Optimal Relay Selection in IEEE 802.16j Multihop Relay Vehicular Networks

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***Abstract*—This paper examines the IEEE 802.16j multihop relay (MR) technology that improves vehicle-to-infrastructure communications. We study the selection of optimal relay station (RS) for a vehicular subscriber station (SS) that maximizes the end-to-end capacity, assuming that the locations of vehicular SSs are known. By incorporating a highway mobility model, the problem can be formulated into a nonlinear optimization problem and solved for the optimal locations of RSs that guarantee maximal end-to-end capacities to SSs. Numerical results from a case study show that the selection of the corresponding optimal RS increases the expected end-to-end capacity for individual SSs by 50%, as compared with the method without using relays.**

***Index Terms*—Capacity, highway mobility, IEEE 802.16j, multihop relay (MR), vehicular communications.**

I. Introduction

The DEMAND for wireless vehicular communications has increased in recent years. Many automobile manufacturers have shown their interest in integrating communication devices with vehicles to provide added values in safety, entertainment, and mobile commerce. For future vehicular networks, one of the major goals of network operators is to provide quality of service (QoS) for both safety applications and conventional nonsafety applications [1]. Dedicated short-range communication (DSRC) has been proposed as a key enabling technology for safety applications [2]. While DSRC is designed for short-to-medium-range (up to 1 km) communication services, IEEE 802.16 [3] provides longer range communications with the measured transmission range of a few kilometers. Taking advantage of both systems, an integrated IEEE 802.16/DSRC network would allow for a wider choice in data rate and network coverage to satisfy the requirement of the desired vehicular communications [4]. In this paper, we focus on the provision of vehicle-to-roadside communications for nonsafety applications such as in-vehicle Internet access.

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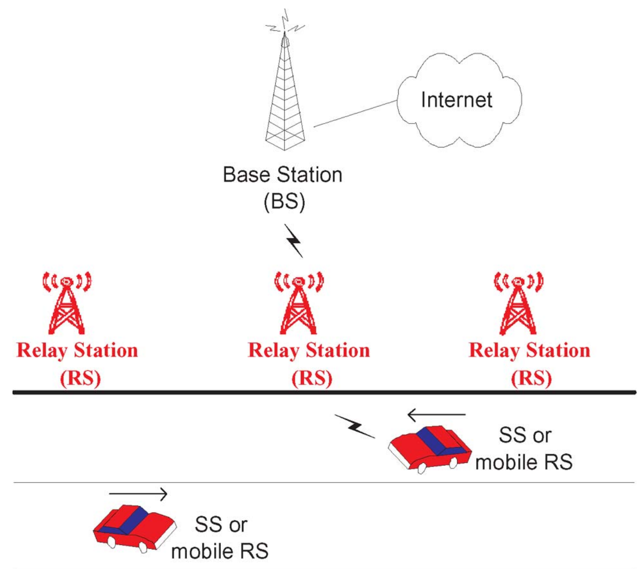


Fig. 1. IEEE 802.16j vehicular network.

Although IEEE 802.11 is the recommended wireless protocol for intelligent transportation systems [2], the performance of IEEE 802.11 is limited in vehicular environments due to the contention and nondeterministic nature of its wireless media access [5]. IEEE 802.16 [3] has emerged as a promising technology for ubiquitous mobile broadband wireless services of metropolitan scale due to its long range and high data rate features. The IEEE 802.16j standard [6] has been proposed by standardization bodies for supporting mobile and multihop relay (MR) in vehicular communications. One of the important usage models defined in the IEEE 802.16j standard is for transport systems, such as highways, railways, and near-land rivers and seas [7].

In this paper, we consider an IEEE 802.16j MR network for vehicular communications. A vehicular subscriber station (SS) accesses the Internet through IEEE 802.16j base stations (BSs), which have wired connections to the Internet. Relay stations (RSs) are deployed along the road as roadside units (RSUs). The RSs are not directly connected to the wired backhaul and are responsible for relaying data between the SSs and the BS. Fig. 1 depicts an example of an IEEE 802.16j vehicular network for highway deployment, where each vehicle is equipped with an IEEE 802.16 SS (and RS if possible). An SS directly connects either to a BS or to an RS, depending on the location of the SS and other routing criteria.

In an IEEE 802.16j vehicular network, RSs are responsible for relaying control messages and data packets between the BSs and the SSs. The proper selection of an RS to serve a particular vehicular SS is crucial in achieving good end-to-end throughput performance. We study the problem in selecting the optimal RS to achieve the maximum end-to-end capacity for vehicular SSs. Our approach to selecting an RS is to first identify the location of the optimal RS for a given SS and then select the most appropriate one from (possibly) many candidate RSs. The optimal RS may be a stationary RSU or a vehicular RS [8], similar to the scenario studied by Taleb *et al.* [9]. We consider that the battery life of an RS is long or unlimited so that the energy-saving strategy is not considered.

