The Impact of Stationary Nodes on the Performance of Wireless Mobile Networks

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Abstract

In this paper, impact of the stationary nodes on the link excess life as an important performance parameter of wireless mobile networks is investigated. First, a model for the link excess life is introduced. Based on this model, the relation between the probability density function (PDF) of the link excess life and the PDF of relative velocity is explored. In fact, the PDF of relative velocity is divided into three PDFs according to the three categories of links. The effect of each group on the resultant PDF of global link excess life for different percentages of stationary nodes is explored. Moreover, an approximation method defined in our previous work is proposed as a tool to evaluate the PDF of link excess life for these three categories of links. Indeed, the proposed method could be easily generalized to solve a more general version of the problem, i.e. determining link excess life when different categories of nodes with different velocity ranges present in the network. A simulation framework is also developed and extensive simulation experiments are performed to validate the theoretical results.

1. Introduction

Wireless networks are of the most emerging technologies driven by constant evolution of communication equipments and the proliferation of smaller devices. Thus, performance analysis of such systems in the presence of different factors is an important issue. One of the factors that has a great impact on the design, analysis, and performance of such networks is mobility [1]. In fact, topology of wireless mobile networks is prone to continuous changes which considerably degrades the performance of the routing protocols [2]. In this context, one of the crucial aspects to be addressed is the stability of the established routing paths (also called *path duration*) that is the time interval from when the route is established until one of the links along the route becomes unavailable. Indeed, this metric significantly affects the performance of on-demand routing protocols [3]. When a link is broken down all the paths using this link are torn down too, and new paths must be checked to exist or established which is a resource consuming task [4]. Hence, the performance of wireless mobile networks is mainly dependent to the excess life of individual links. Link excess life (LEL), or link availability in some contexts, is the probability that a wireless link between two mobile nodes exists at time $t+t_0$, given that a link exists at time t_0. LEL is also an important parameter in topology control [5].

In fact, the knowledge of LEL can serve as the groundwork for further analysis of network performance, as well as a guide to design ad hoc and sensor network protocols. Although a great work is done to investigate the link duration and LEL in different scenarios [2,3,5-8], usually it is assumed that, all the nodes are constantly moving which is rare in several scenarios. Actually, in several real scenarios, some nodes are stationary or pausing. For example, in wireless mesh networks presence of stationary nodes is an intrinsic assumption. This is explicitly considered in different mobility models [9]. The effect of pause time of nodes on the link stability for RWP model is empirically investigated in [10]. Our evaluations show that the presence of stationary nodes has a noticeable impact on the LEL and consequently on path duration. Here, a framework is proposed that enables protocol designers to investigate the effect of stationary nodes theoretically.

This method could be easily generalized to evaluate the LEL in the networks built of different kinds of nodes with different velocity distributions. Moreover, a general method for approximation of LEL given the PDF of relative velocity of nodes is provided as a tool to evaluate the different parts of the final PDF of LEL.

2. Link excess life modeling

We use the model presented in our previous work for link excess life modeling [11]. Our model consists of a radio propagation model (disk model), a mobility model (*Boundless Random Direction Model* or BRDM), and a geometric model. A simplified version of BRDM is proposed as *Constant Velocity* (CV) model in [8] which allows only fixed velocity values. Briefly, we use the following assumptions in BRDM:

1. Nodes initially select their velocities according to a pre-specified distribution and do not change the direction or the velocity. Each node remains stationary with a probability of p_p .
2. Direction of each node is uniformly distributed over $[0,2\pi)$.
3. Node's speed, its direction and its location are mutually independent.
4. Nodes are uniformly distributed among the region with density ρ at the starting time.

2.1. Simulation method

To validate the theoretical results of this paper, a simulation framework is developed [12]. To simulate the BRDM mobility model with infinite region a two-dimensional toroidal region is used with side S , where $S \gg R$ (R is the transmission range). Both movements and radio transmissions are considered toroidal to exactly simulate the infinite region (Figure 1). Initially, all the nodes are distributed uniformly among the region. Each node remains stationary with a probability of p_p for the entire simulation period. Non-stationary nodes start to move and after a warm up period each node (whether stationary or non-stationary) detects its physical neighbors and waits for them to exit from the transmission range, and then calculates this interval as LEL. This value is then used to derive the empirical PDF of LEL.

