

Stochastic Properties and Application of City Section Mobility Model

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Abstract—Node mobility has a direct impact on the performance evaluation of various network mobility protocols. Unfortunately, most of the analysis on mobility protocols used Random Waypoint mobility model which does not represent real-world movement patterns of mobile nodes. In this paper, we have analyzed City Section mobility model, a realistic mobility model for the movement in the city streets. We have developed an analytical model to derive certain stochastic properties, such as, expected epoch length, expected epoch time, expected number of subnet crossings and subnet residence time of this model. Finally, we have applied the model to calculate the signaling cost of NEMO BSP and compared it with Random Waypoint mobility model. Results show that the use of realistic mobility model leads to better estimation of the signaling cost of network mobility protocol.

Index Terms—Mobility Model, Handover, Network Mobility, Performance Evaluation, Mathematical Modeling

I. INTRODUCTION

Increasing demand for mobility in wireless data networks has given rise to various mobility management schemes. Network mobility has been extensively studied for the last few years. IETF has proposed NETwork MOBility Basic Support Protocol (NEMO BSP) [1] to support the mobility of a network. To simulate network mobility, mobility models which try to mimic the movement pattern of mobile networks are used. Mobility should be modeled in a realistic manner, otherwise simulation result may not fit well in a real world deployment. Previous research [2] has also illustrated that the choice of a mobility model can significantly affect the performance evaluation of network protocols. Examples of various mobility models are Random Walk, Random WayPoint (RWP), Random Direction, Gauss-Markov, and City Section. Among these entity mobility models, Random Waypoint model is the most common and frequently used model due to its simplicity. But the movement pattern represented by RWP model is not realistic. It picks a random speed and direction, resulting in sharp turns and sudden stops frequently which is very unusual in real scenarios.

In contrast, City Section (CitySec) mobility model, introduced by Davies [2], [3], [4], represents movement behavior that is influenced by constraints in the environment. In real life scenarios, mobile nodes do not have the ability to travel freely; they have to follow traffic regulations, avoid obstacles,

buildings etc. In fact, City Section mobility model is a realistic movement pattern for vehicles in a city.

There exists some research works on street mobility models in the literature and most of those are simulation based. Martinez et al. [5] develop a simulation tool called *CityMob* which is a mobility pattern generator to be used with the ns-2 simulator. Saha et al. [4] analyze a realistic street mobility model using a real street map; their tool generates scenarios in a format that is compatible with ns-2 format. Jardosh et al. [6] propose a mobility model that enables the inclusion of obstacles to restrict node movement and wireless transmissions in ad hoc network simulations. Haerri et al. [7] present Vanet-MobiSim, another generator of realistic vehicular movement traces for telecommunication networks simulators. Bettstetter et al. [8] analyze the stochastic properties of the RWP model. Though most of the work on street mobility models are simulation based, they are not analytically tractable. This work differs from previous works in this respect and presents a detailed mathematical analysis of the City Section mobility model.

Our *objective* in this paper is to develop an analytical model for a realistic mobility model to simulate the movement of a Mobile Network in a section of a city. The mathematical analysis presented in this paper explains analytically how certain parameters of CitySec model can influence its epoch length, epoch time, number of subnet crossings, and subnet residence time, thus giving a deeper understanding of the behavior of the model.

Our *contributions* in this paper are (i) developing an analytical model to derive equations for expected epoch length, variance of epoch length, mean epoch time, expected number of subnet crossing, and subnet residence time of CitySec model, and (ii) demonstrating the use of the model to compute the signaling cost of NEMO BSP and showing the difference with RWP model.

The rest of the paper is organized as follows. In section II, the CitySec model is described in brief. In section III, various stochastic properties of the model are derived and analyzed. In section IV, we apply the results of CitySec model on NEMO BSP to find out its signaling cost and compare it with RWP model. Finally section V has the concluding remarks.