The major contributions of this paper are as follows: First, we propose a scheme for locating and selecting the optimal RS, which incorporates link adaptation technology with the objective of maximizing the end-to-end capacity. We formulate the optimal RS selection problem as a nonlinear optimization problem and solve it for a vehicular SS moving along a highway. Second, we provide a detailed case study based on the link capacity data in the Erceg terrain model [10]. Finally, we study the highway mobility pattern in detail for performance analysis on the end-to-end capacity. In our optimal relay analysis, the capacity problem is viewed as an extension to the traditional connectivity problem, where the probability of node locations is studied for a given mobility pattern. Numerical results based on the case study show that, by locating and selecting the corresponding optimal RS, the expected end-to-end capacity for individual SSs can be increased by near 50%, as compared with the method when no relay is used, and the capacity increase is also greater than other relay selection methods.

The remainder of this paper is organized as follows: The system model is described in Section II. In Section III, we study the probabilistic distribution of capacity in a highway mobility pattern. The optimization problem for locating RS is formulated and solved in Section IV. A case study based on the link capacity data in the Erceg model is presented in Section V, and its numerical results are presented in Section VI. The related work is reviewed in Section VII. Finally, Section VIII draws conclusions and presents future work.

II. System Model

A. Communication Protocol

IEEE 802.16j MR networks [6] exhibit many attractive features for supporting vehicular communications, including the support for multihop and mobility, long-range coverage, and wider choices in QoS support. As shown earlier, Fig. 1 is an example of the IEEE 802.16j vehicular network, with its three system components, namely, BS,[1] RS, and SS. The BS is directly connected to the wired backhaul and provides connectivity, management, and control of RSs and SSs. The RSs are responsible for relaying data between the SSs and the BS. When the link condition between a BS and an SS is poor, the data rate of one-hop transmissions between them will be compromised. In such a situation, IEEE 802.16j MR allows one or more RSs to be deployed between BSs and SSs, thereby extending the coverage and enhancing the performance of the network.

Unlike BSs, RSs are not directly connected to a wired backhaul; thus, they can be more rapidly deployed. The functionalities of RSs are considerably less complex than those of BSs, and therefore, the RS deployment cost is also expected to be much lower compared with that of the BS. This feature makes the IEEE 802.16j system an attractive solution for wide-area coverage and economical deployment.

Many transport systems, such as highways, railways, and near-land rivers and seas, have a common highway mobility pattern. IEEE 802.16j defines these transport systems as one of its usage models to support [7]. In this paper, we focus on capacity analysis based on the highway mobility pattern, whereby a moving vehicle carries an SS (and a mobile RS if possible). The SS on the vehicle will directly communicate with a BS or through an RS, which can be a fixed RS mounted on a tower or a lamp post or a mobile RS carried by another vehicle.

B. Link Adaptation in Wireless Networks

The link transmission rate is one of the important factors in the deployment of RSs. IEEE 802.16j uses an adaptive modulation and coding (AMC) scheme for allocating different transmission rates to different channel conditions [11]. The AMC scheme divides the received SNR into N nonoverlapping regions, where N is the number of transmission modes the system supports. The N data rates that the system supports are denoted by C_i, where $i = 1, 2, \ldots, N$. In addition, without loss of generality, we assume that $C_1 < C_2 < \cdots < C_N$. When the received SNR at time t, i.e., SNR(t), is estimated to be in the ith region $(i = 1, 2, \ldots, N)$, i.e., SNR$(t) \in [\mathrm{SNR}_i, \mathrm{SNR}_{i+1})$, transmission mode M_i is assigned to the link, and the data transmission rate over this link is C_i. When SNR$(t) < \mathrm{SNR}_1$, there is no direct connection between the two nodes. When SNR$(t) \geq \mathrm{SNR}_N$, the highest order of transmission mode M_N is applied to the link. When the SNR increases at the receiver, the sender will adopt a higher order transmission mode to transmit at a higher achievable rate of the link. Similarly, as the SNR gets worse, the sender switches its transmission mode to a lower order to adapt to the degraded channel condition.

In AMC, the time-varying distance between two communicating nodes plays a major role in choosing the link transmission rate. Let x be the distance between a communicating pair, then the link data rate $C(x)$ is a step function of x. If capacities are expressed using the discrete step function, then it is difficult to obtain a solution that has a generic form for the optimal RS selection problem (explained later in Section IV). Nevertheless, we use a continuous power function $C(x) = Ax^B$ [12] to express the rate-distance relationship to obtain a generic form of the solution for the optimization problem.

In this paper, the term "link capacity" refers to the data transmission rate in a link, which, in turn, depends on its link transmission mode. The term "end-to-end capacity" refers to the end-to-end data transmission rate or end-to-end throughput. In the rest of this paper, we use "a node is in transmission mode i" and "a node can transmit with rate C_i" interchangeably.

[1] The IEEE 802.16j standard defines BS as multihop relay BS. We simply denote it as BS in this paper.

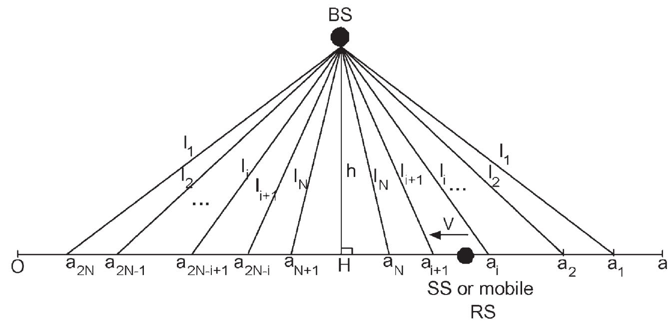


Fig. 2. Generic model of adaptive transmission in highway mobility.

