Energy-efficient Contact Probing in Opportunistic Mobile Networks

Huan Zhou*†, Huanyang Zheng†, Jie Wu† and Jiming Chen*
*State Key Lab. of Industrial Control Technology, Zhejiang University, Hangzhou 310027, China.
†Department of Computer and Information Sciences, Temple University, USA.
zhouhuan117@gmail.com, {huanyang.zheng, jiewu}@temple.edu, jmchen@iipc.zju.edu.cn

***Abstract*—In Opportunistic Mobile Networks (OppNets), data is opportunistically exchanged between nodes who encounter each other. In order to enable such data exchanges, nodes in the network have to probe their environment continually, so as to discover neighbor nodes. This can be an extremely energy-consuming process. If nodes probe very frequently, they will consume a lot of energy, and might be energy inefficient. On the other hand, infrequent contact probing might cause nodes to miss many of their contacts, and thus opportunities to exchange data are lost. Therefore, there exists a trade-off between energy efficiency and the contact opportunities in OppNets. In this paper, in order to investigate this trade-off, we first propose a model to quantify the detecting probability in OppNets, using the Random WayPoint (RWP) model. Then, extensive simulations are conducted to validate the correctness of our proposed model. Finally, based on the proposed model, we analyze the trade-off between energy efficiency and the total number of effective contacts under different situations. Our results show that the good trade-off points are obviously different when the speed of nodes is different. Moreover, the detecting probability increases as the speed of nodes decreases, while the total number of effective contacts increases as the speed of nodes increases.**

***Index Terms*—Opportunistic Mobile Networks, Energy consumption, Contact probing, Random WayPoint model.**

I. Introduction

Recently, with the rapid proliferation of wireless portable devices (e.g., PDAs, smartphones), a new peer-to-peer (P2P) application scenario – Opportunistic Mobile Networks (OppNets) – begins to emerge [1], [2], [3], [4], [5]. In OppNets, it is hard to guarantee end-to-end path due to the time-varying network topology, and thus nodes with data to transmit have to exchange data with relay nodes within their communication range. This data exchange process is referred to as the store-carry-forward mechanism, which works as a basic strategy of data transmission in OppNets [6], [7].

In order to enable such data exchange, nodes in the network have to constantly probe the environment to discover others in the vicinity. Not surprisingly, node discovery is an extremely energy-consuming process. Authors in [8] made measurements on a Nokia 6600 mobile phone to test the energy consumption in the node discovery process, and their results show that the node discovery process is as energy-intensive as making a phone call! Moreover, in OppNets, the inter-contact time is generally much longer than the contact duration, due to node sparsity; this indicates that nodes will waste a lot of energy in the node discovery process if they probe the environment too frequently. Therefore, it is pressing to investigate energy saving in the node discovery process in OppNets.

One strategy to save energy is to increase the time between subsequent node discoveries. The consequence of this is that nodes in the network may miss many chances to contact others, and thus opportunities to exchange data are lost. Moreover, if nodes probe the environment too frequently, they will consume a lot of energy in the node discovery process, and might be energy inefficient. This points to a trade-off between energy efficiency and contact opportunities. For strategies which use a constant contact probing interval, the larger the contact probing interval, the larger the missed contact opportunities, and vice-versa. Since authors in [8] have validated that among all contact probing strategies with the same average contact probing interval, the strategy which probes at constant intervals achieves the best performance. Therefore, in this paper, we only take into account the strategy which uses the fixed contact probing interval. In order to investigate the trade-off between energy efficiency and the contact opportunities in OppNets, we first propose a model to investigate the contact process in OppNets, and quantify the detecting probability using the Random WayPoint (RWP) model. Then, based on the proposed model, we analyze the trade-off between energy efficiency and the total number of effective contacts[1] under different situations. Our contributions in this paper are three-folds:

1) We propose a model to investigate the contact process in OppNets, and derive the detecting probability analytically, based on the RWP model. Given that the contact duration follows a certain distribution, we analytically obtain the relationship between the contact probing interval and the detecting probability.
2) We conduct several simulations to validate the correctness of our proposed model, and our results show that the simulation results are quit close to the theoretical results under different situations, which validate the correctness of our proposed model.

