國 立 交 通 大 學

資訊科學與工程研究所

碩 士 論 文

車用行動通訊網路之連線時間分析

Communication Time Analysis in Vehicular Ad-Hoc Networks

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中 華 民 國 九 十 七 年 六 月

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碩 士 論 文

A Thesis

Submitted to Institute of Computer Science and Engineering

College of Computer Science

National Chiao Tung University

In partial Fulfillment of the Requirements

For the Degree of

Master

In

Computer Science

July 2007

Hsinchu, Taiwan, Republic of China

中華民國九十七年六月

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中文摘要

近年來隨著無線網路快速發展，人們可以無所不在地使用網路，車用行動通訊網路是無線移動網路中一種快速發展的新型態，它是由汽車的移動所構成的網路模式，近來有不少針對車用行動通訊網路效能分析的研究，其中，大部分的研究都是在探討通訊協定、傳送效率或是傳輸延遲，他們大部分的結果都是利用網路模擬或是統計資料來取得。在車用行動通訊網路中，連線時間會影響到資料傳輸與繞徑演算法的表現，所以有必要建立更精確的數學模型來正確預估其連線生命週期，進而改善效能。所以在這篇論文中，我們提出一個數學分析模型來計算出車用行動通訊網路在都會區中的期望連線時間，另外，我們考慮在每個十字路口加上紅綠燈後，所造成連線時間的變化，我們一樣提出數學分析模型來分析其期望連線時間。最後，我們將提出模擬結果來驗證期望連線時間數學模型的正確性。

關鍵字：車用行動通訊網路、無線移動網路、連線時間

Communication Time Analysis in Vehicular Ad-Hoc Networks

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Abstract

Since the recent rapid development of wireless mobile networks, people can access the network ubiquitously. Vehicular ad-hoc networks (VANETs) are an emerging new type of wireless mobile ad-hoc networks (MANETs). It's a mobile network composed of moving vehicles. There are many researches in performance for VANETs. Among those, most researches focus on the communication protocol, delivery ratio, or transmission delay. They are mostly obtained by network simulation or statistical data. In VANETs, communication time will affect data transportation and the performance of the routing algorithm. It's necessary to build a more accurate mathematical model to estimate the communication time. In this thesis, we present a mathematical analysis model to calculate the expected communication time (ECT) of VANETs in urban city. Furthermore, we consider adding a traffic light to each intersection to observe the influence to the ECT. Finally, we present simulation results to validate our mathematical model in ECT.

Keywords: Vehicular ad-hoc network; mobility ad-hoc network; communication time

誌謝

本篇論文的完成，我要感謝這兩年來給予我協助與勉勵的人。首先要感謝我的指導教授 陳健博士，即使這段期間遭遇了不少的挫折，陳老師對我的指導與教誨使我都能在遇到困難時另尋突破，在研究上處處碰壁時指引明路讓我得以順利完成本篇論文，在此表達最誠摯的感謝。同時也感謝我的論文口試委員，交通大學的曾煜棋教授、簡榮宏教授以及工業研究院的蔣村杰博士，他們提出了許多的寶貴意見，讓我受益良多。

感謝與我一同努力的學長張哲維、陳盈羽，由於我們不斷互相討論及在論文上的協助，使我能突破瓶頸，研究也更為完善。另外我也要感謝實驗室的同學、學弟們，王振仰、林政一、楊智強以及楊祐華等人，感謝他們陪我度過這兩年辛苦的研究生活，在我需要協助時總是不吝伸出援手，陪我度過最煩躁與不順遂的日子。

最後，我要感謝家人對我的關懷及支持，他們含辛茹苦的栽培，使我得以無後顧之憂的專心於研究所課業與研究，我要向他們致上最高的感謝。

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Chapter 1: Introduction

In this thesis, we mainly discuss the communication time analysis in Vehicular Ad Hoc Networks (VANETs) in urban city. We present a mathematical model to analyze the communication time. In the mathematical analysis model in [1], authors presented a mathematical model to analyze Expected Link Life Time (ELLT). Their mathematical analysis model can't approach the trajectory of vehicle movement, because they assume no turn probability exists between two vehicles during their communication time. Therefore, we add the condition of turn probability to analyze communication time. Nevertheless, this problem will become more complex if we consider the turn probability of vehicles, because if vehicles can turn many times, it is difficult to analyze the communication time. Therefore, in order to simplify this problem, we assume that vehicles have one turn during their communication time at most. Furthermore, we consider adding a traffic light to each intersection to observe the influence and the difference of communication time. Then, we also present simulation results to validate our mathematical model in Expected Communication Time (ECT).

Since the recent rapid development of wireless mobile networks, people can access the network ubiquitously. Vehicular ad-hoc networks (VANETs) is an emerging new type of wireless mobile ad-hoc networks (MANETs). VANETs are distributed, self-organizing communication networks built up from traveling vehicles, and are thus characterized by very high speed and limited degrees of freedom in node movement patterns. VANETs let people acquire information of transmission and traffic situations in real time by using wireless communication and data transmission technology. Nevertheless, it influences the performance of data transportation and routing algorithm due to connection states and route results have a prescription because the locations of vehicles change dynamically. Such particular features often make standard networking protocols inefficient or unusable in VANETs. Therefore, VANETs is a popular research field recently. VANETs have been utilized in many mobility models, like random waypoint mobility model, without restrictions on the movement and directions of vehicles as the Figure 1 indicates. However, in VANETs, the trajectory of vehicle movement is restricted by streets. So the model couldn't reveal all trajectories of mobility nodes in VANETs. In urban city, the Manhattan mobility model is one of the typical mobility models, which has wireless nodes moving in grid topology environment, shown as Figure 2. The discussion of communication time in VANETs are not much, so the main point of this thesis lies on the mathematical analysis of the communication time of VANETs in urban city. Communication time can be utilized in many places, like in delay tolerance network[21][22], how long nodes store packets, or how the ferry[23] transfers data between wireless nodes during limited communication time. For example, in VANETs [20], if two vehicles want to transmit data, we can calculate communication time by their relative direction and speed. In this case they can estimate how much data they can transmit during the period of time, how much bandwidth they need in advance. They can enhance packet delivery ratio and the efficiency of performance of routing algorithm. Besides, [9] also points out that the communication time is a significant factor to the wireless ad hoc network's optimal performance.

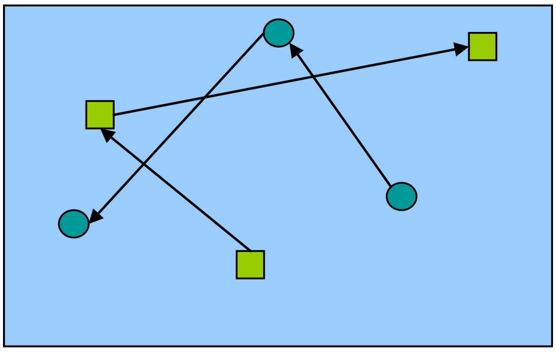

Figure 1: Random Waypoint Mobility Model

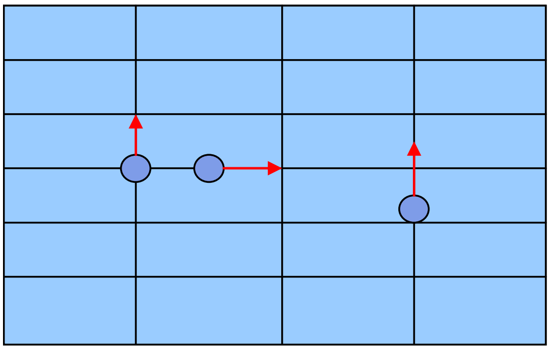

Figure 2: Manhattan Grid Mobility Model

In VANETs, as Figure 3 indicates, communication time represents the time needed to be within another vehicle's transmission range and able to transmit data directly between two vehicles, while ECT means the expected value of communication time. If one vehicle moved out of the transmission area, these two vehicles couldn't transmit data directly. Consequently, analysis of expected communication time is crucial to data transmission and routing algorithm. In [1], it addresses the mobility feature of the Manhattan mobility model in wireless ad hoc network. It assumes that mathematical analysis model didn't consider the probability of turns meeting with the intersection, and it influences the expected communication time. In this thesis, we presented a mathematical analysis model to calculate the ECT of VANETs in urban city. We aim at [1] to improve the imperfection of this mathematical model and establish a more accurate model with turn probability to make the communication time closer to reality. It may be more sophisticated when taking the fact that vehicles can turn at intersections into consideration, though. If vehicles turn several times, the communication time will be hard to estimate. In terms of the perspective of real movement, it's unlikely that we will have two vehicles with extortionate turns in their short communication time. To clarify this point, we use the simulator in [24], the USC mobility generator tool is a set of mobility scenario generators, including the Random Waypoint model, the Reference Point Group Mobility model, the Freeway mobility model, and the Manhattan mobility model. The traces generated by this tool are compatible with the ns-2 simulator. We use the mobility model where nodes move haphazardly in the Manhattan mobility model. We count the number of turns wireless nodes make during their communication time. The consequence is shown in Figure 4, which indicates the average number of turns a wireless node make at one time. Therefore, to simplify the question, we assume that all vehicles will have one turn at most during their communication time. Based on this perspective, we construct a more accurate mathematic analysis model to make the consequence closer to reality. Furthermore, in urban areas, there must be traffic lights to control traffic flow. So we add a traffic light at each intersection. We assume two kinds of signals for each traffic light, red light and green light; the periods for each are the same, and each traffic light operates individually. We analyze how traffic lights influence communication time and mention a mathematical analysis model for analyzing communication time.

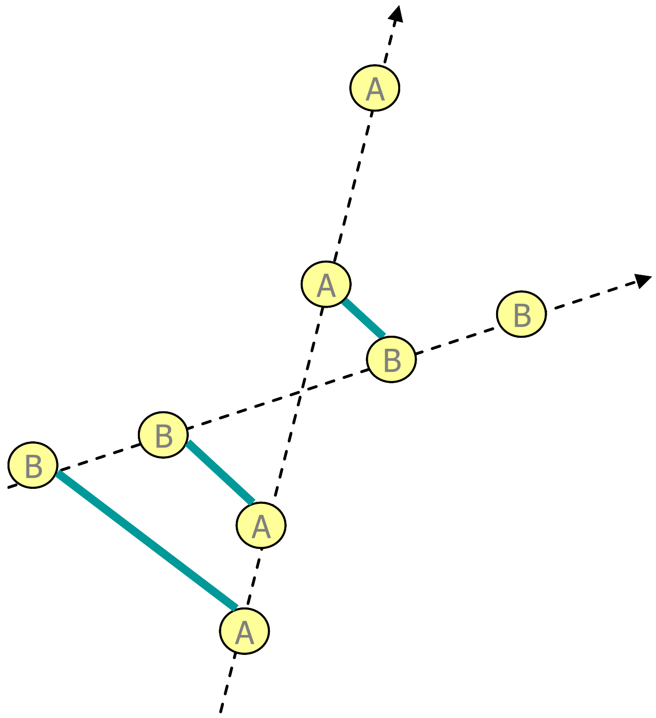

Figure 3: Communication time

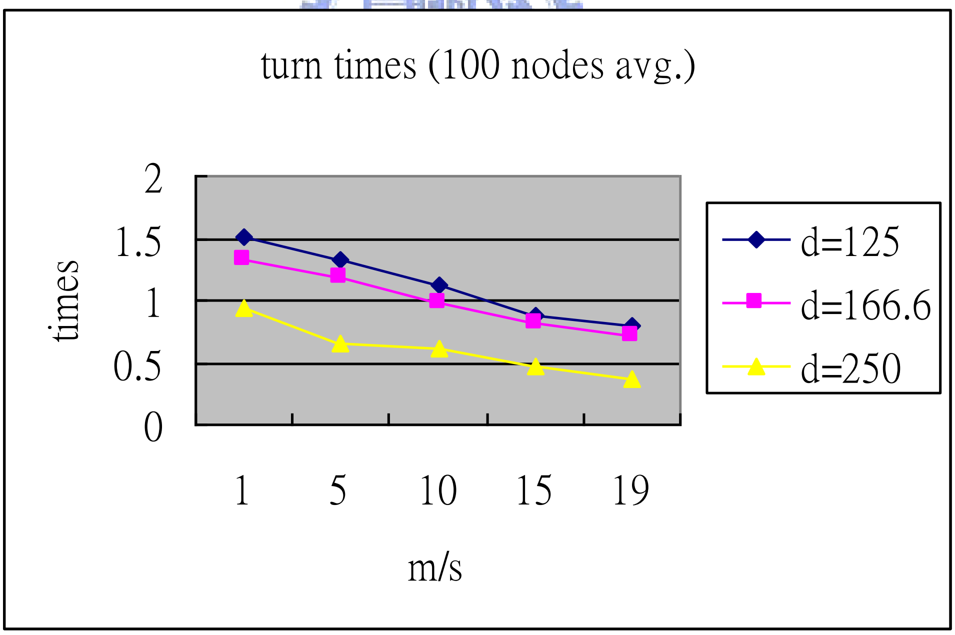

Figure 4: Number of turn during communication time

In urban city, the trajectory of each vehicle is restricted in streets, thus [1] lets the connection between two mobility nodes be separated into three independent parts:

opposite case, parallel case, and vertical case. We add the turn probability where wireless nodes meet intersections to the mathematical analysis model, and we also separate the connection into three independent parts: Opposite to Vertical Case, Parallel to Vertical Case, and Vertical to Opposite or Parallel Case, shown as **Figure 5**. Because of the independence, we use mathematical analysis with probability to analyze each connection style. To demonstrate the consequence from the mathematical analysis, we can use NS2.

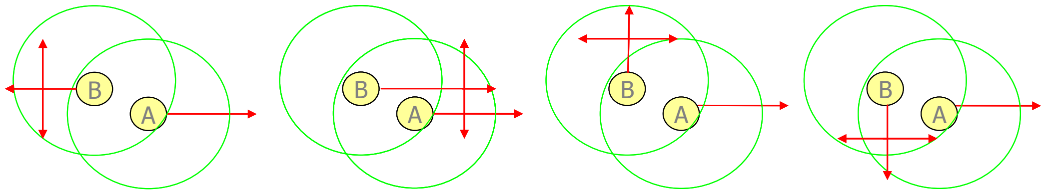

Figure 5: Opposite to Vertical Case; Parallel to Vertical Case; Vertical to Opposite or Parallel case

The organization of the rest of this thesis is as follows. In Chapter 2, we discuss related works about the effect of mobility model on link dynamics characteristics and routing strategy in ad hoc networks. In Chapter 3, the formulations of the ECT of VANETs in an urban city are presented. In Chapter 4, we add traffic lights on each cross and present the formulations of the ECT_{TL} of VANETs in an urban city. Chapter 5 shows the formulation results and the simulation results are confirmed in Chapter 6. Finally, we conclude this thesis in chapter 7.

Chapter 2: Related work

A wireless ad hoc network is composed of direct communication between wireless nodes in an environment without infrastructure. Therefore, the mobility model of nodes affects the performance of the wireless ad hoc network significantly. Among them, [2] demonstrates the characteristics and analyzes the influence among different mobility models.[3] quantified the influence for routing algorithm among different mobility models. [11] analyzed link lifetime and route lifetime in different mobility models. Therefore, we can understand that mobility models play a critical role for routing algorithm in wireless ad hoc network.

The random waypoint mobility model is the most common mobility model in wireless ad hoc network. There are many discussions and researches about it. Among them, [4][5] discuss its characteristics.[6] presents the factor that node communication is relevant and influences of connection ability and performance. Therefore, it points out the research in fields of link lifetime. [19] analyzed link durations in several different mobility scenarios to develop adaptive metrics to identify stable links in a mobile wireless networking environment. [12] analyzed the relation between the speed of wireless nodes and link failure rate. [7] investigated the expected lifetime of a route so that the route discovery protocol can be invoked at the right time without disrupting the communication. [8][9][10] formulate the expected link lifetime and demonstrate their formulations. [13] calculated the longest lifetime path to improve the routing algorithm's performance. [14] presented a new mobility model, Semi-Markov Smooth model, and calculated link lifetime, then investigated the influence of the routing algorithm on link lifetime. [15][16][17][18] utilize the value of the expected link lifetime to apply on routing algorithm and analyze the influence.

The discussion of communication time in VANETs is not much, [25] presents a new model using real street map data gotten from the TIGER (Topologically Integrated Geographic Encoding and Referencing) database, modeling vehicles traveling on these streets, and analyzed the properties of this mobility model and studied the performance of a common ad hoc network routing protocol, DSR, on this model. [26] evaluated the sensitivity of mobility details on VANETs in an urban context and proposed three new but related vehicular mobility models– the Stop Sign Model, the Traffic Sign Model, and the Traffic Light Model. [27] introduced STRAW (Street Random Waypoint), a new mobility model for vehicular networks in which nodes move according to a simplified vehicular traffic model on roads defined by real map data, and analyzed the implications of mobility models in the performance of ad-hoc wireless routing protocols by contrasting the performance of two well-known protocols using both the commonly employed Random Waypoint Model and STRAW.

Since the quick development of networks, VANETs is one recently popular mobility model. However, there are few research and discussion of communication time, especially since the communication time significantly affects routing algorithm and performance in mobility ad hoc network. And in urban areas, we can see the Manhattan grid mobility model frequently. [2] mentioned Manhattan grid mobility model and analyzed its movement behavior. [1] formulated communication time in MANET under Manhattan grid mobility model. Therefore, it inspires our motivation to take a research in the communication time of VANETs in urban city. In this thesis, we mentioned two mathematic analysis models of communication time, one is with turn probability, and the other is with traffic light.

Chapter 3: Expected communication time in VANETs

ECT means the average time for two wireless nodes to transmit data to each other directly in all situations. In [9], it mentions that ECT has significant impact on wireless network. There are some researches on the expected link lifetime in a random waypoint mobility model. There are also some researches on the expected link lifetime in Manhattan Grid Mobility Model. For example, [2] mentioned the Manhattan grid mobility model and [1] that mentioned a mathematical model that can analyze the expected link lifetime on the Manhattan grid mobility model. However, there are few researches on VANETs in an urban city.