III. Capacity Distribution in Vehicular Networks With a Highway-Mobility Pattern

A. Capacity With a Distance-Dependent Path-Loss Model

For moving vehicles, the internode distances change with time, which, in turn, affect the received SNR due to path loss of the wireless channel. In this paper, for the ease of analysis, link adaptation is studied based on a distance-dependent path-loss model with simplified shadowing and fade margins as in [13].

Fig. 2 depicts an example of our highway mobility model. The highway on which an SS can travel is modeled as a straight line that is h distance away from the BS. Let H be the point where the location of the BS is projected onto the highway; therefore, the distance between the BS and H is h. Let an SS start at a distance a away from the reference point O and move toward it. The distance between the SS and the BS decreases as the SS is moving toward the point H and then increases as it is moving away from the point H. Let $l_1, l_2, \ldots, l_N$ be the maximum link distance that a corresponding link rate of $C_1, C_2, \ldots, C_N$ can be supported, and as in Section II-B, $C_1 < C_2 < \cdots < C_N$ with $l_1 > l_2 > \cdots > l_N$. Let the point $i = 1, 2, \ldots 2N$ be the location where a transmission mode switch is needed, i.e., the transmission rate C_i needs to be switched to C_{i+1} or C_{i-1}. As shown in Fig. 2, each switching point i is associated with a_i, which is its distance to the reference point O, and l_i, which is its distance to the BS, for $i \leq N$ and l_{2N-i+1} for $i > N$. The switching distances l_i and l_{i+1} can be computed according to a specific path-loss model or empirically measured.

Let L be the distance between the BS and an SS, and let P_i be the probability that the link data rate $C(x)$ is equal to C_i, $i = 1, 2, \ldots, N$; then

$$P_i = \begin{cases} P(l_{i+1} < L \leq l_i), & \text{for } i = 1, 2, N-1 \\ P(0 < L \leq l_i), & \text{for } i = N. \end{cases} \tag{1}$$

The capacity between an SS and the BS is studied in terms of the SS's location on the highway, namely, its distance to the reference point O. Note that, as the model shown in Fig. 2, while an SS moves along the highway segment covered by the BS, there are two locations where it would switch its transmission rate to C_i for $i \neq N$. The two locations, defined by their distances to the reference point O, are a_i and a_{2N-i+1}, which correspond to $L = l_i$. There is only one location where the rate is switched to C_N, i.e., the point N with a_N as its distance to the reference point. In the following section, we calculate the probability P_i by first deriving the probabilistic distribution of node locations in the highway mobility pattern.

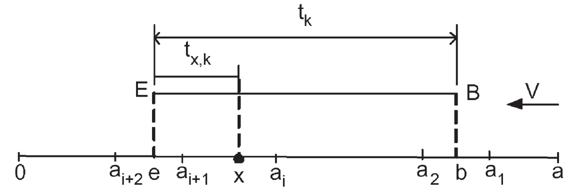


Fig. 3. Movement period of a mobile node.

B. Probabilistic Distribution of Node Locations in the Highway Mobility Pattern

Vehicles traveling on a highway are guided to move along a fixed path and in a certain direction. A mobile node carried by a vehicle moves at a certain speed on a highway and may change its speed along the way; however, it may only be allowed to change its direction at a designated location such as at the end of the highway segment or at a "U-turn" point of the highway. In our proposed generic highway mobility model, a node initially chooses a random destination E_1 on a highway and moves at a constant speed v_1 toward E_1. Once the node reaches E_1, it randomly chooses another destination E_2 ahead and moves at another constant speed v_2 toward E_2. This process is repeated until the node reaches the end of the highway. For the ease of analysis, if the highway is not a straight line, it will be modeled as a few straight-line highway segments.

We now assume that a node moves at a speed V on a straight-line highway segment with length a. A random variable X denotes the location of the node, where $X \in [0, a]$. The speed V is a random variable, and its magnitude may change at any location along the highway segment. We define a *movement period* as the trajectory of a node when the node travels at a constant speed. Let random variables B and E denote the beginning and ending locations of a movement period, with distances b and e to the reference point at the left end of the highway, as shown in Fig. 3. Because the node moves in a single direction, $b > e$ holds in any movement period. B and E are randomly chosen on the highway segment, which follow uniform distributions.

To derive the probability density function (pdf) $f_X(x)$, let us first calculate the cumulative distribution function (cdf) $F_X(x) = P(X \leq x)$, which denotes the probability that a node is located in $[0, x]$ at an arbitrary instant of time.

For a movement period k, let t_k denote the duration of this period, and let $t_{x,k}$ denote the duration that the node spends within $[0, x]$ during period k. If the kth movement period does not intersect $[0, x]$, $t_{x,k} = 0$. Fig. 3 shows the concept of t_k and $t_{x,k}$.