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II. CITY SECTION MOBILITY MODEL

The simulation area used in CitySec model [3] is represented by a grid of streets forming a particular section of a city. The model sets the speed limits of each street. Each Mobile Network (MN) begins the simulation at a predefined intersection of two streets. It then randomly chooses a destination, also represented by intersection of two streets. Moving to this destination involves (at most) one horizontal and one vertical movement. Upon reaching the destination, the MN pauses for some random time and the same process is repeated. Each such cycle is termed as an *epoch*. Following are the assumptions of CitySec model:

- Roads are parallel to axes.
- Starting point and each destination point are assumed to be in road intersections.

III. STOCHASTIC PROPERTIES OF CITYSEC MODEL

Let the environment be a rectangular area of dimension $a \times b$ as shown in Fig. 1. Let there be N_s horizontal roads (*streets*) and N_a vertical roads (*avenues*) and streets be S_y distance apart and avenues be S_x distance apart. So number of streets and number of avenues are

$$N_a = \frac{a}{S_x} + 1 \quad (1)$$

$$N_s = \frac{b}{S_y} + 1 \quad (2)$$

Let us consider that in epoch i , MN moves from point S^i to point D^i via intermediate point I^i , involving (at most) one horizontal and one vertical movement. So the movement pattern in each epoch of CitySec model can be represented by $(S^i, V_x^i, I^i, U_{I^i})$, $(I^i, V_y^i, D^i, U_{D^i})$. Here, V_x^i and V_y^i are speeds of MN on the two road segments and the pause time at point P^i is $U_{P^i} \in [0, U_{max}]$. The pause times are chosen from a bounded random distribution. In such epoch when the starting point and destination point are on the same (horizontal or vertical) road segment, the intermediate point I^i coincides with D^i . Next, we are going to derive different stochastic properties of City Section mobility model.

A. Epoch Length

In each epoch, the MN moves along (at most) two road segments. Let L_x^i and L_y^i be the lengths of those two road segments during i th epoch. So $L_x^i = |I_x^i - S_x^i|$ and $L_y^i = |D_y^i - I_y^i|$. So the total distance covered by the MN during i th epoch is,

$$L^i = L_x^i + L_y^i \quad (3)$$

Therefore, time required for i th epoch is,

$$t_i = \frac{L_x^i}{v_x^i} + \frac{L_y^i}{v_y^i} + U_{I^i} + U_{D^i} \quad (4)$$

Let us number each of the avenues as $1, 2, \dots, N_a$ th avenue from left to right and each of the streets as $1, 2, \dots, N_s$ th street from top to bottom. The starting point and the destination point of each epoch can only be any two points among these

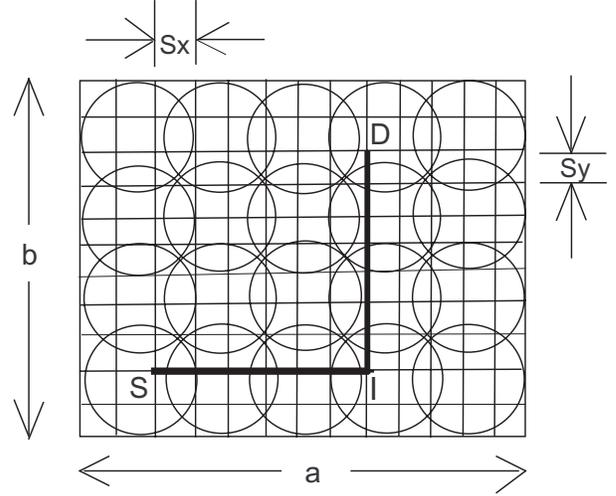


Fig. 1. Road network in City Section mobility model.

