The Requirement for Mobile Relay Nodes Under Highway Scenarios

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Abstract As we access data widely in our daily life, the present situation is that there is a lot of demand for data access in the process of moving while there used to access data in the static context. Under this situation, using the mobile relay nodes (MRN) in conventional cellular communication to support auxiliary transmission communication can effectively improve the ability of data transmission in the process of mobile performance. In this paper, we discuss that under the driving on the highway scenario, with the using of mobile relay nodes, we chose the whole vehicle as the communication transfer object and the middle vehicle carry as mobile relay node (MRN). Under the condition of considering the link capacity, this paper analyzes the traffic flow with the demand of the mobile relay nodes (MRNs) and conveys a digital expression. Simulation and probability analyses indicate that for three different traffic flows, it is expounded to the change of traffic to the mobile relay nodes (MRNs) demand changes.

Keywords Highway communication · Vehicle-to-vehicle · Relay node · Assist transmission

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1   Introduction

Now in our daily life, while the dependent of communication network is gradually increasing, the results then lead to the daily data traffic increasing gradually. For these extra data accesses, we need to rebuild more communication facilities, such as building more base station (BS) to improve the utilization rate of data transmission. But because urban planning pattern has fixed in our society, it is hard to improve the transfer ability of communication through rebuild the construction of macro-base station. To solve these facing problems, the concept about relay nodes (RNs) to support auxiliary transmission is presented, while it is also known as the single-hop transmission. The function of relay nodes (RNs) is to enhance the ability of communication in the base station coverage [1]. Follow to different application environments, the mature small cells include femtocell for indoor, microcell for outdoor, and picocell for both. Those small cells act as the extension to 3G/4G macro-cellular to provide customer better wireless internet and voice data service at a lower overhead. Relay nodes (RNs) are divided into two kinds, mobile relay nodes (MRNs) and fixed relay nodes (FRNs). Similar to their name, they are respectively applied to improve transmission communication ability in the process of moving and stationary.

The remainder of the paper is organized as follows. Section 2 reviews related work in the literature. Section 3 derives the system model and analyzes the probability of the MRN requirement. Simulation and numerical results are provided in Sect. 5. Section 6 proposes the conclusion.

2   Related Work

Recent years, the fixed communication can be compensated through wire transmission; however, the requirement of mobile communications capacity is growing. In addition to the normal utilization, using the vehicles is also increasing, for example, car and subway train. The utilization of communication transmission system in these media still exists some problems and application prospects. First, the car adopts wireless transmission channel in the process of high-speed moving, while the channel model is the multi-path random channel. When the speed of the mobile station is too high, the receiving signal carrier occurs Doppler shift which will produce distortion and inter-symbol interference. Though the working relay node still have a Doppler shift in the process of the auxiliary transmission, relative to the each other users affected by Doppler shift, the application of the relay nodes is obvious to improve this problem [2]. Second, as the users are surrounded in the vehicular, the signal accomplishes the direct transmission process through the wireless penetrate of the vehicles, resulting in vehicular penetration loss (VPL). To reduce the energy consuming, the technology of vehicular crowd cell exploits MRN which derive from 3GPP R12 [3]. These two points mean it is need more capacity

to complete transmission, so it is essential to utilize relay to compensate the loss of transmission [4]. Third, the on-board network is also a trending topic under the situation of the highway. According to the IEEE- and ASTM-adopted Dedicated Short Range Communication (DSRC) standard, a lot of reference about highway cooperative collision avoidance is showing up, which is available to enhance the security in the daily life. Thus, to improve the vehicular transmission performance, we discuss the highway scenario in this paper, with using vehicular-to-vehicular (V2 V) model as the communication model, to analyze the quantity of MRNs.

3 System Model

In this section, there is a simple highway model, where we only consider the single-track vehicles, and all the vehicles have a constant speed v m/s.