We now observe the process for K movement periods. As K goes to infinity, the time that a node spends within $[0, x]$ during K movement periods, divided by the total duration of the K movement periods, converges toward $P(X \leq x)$. That is

$$P(X \leq x) = \lim_{K \to \infty} \frac{\sum_{k=1}^{K} t_{x,k}}{\sum_{k=1}^{K} t_k}. \tag{2}$$

Let D denote the distance traveled by the mobile node over an entire movement period, V denote the speed of the node during the movement period, and T denote the duration that the node stays in the movement period. Similarly, let D_x denote the distance of a movement period that intersects with $[0, x]$, and let T_x denote the duration that the node spends within $[0, x]$ during the movement period. Note that $T_x = D_x/V$. D, V, T, D_x, and T_x are random variables. As V and D are independent, V and D_x are also independent, and hence, from (2), we get

$$P(X \leq x) = \lim_{K\to\infty} \frac{\sum_{k=1}^{K} t_{x,k}}{\sum_{k=1}^{K} t_k} = \frac{E[T_x]}{E[T]} = \frac{E[D_x]}{E[D]}. \tag{3}$$

From (3), we derive two lemmas with regard to $E[D]$ and $E[D_x]$. Their proofs are given in Appendixes A and B.

Lemma 1: The expected distance traveled by a mobile node over an entire movement period can be expressed as $E[D] = a/4$, where a is the length of the highway segment, as shown in Fig. 2.

Lemma 2: The expected distance traveled by a mobile node over a movement period intersecting with $[0, x]$ can be expressed as $E[D_x] = (x^2/2a)(\ln a - \ln x) + (x^2/4a)$.

From (3), Lemmas 1 and 2, we derive the following theorem.

Theorem 1: The cdf of the location of a mobile node traveling along a line segment with length a is

$$F_X(x) = \begin{cases} \frac{2x^2}{a^2}(\ln a - \ln x) + \frac{x^2}{a^2}, & \text{for } 0 < x \leq a \\ 0, & \text{for } x \leq 0 \\ 1, & \text{for } x > a. \end{cases} \tag{4}$$

From (4) and (1), we obtain the following theorem:

Theorem 2: The probability of a mobile node traveling along a line segment with length a in transmission mode i is

$$\begin{aligned} P_i(i \neq N) = & \frac{(1 + 2\ln a)\left(a_i^2 - a_{i+1}^2\right)}{a^2} \\ & - \frac{2a_i^2 \ln a_i - 2a_{i+1}^2 \ln a_{i+1}}{a^2} \\ & + \frac{(1 + 2\ln a)\left(a_{2N-i}^2 - a_{2N-i+1}^2\right)}{a^2} \\ & - \frac{2a_{2N-i}^2 \ln a_{2N-i} - 2a_{2N-i+1}^2 \ln a_{2N-i+1}}{a^2} \end{aligned} \tag{5}$$

$$\begin{aligned} P_i(i = N) = & \frac{(1 + 2\ln a)\left(a_N^2 - a_{N+1}^2\right)}{a^2} \\ & - \frac{2a_N^2 \ln a_N - 2a_{N+1}^2 \ln a_{N+1}}{a^2} \end{aligned} \tag{6}$$

where a_i, a_{i+1}, a_{2N-i}, and a_{2N-i+1} are the switching points of transmission mode i. The pdf of the location X of a mobile node moving along a highway segment with length a according to the highway mobility model is then expressed as $f_X(x) = (4/a^2)(x \ln a - x \ln x)$ for $0 < x < a$, and 0 otherwise.

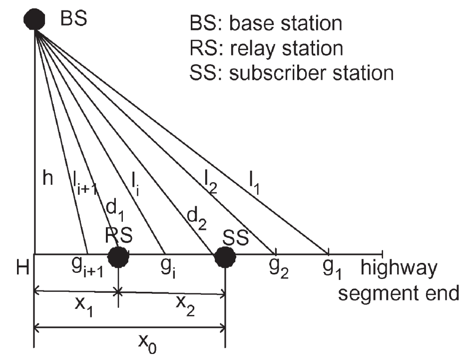


Fig. 4. Locating the optimal RS.

IV. Locating the Optimal Relay Station

If each SS directly communicates with the BS, the expected capacity in the system is $E[C] = \sum_{i=1}^{N} P_i C_i$. According to existing path-loss models for different terrains studied by Joseph and Martens [13], the transmission rate drops faster than linear when the transmitter–receiver distance increases.

Due to the fast attenuation of rate over distance, transmitting through relay nodes is more efficient than directly transmitting over a long-distance link. Through relaying, a single low-SNR link is replaced with multiple higher SNR links over which higher transmission rates can be supported. Hence, higher end-to-end capacities can be achieved for SSs. Selecting different RSs can result in different end-to-end capacities achieved for a particular SS. We are interested in locating the optimal RS such that the end-to-end capacity of an SS is maximized. In this paper, we consider only one- or two-hop transmissions between a BS and an SS as smaller topologies are preferred in most deployments, due to the resulting lower complexity and lower cost in the overall system [14].