$N_a N_s$ points on the grid. So while considering only horizontal movement path along SI street segment (Fig. 1), both the points S and I can be selected from a street having a maximum of N_a discrete values. The probability mass function (pmf) of a randomly selected point's location on a horizontal line of N_a discrete points can be given by

$$f_{P_x}(x) = \begin{cases} \frac{1}{N_a}, & \text{when } x \in \{1, 2, \dots, N_a\} \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

Since the random selection of these two points are independent of each other, their joint pmf would be

$$\begin{aligned} f_{P_{x_1}, P_{x_2}}(x_1, x_2) &= f_{P_{x_1}}(x_1) \cdot f_{P_{x_2}}(x_2) \\ &= \begin{cases} \frac{1}{N_a^2}, & \text{when } x_1, x_2 \in \{1, 2, \dots, N_a\} \\ 0, & \text{otherwise} \end{cases} \end{aligned}$$

1) *Expected Epoch Length*: Let us first find out the expected length that a Mobile Network travels in horizontal direction in an epoch. Let L_x be the length of one instance.

$$L_x = |P_{x_1} - P_{x_2}| \quad (6)$$

The values of L_x can be found from the $N_a \times N_a$ matrix below. Each entry of the matrix is given by,

$$M(i, j) = S_x |i - j|, \text{ where } 1 \leq i, j \leq N_a \quad (7)$$

$$\begin{pmatrix} 0 & S_x & 2S_x & \dots & (N_a - 1)S_x \\ S_x & 0 & S_x & \dots & (N_a - 2)S_x \\ 2S_x & S_x & 0 & \dots & (N_a - 3)S_x \\ 3S_x & 2S_x & S_x & \dots & (N_a - 4)S_x \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ (N_a - 2)S_x & (N_a - 3)S_x & (N_a - 4)S_x & \dots & S_x \\ (N_a - 1)S_x & (N_a - 2)S_x & (N_a - 3)S_x & \dots & 0 \end{pmatrix}$$

The values of L_x can be $0, S_x, 2S_x, 3S_x, \dots, (N_a - 1)S_x$ depending on the location of points P_{x_1} and P_{x_2} . So the

expected value of L_x is given by,

$$\begin{aligned} E(L_x) &= \frac{1}{N_a^2} [N_a \times 0 + 2\{(N_a - 1)S_x + (N_a - 2)2S_x \\ &\quad + \dots + 2(N_a - 2)S_x + 1(N_a - 1)S_x\}] \\ &= \frac{2S_x}{N_a^2} \sum_{i=1}^{N_a-1} (N_a - i)i \\ &= \frac{S_x(N_a^2 - 1)}{3N_a} \end{aligned}$$

Substituting $a = S_x(N_a - 1)$, we get

$$E(L_x) = \frac{a(N_a + 1)}{3N_a} \quad (8)$$

Similarly, for vertical movement,

$$E(L_y) = \frac{b(N_s + 1)}{3N_s} \quad (9)$$

Now adding Eqns. (8) and (9), the expected epoch length can be obtained.

$$E(L) = \frac{a(N_a + 1)}{3N_a} + \frac{b(N_s + 1)}{3N_s} \quad (10)$$

In Fig. 2, the expected epoch length of CitySec model is compared with that of RWP Model [8]. Here, $E(L)/a$ is plotted against b/a for different number of avenues for CitySec model using Eqn. (10); number of streets (N_s) is obtained by $N_s \approx (b/a)N_a$ (see Eqns. (1) and (2)). It is found that expected epoch length of CitySec mobility model is much higher than that of RWP mobility model irrespective of the value of N_a . For large values of N_a and N_s , Eqn. (10) reduces to

$$E(L) = \frac{a}{3} + \frac{b}{3} \quad (11)$$

For a square grid of size $a \times a$, $E(L) = 2a/3$. This expected epoch length of City Section mobility model gives a measure of the distance covered by a mobile node in an epoch on the average which is required while analyzing mobility and handover protocols.