To simulate random waypoint (RWP) mobility model [4], a traditional region is used for movement and transmission. A warm up time about 1000 seconds is considered to eliminate the transient effects of RWP [13]. All the nodes start to move at time zero and after 985 seconds, some of the nodes become stationary. Hence, the stationary nodes will have the same distribution as the moving ones.

2.2. General geometric model

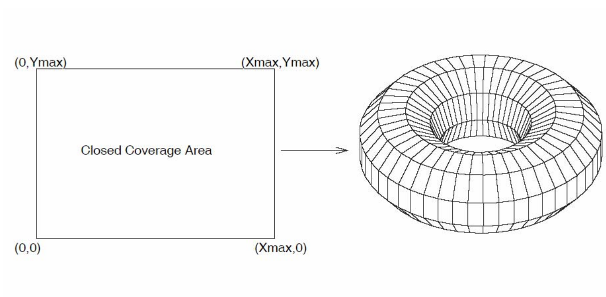

Figure 1. Rectangular simulation region is wrapped around to simulate infinite borderless region in BRDM model [9].

To evaluate the LEL a geometric model is used [11]. Here, the model is briefly described. Consider two wireless nodes, WN_1 and WN_2 with velocity vectors $\vec{V_1}$ and $\vec{V_2}$ respectively. The relative velocity vector of WN_2 with respect to WN_1 is defined as $\vec{V_r}=\vec{V_1}-\vec{V_2}$ with a magnitude of $v_r \triangleq |\vec{V_r}|$ and $f_{v_r}(v_r)$ is defined as the PDF of v_r bounded in $[v_{r,\min}, v_{r,\max}]$. Now, we try to evaluate the time interval in which WN_2 remains in the transmission region of WN_1. This time interval is the excess life of the active link between WN_1 and WN_2 and is obtained by:

$$\tau = P/v_r \tag{1}$$

where P is the length of the relative trajectory in the transmission range. The CDF of τ can be obtained by

$$F_{\tau|L}(\underline{\tau}\,|\,l) = pr(\frac{P}{v_r} < \underline{\tau}\,|\,L = l) = \int_{v_r} F_{P|L,v_r}(\underline{\tau} v_r\,|\,l, v_r) f_{v_r|L}(v_r\,|\,l)\,dv_r \tag{2}$$

where L is the random position of the link, i.e. $L=((X_1,Y_1),(X_2,Y_2))$ in the Cartesian coordinate system where (X_1,Y_1) and (X_2,Y_2) are the coordinates of WN_1 and WN_2 respectively. l and $\underline{\tau}$ are values of random variables L and τ respectively. Differentiating (2) on τ , provides the PDF from CDF as

$$f_{\tau|L}(\tau\,|\,l) = \int_{v_r} v_r . f_{P|L,v_r}(\tau v_r\,|\,l, v_r) f_{v_r|L}(v_r\,|\,l)\,dv_r \tag{3}$$

and the PDF of LEL is obtained as

$$f_\tau(\tau) = \int_l f_L(l) f_{\tau|L}(\tau\,|\,l)\,dl \tag{4}$$

2.3. Geometric model for BRDM

For BRDM, the CDF of P is obtained as [11]

$$F_{P|r}(p_0\,|\,r) = F_{\beta|r}(Arc\cos(\frac{R^2 - p_0^2 - r^2}{2 p_0 r})\,|\,r) \tag{5}$$