Research was supported by the Open Research Project of the State Key Laboratory of Industrial Control Technology, Zhejiang University, China (No. ICT1324)

[1] The contact opportunities are defined as the total number of effective contacts.

3) Based on the proposed model, we obtain the number of effective contacts over a certain period, denoted as the total number of effective contacts, and then the trade-off between energy efficiency and the total number of effective contacts in OppNets are analyzed.

The remainder of this paper is organized as follows. We present the related work in Section II, and introdice the network model in Section III. Section IV proposes a model to investigate the contact probing process in OppNets, and derives the detecting probability analytically, based on the RWP model. Extensive simulations are conducted to validate the correctness of the proposed model in Section V. Then, based on the proposed model, the trade-off between energy efficiency and the total number of effective contacts are analyzed in Section VI. At last, we conclude the paper in Section VII.

II. Related Work

Stochastic event capturing schemes have been well investigated in wireless sensor networks [9], [10]. In [9], optimal visiting routes are designed for mobile sensors to capture events, which randomly happen at different Points of Interest (PoIs). In [10], energy-aware optimization of the periodic schedule for static sensors to capture events are investigated, and four design points: (i) synchronous periodic coverage without coordinated sleep, (ii) synchronous periodic coverage with coordinated sleep, (iii) asynchronous periodic coverage without coordinated sleep, and (iv) asynchronous periodic coverage with coordinated sleep, are all considered. In our study, we focus on investigating the contact process in OppNets, which is more complicated than the memoryless event arrival and departure process in wireless sensor networks.

Note that nodes consume a lot of energy in the contact probing process, and a high probing frequency means a large amount of energy consumption. Therefore, some works have investigated the contact probing process to save energy [8], [11], [12] in OppNets. In [8], the impact of contact probing on the probability of missing a contact and the trade-off between the missing probability and energy consumption in bluetooth devices are investigated. In [11], the impact of contact probing on link duration and the trade-off between the energy consumption and throughput are investigated. In addition, this paper also provides a framework for computing the optimal contact-probing frequency under energy limitations. In [12], two novel adaptive schemes for dynamically selecting the parameters of the contact probing process are introduced and evaluated, in order to switch between low-power, slow discovery modes and high-power, fast discovery modes, depending on a mobility context.

Different from all the existing works above, our paper focuses on investigating the contact probing process in OppNets using the RWP model, and proposes a model to analyze the trade-off between energy efficiency and the total number of effective contacts under different situations.

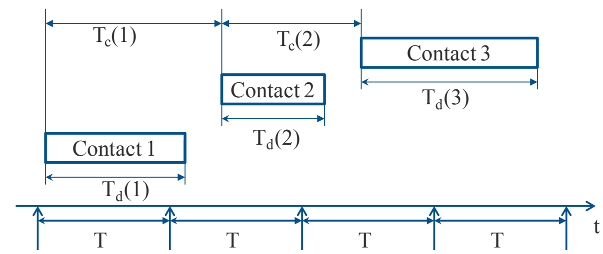


Fig. 1. Illustrating the contacts between two nodes at a constant probing interval T.

III. Network Model

This section introduces the network model related to the contact probing process in OppNets. There have been many mobility models available for evaluating the contact probing process in OppNets, including the Random WayPoint (RWP) Model [13], random walk [14], and realistic mobility trace [15]. In this paper, we focus on investigating the RWP model. In the RWP Model, for practical purposes, we consider a two-dimensional system space $\mathcal{S}$ of size S as a square area of width s or a circular region with radius s. With this mobility model, each node selects a target location to move at a speed V selected from a uniformly distributed interval $[V_{min}, V_{max}]$. Once the target is reached, the node pauses for a random time and then selects another target with another speed to move again. This process repeats in this manner. For simplicity, we assume that nodes move at the same speed V, and the pausing time is equal to 0.