2) *Variance of Epoch Length*: The variance of epoch length can tell us how the epoch lengths vary about its mean value and gives some indication of the randomness of the CitySec mobility model. First, the second moment of L_x is obtained by,

$$\begin{aligned} E(L_x^2) &= \frac{1}{N_a^2} [N_a(0^2) + 2\{(N_a - 1)S_x^2 + (N_a - 2)(2S_x)^2 \\ &\quad + \dots + 2\{(N_a - 2)S_x\}^2 + 1\{(N_a - 1)S_x\}^2\}] \\ &= \frac{2S_x^2}{N_a^2} \sum_{i=1}^{N_a-1} (N_a - i)i^2 \\ &= \frac{S_x^2(N_a^2 - 1)}{6} \end{aligned}$$

Substituting $a = S_x(N_a - 1)$, we get

$$E(L_x^2) = \frac{S_x(N_a + 1)a}{6} \quad (12)$$

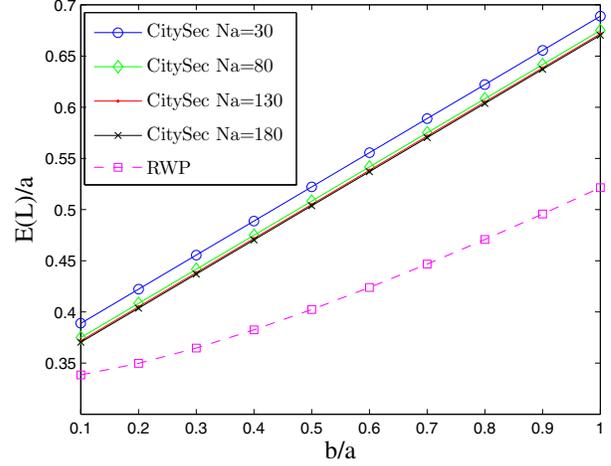


Fig. 2. Expected epoch length of City Section and RWP mobility model within $a \times b$ rectangle.

Similarly,

$$E(L_y^2) = \frac{S_y(N_s + 1)b}{6} \quad (13)$$

The second moment of L is therefore given by,

$$E(L^2) = \frac{S_x(N_a + 1)a}{6} + \frac{S_y(N_s + 1)b}{6} \quad (14)$$

Now the variance of L_x can be obtained by,

$$\begin{aligned} V(L_x) &= E(L_x^2) - (E(L_x))^2 \\ &= \frac{S_x^2(N_a^2 - 1)}{3} \left[\frac{1}{2} - \frac{(N_a^2 - 1)}{3N_a^2} \right] \end{aligned}$$

For large N_a , $N_a^2 - 1 \approx N_a^2$. So

$$V(L_x) = \frac{S_x^2(N_a^2 - 1)}{18} = \frac{E(L_x^2)}{3} \quad (15)$$

Similarly,

$$V(L_y) = \frac{S_y^2(N_s^2 - 1)}{18} = \frac{E(L_y^2)}{3} \quad (16)$$

Therefore, the variance of the epoch length is given by,

$$V(L) = \frac{S_x^2(N_a^2 - 1)}{18} + \frac{S_y^2(N_s^2 - 1)}{18} \quad (17)$$

B. Epoch Time

The next step is to find out the duration of each epoch using the result of epoch length as follows:

$$T = \frac{1}{v}L \quad (18)$$

Let the speed of the MN vary between V_x^{min} to V_x^{max} for some horizontal road segment. So for uniform speed distribution, the probability density function of MN's speed in horizontal direction can be given by