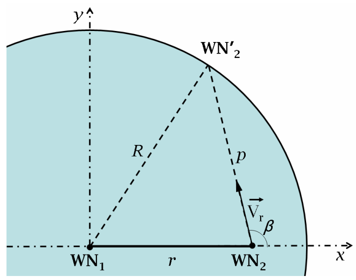

Figure 2. Relative motion of two wireless nodes

$$F_{P|r}(p|r)=\begin{cases} 0 & p\le R-r \\ \frac{1}{\pi}Arc\cos(\frac{R^2-p^2-r^2}{2pr}) & R-r\le p\le R+r \\ 1 & p\ge R+r \end{cases} \quad (6)$$

where, r is the distance between two nodes at time t_0. Recalling (4), the PDF of LEL is obtained as:

$$f_\tau(\tau)=\int_{r=0}^{R} f_r(r).f_{\tau|r}(\tau\,|\,r)dr \quad (7)$$

Further calculations of the BRDM model is reported in Appendix I. From (1), the *scaling property* of $f_\tau(\tau)$ can be achieved as follows: if R (and consequently P) is scaled by factor ω and random variable v_r is scaled by factor ψ, then random variable τ will be scaled by ω/ψ.

3. Superposition property of the link excess life

Suppose the PDF of the relative velocity could be expressed as a weighted summation of M PDFs as

$$f_{v_r|L}(v_r\,|\,l)=\sum_{k=1}^{M} c_k.\hat{f}_{v_r,k|L}(v_r\,|\,l) \quad (8)$$

where M is a positive integer and obviously the summation of c_k values must be 1. Substituting the above expression in (3) and (4) gives

$$f_\tau(\tau)=\sum_{k=1}^{M} c_k f_{\tau,k}(\tau) \quad (9)$$

where $f_{\tau,k}(\tau)$ is the PDF of LEL corresponding to the $\hat{f}_{v_r,k|L}(v_r\,|\,l)$. This property is held for the CDF of LEL, too. A special case is when the links are partitioned into M categories and each $\hat{f}_{v_r,k|L}(v_r\,|\,l)$ corresponds to one partition of links.

4. The effect of stationary nodes

Consider each node is stationary (or pausing for a long time) with probability of p_p independent of its position. It is assumed that the stationary nodes are distributed among the network area with a distribution like the asymptotic distribution of the moving nodes. Moreover, velocity values are independent of node positions. A randomly selected link has three situations: *double stationary* (both ends are stationary), *single stationary* (only one end is stationary), or *double moving* (both ends are moving). Hence, the relative velocity PDF is:

$$f_{v_r,p}(v_r)= p_p{}^2.\delta(v_r)+2p_p(1-p_p)f_v(v)+(1-p_p)^2 f_{v_r}(v_r) \quad (10)$$

where $f_{v_r,p}(v_r)$ and $f_{v_r}(v_r)$ are respectively the PDFs of relative velocity with and without considering stationary nodes and $f_v(v)$ is the PDF of absolute velocity values. The first and the second terms correspond to *double stationary* and *single stationary* links, respectively. In case of *single stationary* links, the relative velocity is equivalent to the absolute velocity of moving end of the link, i.e. $f_v(v)$. The third term corresponds to *double moving* nodes.

If absolute or relative velocity is dependent to the position of the nodes, all the terms of (10) are conditioned on L. The PDF of global LEL would be achieved from (10) by applying the superposition property:

$$f_{\tau,p}(\tau)= p_p{}^2 f_{\tau,2}(\tau)+2p_p(1-p_p)f_{\tau,1}(\tau)+(1-p_p)^2 f_\tau(\tau) \quad (11)$$

where $f_{\tau,p}(\tau)$, $f_{\tau,2}(\tau)$, $f_{\tau,1}(\tau)$, and $f_\tau(\tau)$ are the global PDF of LEL and PDF of LEL corresponding to *double stationary*, *single stationary*, and *double moving* nodes, respectively. It is worthwhile to note that for *double stationary* nodes (first term of (11)), the corresponding LEL will be infinite. Thus, its PDF could be expressed as a Dirac delta function at infinity as

$$f_{\tau,2}(\tau)=\lim_{x\to+\infty}\delta(\tau-x) \quad (12)$$

If distribution of stationary nodes and distribution of moving nodes are different, p_p will be a function of location, i.e., $p_p(l)$ and the PDF of LEL would be obtained for each area of the network approximately.