Fig. 4 depicts the generic optimal relay-locating problem for the highway mobility pattern. As shown, H is the point where the BS is projected on the highway, and h is the distance between the BS and H. x_0 is the distance between an SS and H at a given time. The candidate RS is located between H and the SS.

Let us denote the distance between an RS and H as x_1, the distance between the RS and a specific SS as x_2, and $x_1 + x_2 = x_0$. The distance between the BS and the RS is denoted by d_1, and the distance between the SS and BS is d_2. The problem in locating an optimal RS can then be defined as follows: Given a path-loss pattern and an SS with distance x_0 from H, locate the optimal RS with a distance x_1^* from H that maximizes the end-to-end capacity between the BS and the SS.

Let the two-hop capacity between a BS and an SS be C_{e2e}, the one-hop capacity between the BS and the RS be C_1, and the one-hop capacity between the RS and the SS be C_2. We assume that all nodes operate in the half-duplex mode and RSs employ the decode-and-forward scheme. In addition, we assume that only one link can transmit at a time within a cell controlled by a BS and there is no intracell interference. If the BS transmits S bits to the SS over the two-hop transmission, the BS first sends the bits to the RS, and the RS, in turn, relays the S bits to the SS. Because only one node can transmit at a time in the cell, the transmissions over the relay link and the access link are nonconcurrent. According to Kim and Liu's analysis [15], the end-to-end capacity is

$$C_{e2e} = \left[\frac{1}{C_1} + \frac{1}{C_2}\right]^{-1} = \frac{C_1 C_2}{C_1 + C_2}. \tag{7}$$

The problem in locating the optimal RS is then expressed as

$$\text{Maximize}: C_{e2e} = \frac{C_1 C_2}{C_1 + C_2} \tag{8}$$

$$\text{subject to}: x_1 + x_2 = x_0. \tag{9}$$

As IEEE 802.16 medium access control (MAC) is TDMA based, transmissions are conducted in the allocated minislots. The number of minislots used in a given transmission is therefore inversely proportional to the capacity of the link. Hence, from (8), the optimal RS is the one that minimizes the total number of data minislots required by the entire route to deliver a certain amount of bits. Here, the link cost metric is defined as the inverse of the link transmission rate.

If capacities are expressed using the AMC discrete step function, it is difficult to obtain a solution that has a generic form for the optimization problem expressed in (8). Nevertheless, using a fitted power function $C(x) = Ax^B$ [12] to express the rate–distance relationship, the problem becomes tractable, and a generic form of the solution can be found.[2] Let the one-hop capacity between the BS and the RS, i.e., C_1, be modeled as $C_1(x_1) = A_1 x_1^{B_1}$. Similarly, the one-hop capacity between the RS and the SS, i.e., C_2, is modeled as $C_2(x_2) = A_2 x_2^{B_2}$. Using the two capacity functions ($A_1 \neq A_2$ and $B_1 \neq B_2$), the optimization problem in (8) is rephrased as

$$\text{Maximize}: C_{e2e} = \frac{A_1 x_1^{B_1} \cdot A_2 x_2^{B_2}}{A_1 x_1^{B_1} + A_2 x_2^{B_2}} \tag{10}$$

$$\text{subject to}: x_1 + x_2 = x_0. \tag{11}$$

Solving the optimization problem in (10) using the method of Lagrange multipliers, we get

$$x_1 = \left(\frac{A_2 B_1}{A_1 B_2}\right)^{\frac{1}{B_1+1}} \cdot (x_0 - x_1)^{\frac{B_2+1}{B_1+1}}. \tag{12}$$

Equation (12) is an implicit expression, and it is prohibitively difficult to obtain a generic form of the solution. Fortunately, in a practical system, A_1, A_2, B_1, and B_2 can be found using a curve-fitting method. An approximate solution can be obtained using an iterative method subject to an error bound. In the following section, we will provide a case study to illustrate the method for locating the optimal RS.

V. Case Study

The case study is based on the link capacity data in the Erceg model [10] recommended by the IEEE 802.16 standard. The Erceg model covers three most common suburban terrain categories found across the United States. The path-loss model for each terrain is named Erceg A, Erceg B, and Erceg C. Among the three models, the transmission rate in the Erceg A model attenuates most rapidly over distance, whereas that in the Erceg C model attenuates the slowest. The Erceg B model, which is considered in this case study, captures the intermediate path-loss condition.

TABLE I
Link Data in the Erceg B Model

TX scheme	Data rate (Mbps)	l_i (km)	g_i (km)	Probability
Null	0	>3.2	>3.0397	0.0364
BPSK 1/2	1.269	3.2	3.0397	0.1004
QPSK 1/2	2.538	2.7	2.5080	0.0537
QPSK 3/4	3.816	2.5	2.2913	0.2032
16-QAM 1/2	5.085	1.9	1.6155	0.0823
16-QAM 3/4	7.623	1.7	1.3748	0.1995
64-QAM 2/3	10.161	1.3	0.8307	0.0641
64-QAM 3/4	11.439	1.2	0.6633	0.2604

The case study is based on the generic optimal relay selection problem for the highway mobility pattern shown in Fig. 4. Each capacity switching point i has a distance g_i to the point H, and $g_i = \sqrt{l_i^2 - h^2}$. The Erceg B data from Joseph and Martens's study [13] are retabulated in columns 1–4 in Table I, assuming $h = 1$ km and 10% of MAC overhead [16].