$$f_V(v_x) = \frac{1}{V_x^{max} - V_x^{min}} \quad (19)$$

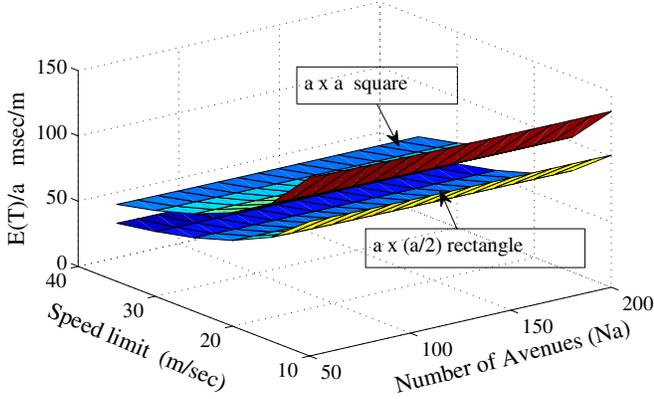


Fig. 3. Expected epoch time of CitySec mobility model as a function of speed limit and number of avenues (streets).

The expected time required for movement on horizontal road segment in an epoch is thus,

$$E(T_x) = E(L_x) \int_{V_x^{min}}^{V_x^{max}} \frac{1}{v_x} f_V(v_x) dv_x \quad (20)$$

$$= E(L_x) \frac{\ln(V_x^{max}/V_x^{min})}{V_x^{max} - V_x^{min}}$$

Similarly, for movement on vertical road segment

$$E(T_y) = E(L_y) \frac{\ln(V_y^{max}/V_y^{min})}{V_y^{max} - V_y^{min}} \quad (21)$$

Adding Eqns. (20) and (21), the expected epoch time can be found as,

$$E(T) = \frac{a(N_a + 1) \ln(V_x^{max}/V_x^{min})}{3N_a(V_x^{max} - V_x^{min})} + \frac{b(N_s + 1) \ln(V_y^{max}/V_y^{min})}{3N_s(V_y^{max} - V_y^{min})} \quad (22)$$

In Fig. 3, the expected epoch time of *City Section* mobility model is shown for $a \times a$ square and $a \times (a/2)$ rectangular road networks. Here, we assumed $V_x^{min} = V_y^{min} = 2$ m/sec, and $V_x^{max} = V_y^{max} = V^{max}$. We find that the expected epoch time decreases with the increase of V^{max} , which is quite obvious. On the other hand, expected epoch time increases with the increase in number of avenues (N_a) and streets (N_s). Higher value of N_a means larger grid dimensions for fixed inter-road spacing (see Eqns. (1) and (2)), resulting in higher epoch time.

C. Pause Time

For safety at road intersections, there is random pause time between 0 to U_{max} in order to avoid collisions. The expected pause time of the MN at each intersection of its path can be given by,

$$E(U) = \int_0^{U_{max}} \frac{udu}{U_{max}} = \frac{U_{max}}{2} \quad (23)$$

D. Number of Subnet Crossing

Let us consider that the road network of dimensions $a \times b$ (Fig. 1) is covered by Access Points (AP); let there be n rows of APs and m APs in each row. In total, there will be mn APs to cover the rectangular area. Let the radio coverage area of each AP be a circular region of radius r and two successive APs overlap at a maximum length of l along its diameter. So

$$a = 2rm - (m - 1)l \quad (24)$$

$$b = 2rn - (n - 1)l \quad (25)$$

Let the radius r of each subnet be greater than the spacing between successive road segments, i.e., $r > S_x$ and $r > S_y$. Let us assume that $2r = KS_x = KS_y$ and $l = S_x/2 = S_y/2$. Now from Eqn. (1), we get $a = (N_a - 1)S_x$. Equating this value of a with Eqn. (24), we get,

$$m = \left\lceil \frac{2N_a - 3}{2K - 1} \right\rceil \quad (26)$$

Similarly, we can have

$$n = \left\lceil \frac{2N_s - 3}{2K - 1} \right\rceil \quad (27)$$

Let us first consider the movement along horizontal direction. If the distance between the two endpoints is less than the diameter of an AP's coverage area i.e., between 0 to $(K-1)S_x$, there will be at most one subnet crossing. For any distance between KS_x to $(2K-1)S_x$, there will be at most two subnet crossings, and so on. Thus, if the point S is at first avenue and point I is at N_a th avenue, then the distance of the road segment will be $(N_a - 1)S_x$ and there will be at most m subnet crossings. Thus we can find out the expected number of subnet crossings in an epoch for movement along horizontal direction as,