In summary, to obtain the PDF of LEL for different percentages of stationary nodes, it is sufficient to have the PDF of LEL corresponding to $f_v(v)$ and $f_{v_r}(v_r)$. This approach can be easily generalized for networks with several categories of nodes with different velocity PDFs such as vehicles, bicycles, and pedestrians. The effect of each category of links on the global LEL can be analyzed separately, e.g., when 4 categories of nodes exist in the network, there are $\binom{4}{2}+4$ categories of links. Given the PDF of LEL for each category of links (experimentally or theoretically), the global PDF of LEL is achieved through superposition property for different number of nodes in each node category.

Some examples of the above-mentioned method are presented below.

4.1. Constant velocity model

For constant velocity model, $f_\tau(\tau)$ is obtained in closed form (Appendix I). Since $f_v(v)=\delta(v-v_{cte})$, the PDF of LEL for the *single stationary* links ($f_{\tau,1}$) is achieved from (16). It is depicted in a curve of Figure 3 for $v_{cte}=1$. The final results for 0%, 25%, 50%, and 75% stationary nodes is depicted in Figure 4 for *R*=100m and $v_{cte}=1$.

4.2. BRDM with uniform velocity

For BRDM with uniform absolute node velocity over (0,2], $f_\tau(\tau)$ can be obtained using the approximation method mentioned in [11] or by numerical calculation of (14). The PDF of LEL for the category of links with single

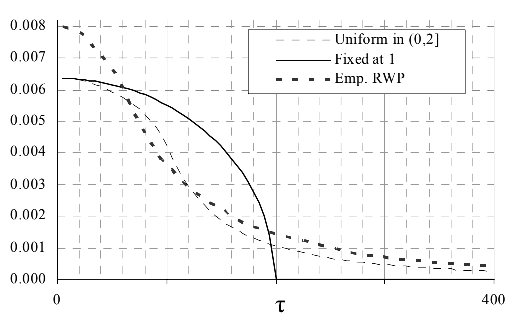

Figure 4. PDF of LEL for *single stationary* links ($f_{,1}$) in BRDM model with uniform velocity distribution over (0,2] m/s, constant velocity model with v_{cte}=1 m/s, and empirical result for RWP model with uniform motion step velocity over [0.158, 3.153]m/s in a 1km×1km region. Transmission range is *R*=100m.

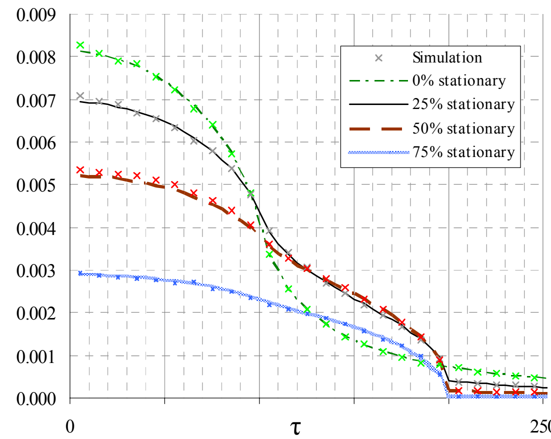

Figure 3. Effect of the number of stationary nodes on the link excess life PDF in constant velocity model with v_{cte}=1 m/s and R=100m. (Consider a weighted delta function at infinity as described in the context)

stationary end ($f_{\tau,1}$) is obtained from (19) that is depicted in a curve of Figure 3. The result is depicted in Figure 5. In this figure $f_\tau(\tau)$ is obtained using the approximation method mentioned in [11] with *M*=25 points.