In OppNets, nodes to be in contact with each other only if they are within communication range of each other, and the time when nodes are in contact with each other continuously is called the contact duration, while the time between subsequent contacts is defined as the inter-contact time. We assume that the contact duration T_d is i.i.d. stationary random variables with Cumulative Distribution Function (CDF) of $F_{T_d}(t)$, and the inter-contact time T_c is stationary random variables with CDF of $F_{T_c}(t)$. Fig. 1 gives an example about the contact duration T_d and the inter-contact time T_c between two nodes at a constant probing interval T. We further assume that each probe consumes equal energy so that the energy consumption rate of the node can be converted to the average contact probing frequency.

In order to enable data exchanges, nodes in the network have to constantly probe the environment to discover others in the vicinity. Here, we consider that a certain node A, probes its environment; all nodes which hear the probe respond to A with some information (e.g., identity, services available etc.). Based on this information, A may choose to exchange data with some of its neighbors. We assume that there are N nodes (e.g., portable devices with bluetooth) in the network, and they have the same communication range of r. Since the normal communication range of portable devices with bluetooth is less than $10m$ [16], we assume that $r \leq 10m$. We define two nodes A and B, to be in contact, if they are within communication range of each other. If neither node probes its vicinity during the contact duration, then we have a missed contact. Therefore, we divide the contact in OppNets into two kinds: the effective contact and the missed contact. The effective contact happens when one of the two nodes probes its environment during their contact with each other. Since this kind of contact between two nodes can be discovered by each other, we regard this kind of contact as the effective contact, which can be used for data exchanges. The missed contact happens when neither of the two nodes probes its environment during their contact with each other. Since this kind of contact between two nodes can not be detected by each other, we refer to this kind of contact as the missed contact. Note that the contact in OppNets is infrequent, and the contact process has significant effect on the performance of different applications in OppNets. Therefore, in the next section we will propose a model to investigate the contact process in OppNets.

IV. Modeling the contact process

In OppNets, unlike traditional connected networks (e.g., P2P networks and Internet-accessible networks), nodes are intermittently connected [17], [18]. Nodes in the network can communicate with each other only when they move into the transmission range of each other. Due to frequent link disconnections and dynamic topology in OppNets, contact schedules among nodes are not known in advance. Therefore, nodes in the network have to probe the environment continuously, so as to find the contact which can be used for data exchange. In this part, we will propose a model to investigate the contact process in OppNets.

A. The Detecting Probability

Let us define P_d (detecting probability) as the probability that a contact between two nodes can be detected by one another in OppNets, or that the contact is an effective contact. For the following analysis, we assume that for node A, a contact with node B is detected, only if B is detected by A's probes. We will relax this later, to compute the detecting probability when either A or B's probes detect each other. Let us consider the contact probing strategy, where each node probes for contacts at a constant probing interval of T (See Fig. 1).

There will be a set of different possibilities for calculating the detecting probability, P_d, depending on the lengths of the probing interval T and the contact duration T_d. Note that if $T_d \geq T$, the contact will always be detected. Therefore, we have the following theorem:

***Theorem** 1:* For a certain node A, with a constant probing interval T, the detecting probability P_d can be expressed as:

$$\begin{aligned} P_d &= \frac{1}{T}\int_0^T Pr\{T_d + t \geq T\}dt \\ &= 1 - \frac{1}{T}\int_0^T F_{T_d}(t)dt. \end{aligned} \tag{1}$$

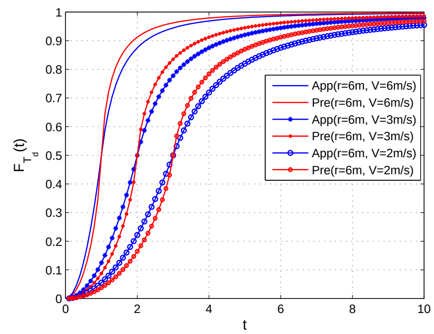


Fig. 2. Comparisons between the approximate value and the precise value of $F_{T_d}(t)$ under different situations.