$$E(C_x) = \frac{2}{N_a^2} [(N_a - 1) + (N_a - 2) + \dots + N_a - (K - 1) + 2\{(N_a - K) + (N_a - K - 1) + \dots + (N_a - 2K + 1)\} + \dots + m\{(N_a - (m - 1)K) + (N_a - (m - 1)K - 1) + \dots + (N_a - mK + 1)\}]$$

$$= \frac{2}{N_a^2} \left[KN_a \sum_{i=1}^m i - K^2 \sum_{i=2}^m i(i - 1) - \sum_{i=1}^{K-1} i \sum_{j=1}^m j \right]$$

$$= \frac{m(m + 1)K}{6N_a^2} (6N_a - 4mK + K + 3)$$

Similarly, for movement along vertical direction,

$$E(C_y) = \frac{n(n + 1)K}{6N_s^2} (6N_s - 4nK + K + 3) \quad (28)$$

The expected number of subnet crossing in an epoch is thus

$$E(C) = E(C_x) + E(C_y) \quad (29)$$

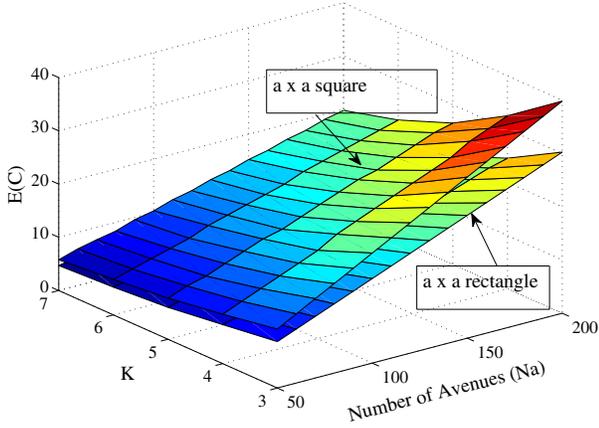


Fig. 4. Expected number of subnet crossings of City Section mobility model as a function of K and number of avenues.

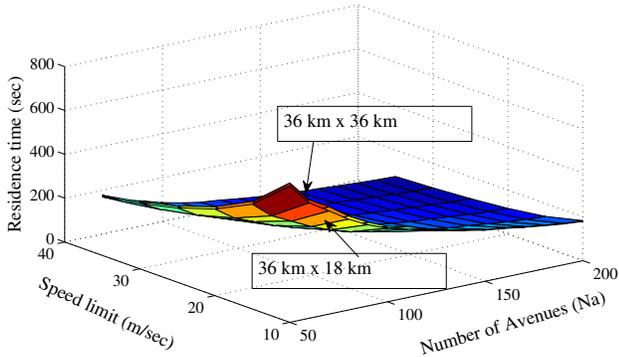


Fig. 5. Residence time of City Section mobility model as a function of speed limit and number of avenues.

In Fig. 4, the expected number of subnet crossings of CitySec mobility model is shown for $a \times a$ square and $a \times (a/2)$ rectangular road networks. We find that the expected number of subnet crossings decreases with the increase in the value of K (i.e., $2r/S_x$). Higher values of K mean larger coverage area for access points, resulting in fewer number of subnet crossings. On the other hand, expected number of subnet crossings increases with the increase in number of avenues (N_a) and streets (N_s). Higher values of N_a and N_s mean larger grid dimensions for fixed inter-road spacing (see Eqns. (1) and (2)), resulting in higher number of subnet crossings.