4.3. RWP model

RWP [4] has some basic differences with BRDM which make it complicated to analyze in a similar approach. An important issue in RWP concerns steady state velocity. In RWP, velocity distribution of each motion step differs from the steady state velocity distribution observed along the time. Intuitively, faster motion steps finish soon and slower ones endure more in the network. Hence, a random observer visits slower nodes more often. Thus, the observed average velocity in a random time instance must be lower than the expected value of each motion step velocity distribution. For example, if nodes select their velocity uniformly in range [V_{min},V_{max}], the observed velocity will be [17]:

$$f_v(v)=\frac{1}{v}\left(\ln\frac{V_{max}}{V_{min}}\right)^{-1} \qquad (13)$$

However this property has a great impact on the relative velocity distribution. Figure 6 depicts some PDFs of relative velocity distributions for different models with the same average steady state velocity.

Although theoretical analysis of RWP is complicated, it possesses the superposition property. The PDF of LEL for *single stationary* links ($f_{\tau,1}$), in RWP model could be achieved empirically as depicted in Figure 3. To do so,

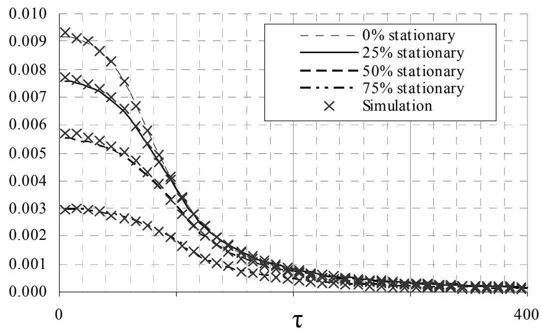

Figure 7. Effect of the number of stationary nodes on the link excess life PDF in BRDM model with uniform velocity distribution over (0,2] m/s and *R*=100m. (Consider a weighted delta function at infinity as described in the context)

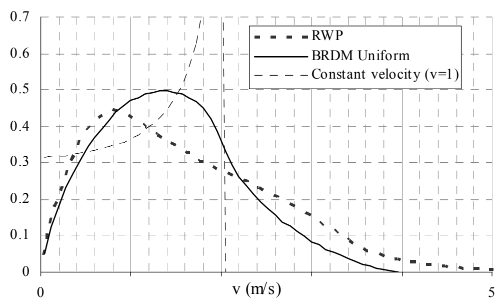

Figure 7. Relative velocity distribution PDF for RWP model without stationary nodes and uniform motion step velocity over [0.158, 3.153] m/s, BRDM with uniform velocity distribution over (0,2] m/s, and constant velocity model with v_{cte}=1. RWP model is sampled at 1000s in a 1km×1km region with *R*=100m.

one approach is to substituting two empirical $f_{\tau,p}(\tau)$ functions for two different values of p_p in (11). Figure 7 shows how the PDF of LEL for 25% and 75% of stationary nodes can be achieved if two empirical PDFs of LEL for zero 0% and 50% of stationary nodes are given.

5. Conclusions

In this paper, the effect of stationary nodes on the link excess life PDF (as an important parameter in performance and connectivity evaluation of wireless mobile networks) was investigated. A mobility model (BRDM) and a general geometric model from our previous work were used to approximating the PDF of LEL and investigation of the effect of stationary nodes on the global link excess life PDF. Relative velocity and steady state velocity in RWP mobility model were discussed. Finally, the impact of different percentages of stationary nodes on the PDF of LEL was evaluated approximately using some empirical

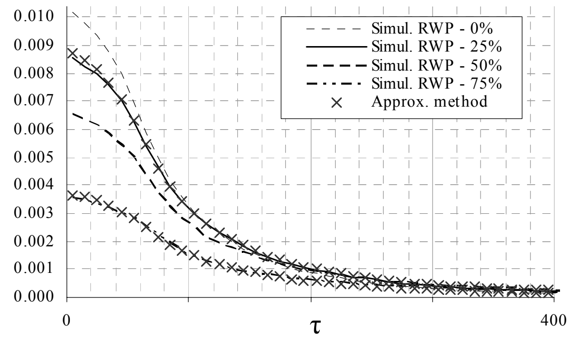

Figure 5. Empirical and approximated PDFs of LEL for different percentages of stationary nodes using RWP model with uniform velocity selection over [0.158, 3.153]m/s (average steady state velocity = 1m/s) and *R*=100m in a 1km×1km region. (Consider a weighted delta function at infinity as described in the context)

results. To validate the obtained results extensive simulation experiments were performed.

