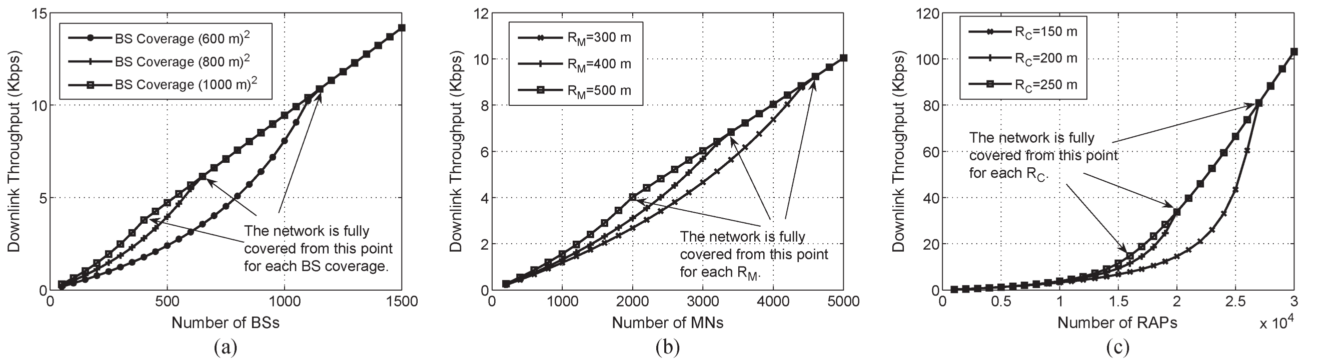

Fig. 8. Impact of the infrastructure node's coverage size on downlink throughput for each type of infrastructure deployments. (a) Network with deployment of BSs. (b) Network with deployment of WMBs. (c) Network with deployment of RAPs.

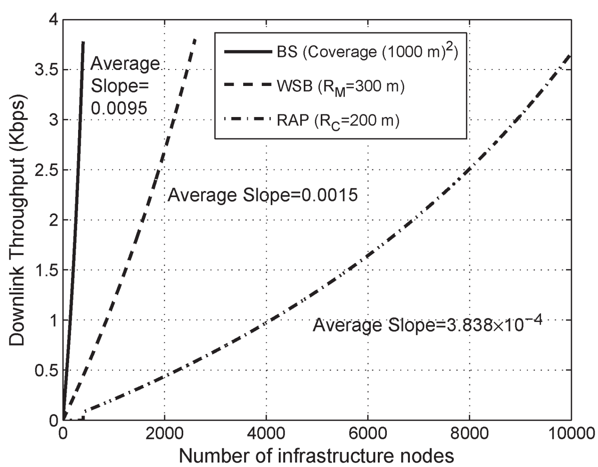

Fig. 9. Comparison of the number of deployed infrastructure nodes in the hybrid mode.

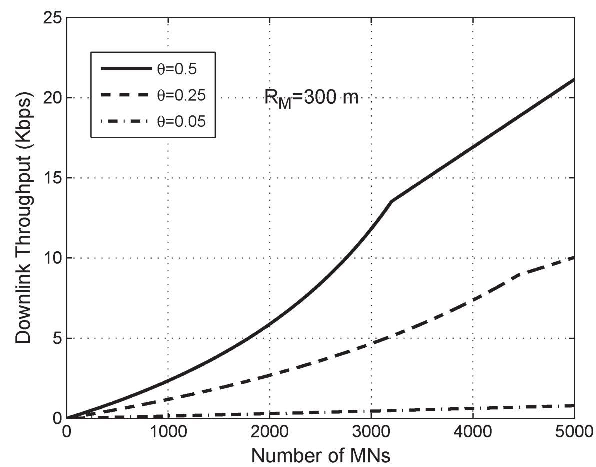

Fig. 11. Impact of θ on the downlink throughput for the deployment of WMBs.