Proof: Assume that node A probes its vicinity at time $\{T, 2T, ...\}$, here we consider the period $[0, T]$ to calculate the detecting probability. Note that a contact will be detected by A if (a) it happens when A probes its vicinity at time T; (b) it happens during period $(0, T)$, but the contact duration is long enough to be detected by the probing time T. Therefore, the detecting probability P_d is the sum of these two parts, and can be expressed as Eq. 1. ∎

Note that when the contact duration T_d is distributed according to a given distribution, we can analytically obtain the relationship between energy consumption and the detecting probability. As shown in [19], CDF of the contact duration T_d for the RWP model can be expressed as:

$$F_{T_d}(t) = \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\frac{r + Vt}{\sqrt{|r^2 - V^2t^2|}}), \tag{2}$$

where r is the transmission range of nodes, and V is the moving speed of nodes.

Note that the above equation is hard to integrate. Therefore, in order to facilitate the modeling, we simplify the above expression of T_d as follows:

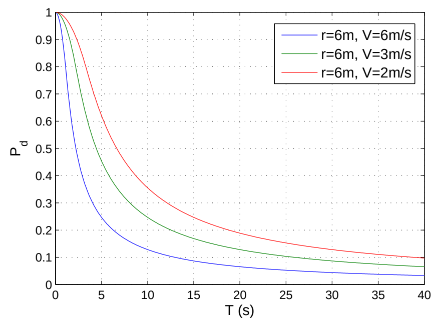
$$F_{T_d}(t) = \begin{cases} \frac{V^2t^2}{2r^2}, & t \leq \frac{r}{V}, \\ 1 - \frac{r^2}{2V^2t^2}, & t > \frac{r}{V}. \end{cases} \tag{3}$$

The appendix describes how to obtain the above expression.

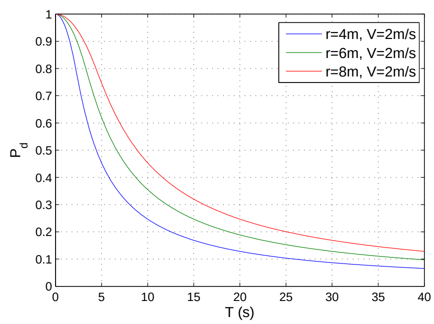
Fig. 2 shows the comparison between the approximate value of $F_{T_d}(t)$ and the precise value of $F_{T_d}(t)$ under different situations. It can be found that as the contact duration T_d increases, the approximate value of $F_{T_d}(t)$ and the precise value of $F_{T_d}(t)$ are very close to each other, especially when $r = 6m$, $V = 6m/s$. Therefore, in the following, we will use the approximate value of $F_{T_d}(t)$ instead of the precise value of $F_{T_d}(t)$ to calculate the detect probability P_d directly.

When we substitute Eq. (3) into Eq. (1), then we obtain the expression of the detecting probability P_d as follows:

$$P_d = \begin{cases} 1 - \frac{T^2V^2}{6r^2}, & T \leq \frac{r}{V}, \\ \frac{4r}{3TV} - \frac{r^2}{2T^2V^2}, & T > \frac{r}{V}, \end{cases} \tag{4}$$

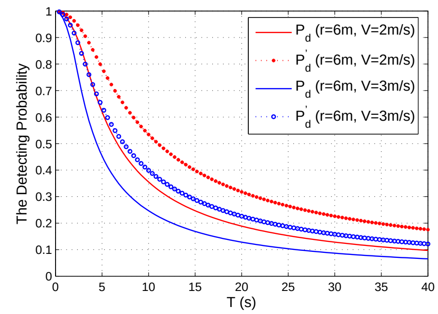


(a) When the speed V changes

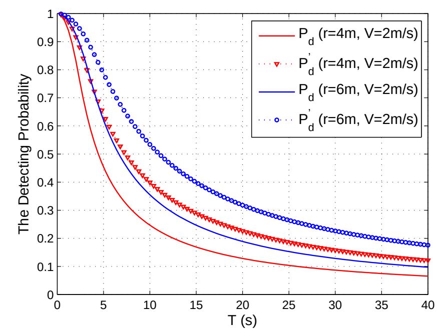


(b) When the communication range r changes

Fig. 3. The detecting probability P_d under different situations.