In this model, as Fig. 1 shows, there are n exit/entrance in the highway, and in each exit/entrance, the vehicles new into the entrance obey the Poisson distribution, where the distribution of average is λ_n (n is the nth exit/entrance, $1 \leq n$ and n as an integer). In the $(n + 1)$th section connecting, we assume that the vehicles from the nth to the $(n + 1)$th account for α_n of all the nth vehicles, and deduce the probability of the vehicles pulling away $1 - \alpha_n$. Similarly, we can deduce all the vehicles driving on the nth which are also object to a Poisson distribution [5], where the distribution of average is C_{n+1}:
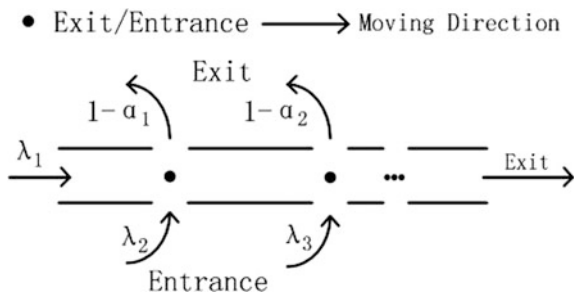
$$C_{n+1} = \lambda_{n+1} + \sum_{n=1}^{n} \lambda_n \times \alpha_n. \tag{1}$$

Also, all the vehicles T_n in each highway denote:

$$T_n = \frac{C_n}{v} \times d_n \tag{2}$$

Molisch [6] in this paper, we choose D = 100 m as the working coverage of the MRN to calculate the transmit power. Because of the d_{break} existing, the transmit power is

Fig. 1 The model of the highway with many exit/entrances

$$P_{ri} = P_{ti} \times cL_i^{-2}, \tag{3}$$

where P_r is the receive transmit power (considering the P_r of the each user is constant); P_t is the transmit power of MRN; i denotes the ith vehicle in the working coverage. Also, $P_{ti} = \frac{P_{ri} \times L_i^2}{c}$.

Similarly, the working coverage (D) of MRN is 100 m, so we can deduce all the vehicles moving in the working coverage (D) which is also object to a Poisson distribution, where the distribution of average is

$$A_n = \frac{C_n}{v} \times 100. \tag{4}$$

Though we consider that the quantities of the vehicles obey Poisson distribution in working coverage of the mobile relay nodes (100 m), but the position of these vehicles obeys uniform distribution, which means the location of the vehicles is interval distribution in the coverage. So the probability distribution for P_r is expressed as

$$\Pr(x; m) = \frac{1}{m} \tag{5}$$

(m denote the quantity of the vehicles in the scope of the mobile relay nodes).

With the consideration of the different situations, we can assume three conditions about the deployment of MRNs:

(1) There is no need for the MRN in the working coverage;
(2) There needs only 1 MRN in the working coverage;
(3) There needs at least 2 MRNs in the working coverage.

4   Probability Analysis

4.1   No MRN Existing

Because there is no MRN for auxiliary transmission, which means there is no vehicle existing in the scope of this 100 m section, so the probability of no vehicle expression is

$$\Pr\{k=0\} = \frac{A_n^0}{0!} e^{-A_n} = e^{-A_n}. \tag{6}$$

4.2 Only One MRN Existing

When we consider the only one mobile relay node (MRN) in the model, it can be continued to maintain the utilization of the MRN until the critical stability limit in the working coverage. When we assume the critical stability limit is m, we can calculate the probability as follows:

$$\Pr\{0 < k \le m\} = \frac{A_n^1}{1!}e^{-A_n} + \frac{A_n^2}{2!}e^{-A_n} + \frac{A_n^3}{3!}e^{-A_n} + \cdots = \sum_{k=1}^{m} \frac{A_n^k}{k!}e^{-A_n}. \quad (7)$$

After the probability formula is confirmed, there are two kinds of circumstances about the value of the m as follows: P_r denotes the receive power of the vehicle and $P_{tsum} = \varepsilon$ is the peak efficiency rating, namely ε.

(1) m is the odd number which is marked is m_1, namely $m_1 = 2k_1 + 1$. So the MRN is on the $(k + 1)$th vehicle, and the distance of the each vehicle is $L_i = \frac{D}{m-1} \times |k_1 + 1 - i|$.

So the probability of P_{tsum} is

$$P_{tSUM} = \sum_{i=1}^{m} P_{ti} = \sum_{i=1}^{m} \frac{P_r \times L_i^2}{c} = \frac{P_r}{c} \sum_{i=1}^{m} (k_1 + 1 - i)^2 = \frac{D^2 \times P_r \times k_1(k_1+1)(2k_1+1)}{12ck_1^2} = \varepsilon$$

$$(8)$$

$$2k_1 + \frac{1}{k_1} = \frac{12c \times \varepsilon}{D^2 \times P_r} - 3 \quad (9)$$

subject to k_1 is a integer a number

(2) m is the even number which is marked as m_2, namely $m_2 = 2k_1 + 1$. So the MRN is on the kth vehicle, and the distance of the each vehicle is $L_i = \frac{100}{m-1} \times |k - i|$

$$P_{tSUM} = \sum_{i=1}^{m} P_{ti} = \sum_{i=1}^{m} \frac{P_r \times L_i^2}{c} = \frac{P_r}{c} \sum_{i=1}^{m} (k_2 - i)^2 = \frac{D^2 \times P_r \times (2k_2^3 + k_2)}{12ck_2^2} = \varepsilon \quad (10)$$

$$2k_2 + \frac{1}{k_2} = \frac{12c \times \varepsilon}{D^2 \times P_r} \quad (11)$$

subject to k_2 is a integer.