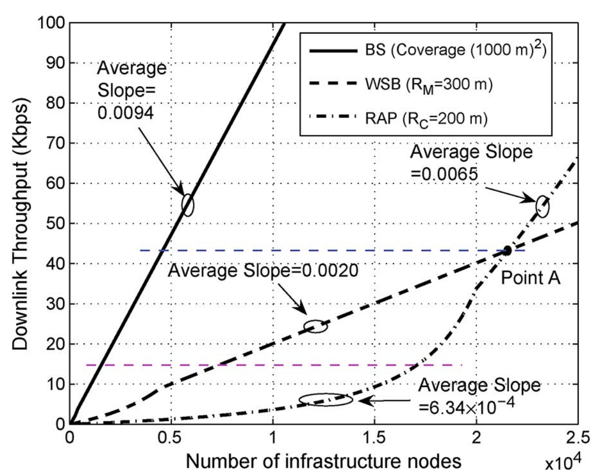

Fig. 10. Comparison of the number of deployed infrastructure nodes in the infrastructure mode.

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.

TABLE III
ESTIMATED DEPLOYMENT COST(K€)

Deployment Cost	BS	MG (MR)	RAP
CAPEX	58.9	10.9 (7.0)	3.0
OPEX (per year)	13.4	2.9 (2.0)	1.4
5-Year Cost	125.9	25.4 (17.0)	10.0

REFERENCES

[1] F. Bai and B. Krishnamachari, "Exploiting the wisdom of the crowd: Localized, distributed information-centric VANETs," *IEEE Commun. Mag.*, vol. 48, no. 5, pp. 138–146, May 2010.

[2] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 584–616, 4th Quart. 2011.

[3] F. Martinez, C. Toh, J. Cano, C. Calafate, and P. Manzoni, "Emergency services in future intelligent transportation systems based on vehicular communication networks," *IEEE Intell. Transp. Syst. Mag.*, vol. 2, no. 2, pp. 6–20, Summer 2010.

[4] R. Lu, X. Lin, X. Liang, and X. Shen, "A dynamic privacy-preserving key management scheme for location-based services in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 127–139, Mar. 2012.

[5] T. Luan, L. Cai, J. Chen, X. Shen, and F. Bai, "VTube: Towards the media rich city life with autonomous vehicular content distribution," in *Proc. IEEE SECON*, Salt Lake City, UT, USA, Jun. 2011, pp. 359–367.

[6] S. Céspedes, N. Lu, and X. Shen, "VIP-WAVE: On the feasibility of IP communications in 802.11 p vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 82–97, Mar. 2013.

[7] R. Lu, X. Lin, T. Luan, X. Liang, and X. Shen, "Pseudonym changing at social spots: An effective strategy for location privacy in VANETs," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 86–96, Jan. 2012.

[8] J. Lin, S. Chen, Y. Shih, and S. Chen, "A study on remote on-line diagnostic system for vehicles by integrating the technology of OBD, GPS, and 3G," *World Acad. Sci. Eng. Technol.*, vol. 56, no. 56, pp. 435–441, Aug. 2009.

[9] M. Ramadan, M. Al-Khedher, and S. Al-Kheder, "Intelligent anti-theft and tracking system for automobiles," *Int. J. Mach. Learn. Comput.*, vol. 2, no. 1, pp. 83–88, Feb. 2012.

[10] KPMG's Global Automotive Executive Survey. [Online]. Available: http://www.kpmg.com/GE/en/IssuesAndInsights/ArticlesPublications/Documents/Global-automotive-executive-survey-2012.pdf

[11] T. Luan, X. Ling, and X. Shen, "MAC in motion: Impact of mobility on the MAC of drive-thru Internet," *IEEE Trans. Mobile Comput.*, vol. 11, no. 2, pp. 305–319, Feb. 2012.

[12] V. Bychkovsky, B. Hull, A. Miu, H. Balakrishnan, and S. Madden, "A measurement study of vehicular Internet access using in situ Wi-Fi networks," in *Proc. ACM MobiCom*, 2006, pp. 50–61.

[13] A. Mahajan, N. Potnis, K. Gopalan, and A. Wang, "Modeling VANET deployment in urban settings," in *Proc. ACM MSWiM*, 2007, pp. 151–158.

[14] N. Banerjee, M. Corner, D. Towsley, and B. Levine, "Relays, base stations, and meshes: Enhancing mobile networks with infrastructure," in *Proc. ACM MobiCom*, 2008, pp. 81–91.