(a) When the speed V changes



(b) When the communication range r changes

Fig. 4. Comparison between P_d and P'_d under different situations.

where T is the contact probing interval.

Fig. 3 shows the relationship between the detecting probability P_d and the contact probing interval T under different situations. Fig. 3(a) shows the relationship between the detecting probability P_d and the contact probing interval T graphically when the speed V changes, and Fig. 3(b) shows the relationship between the detecting probability P_d and the contact probing interval T graphically when the communication range r changes. It can be found that the detecting probability P_d decreases as the contact probing interval T increases under different situations. This is reasonable because if T is smaller, nodes in the network will probe their environments more frequently, resulting in the increase of the detecting probability P_d. It is worth noticing that the upper-bound of P_d is 1 when $T = 0$, and the lower-bound of P_d is 0 when T is close to ∞. It can be also found that the detecting probability P_d decreases as V increases, and increases as r increases. The main reason is that the contact duration T_d increases as r increases or V decreases, while larger contact duration results in the increase of the detecting probability P_d.

B. Double Detection

In the above, we only give the detecting probability when a contact between two nodes A and B is detected by node A's probes. Actually, if node B has detected the contact, and sends the probing information to node A, then this contact can also be discovered by node A. Therefore, a contact between nodes A and B is detected if either node probes the environment during their contact with each other. Consider the case when nodes A and B are independently probing the environment periodically with a constant probing interval T. Suppose one node probes at times of T, $2T$, . . ., nT, and the other probes at y, $y+T$, . . ., $y+(n-1)T$. Then, the probability that during a contact with each other, either node discovers the other, is given by:

$$P'_d(T, y) = \frac{1}{T}[\int_0^y Pr\{T_d + t \geq y\}dt + \int_y^T Pr\{T_d + t \geq T\}dt] = \frac{1}{T}[T - \int_0^y F_{T_d}(t)dt - \int_0^{T-y} F_{T_d}(t)dt]. \tag{5}$$

Since the two nodes are probing independently, y is uniformly distributed in $[0, T]$. Then we obtain:

$$P'_d = \frac{1}{T^2}\int_0^T [\int_0^y Pr\{T_d + t \geq y\}dt + \int_y^T Pr\{T_d + t \geq T\}dt]dy = \frac{1}{T^2}\int_0^T [T - \int_0^y F_{T_d}(t)dt - \int_0^{T-y} F_{T_d}(t)dt]dy = \frac{1}{T^2}\int_0^T [T - 2\int_0^y F_{T_d}(t)dt]dy. \tag{6}$$

When we substitute Eq. (3) into Eq. (6), then we obtain the

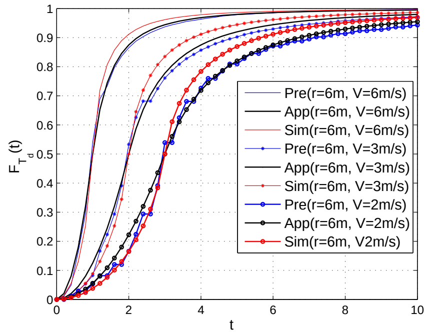


Fig. 5. Comparison between simulation results and theoretical results of $F_{T_d}(t)$ under different situations.