In this chapter, we reform the mathematical model in [1], and add the probability of turn to the mathematical model to make the consequence closer to the reality of VANETs. Furthermore, to simplify the question, we assume that two vehicles have one turn at most during communication time, and we postulate the probability of turn p_{turn} when meet with the intersection.

We assume that there is a connection of two mobility nodes, MN_A and MN_B, in urban city, and we can separate the connection into three situations:

1. The direction of movement between MN_A and MN_B is opposite to vertical.
2. The direction of movement between MN_A and MN_B is same to vertical.
3. The direction of movement between MN_A and MN_B is vertical to opposite or same.

We respectively use $T_{\leftrightarrow\Rightarrow\perp}(v_A)$ 、 $T_{\rightarrow\rightarrow\Rightarrow\perp}(v_A)$ 、 $T_{\perp\Rightarrow\leftrightarrow\|\rightarrow\rightarrow}(v_A)$ to describe it. The ECT in an urban city is described as Equation 1, and we separated the paragraph to three parts to analyze the mathematical model of ECT.

$$\overline{T}_{link}(v_A) = \frac{1}{4}\overline{T}_{\leftrightarrow\Rightarrow\perp}(v_A) + \frac{1}{4}\overline{T}_{\rightarrow\rightarrow\Rightarrow\perp}(v_A) + \frac{1}{2}\overline{T}_{\perp\Rightarrow\leftrightarrow\|\rightarrow\rightarrow}(v_A)$$

When the speed of MN_A is v_A :

$\overline{T}_{link}(v_A)$: ECT of MN_A

$\overline{T}_{\leftrightarrow\Rightarrow\perp}(v_A)$: ECT of MN_A under opposite to vertical case

$\overline{T}_{\rightarrow\rightarrow\Rightarrow\perp}(v_A)$: ECT of MN_A under parallel to vertical case

$\overline{T}_{\perp\Rightarrow\leftrightarrow\|\rightarrow\rightarrow}(v_A)$: ECT of MN_A under vertical to opposite or parallel case

Equation 1: ECT of VANETs in urban city

Before discussing ECT, we have some basic assumptions:

1. The transmission range of every node is a circle with radius R.
2. The average moving speed of every node is distributed between maximum $v_{\max}$ and minimum $v_{\min}$ equally.
3. The moving direction of every node—moving upward, downward, leftward or rightward—has the same probability.
4. MN_B has one turn at most during communication time with MN_A, and the probability of turning when meeting the cross is p_{turn}.

3.1 Opposite to Vertical Case

In the opposite to vertical case, the relative direction between mobility nodes, MN_A and MN_B, is opposite. When MN_B meets the cross, it has probability of turn p_{turn} and lets the relative direction become vertical. In Figure 6 and Figure 7, the dotted lines represent streets. The definitions of symbols are represented as follow：

1. v_A ：speed of MN_A

2. v_B ：speed of MN_B

3. I ：horizontal street

4. J ：vertical street

5. d ：distance between adjacent street

6. s ：distance from MN_B enters range of MN_A to MN_B meets first cross

Among them, to take care more when MN_B enters the range of MN_A, since the location of MN_A will change within a fixed range. As Figure 8 indicates, we can see the value of s will vary with the varying location of MN_A. It also means the distance where MN_B meets the first cross after entering the range of MN_A will vary, and furthermore ECT will also vary. Consequently, we calculate the communication time formed by each location of MN_A and MN_B, sum up the total amount, and average it. In Figure 8, we set the standard value of s when MN_B enters the range of MN_A and MN_A is on cross at the same time. We assume the coordinate of MN_A is (0,0) and the distance from MN_B enter range of MN_A through i_{th} street to MN_B meet first cross is S_i.

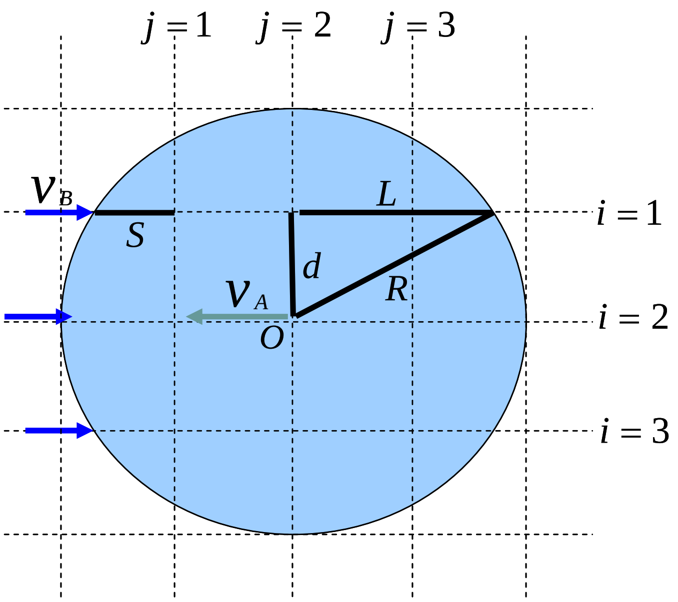

Figure 6: Opposite case of VANETs in urban city

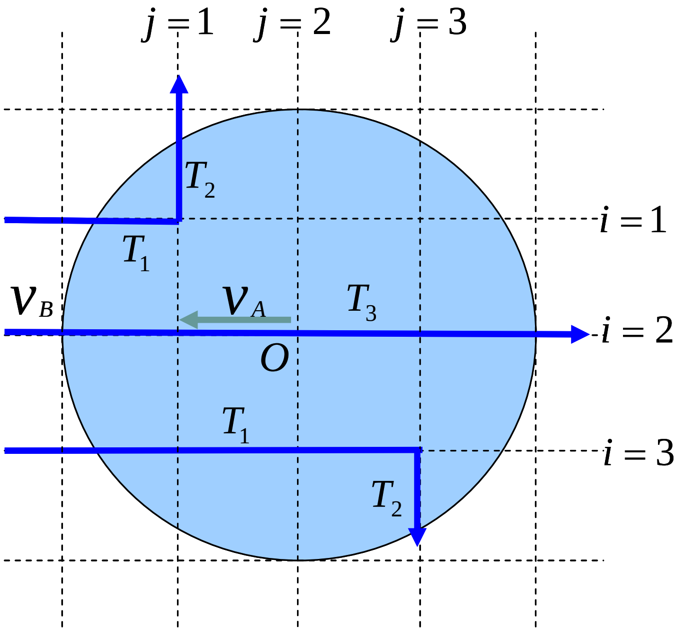

Figure 7: Opposite to Vertical Case with turn probability p_{turn}

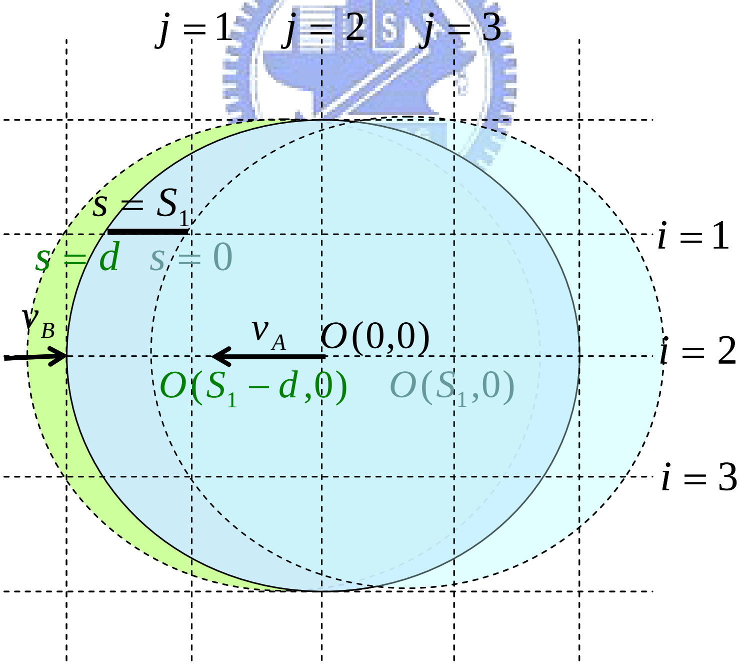

Figure 8: Relation of s and location of MN_A

As Equation 2 indicates, we calculate the parameters completely in Figure 6 before calculating ECT.

$$L_i = \sqrt{R^2 - \left(\left(\left\lceil \frac{R}{d} \right\rceil - i \right) \times d \right)^2}$$

$$S_i = L_i - \left\lfloor \frac{L_i}{d} \right\rfloor \times d$$

$$C_i = 2 \times \frac{L_i - S_i}{d} + 1$$

Equation 2: Calculate parameters of Opposite to Vertical Case

C_i represents the maximum count of crosses that MN_B on number i street passed through during communication time. The maximum value means that MN_B may be unable to reach some crosses during the communication time if v_B is smaller than v_A. Therefore, we define a new parameter $v_{B(i,j)}$ further, see Equation 3, representing the minimum speed MN_B that can reach number (i, j) cross. We separate this case into two parts, one is that MN_B can reach all crosses and has a probability of turning, the other is that MN_B can't reach some crosses.

$$v_{B(i,j)} \geq \frac{s_i + (j-1)d}{2L_i - (s_i + (j-1)d)} v_A$$

$$v_{B(i,j)} = v_{B\min}$$

Equation 3: Minimum speed that v_B can reach number j cross

Consequently, we calculate T_1, T_2, and T_3 in Figure 7 respectively. T_1 represents the communication time from when MN_B enter range of MN_A to when MN_B meets a cross. T_1 represents the communication time from when MN_B turn at cross to when MN_B leave range of MN_A. T_3 represents the communication time that MN_B moves straight during MN_A and MN_B connect. It includes two parts, one part is the situation that MN_B can't reach some crosses, for example,

MN_B can reach cross number j but can't reach cross number $j+1$. The other part is that MN_B can reach each cross but MN_B keeps straight when meeting crosses, therefore we use the remainder probability to calculate ECT after subtracting the probability of turning.

We use coordinate to calculate T_2, shown by Figure 8. The location of MN_A varies when MN_B contacts with MN_A, therefore we list the coordinate range of s and MN_A as follow.

1. s ： $0 \le s < d$
2. MN_A ： $(S_i - d, 0) \le MN_A < (S_i, 0)$

We calculate the coordinate of MN_A and MN_B when MN_B is at cross respectively, then we assume MN_B will leave the range of MN_A through T_2 after turning. Since we know the directions of MN_A and MN_B, we can calculate the coordinates of MN_A and MN_B after T_2. At this time, the distance of two mobility nodes is R. Consequently we can get T_2 through solving the equation as Equation 4 indicates.

$$T_1 = \frac{s + (j-1)d}{v_B}$$

$$MN_B \ turn \ to \ down$$

$$\left(\left(j - \left\lceil \frac{C_i}{2} \right\rceil\right)d - S_i + s + (T_1 + T_2)v_A\right)^2 + \left(\left(\left\lceil \frac{R}{d} \right\rceil - i\right)d - v_B T_2\right)^2 = R^2$$

$$MN_B \ turn \ to \ up$$

$$\left(\left(j - \left\lceil \frac{C_i}{2} \right\rceil\right)d - S_i + s + (T_1 + T_2)v_A\right)^2 + \left(\left(\left\lceil \frac{R}{d} \right\rceil - i\right)d + v_B T_2\right)^2 = R^2$$

$$Solve \ this \ eqation, \ \ get \ T_2$$

$$T_3 = \frac{2L}{v_A + v_B}$$

Equation 4: Calculate T_1, T_2 and T_3 of Opposite to Vertical Case

We need to get distribution probability of the variable parameters to calculate the expected value. Because v_B distributes between $v_{\max}$ and $v_{\min}$ equally, and s also distributes among varying range equally, so we can get their PDF simply shown as Equation 5:

$$f(v_B) = \frac{1}{v_{\max} - v_{\min}}$$

$$f(s) = \frac{1}{range \text{ of s}}$$

Equation 5: PDF of v_B and s

Finally, we calculate the average communication time of two mobility nodes which can transfer data directly in all possible, shown as Equation 6. Separating it into three parts, we calculate the first part： the communication time for MN_B meeting one cross and turning, same as $T_1 + T_2$. We calculate $T_1 + T_2$ of each cross respectively, because MN_B can meet C_i crosses at most. Furthermore, there are many different way for MN_B to enter the range of MN_A, for example that MN_B may enter the range of MN_A from the i_{th} street or the $i+1_{th}$ street. Finally we get the sum of all situation and average. Then we calculate the second part：part of MN_B can’t reach some cross, means MN_B may can reach some streets but can’t reach the next street, for example that MN_B can reach street j_{th} but can’t reach street $j+1_{th}$ street. The third part：MN_B can run through C_i crosses during communication time, we calculate the communication time by remainder probability, contracted probability of turn first, means probability of going straight. In the end, we sum the three parts above to get the ECT of opposite to vertical case. Among them, σ is the extreme minimum value to avoid some problems in mathematics like dividing by zero when v_B is equal to v_A.

$$
\begin{aligned}
&\overline{T}_{\leftrightarrow\Rightarrow\perp}(V_A) \\
&= E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B, i, j)\right] \\
&= E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B, j) \middle| i=1\right] * p(i=1) \\
&+ E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B, j) \middle| i=2\right] * p(i=2) + \ldots \\
&+ E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B, j) \middle| i=\left\lceil \frac{R}{d} \right\rceil\right] * p\left(i=\left\lceil \frac{R}{d} \right\rceil\right) \\
&= E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B) \middle| i=1, j=1\right] * p(i=1) * p_{turn} + \ldots \\
&+ E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B) \middle| i=1, j=C_i\right] * p(i=1) * p_{turn} + \ldots \\
&+ E_{\leftrightarrow\Rightarrow\perp}\left[t_{\leftrightarrow\Rightarrow\perp}(v_B) \middle| i=\left\lceil \frac{R}{d} \right\rceil, j=C_i\right] * p\left(i=\left\lceil \frac{R}{d} \right\rceil\right) * p_{turn} \\
&= \int_{s=0}^{d-\sigma} \sum_{I=1}^{\left\lceil \frac{R}{d} \right\rceil} \sum_{J=1}^{C_i} p(i=I) \left(\int_{v_{B(i,j)}}^{v_{B\max}} (T_1+T_2) f(v_B) dv_B\, p_{turn} + \int_{v_{B(i,j-1)}}^{v_{B(i,j)}} T_3 f(v_B) dv_B \left(1-2*(j-1)p_{turn}\right) \right) f(s) ds \\
&+ \int_{s=0}^{d-\sigma} p(i=I) \int_{v_{B(i,C_i)}}^{v_{B\max}} T_3 f(v_B) dv_B \left(1-2*C_i p_{turn}\right) f(s) ds
\end{aligned}
$$

$$
\begin{aligned}
&if \;\; 2*C_i p_{turn} > 1, \;\; C_i = \frac{1}{2*p_{turn}} \\
&if \;\; i=\left\lceil \frac{R}{d} \right\rceil, \;\; p\left(i=\left\lceil \frac{R}{d} \right\rceil\right) = \frac{1}{2\left\lceil \frac{R}{d} \right\rceil - 1} \\
&otherwise, \;\; p(i=I) = \frac{2}{2\left\lceil \frac{R}{d} \right\rceil - 1} \\
&if \;\; (1-p_{turn}) < 0, \;\; T_3 = 0
\end{aligned}
$$

Equation 6: ECT formulation of Opposite to Vertical Case

3.2 Parallel to Vertical case

In parallel to vertical case, the relative direction between mobility nodes, MN_A and MN_B, is parallel. When MN_B meets a cross, it has probability of turning p_{turn}

and lets the relative direction become vertical. As Figure 9 shows, the dotted lines represent streets. We separate the communication time into two parts, shown as Figure 10, the first part is MN_B keeping up with MN_A when $v_B > v_A$, then MN_B connects with MN_A when MN_B enters the range of MN_A. Second part is on the contrary. We aim at the first part to discuss as following because two parts are the same.

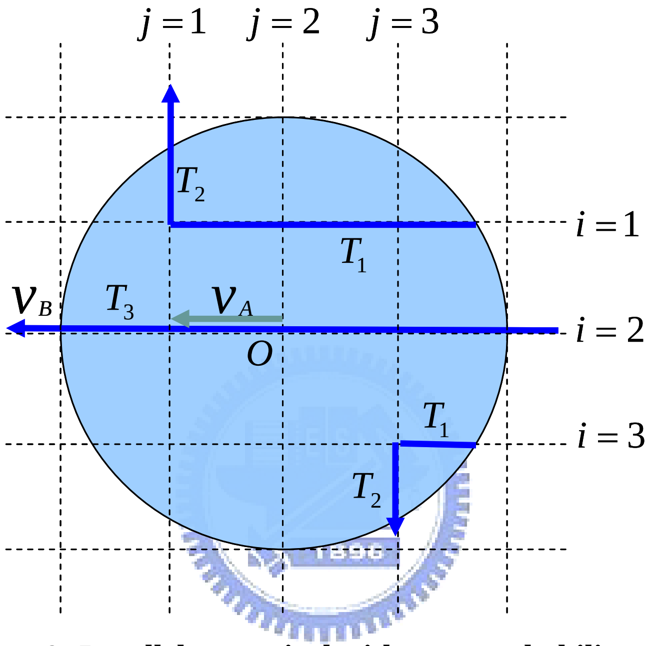

Figure 9: Parallel to vertical with turn probability p_{turn}

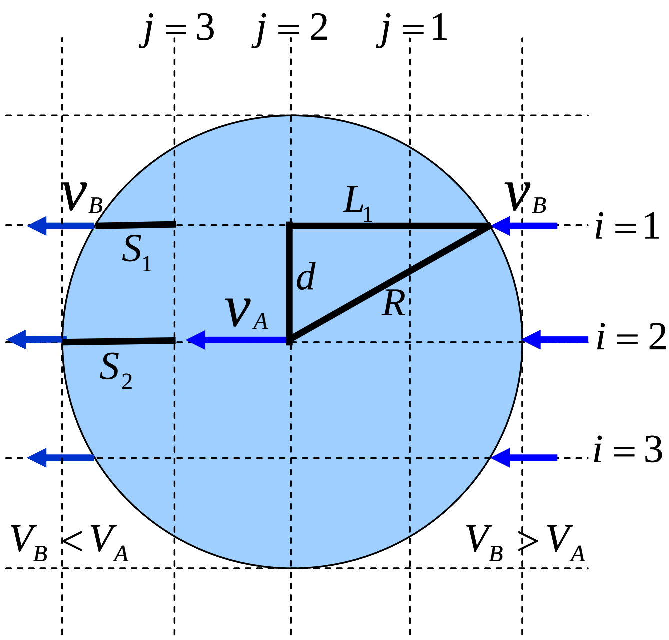

Figure 10: Parallel case of VANETs in urban city

In this case, same as the Opposite to Vertical Case, the location of MN_A will vary in fixed range when MN_B enters range of MN_A, as Figure 11 indicates. Communication time also varies, therefore we calculate each communication time formed by each location of MN_A and MN_B, sum up total amount and average it same as opposite to vertical case. In Figure 11, we set the standard value of s when MN_B enter range of MN_A and MN_A is on cross (blue part) at the same time. We assume the coordinate of MN_A is $(0,0)$ and the distance from MN_B enter range of MN_A through i street to MN_B meet first cross is S_i.