As shown in (1) and (2), we can calculate the k_1 and k_2 values. Under the condition of such values, we can obtain the final result m_{max}, $m_{max} = Max\{m_1, m_2\}$.

So

$$\Pr\{0 < k \leq m_{max}\} = \frac{A_n^1}{1!}e^{-A_n} + \frac{A_n^2}{2!}e^{-A_n} + \frac{A_n^3}{3!}e^{-A_n} + \cdots = \sum_{k=1}^{m_{max}} \frac{A_n^k}{k!}e^{-A_n}. \qquad (12)$$

4.3 At Least Two MRN Existing

From Sect. 2, we could obtain the m_{max}, which can maintain the maximum in the mobile relay node. So, when parts of the vehicle are more than maximum, there is need to add additional mobile relay nodes to guarantee the performance of the transmission.

First, we only can consider at least one extra relay probability is expressed as

$$\Pr\{m_{max} < k\} = 1 - \left(\frac{A_n^0}{0!}e^{-A_n} + \frac{A_n^1}{1!}e^{-A_n} + \frac{A_n^2}{2!}e^{-A_n} + \cdots\right) = 1 - \sum_{k=0}^{m_{max}} \frac{A_n^k}{k!}e^{-A_n}. \quad (13)$$

So we can analyze the next step:

Step 1 Two mobile relay nodes, namely $D_1 = \frac{D}{2}$ instead of D in Sect. 2, so the existing probability is

$$\Pr\{m_{1max} < k \leq m_{2max}\} = \frac{A_n^{m_{1max}+1}}{(m_{1max}+1)!}e^{-A_n} + \frac{A_n^{m_{1max}+2}}{(m_{1max}+2)!}e^{-A_n} + \cdots + \frac{A_n^{m_{2max}}}{m_{2max}!}e^{-A_n}$$
$$= \sum_{k=m_{1max}+1}^{m_{2max}} \frac{A_n^k}{k!}e^{-A_n}.$$

$$(14)$$

Step 2 Three mobile relay nodes, namely $D_3 = \frac{D}{3}$ instead of D in Sect. 2, so the existing probability is

$$\Pr\{m_{2max} < k \leq m_{3max}\} = \frac{A_n^{m_{2max}+1}}{(m_{2max}+1)!}e^{-A_n} + \frac{A_n^{m_{2max}+2}}{(m_{2max}+2)!}e^{-A_n} + \cdots + \frac{A_n^{m_{3max}}}{m_{3max}!}e^{-A_n}$$
$$= \sum_{k=m_{2max}+1}^{m_{3max}} \frac{A_n^k}{k!}e^{-A_n}.$$

$$(15)$$

By that analogy,we can obtain the following:

Step 3 There is Z mobile relay nodes, namely $D_z = \frac{D}{Z}$ instead of D in Sect. 2, so the existing probability is

$$
\begin{aligned}
\Pr\{m_{(z-1)\max} < k \le m_{z\max}\} &= \frac{A_n^{m_{(z-1)\max}+1}}{(m_{(z-1)\max}+1)!}e^{-A_n} + \frac{A_n^{m_{(z-1)\max}+2}}{(m_{(z-1)\max}+2)!}e^{-A_n} + \cdots + \frac{A_n^{m_{z\max}}}{m_{z\max}!}e^{-A_n} \\
&= \sum_{k=(z-1)\max+1}^{m_{z\max}} \frac{A_n^k}{k!}e^{-A_n}.
\end{aligned}
$$

(16)

We think the upper limit is z MRNs, so the else probability is

$$
\Pr\{m_{z\max} < k\} = 1 - \sum_{k=0}^{m_{z\max}} \frac{A_n^k}{k!}e^{-A_n} = t.
$$

(17)

If the probability over than t $= 10^{-6}$, we do not consider rebuild another MRN.

5 Simulation Results

Considering the third entrance (n = 3), we assume and analyze the demand of MRN under the following situation as shown in Table 1. We can get the result $m_{1\max} = 40$; $m_{2\max} = 166$; $m_{3\max} = 376$, and assume the three cases as shown in Table 2.