E. Subnet Residence Time

Since in each epoch, the MN pauses at two different points, the average residence time of a MN in a subnet can be estimated as follows:

$$T_r = \frac{E(T) + 2E(U)}{E(C)} \quad (30)$$

In Fig. 5, the residence time of *City Section* mobility model is shown for $36 \text{ km} \times 36 \text{ km}$ square and $36 \text{ km} \times 18$

km rectangular road networks. Here we used $U_{max} = 2 \text{ sec}$, $V_x^{min} = V_y^{min} = 2 \text{ m/s}$, $K = 5$. We find that the residence time decreases with the increase of speed limit as less time is required to cross the coverage area of an AP. Residence time also decreases with the increase in number of avenues (N_a) and streets (N_s). Higher values of N_a (N_s) result in increased $E(C)$ values, but the value of $E(T)$ is not affected much. As a result, the residence time decreases (see Eqn. (30)).

IV. SIGNALING COST OF NEMO BSP

To demonstrate the application of the developed model, we use the results of CitySec mobility model to compute the signaling cost of NEMO BSP. We consider a mobile network having a number of mobile hosts (N_{mh}) moving together and being managed by NEMO BSP. Previous work [9] has derived the signaling costs of NEMO BSP which consists of two components: location update cost (Ψ^{LU}) and lookup cost (Ψ^{LUP}). Since the lookup cost does not vary for different mobility models, we consider only the location update (LU) cost which is given by,

$$\Psi^{LU} = [N_{mh}\{2(l_{mh} - 2 + 2\theta)\delta_{LU} + \gamma_h\} + N_{mr}\{2(l_{mr} - 1 + \theta)\delta_{LU} + \gamma_r\}]/T_r \quad (31)$$

Here, N_{mr} = number of mobile routers (MR),
 T_r = residence time for MR/MH
 N_{cn} = average number of CN communicating,
 δ_{LU} = per hop message transmission cost for LU,
 θ = proportionality constant of signaling cost over wired and wireless link,

l_{mh} = average number of hops between MH and HA-H,
 l_{mr} = average number of hops between MH and HA-M,
 γ_h = update processing cost at HA-H,
 γ_r = update processing cost at HA-M,

The comparison with RWP model is based on the analysis presented in [8] which assumes that the coverage area of each AP is a square that is not realistic. For the sake of comparison, we are assuming the dimensions of each AP's coverage area of RWP model to be $2r \times 2r$. The parameters relating to NEMO BSP have been taken from the previous works [9], [10]: $\delta_{LU} = 0.2$, $\theta = 10$, $\gamma_h = 30$, $\gamma_r = 1.5 \times \gamma_h$, $l_{mh} = l_{mr} = 35$, and $N_{mr} = 2$. Other parameters values relating to mobility models are: $a=36 \text{ km}$, $b = 24 \text{ km}$, $S_x = 200 \text{ m}$, $S_y = 200 \text{ m}$, $K = 5$, $V_x^{max} = V_y^{max} = 30 \text{ m/s}$, $V_x^{min} = V_y^{min} = 5 \text{ m/s}$, and $U_{max} = 4 \text{ sec}$.

Fig. 6 shows the impact of the number of mobile hosts on location update cost of NEMO BSP for both City Section and RWP mobility models. Results show that the location update cost of City Section model is much less and different than that of RWP model.

Fig. 7 shows the subnet residence times of RWP and CitySec model for varying speed of the mobile network. It is found that subnet residence time of City Section mobility model varies a lot with that of RWP mobility model.