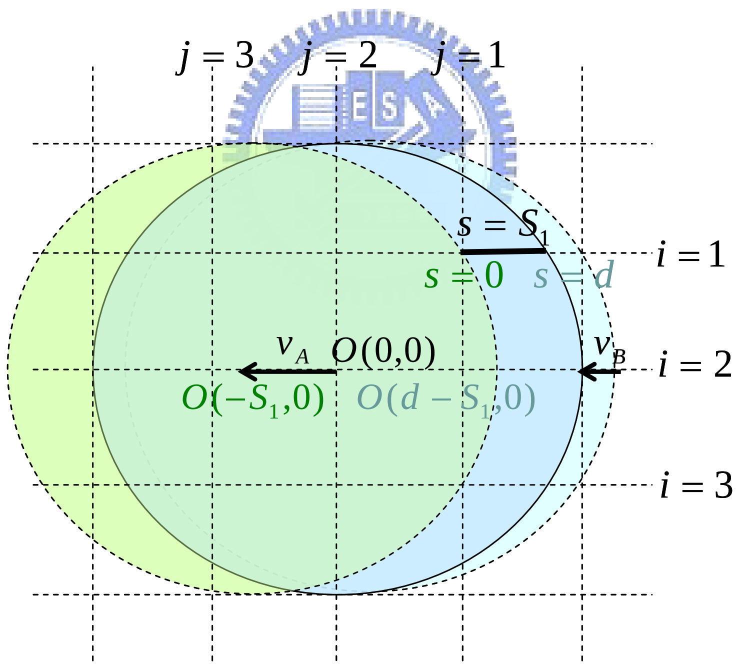

Figure 11: Relation of s and location of MN_A

As Equation 7 indicates, we calculate parameters completely in Figure 10 before calculating ECT.

$$L_i = \sqrt{R^2 - \left(\left(\left\lceil \frac{R}{d} \right\rceil - i\right) \times d\right)^2}$$

$$S_i = L_i - \left\lfloor \frac{L_i}{d} \right\rfloor \times d$$

$$C_i = \left\lfloor \left(\frac{2L_i}{v_B - v_A} v_B - S_i \right) \Big/ d \right\rfloor + 1$$

Equation 7: Calculate parameters of Parallel to Vertical Case

C_i represents the maximum value of crosses MN_B can meet in the i_{th} street. It is different from the C_i of opposite to vertical case, because C_i in this case guarantees the number of crosses that MN_B can reach. In other words, MN_B certainly can reach C_i crosses in the range of MN_A, besides the factor that MN_B may turn. The situation that v_B is too small to reach some cross for MN_B in range of MN_A will not occur because $v_B > v_A$.

Consequently, we calculate T_1, T_2 and T_3 respectively shown as Figure 9. T_1 represents the communication time from when MN_B enters the range of MN_A to meet the cross. T_2 represents the communication time from MN_B turns at the cross to leave the range of MN_A. T_3 represents the communication time that MN_B moves straight during MN_B is connecting with MN_A. In other words, MN_B can reach each cross but MN_B keep straight when meeting crosses, therefore we use the remainder probability to calculate ECT after subtracting probability of turn. We use coordinates to calculate T_2, shown as Figure 9. The location of MN_A varies when MN_B contacts with MN_A, therefore we list the coordinate range of s and MN_A as follow.

1. s ： $0 \le s < d$

2. MN_A : $(S_i - d, 0) \le MN_A < (S_i, 0)$

We calculate the coordinate of MN_A and MN_B when MN_B is at cross respectively, then we assume MN_B will leave the range of MN_A through T_2 after turning. Because knowing the direction of MN_A and MN_B, we can calculate the coordinate of MN_A and MN_B after T_2. At this time, the distance of two mobility nodes is R. Consequently we can get T_2 through solve the equation as Equation 8 indicates.

$$T_1 = \frac{s + (C_i - j)d}{v_B}$$

$$MN_B \text{ turn to down}$$

$$\left(\left(j - \left\lceil \frac{C_i}{2} \right\rceil\right)d + S_i - s + (T_1 + T_2)v_A\right)^2 + \left(\left(\left\lceil \frac{R}{d} \right\rceil - i\right)d - v_B T_2\right)^2 = R^2$$

$$MN_B \text{ turn to up}$$

$$\left(\left(j - \left\lceil \frac{C_i}{2} \right\rceil\right)d + S_i - s + (T_1 + T_2)v_A\right)^2 + \left(\left(\left\lceil \frac{R}{d} \right\rceil - i\right)d + v_B T_2\right)^2 = R^2$$

$$\text{Solve this eqation, get } T_2$$

$$T_3 = \frac{2L_i}{|v_A - v_B|}$$

Equation 8: Calculate T_1, T_2 and T_3 of Parallel to Vertical Case

Finally, we calculate the average communication time of two mobility nodes which can transfer data directly in all possible, shown as Equation 9. Separating it into two parts, we calculate the first part： the communication time for MN_B meeting one cross and turning, same as $T_1 + T_2$. We calculate $T_1 + T_2$ of each cross respectively, because MN_B can meet C_i crosses at most. If we calculate the part of $v_B > v_A, v_B$ will vary between $v_A + \sigma$ and $v_{\max}$. There are many different way for MN_B to enter range of MN_A, for example that MN_B may enter range of MN_A from number i street or number $i+1$ street. Therefore, we sum of all situations and average to get ECT. And second part：T_3, we calculate the situation that MN_B goes straight during connecting.

$$
\begin{aligned}
&\overline{T}_{\rightarrow\rightarrow\Rightarrow\perp}(V_A) \\
&\overline{T}_{\rightarrow\rightarrow\Rightarrow\perp}(V_A) \\
&= E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B, i, j)\right] \\
&= E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B, j) \middle| i = 1\right] * p(i=1) \\
&+ E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B, j) \middle| i = 2\right] * p(i=2) + \ldots \\
&+ E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B, j) \middle| i = \left\lceil \frac{R}{d} \right\rceil\right] * p\left(i = \left\lceil \frac{R}{d} \right\rceil\right) \\
&= E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B) \middle| i = 1, j = 1\right] * p(i=1) * p_{turn} + \ldots \\
&E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B) \middle| i = 1, j = C_i\right] * p(i=1) * p_{turn} + \ldots \\
&+ E_{\rightarrow\rightarrow\Rightarrow\perp}\left[t_{\rightarrow\rightarrow\Rightarrow\perp}(v_B) \middle| i = \left\lceil \frac{R}{d} \right\rceil, j = C_i\right] * p\left(i = \left\lceil \frac{R}{d} \right\rceil\right) * p_{turn} \\
&= \sum_{i=1}^{\left\lceil \frac{R}{d} \right\rceil} p(i = I) \left(\sum_{j=1}^{C_i} \int_{s=0}^{d-\sigma} \int_{v_A+\sigma}^{v_{B\max}} (T_1 + T_2) p_{turn} f(v_B) f(s) dv_B ds + \int_{s=0}^{d-\sigma} \int_{v_A+\sigma}^{v_{B\max}} T_3 (1 - 2 * C_i p_{turn}) f(v_B) f(s) dv_B ds \right)
\end{aligned}
$$

$$
\begin{aligned}
&if \;\; 2 * C_i p_{turn} > 1, \;\; C_i = 1 / 2 * p_{turn} \\
&if \;\; i = \left\lceil \frac{R}{d} \right\rceil, \;\; p_i = \frac{1}{2\left\lceil \frac{R}{d} \right\rceil - 1} \\
&otherwise, \;\; p_i = \frac{2}{2\left\lceil \frac{R}{d} \right\rceil - 1} \\
&if \;\; (1 - 2 * p_{turn}) < 0, \;\; T_3 = 0
\end{aligned}
$$

Equation 9: ECT formulation of Parallel to Vertical Case

3.3 Vertical to Opposite or Parallel case

In vertical to opposite or parallel case, the relative direction between mobility nodes, MN_A and MN_B, is vertical. When MN_B meets a cross, it has probability of turning p_{turn} and lets the relative direction become opposite or parallel. As Figure 12 indicates relative velocity of v_A and v_B, and some parameters we define as following：

1. v_r ：relative velocity
2. $\angle\phi$ ： $\angle EIP$, angle of v_r
3. $\angle\alpha$ ： $\angle PIO$, one of the factors influencing ECT in this case, is the angle of horizontal and the line formed by the point of MN_B enters MN_A to origin.

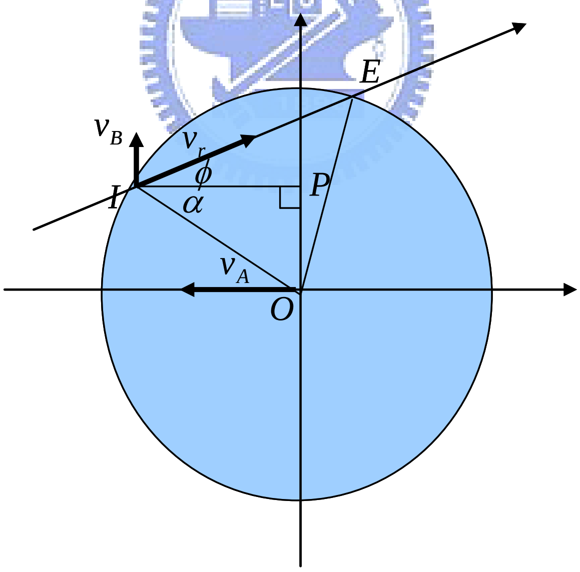

Figure 12: Vertical case

We reuse the partial method to calculate the ECT of vertical to opposite or parallel case in [1], for example we reuse the angle representation $\angle\alpha$ to calculate the communication time. Therefore, we repeat how we get $\angle\alpha$ as following segment. [1] explained ECT can be formulated as Equation 10 if MN_B goes straight in range of MN_A.

$$\begin{aligned}
&\overline{T}_{\perp}(v_A) \\
&= E_{\perp}[t_{\perp}(v_B,\alpha,\phi)] \\
&= E_{\perp}[t_{\perp}(v_B,\alpha)] \\
&= \int_{v_{B\min}}^{v_{B\max}} \int_{-\left(\pi/2+\phi\right)}^{\pi/2-\phi} t(v_B,\alpha) f_{\perp}(v_B,\alpha)\, d\alpha\, dv_B
\end{aligned}$$

Equation 10: ECT formulation of Vertical Case

We define mathematic symbol in Equation 11 as follow：

1. $t(v_B,\alpha)$ ：The period of MN_B in range of MN_A, communication time, as equation shows.

2. $f_{\perp}(v_B,\alpha)$：PDF of v_B and α, as Equation 12 indicates, separated into two part, see Equation 5 and Equation 13. We explain process to get PDF of α in Equation 13 as follow segment.

3. $\pi/2-\phi$ ：Maximum value of $\angle\alpha$, it also means MN_B will have no connection with MN_A if the $\angle\alpha$ of MN_B enters the range of MN_A bigger than maximum value.

4. $-\left(\pi/2+\phi\right)$ ：Minimum value of $\angle\alpha$, it also means MN_B will have no connection with MN_A if the $\angle\alpha$ of MN_B enters the range of MN_A smaller than minimum value.

$$
\begin{aligned}
& t_{\perp}(v_B,\alpha,\phi) \\
& = \frac{2R\cos(\alpha+\phi)}{v_r} \\
& = \frac{2R(v_A\cos\alpha - v_B\sin\alpha)}{{v_A}^2+{v_B}^2} \\
& = t_{\perp}(v_B,\alpha)
\end{aligned}
$$

Equation 11: ECT of Vertical Case

$$f_{\perp}(v_B,\alpha) = f_{\alpha|v_B}(\alpha \mid v_B) f(v_B)$$

Equation 12: PDF of v_B and α

MN_B can enter range of MN_A from the underside of MN_A.the period from when MN_B enters the range of MN_A to when it leaves is the communication time we want to analyze. Nevertheless, different α causes different communication time, so we need to calculate the communication time in all possible entrance angles, multiply its corresponding PDF of v_B and α respectively to get ECT. Therefore, we analyze angle α first to get PDF of α, called $f(\alpha)$. Figure 13 indicates the relation of α and entrance point of MN_B, and the range of α between $-\left(\pi/2+\phi\right)$ and $\pi/2-\phi$. We can observe the distance between entrance point for maximum α and minimum α is $2R$, so we can express the relation of α and r as Figure 14 shows. We can calculate CDF of $f(\alpha)$ first then differentiate it to get PDF of α. Equation 13 shows process of demonstrate step by step.

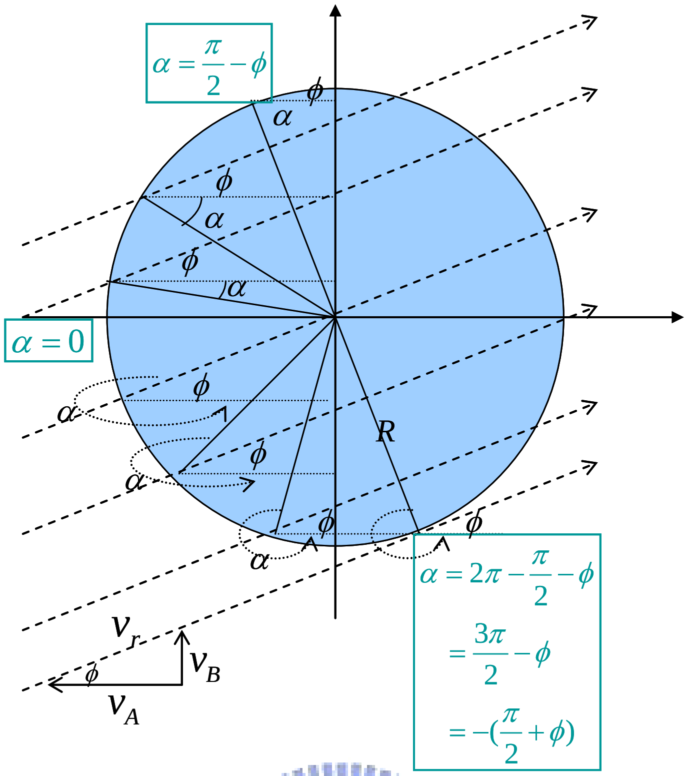

Figure 13: Relationship between entrance point of MN_B and α

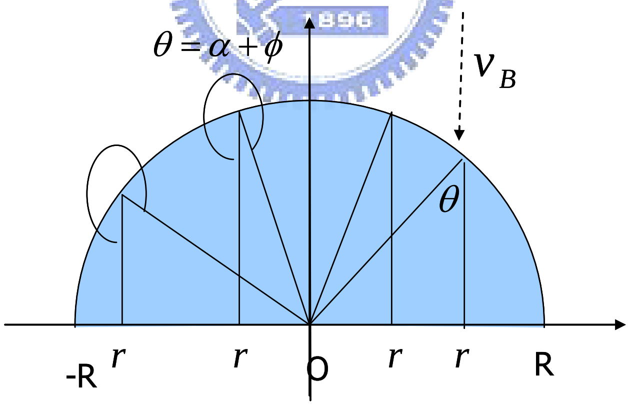

Figure 14: relationship between α and r

$$
\begin{aligned}
& f_{\alpha|v_B}(\alpha \mid v_B) \\
& = \int_{-R}^{r} \frac{1}{2R} dr \\
& = \frac{r}{2R}\Big|_{-R}^{r} \\
& = \frac{R\sin(\alpha+\phi)}{2R} + \frac{1}{2} \quad ,\alpha \in \left[-\left(\frac{\pi}{2}+\phi\right),\left(\frac{\pi}{2}-\phi\right)\right] \\
& f_{\alpha|v_B}(\alpha) \\
& = \frac{d}{d\alpha}\left[\frac{R\sin(\alpha+\phi)}{2R} + \frac{1}{2}\right] \\
& = \frac{\cos(\alpha+\phi)}{2} \quad ,\alpha \in \left[-\left(\frac{\pi}{2}+\phi\right),\left(\frac{\pi}{2}-\phi\right)\right]
\end{aligned}
$$

Equation 13: PDF of α

In this thesis, MN_B turns with probability p_{turn} when meeting a cross and lets the direction become opposite or parallel, as Figure 15 and Figure 16 indicate. A dotted arrow represents relative direction of MN_A and MN_B. We divide it into two parts to calculate: one is that MN_B can't reach some crosses and the other is that MN_B can reach some crosses.