Table 1 The main parameters

Parameter	Values	Parameter	Values
P_r	50 dBm	c	3.5×10^{-4}
v	20 m/s	α_1	0.6
ε	1 w	α_2	0.6

Table 2 The three case parameters

	λ_1	λ_2	λ_3
Case 1	0.1	0.15	0.2
Case 2	1.5	1.5	1.5
Case 3	2.8	3	3.2

(a) Case 1
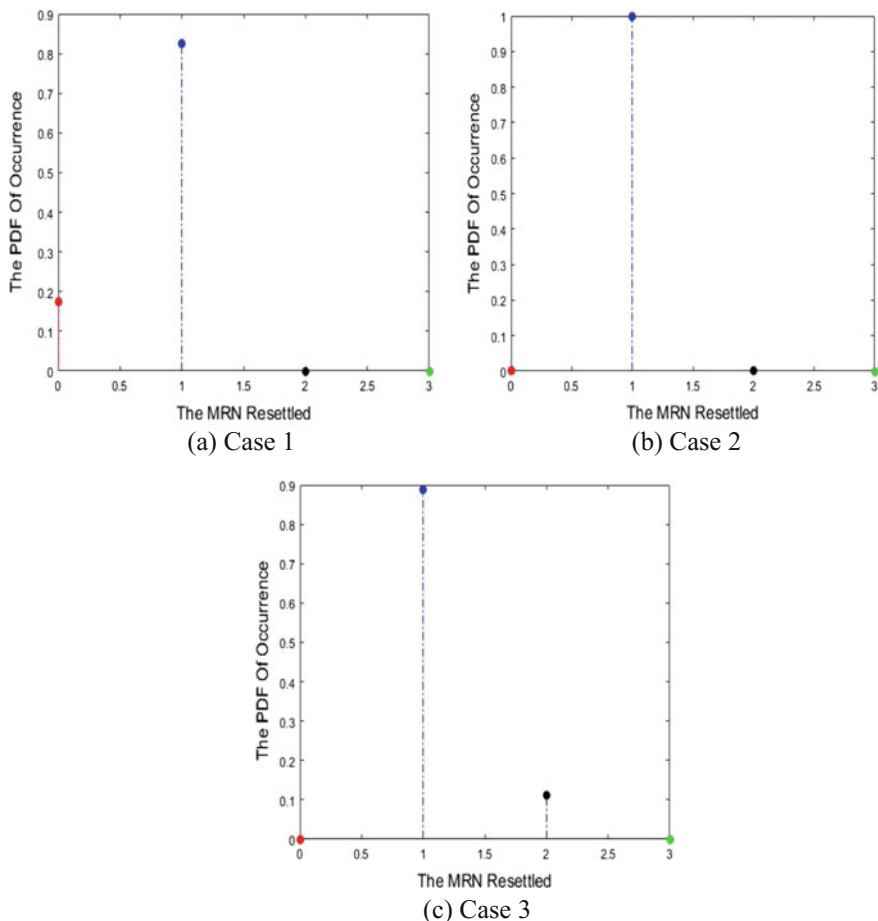
(b) Case 2

(c) Case 3

Fig. 2 The PDF of occurrence in three case

Case 1: In the light traffic time, less vehicle volume pass. As shown in Fig. 2a, in most cases (82%), there all need a MRN which can complete the transmission, but in a few cases (18%), there are no vehicles through the continuous range.

Case 2: In the normal traffic time, normal vehicle volume pass. As shown in Fig. 2b, in nearly all cases (99%), there all need a MRN which can complete the transmission

Case 3: In the heavy traffic time, more vehicle volumes pass. As shown in Fig. 2c, in most cases (89%), there all need a MRN which can complete the transmission, but in a few cases (11%), there need two vehicles to support the transmission.

Comparing the three figure, in all case, one MRN is enough to support the transmit mission while each PDF of using one MRN is the highest (82, 99, 89%).

6 Conclusion

In this paper, we discussed transmission models of vehicle carrier user in highway and analyzed the changes of vehicular flow to the distribution of MRN. Especially, we know that vehicular traffic flow is related to the position the MRN. The simulation and numerical result shows the one MRN is nearly efficient to complete the transmission process under three different situations as we discussed above. With the change of traffic flow, the demand of MRN will change slightly. Therefore, how to find out the traffic flow at different times in the highway in order to enhance the coverage of the transmission is the focus of the future research.

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