Fig. 8 shows the location update cost for NEMO BSP using RWP and CitySec model varying speed of MN for various

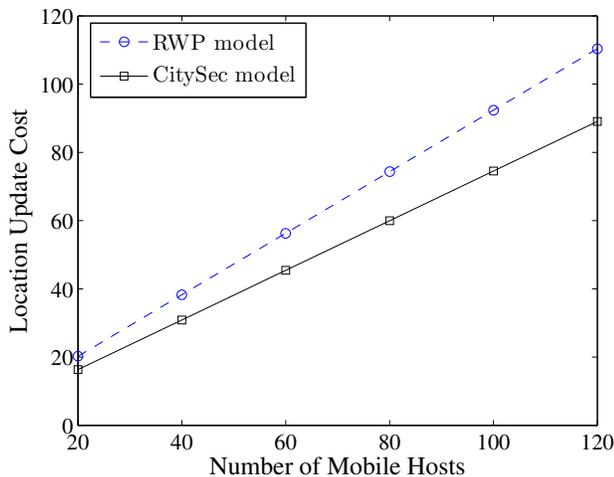


Fig. 6. Location update cost of NEMO BSP vs. number of MHs for CitySec and RWP model.

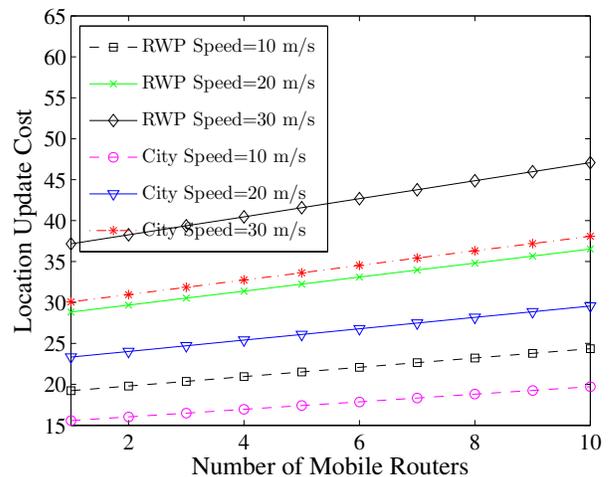


Fig. 8. Location update cost of NEMO BSP vs. Number of Mobile Routers for varying MN speed.

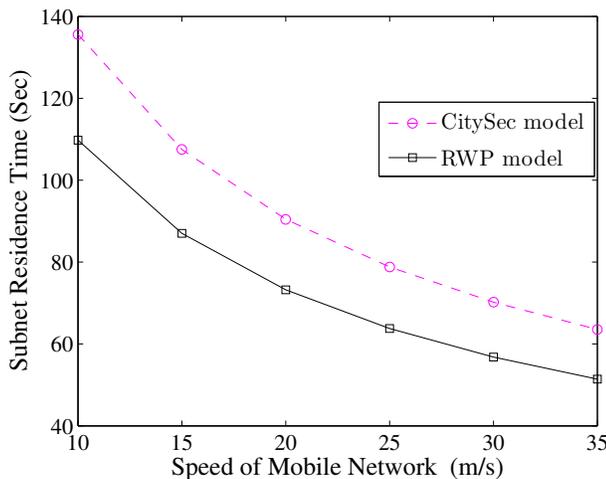


Fig. 7. Subnet residence times of RWP and CitySec models vs. speed of mobile networks.

number of mobile routers. Here also the signaling costs of CitySec model differs much with that of RWP model.

From Figs. 6 - 8, we see that the results obtained from the City Section model for NEMO BSP are different than those obtained from RWP model. Consequently, RWP model cannot be used as an approximation to a realistic model, like City Section mobility model.

V. CONCLUSION

In this paper, we have analyzed City Section mobility model, a realistic model to obtain its stochastic properties. We have derived the expressions for expected epoch length, variance of epoch length, mean epoch time, mean subnet crossings and subnet residence time. These results help in understanding the behavior of CitySec mobility more precisely. We have used the derived stochastic properties for the performance

analysis of of NEMO BSP and compared the results with those using RWP mobility model. Results show that the signaling requirements for these two models are much different. Hence, RWP mobility model cannot be even used as an approximation to a realistic scenario unlike City Section mobility model.

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