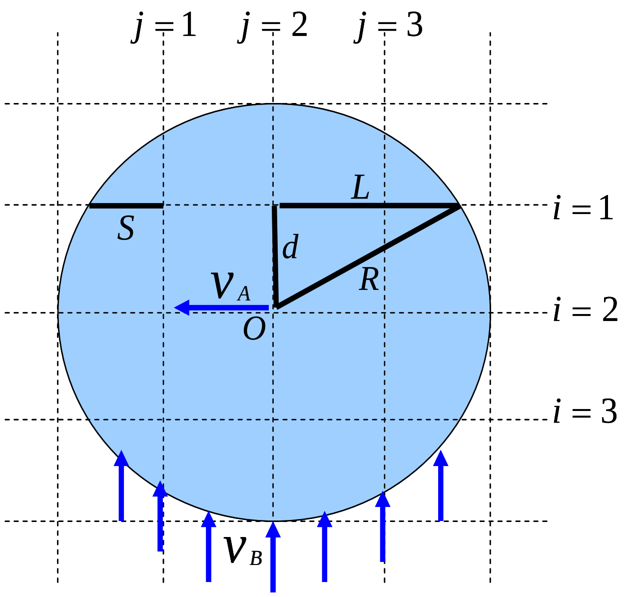

Figure 15: Vertical case of VANETs in urban city

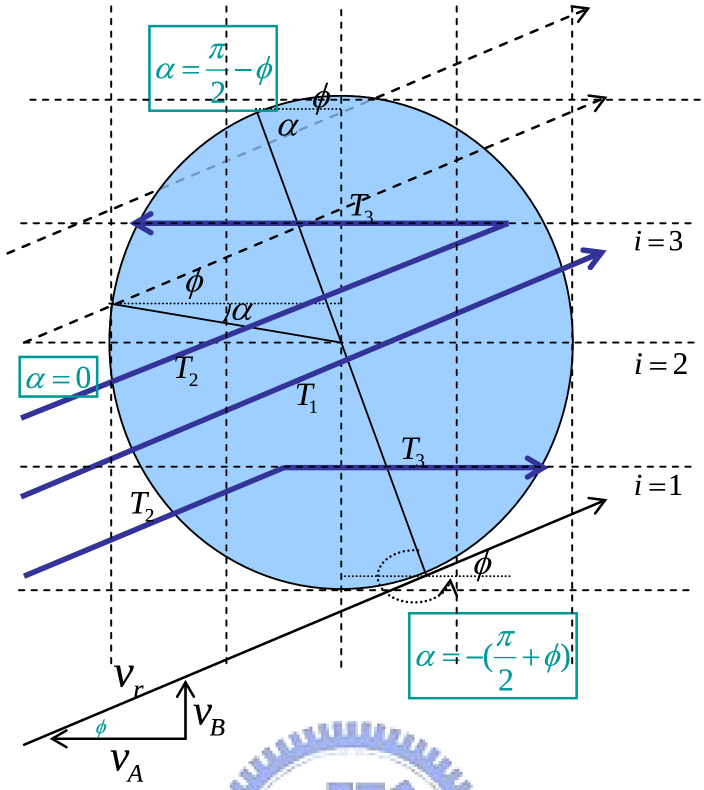

Figure 16: Vertical to Opposite or Parallel Case with turn probability p_{turn}

In order to calculate easily, we define some particular angles first, shown as Equation 14, see the definition of symbols as follow. θ_{Ri} and θ_{Li} can be referred to Figure 17, θ_{Hi} can be referred to Figure 18.

1. θ_{Ri} ： α for intersect of number i street and right boundary of MN_A.
2. θ_{Li} ： α for intersect of number i street and left boundary of MN_A.
3. θ_{Hi} ：Critical angle α that MN_B can reach number i_{th} street, means MN_B exactly touches i_{th} street on boundary of MN_A when MN_B is leaving MN_A if MN_B enter range of MN_A from angle α. For example, if entrance angle α is smaller than this critical angle, MN_B can't reach i_{th} street, on the contrary, MN_B can reach.

$$\theta_{R_i} = -\left(\frac{\pi}{2} + \cos^{-1}\left(\frac{R - i \times d}{R}\right)\right)$$

$$\theta_{L_i} = -\left(\sin^{-1}\left(\frac{R - i \times d}{R}\right)\right)$$

$$\theta_{H_i} = -2\left(\frac{\pi}{2} + \phi\right) - \theta_{R_i} \;, \theta_{H_0} = -\left(\frac{\pi}{2} + \phi\right)$$

Equation 14: Specific value of angle α

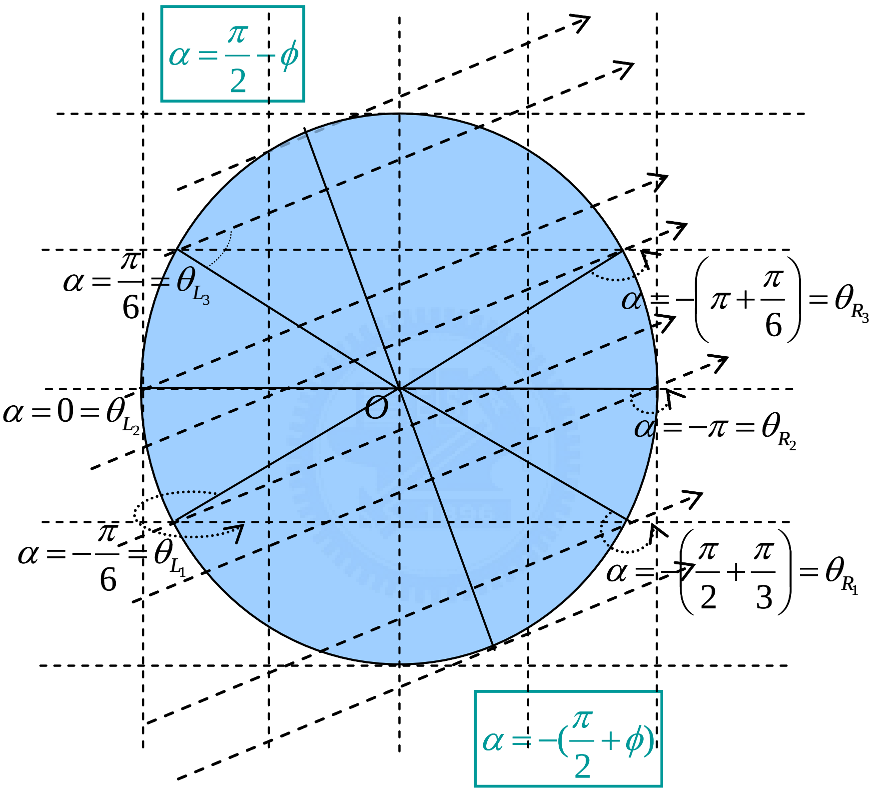

Figure 17: Specific value of angle α

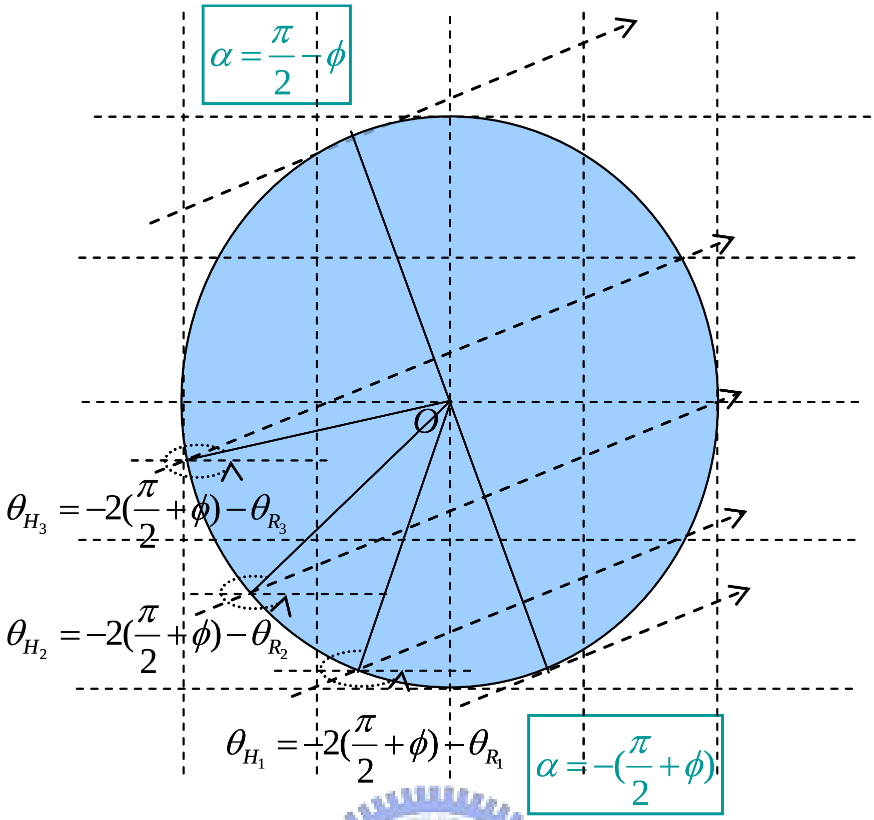

Figure 18: Value of θ_{H_i}

Furthermore, the range of α is different depending on v_B. As Figure 19 indicates, we can observe the angle of relative direction becomes θ from ϕ after v_B increased, so the range of α is changed too. We divide v_B into several segments to induce easily, as Figure 20 shows, we divide v_B into two segments and let the minimum value of α fall in $\overline{ST}$ and $\overline{TU}$ respectively. It is because in the first segment $\overline{ST}$, there are some angle α that let MN_B can't reach the first street, but in the second segment $\overline{TU}$, MN_B can reach first street from any entrance point with angle α. Therefore we can ignore the problem whenever MN_B can reach the first street or not, and consider whenever MN_B can reach next street or not directly. Equation 15 indicates the segment of v_B.

$$v_{B_s} = \tan^{-1}\left(-\theta_{R_s} - \frac{\pi}{2}\right)v_A$$

$$v_{B_0} = 0,\ \ v_{B_{\left\lceil \frac{R}{d} \right\rceil}} = v_{\max}$$

Equation 15: Segment of v_B

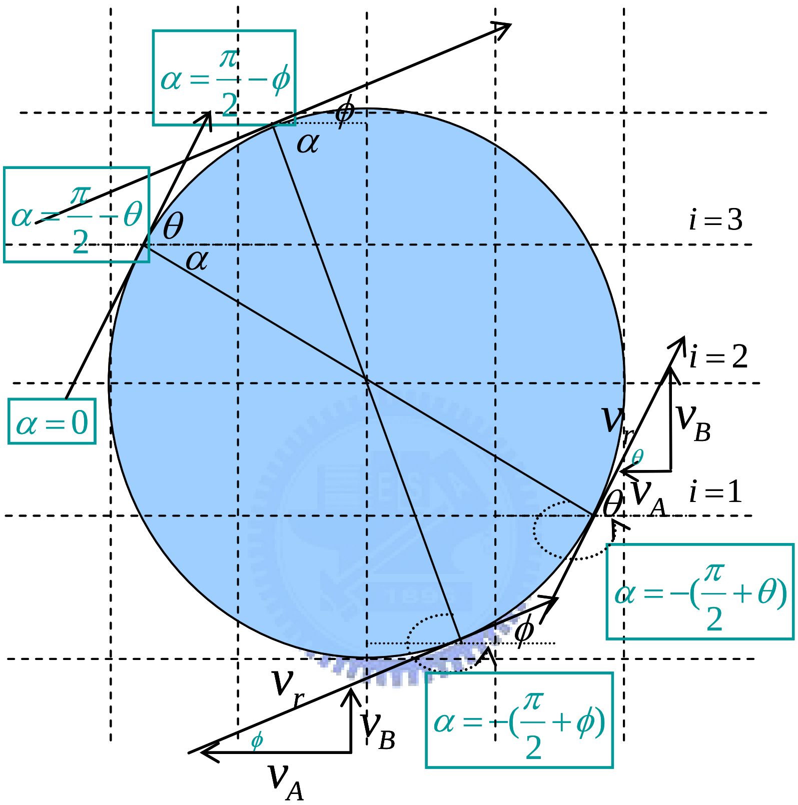

Figure 19: Relationship between v_B and range of angle α

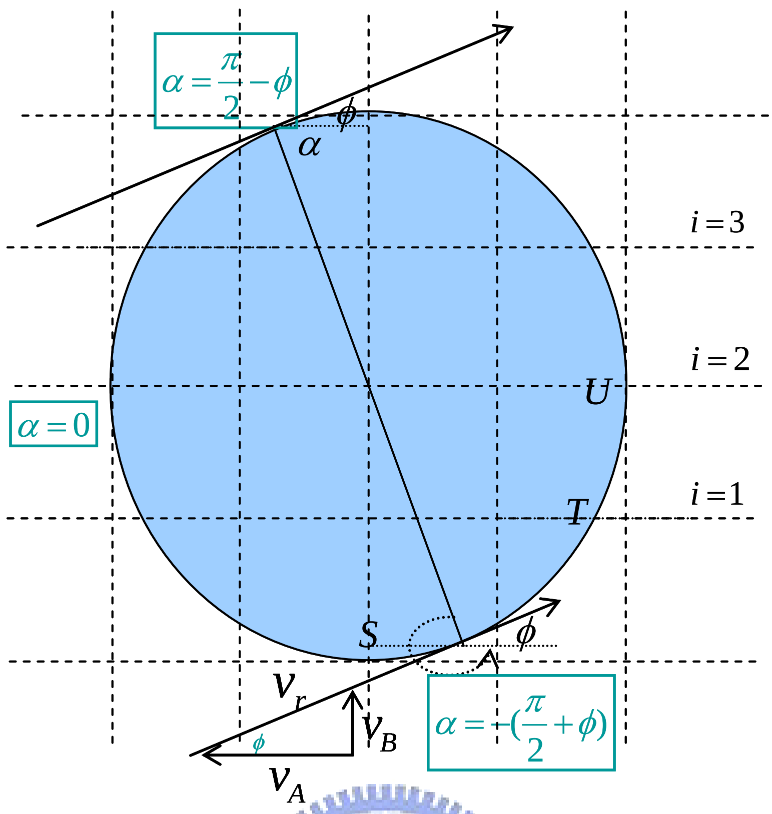

Figure 20: Segment of v_B

After preparing above, we utilize symbols already defined to calculate T_1, T_2, T_3, and T_4 in Figure 16 respectively. As Equation 16 indicates, T_1, T_2, T_3, and T_4 represent the average communication time in all situations, so we integrate α and v_B respectively. Furthermore, we mention above that we divide it into two parts, one part is that MN_B can't reach some crosses, the other part is that MN_B can reach some crosses. We will focus on each street in our discussion.

T_1 belongs to the first part: we calculate the communication time for each street that MN_B can't reach respectively. For example, MN_B enters the range of MN_A with a speed of v_B, then we can estimate if angle α falls in the range from θ_{H_1} to θ_{H_2}. If yes, it represents MN_B can reach first street but can't reach second street. In other words, when MN_B meets first cross, MN_B goes straight, but MN_B isn't speedy enough to reach second street. Then we take the communication time to multiply remainder probability minus the probability of turning, so we can get the expected value.

T_4 represents the scenario MN_B that can reach each street in range of MN_A, but MN_B always goes straight when meeting crosses. We calculate it individually because the range of angle α is different from T_1. Subsequently T_2 and T_3, belonging to part of MN_B can reach some crosses and turn. T_2 is the period of MN_B touch range of MN_A and MN_B meets a cross, and T_3 is the period of MN_B turns at cross and MN_B leave range of MN_A.

$$T_1 = \int_{v_{B_{s-1}}}^{v_{B_s}} \int_{\theta_{H_{i+s-2}}}^{\theta_{H_{i+s-1}}} \frac{2R[v_A \cos\alpha - v_B \sin\alpha]}{v_A{}^2 + v_B{}^2} \frac{\cos(\alpha+\phi)}{2} f(v_B) d\alpha dv_B$$

$$T_2 = \int_{v_{B_{s-1}}}^{v_{B_s}} \int_{\theta_{H_i}}^{\theta_{L_i}} \frac{R\sin(-\alpha) - \left(\left\lceil \frac{R}{d} \right\rceil - i\right) d}{v_B} \frac{\cos(\alpha+\phi)}{2} f(v_B) d\alpha dv_B$$

Turn right (*Opposite*)

T_3

$$= \int_{v_{B_{s-1}}}^{v_{B_s}} \int_{\theta_{H_i}}^{\theta_{L_i}} \frac{L_i + R\cos\alpha - \frac{\left(R\sin(-\alpha) - \left(\left\lceil \frac{R}{d} \right\rceil - i\right) d\right)}{v_B} v_A}{v_A + v_B} \frac{\cos(\alpha+\phi)}{2} f(v_B) d\alpha dv_B$$

Turn left (*Parallel*)

T_3

$$= \int_{v_{B_{s-1}}}^{v_{B_s}} \int_{\theta_{H_i}}^{\theta_{L_i}} \frac{L_i - R\cos\alpha + \frac{\left(R\sin(-\alpha) - \left(\left\lceil \frac{R}{d} \right\rceil - i\right) d\right)}{v_B} v_A}{|v_A - v_B|} \frac{\cos(\alpha+\phi)}{2} f(v_B) d\alpha dv_B$$

$$T_4 = \int_{v_{B_{s-1}}}^{v_{B_s}} \int_{\theta_{H_{2\left\lceil \frac{R}{d} \right\rceil - 1}}}^{\frac{\pi}{2}-\phi} \frac{2R[v_A \cos\alpha - v_B \sin\alpha]}{v_A{}^2 + v_B{}^2} \frac{\cos(\alpha+\phi)}{2} f(v_B) d\alpha dv_B$$

Equation 16: Calculate T_1, T_2, T_3 and T_4

Finally, we calculate ECT of vertical to opposite or parallel case, as Equation 17 shows. We take T_1, T_2, T_3 and T_4 to multiply a corresponding probability influenced by probability of turn respectively. And we consider all possible situation and calculate respectively, then sum them to get ECT.