Assuming that the highway segment length a is 7 km and $h = 1$ km, the probabilities of one-hop capacity in the Erceg B model are calculated using Theorem 2. The probabilities are shown in column 5 in Table I. In such a configuration, 3.64% of nodes do not have direct connection to the BS.

Using curve-fitting software, we manage to fit the data in columns 1–4 in Table I into power functions $C_1(x_1) = A_1 x_1^{B_1}$ and $C_2(x_2) = A_2 x_2^{B_2}$ to get the optimal solution in (12). The fitted parameters are $A_1 = 7.638$, $B_1 = -1.109$, $A_2 = 16.01$, and $B_2 = -1.706$.

Substituting A_1, B_1, A_2, and B_2 into (12), we get

$$x_1 = 0.05852 \times (x_0 - x_1)^{6.4771}. \tag{13}$$

With a given x_0, we use an iterative method to solve x_1 in (13). For example, given $x_0 = 3.0$ and an error not more than 1%, the solution of (13) is $x_1 = 1.372$. This implies that the solutions for the optimization problem in (10) are $x_1^* = 1.372$ and $x_2^* = 1.628$.[3] The interpretation of the solutions is as follows: When an SS is 3.0 km away from location H (possibly on both sides), and an RS with a distance of 1.372 km from H is selected, then the end-to-end capacity between the BS and SS is maximal.

In a practical system, x_1^* would generally fall between two switching points, i.e., $g_{i+1} < x_1^* \leq g_i$ for some i, where a specific capacity of a BS–RS link is sustained between the points i and $i+1$. Therefore, the optimal RS's distance to H can be anywhere between x_1^* and g_i without compromising the capacities of both BS–RS and RS–SS links. We call the region of $[x_1^*, g_i]$ in Fig. 4 the *selection margin*. As long as the optimal RS is in the *selection margin*, the target end-to-end capacity can be achieved.

[2] The Shannon capacity formula ($C(x) = W \log_2(1 + (M/x^\alpha))$, where W and M are system constants, and α is the path-loss exponent) also leads to the same rate–range relationship with a reference regime of $C(x) > 10$ kb/s and $x < 10$ km [12].

[3] We have proved that the sufficient condition exists for the solutions to be optimized. The proof is omitted due to space limitations.

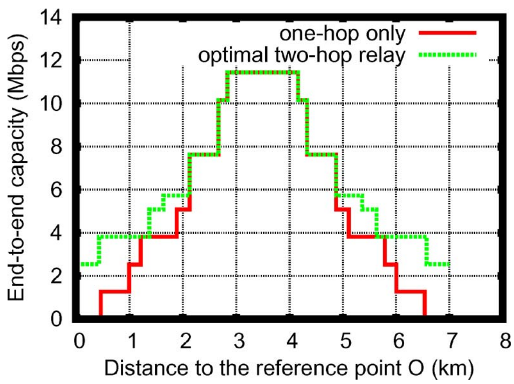


Fig. 5. End-to-end capacity of an SS at different locations.

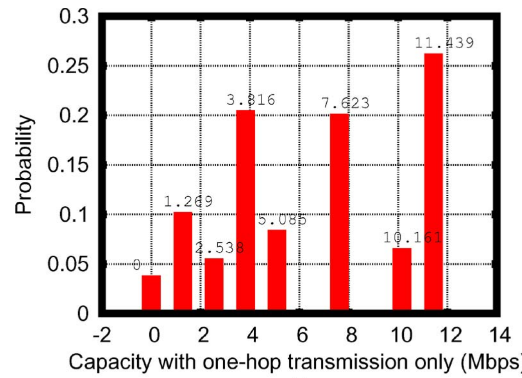
In the actual deployment of vehicular networks, the BS can obtain link capacities at different geographical locations based on specific terrain models or measured results (as in columns 1–4 of Table I). It can then fit the link capacity data into the power functions so that the relevant parameters are found. When these parameters are substituted into (12), the location of the optimal RS x_1 can be solved for a given SS location x_0. Therefore, following the steps illustrated in our case study, the BS can identify the *selection margin* of the optimal RS offline for any possible location of an SS. The optimal RS for each selection margin can preemptively be transmitted to a vehicular SS or as soon as it enters into the segment.[4] Since the BS can find the optimal RS for a particular SS based on precomputed data, the delay in selecting the optimal RS is minimal.