6. Acknowledgements

We thank the members of the High Performance Computing Architectures and Networks (HPCAN) laboratory at Sharif University of Technology and IPM School of Computer Science, specially, Mr. Amin Dehesh and Mr. Mohammad Reza Rahimi.

References

[1] M.M. Zonoozi and P. Dassanayake, “User mobility modeling and characterization of mobility patterns,” IEEE Journal of Selected Areas in Comm., vol. 15, pp. 1239-1252, Sept. 1997.

[2] N. Sadagopan, F. Bai, B. Krishnamachari, and A. Helmy, “PATHS: Analysis of path Duration statistics and the impact on reactive MANET routing protocols,” In Proc. of ACM MobiHoc, Annapolis (MD), June 2003.

[3] F. Bai, N. Sadagopan, and B. Krishnamachari, and Ahmed Helmy, “Modeling Path Duration Distributions in MANETs and their Impact on Reactive Routing Protocols,” IEEE Journal on Selected Areas of Communications (JSAC), Vol. 22, No. 7, September 2004.

[4] D. Johnson and Maltz, “Dynamic source routing in ad hoc wireless networks,” Mobile Computing. Kluwer Academic Publishers, 1996.

[5] P. Santi, “Topology Control in Wireless Ad Hoc and Sensor Networks,”, John Wiley and Sons Ltd, 2005.

[6] A. B. McDonald and T. Znati, “A Path Availability Model for Wireless Ad Hoc Networks,” In Proc. of the IEEE WCNC, September 1999.

[7] P. Samar and S. B. Wicker, “On the Behavior of Communication Links of a Node in a Multi-hop Mobile Environment,” Proc.of the 5th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc), Roppongi, Japan, pp. 145–156, May 2004.

[8] S. Cho and J.P. Hayes, "Impact of Mobility on Connection Stability in Ad Hoc Networks," in Proc. of the IEEE WCNC, March 2005.

[9] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," Wireless Comm. & Mobile Computing (WCMC), vol. 2, no. 5, pp. 483-502, 2002.

[10] J. Boleng, "Normalizing mobility characteristics and enabling adaptive protocols for ad hoc networks," Local and Metropolitan Area Networks Workshop (LANMAN), March 2001.

[11] A. Nayebi, M. R. Rahimi, H. Sarbazi-Azad, "On the Link Excess Life in Mobile Wireless Networks," To be appeared in proc. of ICCTA07, 2007.

[12] A. Nayebi, A. Shamaei, S. Meraji, and M.R. Rahimi, "Object-Oriented Network Simulator-XMulator", http://www.xmultor.org, 2006.

[13] J. Yoon, M. Liu, and B. Noble, "Random Waypoint Considered Harmful," in Proceedings of INFOCOM. IEEE, 2003.

[14] G. Carofiglio, C. Chiasserini, M. Garetto, E. Leonardi. "Analysis of Route Stability in MANETs," Second EuroNGI Workshop on New Trends in Modelling, Quantitative Methods and Measurements, Aveiro, Portugal, November 2005.

[15] Y. Han and R. J. La, "Maximizing path durations in mobile adhoc networks," 40th Annual Conference on Information Sciences and Systems, Princeton, NJ, March 2006.

[16] F. Bai, N. Sadagopan, and Helmy, "Important: a framework to systematically analyze the impact of mobility on performance of routing protocols for ad hoc networks," Proc. IEEE Infocom, 2003.

[17] Y. Han, R. J. La, A. M. Makowski, "Distribution of path durations in mobile ad-hoc networks - Palm's theorem to the rescue," 16th ITC Specialist Seminar on Performance Evaluation of Wireless and Mobile Systems, Antwerp, Belgium August, September 2004.