$$
\begin{aligned}
&\overline{T}_{\perp\Rightarrow\leftrightarrow\|\to\to}(v_A) \\
&= E_{\perp\Rightarrow\leftrightarrow\|\to\to}\left[t_{\perp\Rightarrow\leftrightarrow\|\to\to}(v_B,\alpha,\phi)\right] \\
&= \sum_{s=1}^{S=\left\lceil\frac{R}{d}\right\rceil}\ \sum_{i=1}^{2\left\lceil\frac{R}{d}\right\rceil-s} T_1\left(1-2*(i+s-2)p_{turn}\right) + \sum_{s=1}^{S=\left\lceil\frac{R}{d}\right\rceil}\ \sum_{i=1}^{2\left\lceil\frac{R}{d}\right\rceil-1} (T_2+T_3)p_{turn} \\
&+ \sum_{s=1}^{S=\left\lceil\frac{R}{d}\right\rceil} T_4\left(1-2*\left(2\left\lceil\frac{R}{d}\right\rceil-1\right)p_{turn}\right)
\end{aligned}
$$

$$
\begin{aligned}
&if\ \ 2*(i+s-2)p_{turn} > 1,\ \ T_1 = 0 \\
&if\ \ 2*ip_{turn} > 1,\ \ T_2 = T_3 = 0 \\
&if\ \ 2*\left(2\left\lceil\frac{R}{d}\right\rceil-1\right)p_{turn} > 1,\ \ T_4 = 0
\end{aligned}
$$

Equation 17: ECT formulation of Vertical to Opposite or Parallel Case

Chapter 4: Expected Communication Time with Traffic Light

In this chapter, we add traffic lights to every cross, and analyze the effects on the communication time. We finally suppose a mathematic analysis model to calculate the expected communication time. We suppose there is no correlation between every traffic light, that is, they work individually. Also, with two signals, red light and green light, cars that meet a red light should stop and vice versa. The period of the red lights and green lights is the same. We will use the mathematic analysis model mentioned in Chapter 3. In Chapter 3, there is no traffic light on each cross, so the states of MN_A and MN_B are "move." As the Figure 21 bellow shows, "m" means "move," while "s" means "stop." In this chapter, because of the traffic light, there may be "s" or "m" in MN_A and MN_B. What's more, we can say that the three states $(m,m),(m,s),(s,m)$ coming from the state (m,m) without traffic lights. If there is one of state of MN_A or MN_B is "m", it will engage the communication time without traffic light. The difference lies in the different relative velocity leading to different communication times. They are involved in the communication time of the state without traffic lights. The change of relative velocity results in the change of communication time. We simply model it as a relation of linear of inverse proportion and there is a multiple between the two. We suppose they are $T_{(m,s)}$ and $T_{(s,m)}$, as the Equation 20 shows. We will deduce in the next section. On the other hand, (s,s) is extra communication time when both MN_A and MN_B are waiting for the traffic light, so it is not involved in the communication time. We count respectively the probability of each state, and suppose that the communication time with traffic light is ECT_{TL}. The probability is the proportion composed ECT_{TL}. Then we have (m,s)

and (s,m) divide their corresponding multiple $T_{(m,s)}$ and $T_{(s,m)}$. Finally, we have (m,s) and (s,m), which divide their corresponding multiple $T_{(m,s)}$ and $T_{(s,m)}$ plus (m,m) and that will equal the communication time without a traffic light. Therefore, we can introduce ECT_{TL} inversely.

$$\begin{aligned}&\text{No traffic light:}\\&\text{State(A, B)} = \{(m,m)\}\\&\text{Taffic light:}\\&\text{State(A, B)} = \{(m,m),(m,s),(s,m),(s,s)\}\end{aligned}$$

Figure 21: State of MN_A and MN_B

4.1 Opposite to Vertical Case with Traffic Light

We first count the probability that MN_A and MN_B stop per second respectively. We suppose d means the distance between two streets, and TL means the period of red light. When MN_B enters the transmission range of MN_A, it may meet the red light immediately, or go for d before meeting with the red light. The periods of the red and green lights are the same, and MN_B will meet with one red light after passing by two traffic lights in average. Therefore, MN_B meets red light once during the MN_B goes $1.5d$. The average time of stopping at the red light is $1/2\, TL$, and the formula for probability is shown as Equation 18. And we can calculate the probability of each state in Figure 21. As Equation 19 shows, the probability is the proportion of each state in ECT_{TL}. Then we calculate the multiple of communication time caused by relative velocity, as Equation 20 shows. As for the state of (m,s), $v_A + v_B$ represents the relative velocity at first, and v_A means the relative velocity after MN_B stops. We model the relation of relative velocity and communication time to be a relation of linear of inverse proportion. In this state, if MN_A or MN_B stops, relative velocity must be reduced. So the multiple $T_{(m,s)}$ and $T_{(s,m)}$ must be larger than one. At last, we have ECT_{TL} to multiply the probability of three states $(m,m),(m,s),(s,m)$, have (m,s) and (s,m) divide the multiple $T_{(m,s)}$ and $T_{(s,m)}$. Then add the three states together, it will be equal to ECT without traffic light calculated in Chapter 3. With the ECT we have known, we can introduce ECT_{TL} inversely, as Equation 21.

$$p_{sA} = \frac{1}{2}TL \Big/ \left(\frac{2d}{v_A} + \frac{1}{2}TL\right)$$
$$p_{sB} = \frac{1}{2}TL \Big/ \left(\frac{2d}{v_B} + \frac{1}{2}TL\right)$$

Equation 18: Probability of MN_A and MN_B stop per second

$$p_{h(m,m)} = (1 - p_{sA})(1 - p_{sB})$$
$$p_{h(m,s)} = (1 - p_{sA})p_{sB}$$
$$p_{h(s,m)} = p_{sA}(1 - p_{sB})$$
$$p_{h(s,s)} = p_{sA}p_{sB}$$

Equation 19: Probability of each state happened

$$T_{(m,s)} = \frac{v_A + v_B}{v_A}$$
$$T_{(s,m)} = \frac{v_A + v_B}{v_B}$$

Equation 20: Multiple of communication time in Opposite to Vertical Case

$$ECT_{TL(m,m)} = ECT_{TL} * p_{h(m,m)}$$
$$ECT_{TL(m,s)} = ECT_{TL} * p_{h(m,s)}$$
$$ECT_{TL(s,m)} = ECT_{TL} * p_{h(s,m)}$$
$$ECT_{TL(s,s)} = ECT_{TL} * p_{h(s,s)}$$
$$ECT_{TL(m,m)} + \frac{ECT_{TL(m,s)}}{T_{(m,s)}} + \frac{ECT_{TL(s,m)}}{T_{(s,m)}} = ECT$$
$$\Rightarrow \text{get } ECT_{TL}$$

Equation 21: Calculate ECT_{TL}

4.2 Parallel to Vertical Case with Traffic Light

In this case, besides the multiple increases in communication time $T_{(m,s)}$ and $T_{(s,m)}$, shown as Equation 22, the method of calculating ECT_{TL} is the same as the Opposite to Vertical Case mentioned above. Among the multiple increases in communication time, $|v_A - v_B|$ means the relative velocity before MN_A or MN_B stops. v_A and v_B represent individually the relative velocity after MN_B and MN_A stops. In this case, there might be the situation that the relative velocity when MN_A and MN_B stop is larger than that before they stop. If the relative velocity before MN_A and MN_B stop is smaller, the multiple will be less than one. That is, the part of communication time after they stop will be less. On the other hand, if the relative velocity before MN_A and MN_B stop is larger, the multiple will be more than one. That is, the part of communication time after they stop will be more. Based on Equation 21, bring the increasing multiple in and get the last communication time ECT_{TL}.

$$T_{(m,s)} = \frac{|v_A - v_B|}{v_A}$$

$$T_{(s,m)} = \frac{|v_A - v_B|}{v_B}$$

Equation 22: Multiple of communication time in Parallel to Vertical Case

4.3 Vertical to Opposite or Parallel Case with Traffic Light

In this case, besides the multiple increases in communication time $T_{(m,s)}$ and $T_{(s,m)}$, as Equation 23, the method of calculating ECT_{TL} is the same as the Opposite to Vertical Case mentioned above. Among the multiple of increasing communication time, $\sqrt{v_A^2 + v_B^2}$ means the relative velocity before MN_A or MN_B stop. v_A and v_B represent individually the relative velocity after MN_B and MN_A stop. In this case, the relative velocity when MN_A and MN_B stops must be smaller than that before they stop. If the relative velocity before MN_A and MN_B stop is larger, the multiple will be more than one. That is, the part of communication time after they stop will be more. Based on the Equation 21, bring the increasing multiple in and get the last communication time ECT_{TL}.

$$T_{(m,s)} = \frac{\sqrt{v_A^2 + v_B^2}}{v_A}$$

$$T_{(s,m)} = \frac{\sqrt{v_A^2 + v_B^2}}{v_B}$$

Equation 23: Multiple of communication time in Vertical to Opposite or Parallel Case

Chapter 5: ECT Formulation Result

In chapter 3, Equations 5, 8 and 6 are mathematical analyses of three independent mobility models. We make use of the mobility models in mathematical tool and calculate its ECT. Then, according to Equation 1, we conclude the three outcomes to final. The mathematical tool we use is MATLAB 7.3, the outcome explains the relationship between v_A and ECT. We suppose the maximum moving speed between MN_A and MN_B is 20 m/s, v_B is averagely between the maximum and minimum, and the maximum transportation radius is 250m.

5.1 ECT Formulation Result of Opposite to Vertical Case

In Opposite to Vertical case, Figure 22 and Figure 23 represents the relationship between v_A and ECT. Figure 22 compares with the same distance between streets, different impacts on ECT due to different turn probability p_{turn}. 4×4 represents the distance of adjacent streets as $d=125m$, 8×8 represents the distance of next street as $d=62.5m$, and so on. Five curves represents wireless nodes turning up and down when meeting the cross with turn probability $p_{turn}=1/4,\ 1/8,\ 1/12,\ 1/16,\ 1/1000$ respectively, among them, $1/1000$ can be regarded as MN_B not turning [1]. Figure 22 reveals that as p_{turn} gets larger, the ECT gets larger. That's because in the beginning MN_A and MN_B move in the opposite case, their relative speed $v_r=v_A+v_B$ is higher than the relative speed of the vertical case $v_r=\sqrt{v_A^2+v_B^2}$ after turning. So it will increase the ECT if MN_B turns to the vertical case earlier. In reality, the difference of relative speed between the opposite case and vertical case isn't apparent, so is their addition. In Figure 23, the turn probability of 4×4 is $p_{turn} = 1/4$, and that of 8×8 is $p_{turn} = 1/8$. We aim at supposing MN_B with the same turn probability p_{turn} in the same distance, then compare the effect on ECT due to different interval of street. And the outcome reveals that the interval of street is unobvious to ECT.

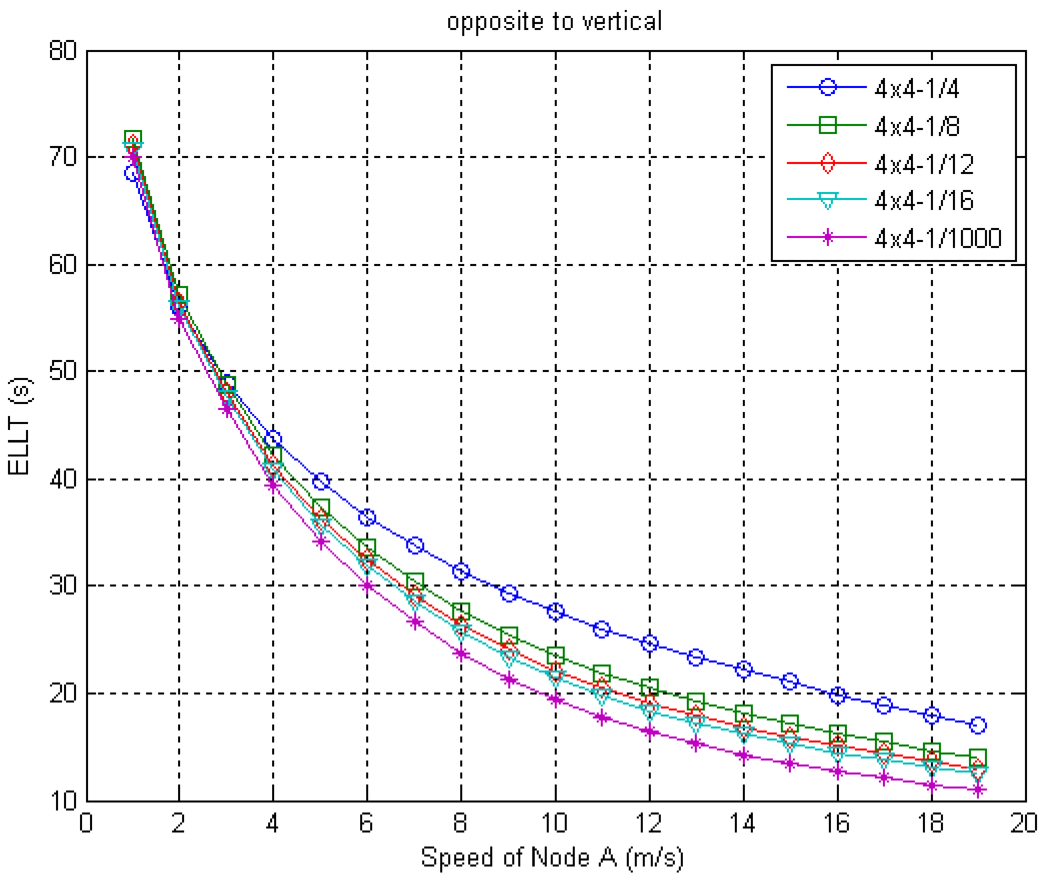

Figure 22: Opposite to Vertical Case with different turn probability

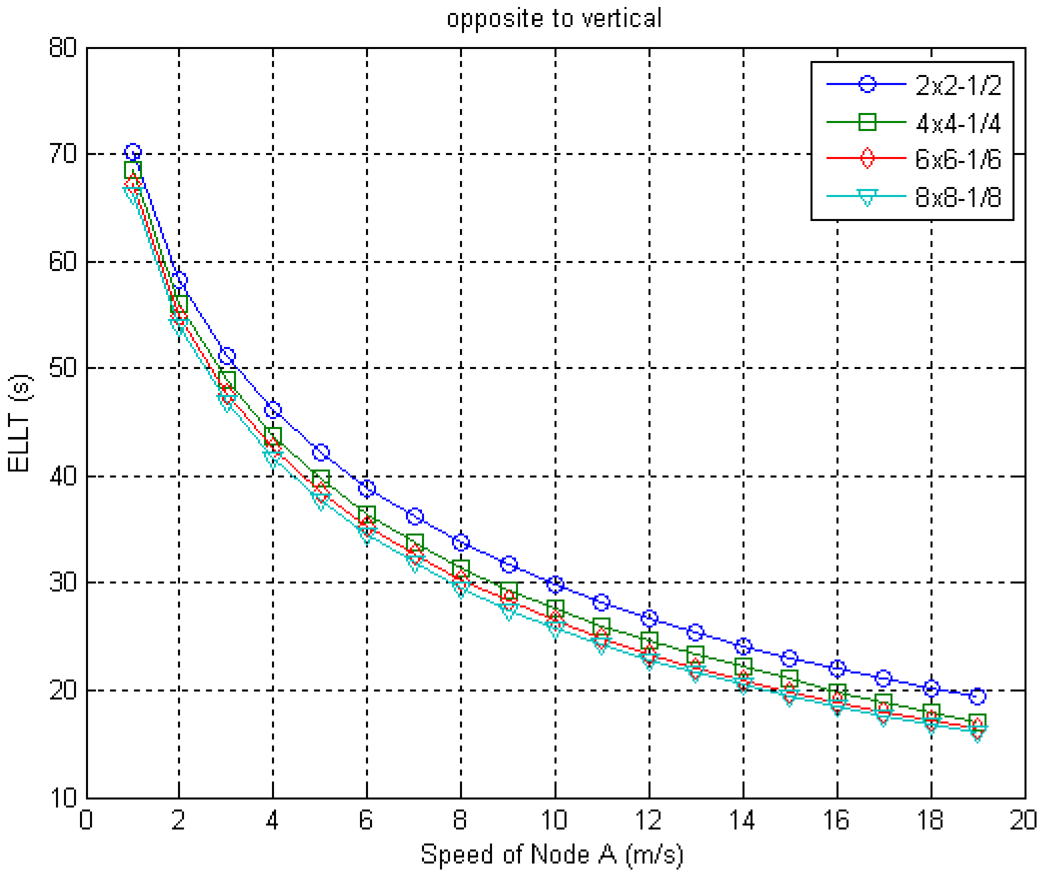

Figure 23: Opposite to Vertical Case with different gird size

5.2 ECT Formulation Result of Parallel to Vertical Case

In parallel to vertical case, we compare ECT in different probabilities of turning p_{turn} when the interval between two streets is the same, as Figure 24 indicates. We can observe how the probability of turning affects ECT. Because origin relative velocity is $v_r = |v_A - v_B|$, after MN_B turns, it becomes $v_r = \sqrt{v_A^2 + v_B^2}$. We can see obviously the relative velocity after turning is bigger than before turning. Therefore, if p_{turn} is bigger, ECT is smaller, in the other hand, if p_{turn} is smaller, ECT is bigger. As Figure 25 shows, we analyze and take apart into two parts, one is $v_B > v_A$ case, and the other is $v_A > v_B$ case. In $v_B > v_A$ case, with the increase of v_A, the probability that MN_B reaches MN_A becomes little, and the part $v_A > v_B$ in ECT becomes less. As for the case of $v_A > v_B$, v_A is smaller at first, and the probability that MN_A reaches MN_B is smaller. If v_A and v_B is small and move paralleled, it will make ECT larger and ECT will increase faster in the beginning. When v_A becomes bigger, the probability that MN_A reaches MN_B becomes bigger, and it should makes ECT increase. But because of the increase of v_A, the ECT reduces. With the correlation of two factors, the increase of ECT becomes alleviative. In Figure 26 we compare how different interval of streets affects ECT with the same turn probability p_{turn} , and it reveals there is little impact on ECT.