VI. Performance Study

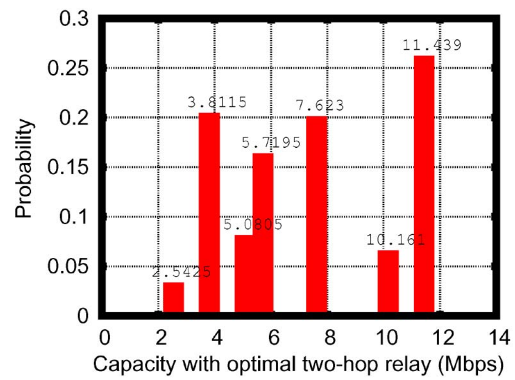
In this section, we evaluate the *optimal two-hop relay* scheme, which works as follows: First, the location of the RS that increases the end-to-end capacity the most is identified. If such an RS exists, the transmission is done via two hops. In cases where the two-hop transmission does not increase the end-to-end capacity, the one-hop transmission is used. The numerical evaluation was conducted using MATLAB for the case study in Section V. The scenario depicted in Fig. 4 was considered, where the highway segment length was assumed to be 7 km and $h = 1$ km. Columns 1–2 of Table I summarize the link rates of this scenario for the Erceg B terrain model. According to the data in Table I, if the one-hop capacity between the BS and the SS is equal to or larger than 7.623 Mb/s, the one-hop transmission is chosen over the two-hop transmission in the optimal two-hop relay scheme.

Fig. 5 compares the end-to-end capacity of the one-hop only transmission and the optimal two-hop relay for our case-study scenario. Let the location of an SS be represented by the distance between the SS and the reference point O on the highway, as shown in Fig. 2. In our scenario, the optimal two-hop relay scheme would select an RS for the two-hop transmission if the SS's location falls outside the range of [2.1252 km, 4.8748 km]. When the SS's location falls inside the range of [2.1252 km, 4.8748 km], the one-hop capacity between the BS and the SS is equal to or larger than 7.623 Mb/s; thus, the one-hop transmission is applied. Fig. 5 shows that, when the SS is farther away from the BS, the two-hop transmission achieves a higher end-to-end capacity compared with the one-hop transmission to the BS.

[4]If multiple RSs are present in the *selection margin*, the decision criteria can be based on many factors, such as the mobility pattern of RSs. The decision criteria are outside the scope of this paper.



(a)



(b)

Fig. 6. End-to-end capacity distributions. (a) Probability distribution of the end-to-end capacities with the one-hop only transmission. (b) Probability distribution of the end-to-end capacities with the optimal two-hop relay.

Fig. 6 plots the probability of end-to-end capacities, where the numbers on top of each column indicate the capacity values in megabits per second. It compares the capacity probability of the one-hop only transmission scenario [see Fig. 6(a)] with that of the optimal two-hop relay [see Fig. 6(b)]. Based on the numerical results in Fig. 6, the expected end-to-end capacity can be increased by 49.86% for the optimal two-hop relay. Furthermore, the optimal two-hop relay extends the network coverage from 96.36% to 100%.[5] The capacity increase can be more significant when the one-hop capacity is lower.

Fig. 7 combines the cdf of the end-to-end capacities using the one-hop only transmission and the optimal two-hop relay scheme. With the one-hop only transmission, 90% of the nodes achieve 0.6 Mb/s or larger capacity, whereas with the optimal two-hop relay scheme, 90% of the nodes can achieve 3 Mb/s or larger capacity. Comparably, with the one-hop only transmission, 70% of the nodes achieve 3.2 Mb/s or larger capacity, whereas with the optimal two-hop relay scheme,

[5]With the one-hop only transmission, 3.64% of the highway area is uncovered (with rate 0), as shown in Fig. 6(a).

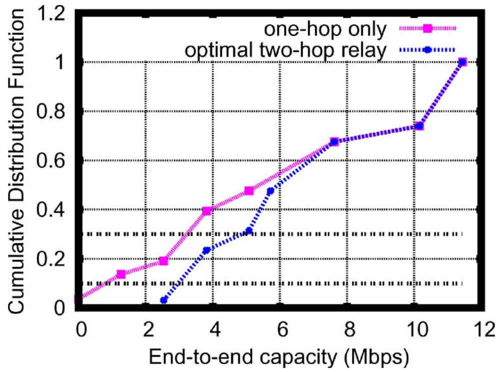


Fig. 7. CDF comparison of the end-to-end capacities between the one-hop only transmission and the optimal two-hop relay scheme.

70% of the nodes can achieve 5.1 Mb/s or larger capacity. When the one-hop capacity between the BS and the SS is equal to or larger than 7.623 Mb/s, the optimal two-hop relay scheme would choose to use the one-hop transmission since transmission through relaying will not increase the end-to-end capacity. Fig. 7 shows that, by applying the optimal two-hop relay scheme, we can significantly increase the overall end-to-end capacity. Our numeric study also shows that the optimal two-hop relay selection scheme always achieves the highest capacities compared with other schemes such as random-selection and middle-point selection methods.

VII. Related Work

Vehicular communications have attracted a number of research interests and efforts in recent years. Similar to our work, many studies aim to improve performance of vehicular networks. Namboodiri *et al.* [14] and Zhao and Cao [17] evaluated the performance improvement using a prediction-based forwarding scheme in vehicular networks. Ling *et al.* [18] proposed preemptive handoff schemes to select the best available network interface for achieving optimal network capacity in vehicular networks with heterogeneous wireless technologies. For IEEE 802.16-enabled vehicular networks, Yang *et al.* proposed a multihop cluster-based protocol [5] to increase the end-to-end throughput while ensuring fairness guarantee among segments. Fiore and Harri studied vehicular mobility patterns and their impact on the network topology and connectivity [19] using metrics such as link duration, nodal degree, and cluster numbers.