[15] J. Eriksson, H. Balakrishnan, and S. Madden, "Cabernet: Vehicular content delivery using WiFi," in *Proc. ACM MobiCom*, 2008, pp. 199–210.

[16] F. Malandrino, C. Casetti, C.-F. Chiasserini, and M. Fiore, "Content downloading in vehicular networks: What really matters," in *Proc. IEEE INFOCOM*, Shanghai, China, Apr. 2011, pp. 426–430.

[17] C. Stefanovi, D. Vukobratovi, F. Chiti, L. Niccolai, V. Crnojevi, and R. Fantacci, "Urban infrastructure-to-vehicle traffic data dissemination using UEP rateless codes," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 94–102, Jan. 2011.

[18] H. Pishro-Nik, A. Ganz, and D. Ni, "The capacity of vehicular ad hoc networks," in *Proc. Allerton Conf.*, 2007, pp. 1156–1163.

[19] N. Lu, T. Luan, M. Wang, X. Shen, and F. Bai, "Capacity and delay analysis for social-proximity urban vehicular networks," in *Proc. IEEE INFOCOM*, Orlando, FL, USA, Mar. 2012, pp. 1476–1484.

[20] G. Zhang, Y. Xu, X. Wang, X. Tian, J. Liu, X. Gan, H. Yu, and L. Qian, "Multicast capacity for hybrid VANETs with directional antenna and delay constraint," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 4, pp. 818–833, May 2012.

[21] M. Wang, H. Shan, L. Cai, N. Lu, X. Shen, and F. Bai, "Throughput capacity of VANETs by exploiting mobility diversity," in *Proc. IEEE ICC*, Ottawa, ON, Canada, Jun. 2012, pp. 4980–4984.

[22] L. Law, K. Pelechrinis, S. Krishnamurthy, and M. Faloutsos, "Downlink capacity of hybrid cellular ad hoc networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 1, pp. 243–256, Feb. 2010.

[23] P. Li, X. Huang, and Y. Fang, "Capacity scaling of multihop cellular networks," in *Proc. IEEE INFOCOM*, Shanghai, China, Apr. 2011, pp. 2831–2839.

[24] S. Kostof and R. Tobias, *The City Shaped*. London, U.K.: Thames & Hudson, 1991.

[25] M. Garetto and E. Leonardi, "Restricted mobility improves delay–throughput tradeoffs in mobile ad hoc networks," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 5016–5029, Oct. 2010.

[26] A. Siksna, "The effects of block size and form in North American and Australian city centres," *Urban Morphol.*, vol. 1, no. 1, pp. 19–33, 1997.

[27] I. W.-H. Ho, K. K. Leung, and J. W. Polak, "Stochastic model and connectivity dynamics for VANETs in signalized road systems," *IEEE/ACM Trans. Netw.*, vol. 19, no. 1, pp. 195–208, Feb. 2011.

[28] H. Xia, "A simplified analytical model for predicting path loss in urban and suburban environments," *IEEE Trans. Veh. Technol.*, vol. 46, no. 4, pp. 1040–1046, Nov. 1997.

[29] J. Lee, R. Mazumdar, and N. Shroff, "Joint resource allocation and base-station assignment for the downlink in CDMA networks," *IEEE/ACM Trans. Netw.*, vol. 14, no. 1, pp. 1–14, Feb. 2006.

[30] F. Baccelli and B. Blaszczyszyn, "Stochastic geometry and wireless networks Volume I: Theory," *Found. Trends Netw.*, vol. 3, no. 3/4, pp. 249–449, Mar. 2009.

[31] F. Baccelli and B. Blaszczyszyn, "Stochastic geometry and wireless networks Volume II: Applications," *Found. Trends Netw.*, vol. 4, no. 1/2, pp. 1–312, Jan. 2009.

[32] M. Haenggi and R. Ganti, *Interference in Large Wireless Networks*. Delft, The Netherlands: Now, 2009.

[33] K. Johansson, "Cost effective deployment strategies for heterogeneous wireless networks," Ph.D. dissertation, Kommunikationsteknik, Kungliga Tekniska högskolan, Stockholm, Sweden, 2007.

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