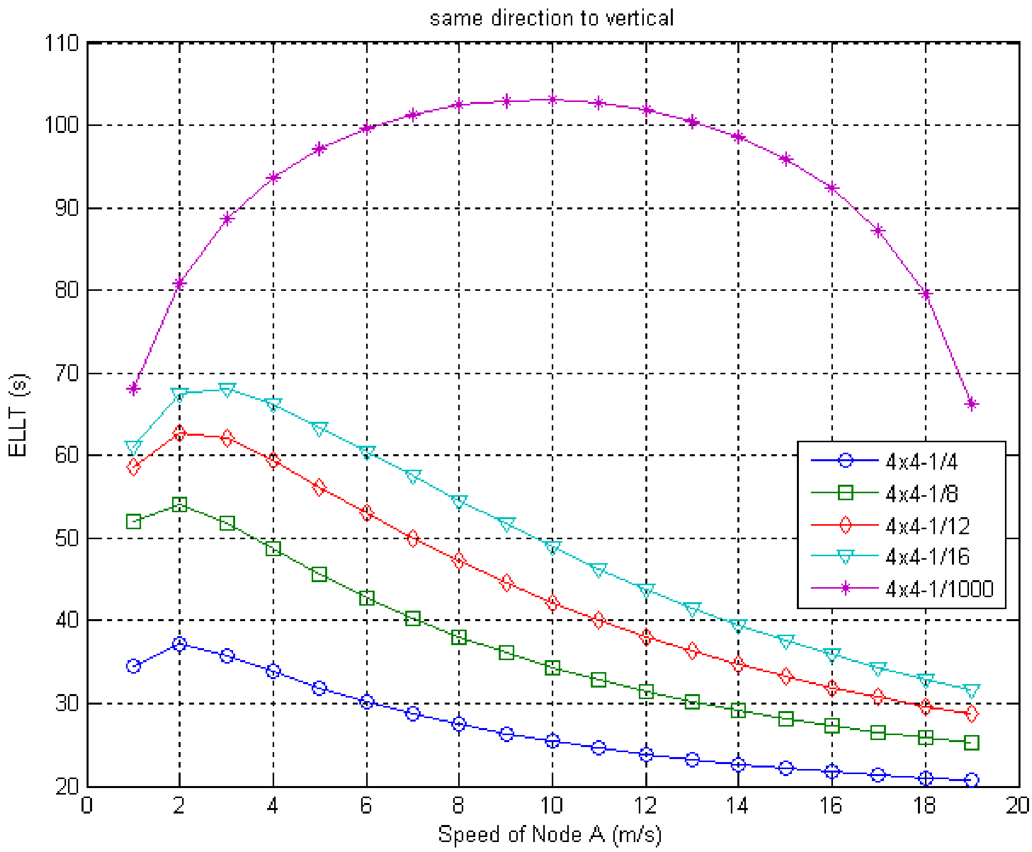

Figure 24: Parallel to Vertical Case with different turn probability

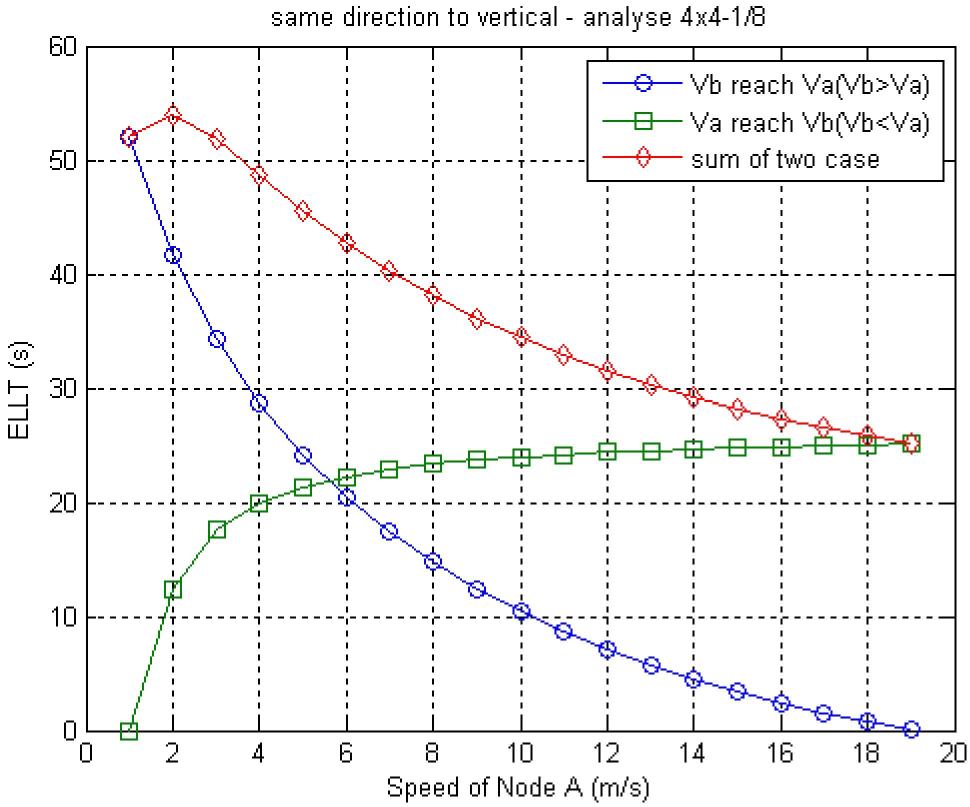

Figure 25: Divide into two case $v_B > v_A$ **and** $v_A > v_B$

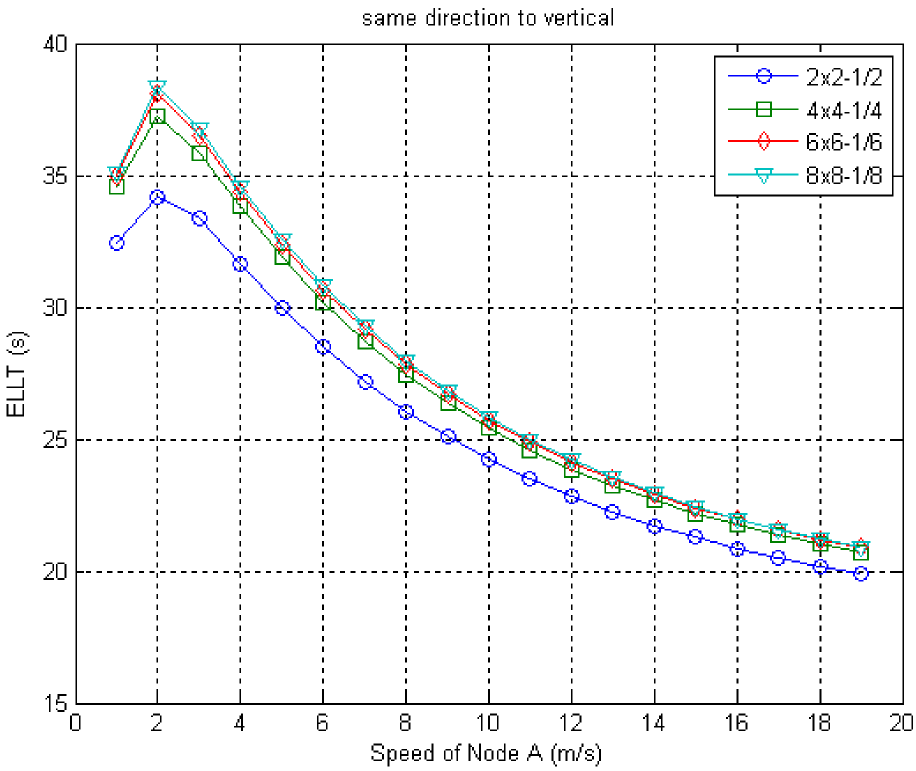

Figure 26: Parallel to Vertical Case with different grid size

5.3 ECT Formulation Result of Vertical to Opposite or Parallel Case

In the vertical to opposite or parallel case, we compare different turn probability p_{turn} and ECT with the same interval street. In Figure 27, it can be seen that the turn probability affects ECT, that is, the larger p_{turn} gets, the larger ECT will be. The parallel case apparently elevates ECT. Though it may become opposite case when MN_B turns, the elevation in Parallel case offers the supplement. If the p_{turn} gets larger, vertical case can change to opposite case or parallel case quickly and adds ECT. In Figure 28 we compare how different interval of street affects ECT under the circumstances of same turn probability p_{turn}.

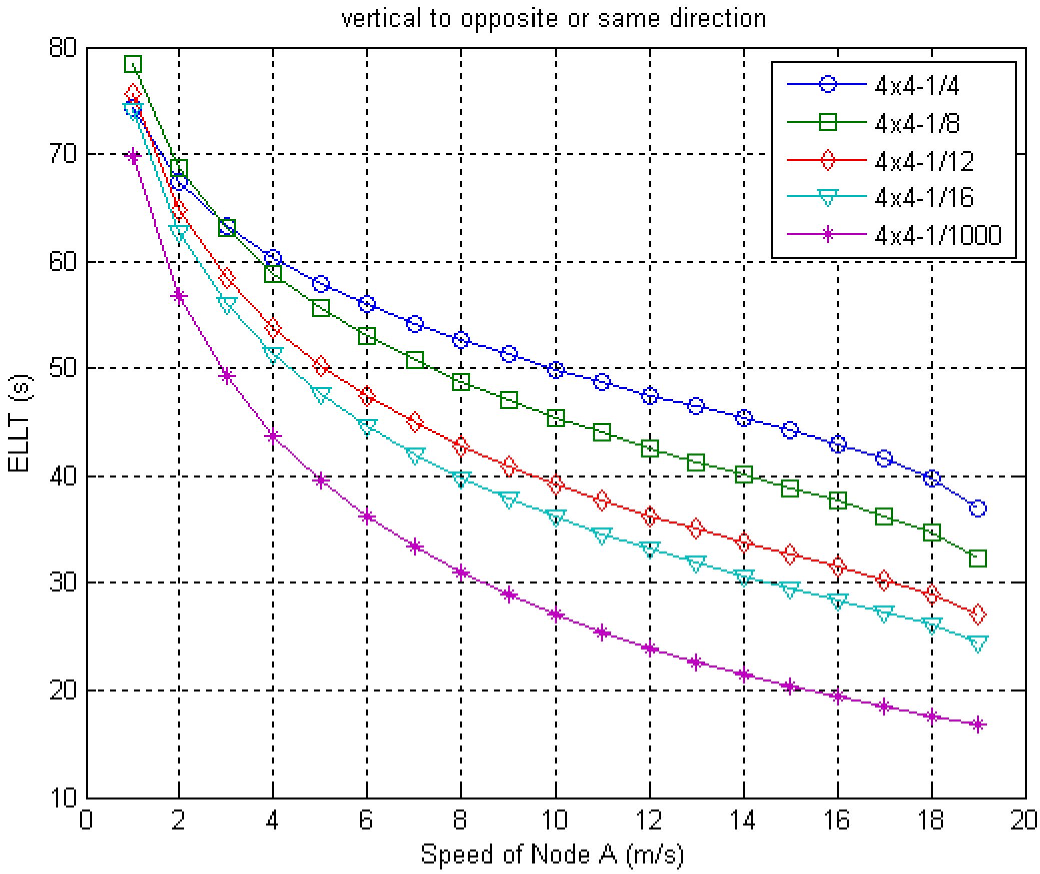

Figure 27: Vertical to Opposite or Parallel Case with different turn probability

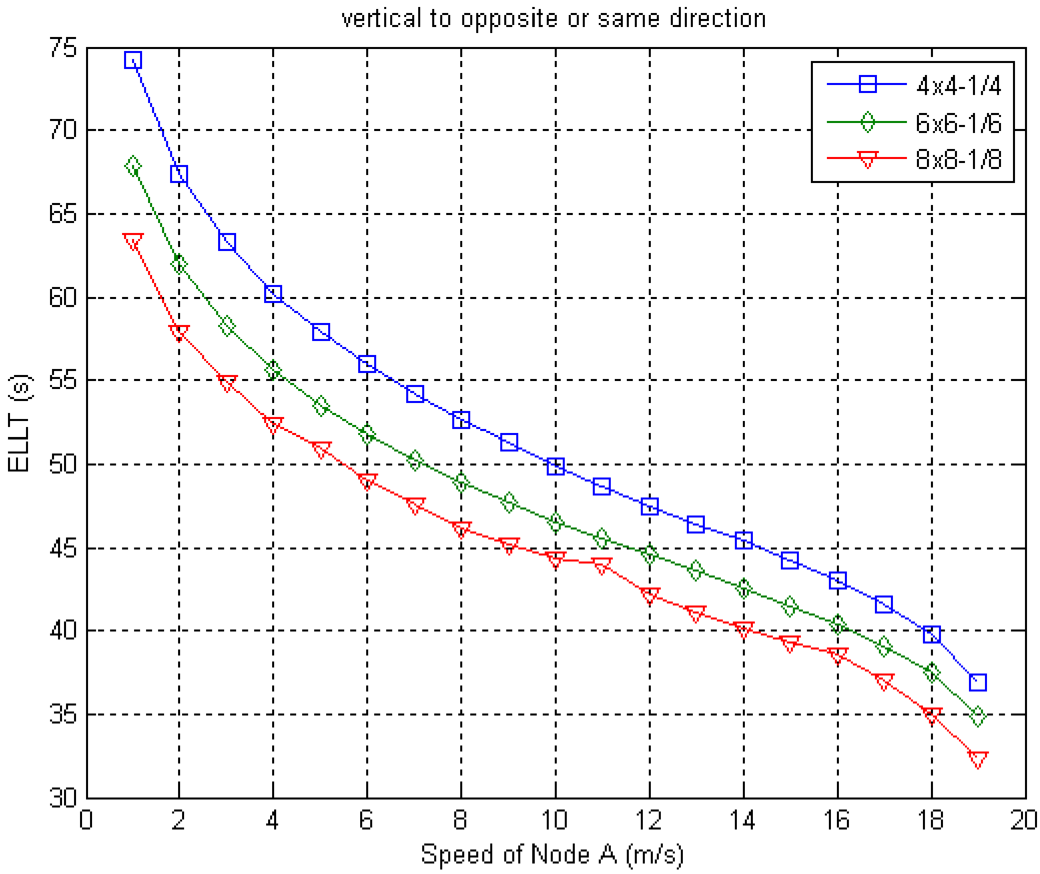

Figure 28: Vertical to Opposite or Parallel Case with different grid size

5.4 ECT Formulation result

In this section, we discuss ECT of three cases combined. We observe ECT in different probability of turn p_{turn} when the interval between two streets is the same in Figure 29. Figure 29 illustrates ECT decreases if MN_B has one turn. The decreasing part is caused by MN_B turning in Parallel to Vertical case mainly, because it will cause ECT to decrease dramatically. Though MN_B with turning will increase ECT a little bit in other two cases. In Figure 30 we compare how different interval of street affects ECT under the circumstances of same turn probability p_{turn}.

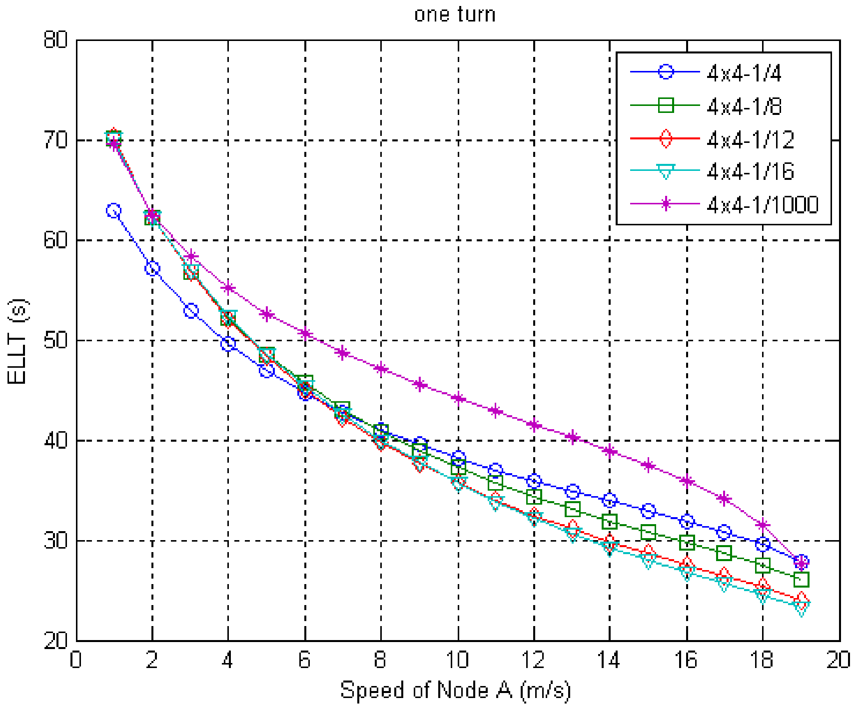

Figure 29: ECT of VANETs in urban city with different turn probability

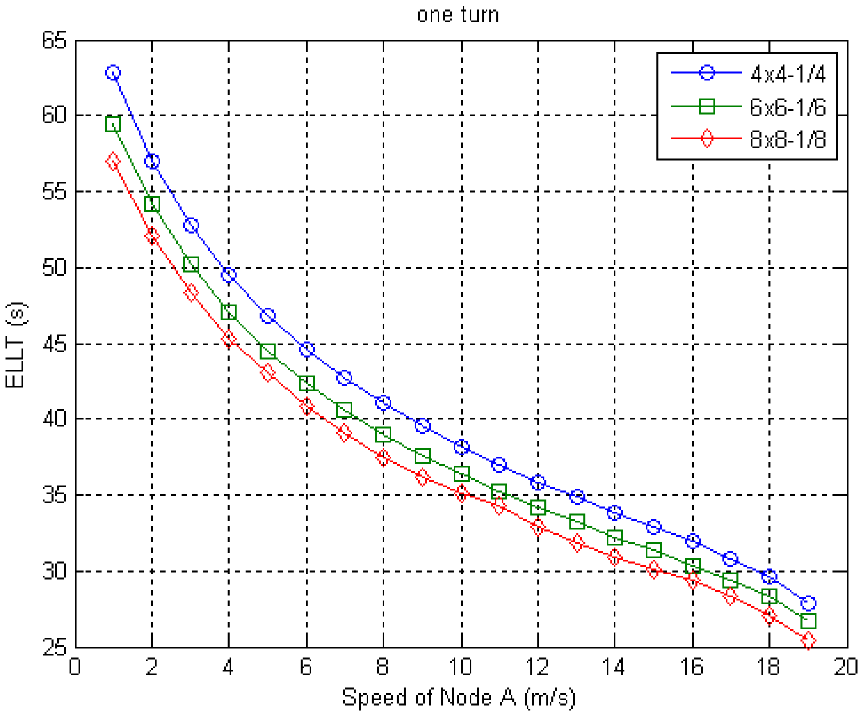

Figure 30: ECT of VANETs in urban city with different grid size

Chapter 6: Formulation and Simulation Comparison

To prove the accuracy of the mathematical analysis model we established, we use a mathematical tool to calculate ECT, use the network simulating tool NS2 to make a Manhattan Grid Mobility Model, and establish several wireless mobile nodes. According to the hypothesis in mathematical analysis model, there is one turn at most during the connection of MN_A and MN_B. We give it turning probability. We will observe if the outcome of NS2 match to MATLAB results.