Similar to our effort to develop a relay-node selection strategy, previously, researchers have studied the relay node placement problem for wireless sensor networks, wireless local area networks, and cellular networks. While some focused on maximizing the lifetime of wireless networks [20], [21], others targeted at maximizing the data rate received at the BS [22] and minimizing the number of relay nodes [23]. The benefits of using relay to improve capacity have been studied by Lin and Hsu [24] and Zhu and Cao [25] for IEEE 802.11 networks.

Related research on route selection has been conducted for IEEE 802.16 mesh networks. Wei *et al.* [26] used a blocking metric for route selection, which was defined as the total number of one-hop neighbors of the nodes along a path. Algorithms for constructing routing trees in IEEE 802.16 mesh networks were proposed by Nahle *et al.* [27] using metrics such as end-to-end data rates.

This paper proposed a relay selection scheme specific to the IEEE 802.16j technology. More research in this area has recently emerged. Lin *et al.* studied the single RS placement problem for static SSs in IEEE 802.16j networks [28]. Theodoros and Kostantinos measured the achievable throughput between an SS and a BS at different distances [29]. Ann *et al.* [30] proposed a path selection method considering the link available bandwidth.

VIII. Conclusions and Future Work

In this paper, we have studied the optimal RS selection problem for maximizing the end-to-end capacity in an IEEE 802.16j-based vehicle-to-infrastructure network. We developed an analytical model for locating and selecting the optimal RS based on the locations of SSs, where higher capacity links are selected in the path. A case study was presented based on the link capacity data in the Erceg terrain model. Numerical results from our case study demonstrate that the end-to-end capacity can be significantly increased by using the selected optimal RS. In actual implementations, the corresponding optimal RS for an SS can be computed offline by the BS using our proposed method to minimize delays.

The current model assumes that the Doppler effect on link capacity is weak and ignorable in the analysis (e.g., when vehicles move in relatively slow speeds). In a practical scenario, a vehicular SS may experience different link capacities at the same location when it is moving toward or away from the BS. In such a case where the Doppler effect is present, the capacity switching points in the highway model shown in Fig. 2 will not be symmetric. We plan to extend the current research to consider the Doppler effect in our future work.

Appendix A
Proof of Lemma 1

As shown in Fig. 3, a movement period has a starting point B and an ending point E in the line segment $[0, a]$. Let $D(b, e)$ be the distance of the movement period, then the expected distance of the movement period is expressed as

$$E[D] = \int_{e=0}^{a} \int_{b=e}^{a} D(b,e) f_B(b) f_E(e) db de$$
$$= \int_{e=0}^{a} \int_{b=e}^{a} (b-e) \frac{1}{a} \frac{1}{b} db de = \frac{a}{4}. \tag{14}$$

■

Appendix B
Proof of Lemma 2

For a movement period k, $e < b$ always holds. The location of a node x may have various locations relative to b and e,

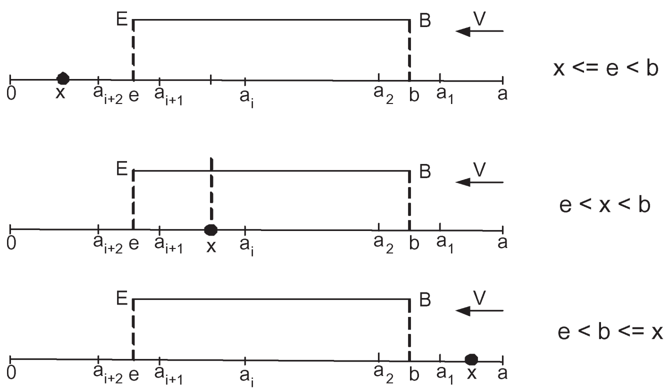


Fig. 8. Various locations of a node.

as shown in Fig. 8. From Fig. 8, the time that the node spends within $[0, x]$ during period k, i.e., $t_{x,k}$, and the distance of movement k that intersects with $[0, x]$, i.e., $D_{x,k}$, can be expressed as follows:

$$\begin{cases} t_{x,k} = 0, D_{x,k} = 0, & \text{for } x \le e < b \\ t_{x,k} > 0, D_{x,k} = x - e, & \text{for } e < x < b \\ t_{x,k} = t_k, D_{x,k} = b - e, & \text{for } e < b \le x. \end{cases} \tag{15}$$

The expected value of D_x can be expressed as

$$\begin{aligned} E[D_x] &= \int_{e=0}^{a}\int_{b=e}^{a} D_{x,k} f_B(b) f_E(e) db de \\ &= \int_{e=0}^{x}\int_{b=x}^{a} (x-e)\frac{1}{a}\frac{1}{b} db de + \int_{e=0}^{x}\int_{b=e}^{x} (b-e)\frac{1}{a}\frac{1}{b} db de \\ &= \frac{x^2}{2a}(\ln a - \ln x) + \frac{x^2}{4a}. \end{aligned} \tag{16}$$

■

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