[18] M. Gerharz, C. de Waal, M. Frank, and P. Martini. "Link stability in mobile wireless ad hoc networks," In Proc. of IEEE LCN, Nov. 2002.

[19] M. Qin and R. Zimmermann. "An Enhanced Link Availability Model for Supporting Multimedia Streaming in MANETs," USC Technical Report USC-CS-TR06-878, 2006.

[20] D. Yu, H. Li and I. Gruber. "Path Availability in Ad-hoc Network," Int'l Conf. on Telecomm. (ICT 2003), Tahiti France, February 2003.

[21] S. Xu and K. Blackmore and H. Jones. "Mobility assessment for MANETs requiring persistent links," In Papers Presented At the 2005 Workshop on Wireless Traffic Measurements and Modeling, June 2005.

[22] P. Samar and S. B. Wicker, "On the Behavior of Communication Links of a Node in a Multi-hop Mobile Environment," Proc.of the 5th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc), Roppongi, Japan, pp. 145–156, May 2004.

Appendix I
Some theoretical results for BRDM

Rearranging the integrations of (7) results in:

$$f_\tau(\tau)=\int_{v_r} f_{v_r}(v_r)\int_r g(r,\tau,v_r)\,dr\,dv_r$$
$$g(r,\tau,v_r)\triangleq f_r(r)\,v_r\,f_{P|r}(\tau v_r\mid r) \quad (14)$$

For a given value of τ, integration region is defined as $\Re(\tau)$ in which f_r, f_{v_r}, and $f_{P|r}$ in (14) have non-trivial values:
$\Re(\tau)=\{(r,v_r)\,|\,0\le r\le R, v_{r,\min}\le v_r\le v_{r,\max}, R-r\le\tau v_r\le R+r\}$ (Figure 8). When $v_{r,\min}=0$, $f_\tau(\tau)$ is obtained from

$$f_\tau(\tau)=\begin{cases} h(0,v_{r,\max},R-\tau v_r) & \tau\le T\\ h(0,R/\tau,R-\tau v_r)+h(R/\tau,v_{r,\max},\tau v_r-R) & T<\tau<2T\\ h(0,R/\tau,R-\tau v_r)+h(R/\tau,2R/\tau,\tau v_r-R) & \tau\ge 2T\end{cases} \quad (15)$$

$$h(v_{\min},v_{\max},r_{\min})\triangleq\int_{V_r=v_{\min}}^{v_{\max}} f_{v_r}(v_r)\int_{r=r_{\min}}^{R} g(r,\tau,v_r)\,dr\,dv_r$$

$$T\triangleq\frac{R}{v_{r,\max}}$$

If all the nodes move with a constant velocity ($|\vec{V}|=1$), like the model proposed in [8], the magnitude of relative velocity vector of the two nodes has a distribution of the form:

$$f_{v_r}(v_r)=\begin{cases}\dfrac{2}{\pi.\sqrt{4-v_r^{\,2}}} & 0\le v_r\le 2\\ 0 & otherwise\end{cases} \quad (16)$$

Using (15) the following PDF is obtained for LEL as

$$f_\tau(\tau)=\frac{1}{\pi^2R^2\tau}[4\tau R+2(R-\tau)(R+\tau)\ln(\frac{R+\tau}{|R-\tau|})] \quad (17)$$

Another case is when the relative velocity is fixed, i.e. $f_{v_r}(v_r)=\delta(v_r-x)$. Then,

$$f_\tau(\tau)=\begin{cases}\dfrac{x_k\sqrt{4R^2-\tau^2x^2}}{\pi R^2} & \tau<\frac{2R}{x}\\ 0 & otherwise\end{cases} \quad (18)$$

and if the relative velocity has uniform distribution over (0,2], the corresponding PDF of LEL is given by

$$f_\tau(\tau)=\frac{4}{3\pi\tau^2}\begin{cases}R-\dfrac{(R^2-\tau^2)^{3/2}}{R^2} & \tau\le R\\ R & \tau>R\end{cases} \quad (19)$$