6.1 Formulation and Simulation Comparison in Opposite to vertical case

In the case, we suppose a node A moves opposite to other nodes B. In other words, node A moves from up to down, and node B moves from down to up. Node A goes from the minimum speed to maximum speed without making a turn, while other nodes B are uniformly distributed in the range of minimum speed and maximum speed. The detailed simulation parameters are listed in Table 1. We suppose these nodes B have one turn at most within the transmission area of A, and there is a turning probability that makes them turn. If these nodes move out of the transmission area of node A, they will initial from the start. We will record every connection time. After simulating for a period of time, we equalize the connection time and get the simulation outcome. Furthermore, when the node moves to the boundary, plan [1] is to initialize the node to a starting point. But this leads to a boundary effect. For example, node B may touch the boundary when connecting to A, and B will be initialized to the starting point. It will break the connection and cause a deviation of simulation outcome and mathematical analysis. We make node B able to appear on another side boundary when touching the boundary. It is just like this two boundaries being connected. Therefore we can eliminate the boundary effect. As Figure 31 shows, our simulation outcome matches mathematic analysis results.

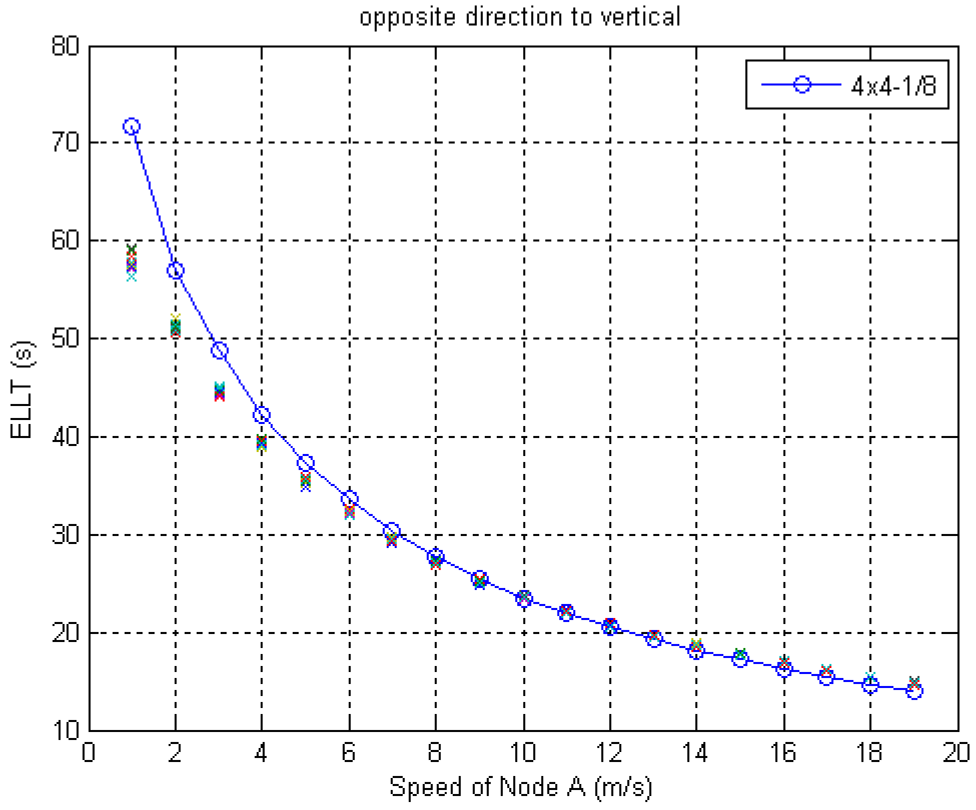

Figure 31: Formulation and Simulation Comparison in Opposite to Vertical Case

Simulator	Ns2-2.30
Node numbers	160
Simulation Time	1000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s

Block Size (*d*)	in Figure 31, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 1: Simulation parameters of Opposite to Vertical Case

6.2 Formulation and Simulation Comparison in Parallel to vertical case

In the case, we suppose a node A moves parallel to other nodes B. In other words, all nodes move from down to up. Other settings are the same as in Section 6.1, and the detailed simulation parameters are listed in Table 2. In Figure 32, we can observe that the theoretical results by MATLAB and the simulation outcome by NS2 match each other. Nevertheless, in this case the simulation outcome is more distributed. Because the ECT simulation of the parallel case is unlike the opposite case, it is diversely distributed. According to the curve of the formulation of the parallel case, the relationship between the speed of a mobile node and its ECT to others nodes under the parallel case differs from the opposite case. Even there is only a slight change on the speed of a mobile node, the ECT of the parallel case might be affected dramatically. This case includes parallel case. As a result, the simulation result of the parallel to vertical case is decentralized.

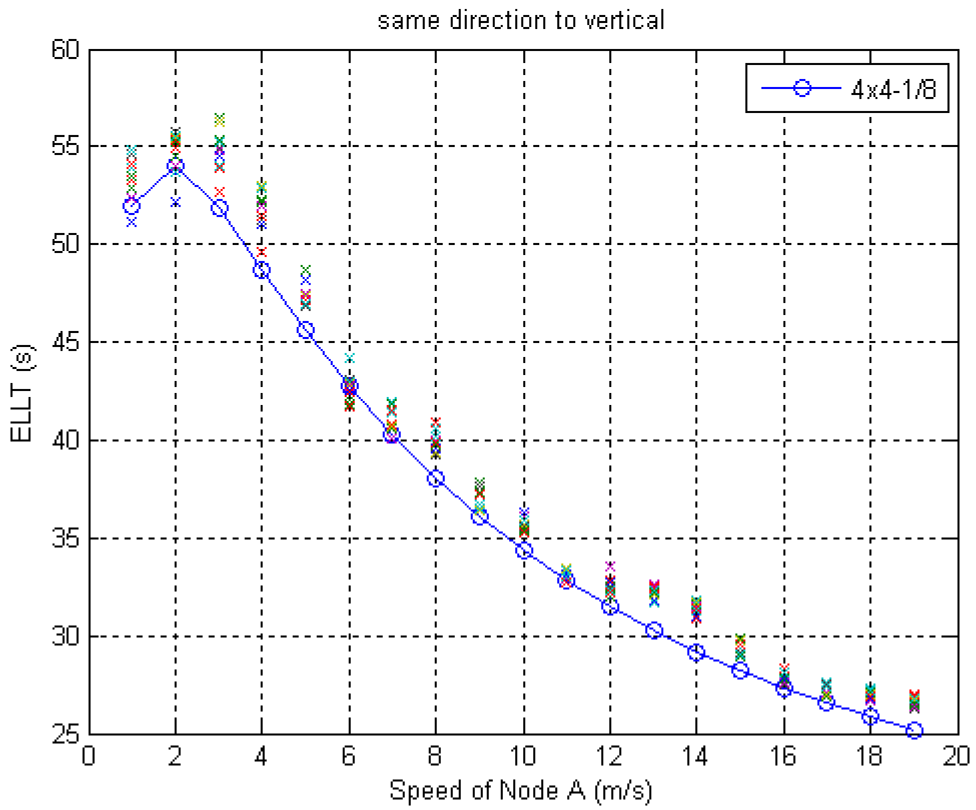

Figure 32: Formulation and Simulation Comparison in Parallel to Vertical Case

Simulator	Ns2-2.30
Node numbers	240
Simulation Time	1000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s
Block Size (*d*)	in Figure 32, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 2: Simulation parameters of Parallel to Vertical Case

6.3 Formulation and Simulation Comparison in Vertical to Opposite or Parallel case

In the case, we suppose a node A moves opposite to other nodes B. In other words, node A moves from left to right, and nodes B move from down to up. Other settings are same as section 4.1. The detailed simulation parameters are listed in Table 3. In Figure 33, we can observe that the theoretical values and the simulation results match each other. Nevertheless, simulation results are also more distributed. Because mobility nodes may turn and let relative direction become parallel. Therefore, this case includes parallel case to induce the decentralized results.

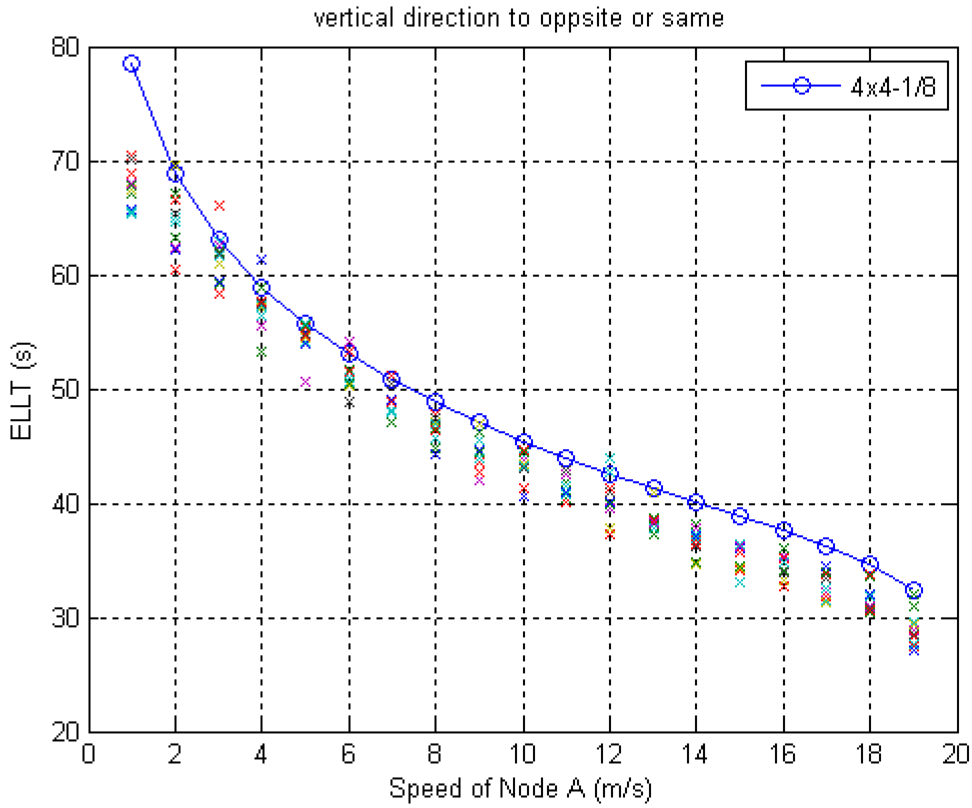

Figure 33: Formulation and Simulation Comparison in Vertical to Opposite or Parallel Case

Simulator	Ns2-2.30

Node numbers	160
Simulation Time	1000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (R)	250 m
Minimum speed ($Smin$)	0 m/s
Maximum speed ($Smax$)	20 m/s
Block Size (d)	in Figure 33, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 3: Simulation parameters of Vertical to Opposite or Parallel Case

6.4 Formulation and Simulation Comparison of VANETs in urban city

In this case, we utilize mobility models established in [24]. One of the mobility models is wireless mobility nodes moving randomly like random waypoint mobility model in an urban city. Consequently, mobility nodes may turn many times during connection. The nodes are initially placed randomly and initially given random direction on this Manhattan Grid topology. The detailed simulation parameters are listed in Table 4. We calculate ECT and get results as Figure 34 shows. We can observe that simulation results are close to MATLAB outcome. There is a deviation about 5 seconds between simulation and theoretical result. Because theoretical value by MATLAB has one turn at most and simulation result by NS2 has unlimited turns. However, we have discussed this in the preceding chapter. As Figure 34 shows, in the situation of unlimited turns, wireless nodes turn about one time average during connecting. Therefore, there isn't a large gap between both results.

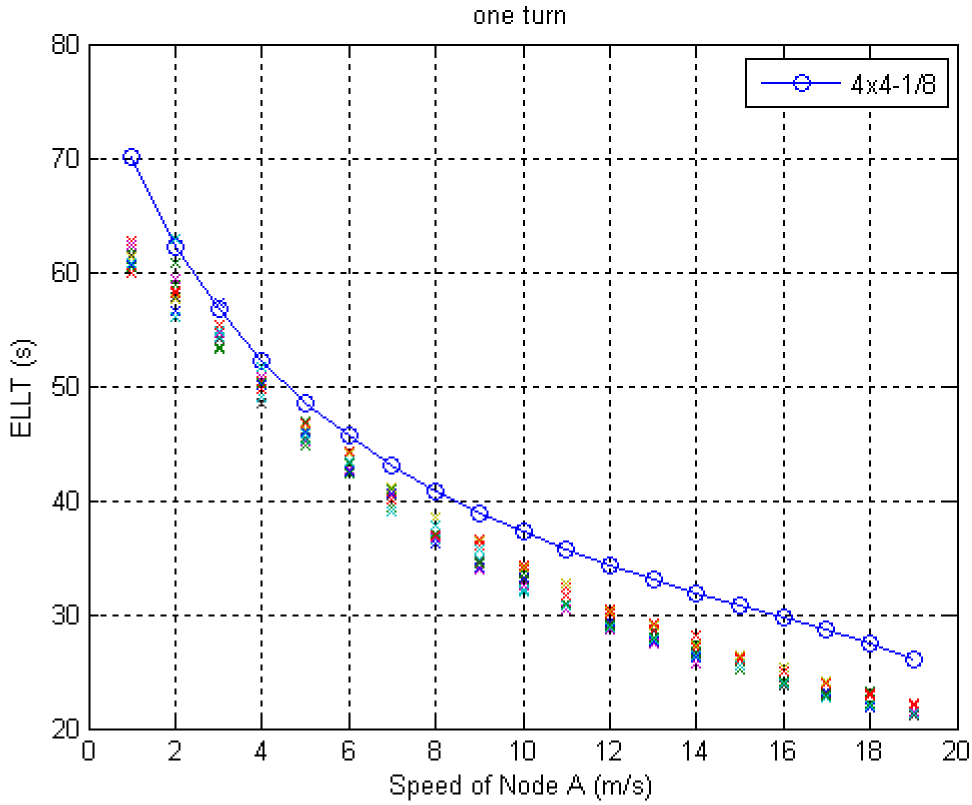

Figure 34: Formulation and Simulation Comparison of VANETs in urban city

Simulator	Ns2-2.30
Node numbers	160
Simulation Time	2000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s
Block Size (*d*)	in **Figure 34**, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 4: Simulation parameters of VANETs in urban city

6.5 Formulation and Simulation Comparison in Opposite to Vertical Case with Traffic Light

In this case, we add a traffic light to every intersection. When the mobility node comes to the intersection, it should see the traffic light first. If it meets a red light, it should stop. If it meets a green light, it could go straight or turn. We suppose that every traffic light in the intersection works individually without any relationship, and the time for every traffic light is the same. The period of red lights and green lights is 30 seconds. The detailed simulation parameters are listed in Table 5. Other settings are the same as Section 6.1. As Figure 35 shows, the blue curve is the theoretical value of communication time without traffic light on the intersection, the green curve is the theoretical value of communication time with traffic light on the intersection, and other nodes means a practical value of communication time with traffic light on the intersection. The figure illustrates that our NS2 simulation result matches MATLAB mathematical analysis result. In this case, we add the factor of traffic lights, so the simulation outcome will be more distributed because the number of red lights met and time of waiting for red light will effect communication time dramatically.

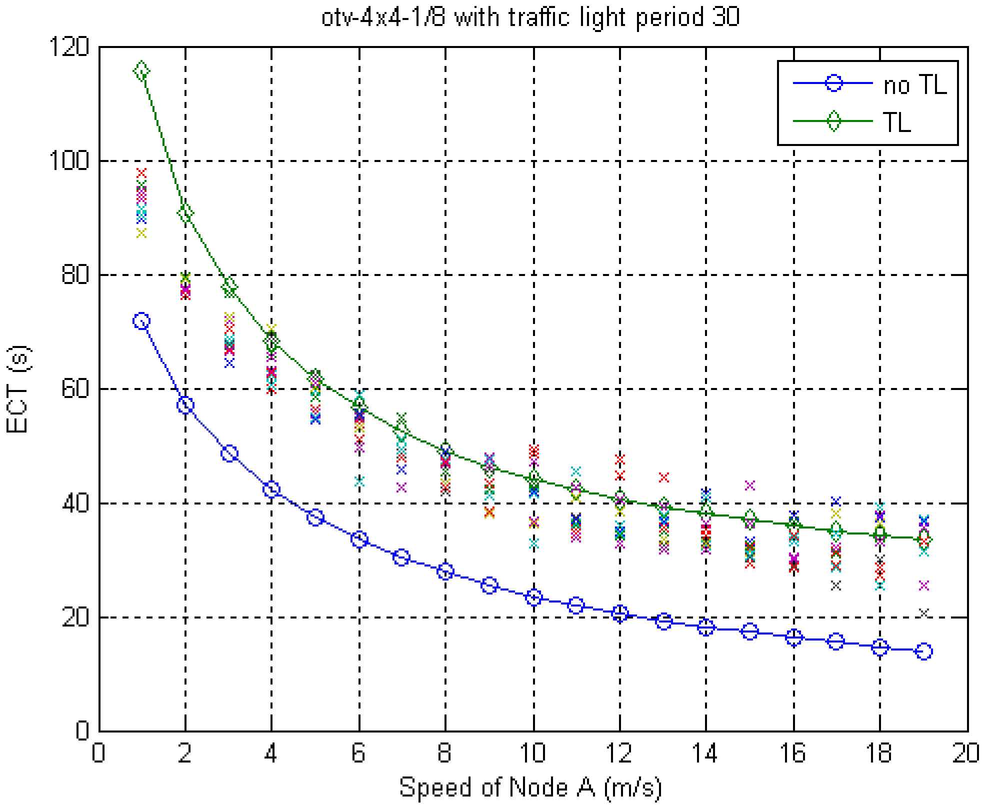

Figure 35: Formulation and Simulation Comparison in Opposite to Vertical Case with Traffic Light

Simulator	Ns2-2.30
Node numbers	160
Simulation Time	2000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s
Traffic light period	red light 30s; green light 30s
Block Size (*d*)	in Figure 35, 4x4：d=125m

Probability of turn (p_{turn})	1/8

Table 5: Simulation parameters of Opposite to Vertical Case with traffic light

6.6 Formulation and Simulation Comparison in Parallel to Vertical Case with Traffic Light

In this case, we add a traffic light to every intersection, and suppose the time of red and green light is the same. The detailed simulation parameters are listed in Table 6. Other settings are the same as in Section 6.2. As Figure 36 shows, our NS2 simulation result matches the MATLAB mathematical analysis result. The theoretical value of communication time with traffic light (green curve) is almost same as the theoretical value of communication time without traffic light (blue curve) when the velocity of MN_A is $10\,m/s$. It is because the relative velocity after one of MN_A and MN_B stops might not smaller than that before one of MN_A and MN_B stops. The multiple of communication time $T_{(m,s)}$ and $T_{(s,m)}$ might be smaller than one. Therefore, this situation of communication time decreasing happened.

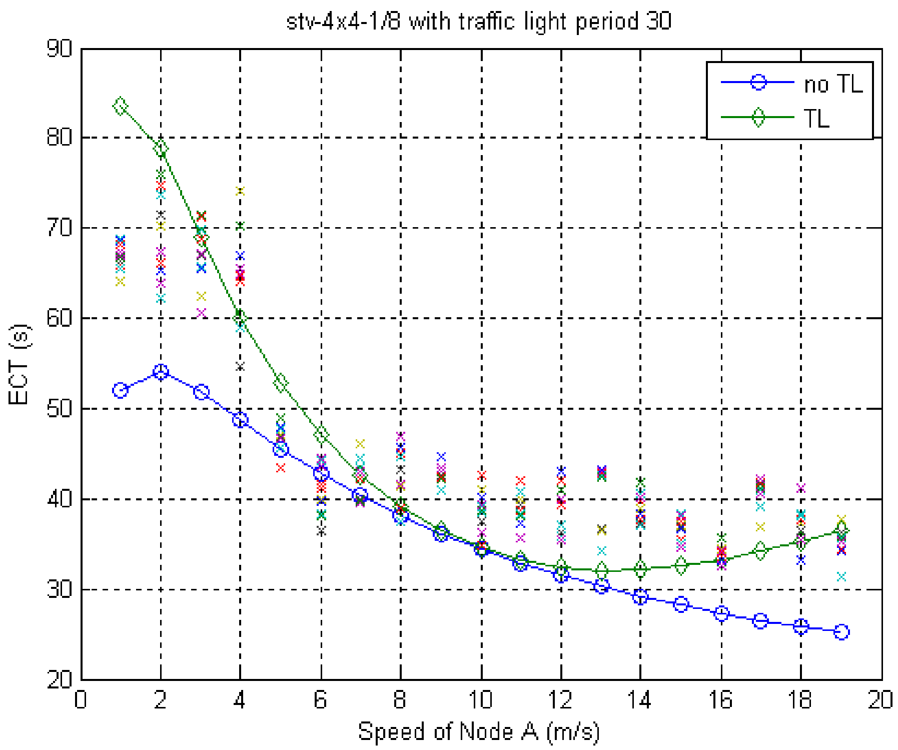

Figure 36: Formulation and Simulation Comparison in Parallel to Vertical Case with Traffic Light

Simulator	Ns2-2.30
Node numbers	240
Simulation Time	2000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s
Traffic light period	red light 30s; green light 30s
Block Size (*d*)	in Figure 36, 4x4：d=125m

Probability of turn (p_{turn})	1/8

Table 6: Simulation parameters of Parallel to Vertical Case with traffic light

6.7 Formulation and Simulation Comparison in Vertical to Opposite or Parallel Case with Traffic Light

In this case, we suppose the time of red and green light is 30 seconds The detailed simulation parameters are listed in Table 7. Other settings are the same as in Section 6.3. As Figure 37 shows, the NS2 simulation is the same as MATLAB mathematical analysis. But we can observe there is a deviation of about 10 to 20 seconds between the theoretical value of the communication time with traffic light (green curve) and the theoretical value of communication time without traffic light (blue curve) when the velocity of MN_A is $10m/s$. Because we overestimate the probability of (s,s) state happened. In NS2, we set traffic lights in each intersection to operate individually. Nevertheless, (s,s) state will never happen when MN_A and MN_B meet in the same intersection in this case. Because the relative direction of MN_A and MN_B is vertical if MN_B haven't turn. This case is different from the previous two cases. We get larger probability of (s,s) state when the velocity of MN_A is larger and lead the deviation to be larger.

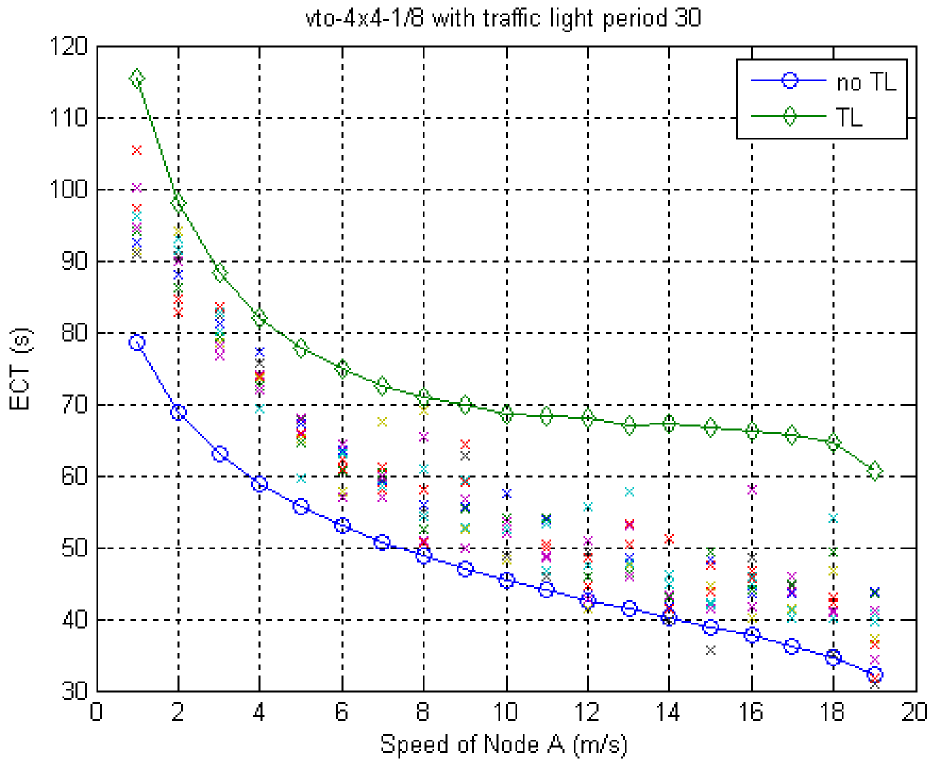

Figure 37: Formulation and Simulation Comparison in Vertical to Opposite or Parallel Case with Traffic Light

Simulator	Ns2-2.30
Node numbers	160
Simulation Time	2000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (*R*)	250 m
Minimum speed (*Smin*)	0 m/s
Maximum speed (*Smax*)	20 m/s
Traffic light period	red light 30s; green light 30s
Block Size (*d*)	in Figure 37, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 7: Simulation parameters of Vertical to Opposite or Parallel Case with

traffic light

6.8 ECT Formulation and Simulation Comparison with Traffic Light

In this case, we add traffic a light to every intersection and set the period of red light and green light be 30 seconds. The nodes are initially placed randomly and initially given random direction on this Manhattan Grid topology. We didn't limit the mobility of nodes. Consequently, mobility nodes may turn many times during connection. The detailed simulation parameters are listed in Table 8. Other settings are the same as Section 6.4. Figure 38 shows. We can observe that NS2 simulation results are close to MATLAB outcome. There is a deviation about 10 seconds between the simulation and theoretical result. The reason we already discussed in Section 6.4.

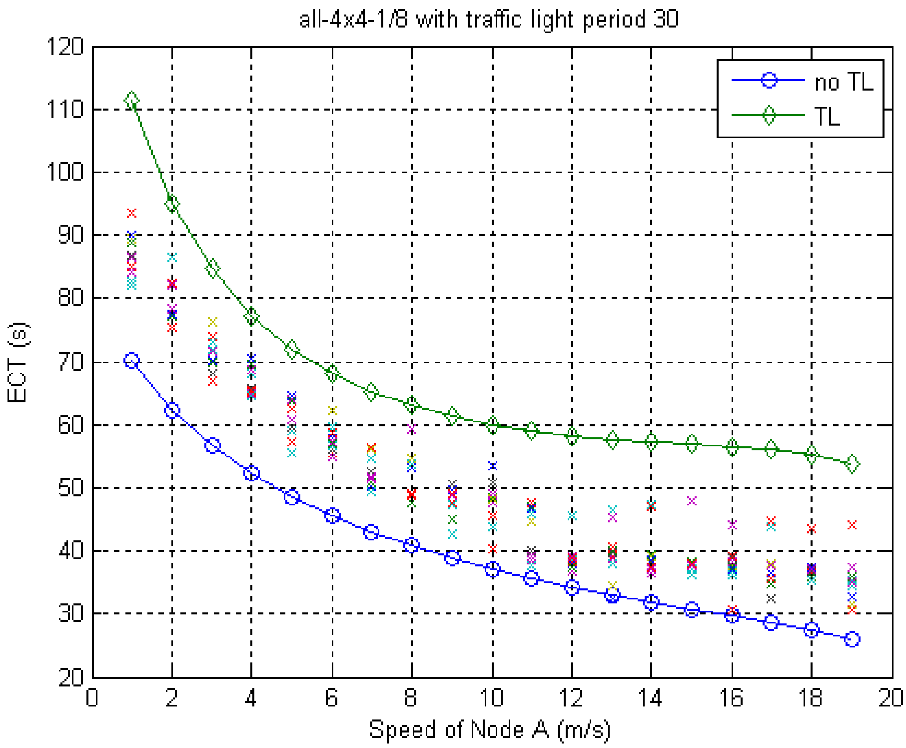

Figure 38: Formulation and Simulation Comparison of VANETs in urban city with Traffic Light

Simulator	Ns2-2.30
Node numbers	160
Simulation Time	2000s
Topology x	1000 m
Topology y	1000 m
Transmission range of a node (R)	250 m
Minimum speed ($Smin$)	0 m/s
Maximum speed ($Smax$)	20 m/s
Traffic light period	red light 30s; green light 30s
Block Size (d)	in Figure 38, 4x4：d=125m
Probability of turn (p_{turn})	1/8

Table 8: Simulation parameters of VANETs in urban city with traffic light

Chapter 7: Conclusion

VANETs is a new type of MANET. There are few researches and discussion of communication time, especially, the communication time significantly affects routing algorithm and performance in mobility ad hoc network. Therefore, we presented a mathematic analysis model of communication time in urban city. Our model can separate to three different cases: Opposite to Vertical Case, Parallel to Vertical Case and Vertical to Opposite or Parallel Case. We analyze each case of ECT and establish mathematical analysis model in order, and we conclude the outcomes above and get ECT in VANETs. We can observe that the communication time is reduced because vehicles make turns. Turning in Parallel to Vertical case makes the connecting time reduce dramatically. Although in two other cases, the turning makes connecting time increase slightly. Furthermore, we add traffic light to each intersection. In our stimulation, we suppose the transmission range is 250 meters and the period of red and green light is 30 seconds. We can observe that the communication time increases about 30 seconds than before after adding the traffic lights. In order to demonstrate the theoretical value of ECT, we use network simulation tool to simulate it. Finally, we get corresponding results.

In the future, we may add acceleration and deceleration to vehicles. In [26], it points out acceleration and deceleration is a significant factor that affect the delivery ratio and packet delay in VANETs, because acceleration and deceleration decreased the average velocity of vehicles.

Reference

[1] Jian-Kai Chen, Chien Chen and Raphael Languebien, " Expected Link Life Time Analysis in MANET under Manhattan Grid Mobility Model," In Proceedings of Mobile Computing, 2007.

[2] T. Camp, J. Boleng, and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," In Proceedings Wireless Communications and Mobile Computing, 2002.

[3] F. Bai, N. Sadagopan, A. Helmy, "IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks," In Proceedings of The IEEE INFOCOM, 2003.

[4] C. Bettstetter, H. Hartenstein, X. Perez-Costa, "Stochastic Properties of the Random Waypoint Mobility Model", In Proceedings of Springer Wireless Networks, 2004.

[5] C. Bettstetter, G. Resta, P. Santi, "The Node Distribution of the Random Waypoint Mobility Model for Wireless Ad Hoc Networks", In Proceedings of IEEE Transactions on Mobile Computing, 2003.

[6] A.J. Goldsmith, S.B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," In Proceedings of IEEE Wireless Communications, 2002.

[7] D. Turgut, S.K. Das, M. Chatterjee, "Longevity of Routes in Mobile Ad hoc networks," In Proceedings of The IEEE VTC, 2001.

[8] P. Samar, S.B. Wicker, "On the Behavior of Communication Links of a Node in a Multi-Hop Mobile Environment," In Proceedings of The Fifth ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2004.

[9] P. Samar and S. B. Wicker, "Link Dynamics and Protocol Design in a Multi–Hop Mobile Environment," In Proceedings of IEEE Transactions on Mobile Computing, Vol. 5, No. 9, pp. 1156-1172, September 2006.

[10] D. Yu, H. Li, I. Gruber., "Path availability in ad hoc network," In Proceeding of 10th International Conference on Telecommunications, 2003.

[11] V Lenders, J Wagner, M May, "Analyzing the Impact of Mobility in Ad Hoc Networks," In Proceedings of ACM/Sigmobile Workshop on Multi-hop Ad Hoc Networks: from Theory to Reality (REALMAN), 2006.

[12] Shu, Xiao Li, Xining, "Link Failure Rate and Speed of Nodes in Wireless Network," In Proceedings of Wireless Communications, Networking and Mobile Computing, 2007.

[13] WEI Xiao-Hai, C Guo-Liang, WAN Ying-Yu, Z Xin-Ming, "Longest Lifetime Path in Mobile Ad Hoc Networks," In Proceedings of Journal of Software, 2006

[14] M Zhao, W Wang, "A novel semi-markov smooth mobility model for mobile ad hoc networks," In Proceedings of IEEE GLOBECOM, 2006

[15] W. Su, S.-J. Lee, and M. Gerla, "Mobility prediction and routing in ad hoc wireless networks," In Proceedings of International Journal of Network Management, 2001.

[16] M. Gerharz, C. de Waal, P. Martini, and P. James, "Strategies for finding stable paths in mobile wireless ad hoc networks," In Proceedings of the 28th Annual IEEE International Conference on Local Computer Networks (LCN '03), 2003.

[17] JA Barria, R Lent, "MANET Route Discovery using Residual Lifetime Estimation," In Proceedings of Wireless Pervasive Computing, 2006.

[18] S Xu, KL Blackmore, HM Jones, "An Analysis Framework for Mobility Metrics in Mobile Ad Hoc Networks," In Proceedings of EURASIP Journal on Wireless Communications and Networking, 2007.

[19] M. Gerharz, C. de Waal, M. Frank, P. Martini, “Link Stability in Mobile Wireless Ad Hoc Networks, ” In Proceedings of The IEEE LCN, 2002.

[20] P Toth, “Book：The Vehicle Routing Problem,” 2001

[21] K Fall, “A delay-tolerant network architecture for challenged internets,” In Proceedings of ACM SIGCOMM, 2003.

[22] S Jain, K Fall, R Patra, “Routing in a delay tolerant network,” In Proceedings of ACM SIGCOMM, 2004.

[23] W. Zhao, M. Ammar, and E. Zegura, “A message ferrying approach for data delivery in sparse mobile ad hoc networks,” In Proceedings of MobiHoc, 2004.

[24] F. Bai, N. Sadagopan, A. Helmy, “IMPORTANT: A framework to systematically analyze the Impact of Mobility on Performance of RouTing protocols for Adhoc NeTworks,” In Proceedings of IEEE INFOCOM, 2003.

[25] AK Saha, DB Johnson, “Modeling Mobility for Vehicular Ad Hoc Networks,” In Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, 2004.

[26] A Mahajan, N Potnis, K Gopalan, A Wang, “Urban Mobility Models for VANETs,” In Proceedings of 2nd Workshop on Next Generation Wireless Networks, 2006.

[27] DR Choffnes, FE Bustamante, “An Integrated Mobility and Traffic Model for Vehicular Wireless Networks,” In Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks, 2005.