expression of P'_d as:

$$
\begin{aligned}
P'_d &= 1 - \frac{2}{T^2}\int_0^T [\int_0^y F_{T_d}(t)dt]dy \\
&= \begin{cases} 1 - \frac{2}{T^2}[\int_0^T \frac{V^2y^3}{6r^2}dy] & T \le \frac{r}{V} \\ 1 - \frac{2}{T^2}[\int_0^{\frac{r}{v}} \frac{V^2y^3}{6r^2}dy + \int_{\frac{r}{v}}^T y + \frac{r^2}{2V^2y} - \frac{4r}{3V}dy] & T > \frac{r}{V} \end{cases} \\
&= \begin{cases} 1 - \frac{V^2T^2}{12r^2} & T \le \frac{r}{V} \\ \frac{8r}{3VT} - (7 + 4In\frac{TV}{r})\frac{r^2}{4V^2T^2} & T > \frac{r}{V}. \end{cases} \qquad (7)
\end{aligned}
$$

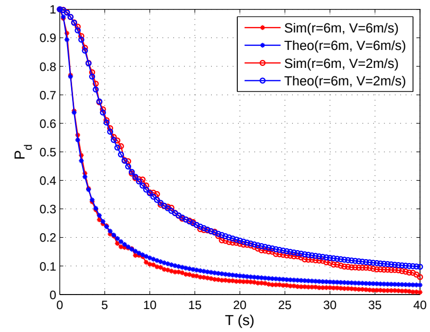
Fig. 4 shows the comparison between P_d and P'_d under different situations. Fig. 4(a) shows the comparison between P_d and P'_d when the speed V changes, and Fig. 4(b) shows the comparison between P_d and P'_d when the communication range r changes. It can be found that, similar to the results in Fig. 3, P'_d also decreases as T or V increases, and increases as r increases. It can be also found that P'_d is much larger than P_d not only when the speed V changes, but also when the communication range r changes.

V. Model Validation

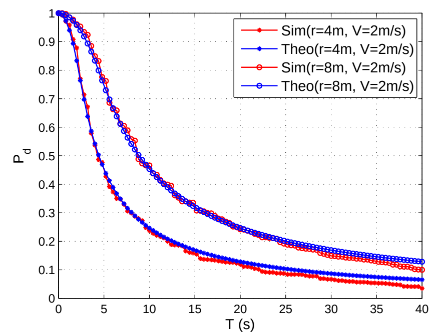
In this section, we conduct several simulations to validate the correctness of our proposed model using MATLAB. In our simulation, we use the network scenario with 20 nodes distributed over $400 * 400m^2$. Nodes in the scenario move according to the RWP model, and they all communicate using a normal communication range r. According to the assumptions above, we consider that nodes have the same moving speed V, and we set the pause time to be $0s$.

Fig. 5 shows the comparison between simulation results and theoretical results of $F_{T_d}(t)$ under different situations. It can be found that with the increase of T, the simulation results of $F_{T_d}(t)$ are much closer to the approximate value of $F_{T_d}(t)$ than the the precise value of $F_{T_d}(t)$ when $r = 6m$, $V = 2, 3and6m/s$. Therefore, we can use Eq. (3) instead of Eq. (2) to calculate the detecting probability P_d directly.

Fig. 6 shows the comparison between simulation results and theoretical results of P_d under different situations. Fig. (6)(a) shows the comparison between the simulation results of P_d and the theoretical results of P_d when the speed V changes, and Fig. 6(b) shows the comparison between the simulation results of P_d and the theoretical results of P_d when the



(a) When the speed V changes



(b) When the communication range r changes

Fig. 6. Comparison between simulation results and theoretical results of P_d under different situations.

communication range r changes. It can be found that the simulation results of P_d are very close to the theoretical results of P_d not only when the the speed V changes, but also when the communication range r changes.

To summarize, we have conducted several simulations to validate the correctness of our proposed model in this section. Via simulations under different situations, we show that the simulation results and the theoretical results of $F_{T_d}(t)$, and P_d are very close to each other, which validate the correctness of our proposed model.

VI. Trade-off between Energy Efficiency and the Total Number of Effective Contacts

In this section, we introduce the trade-off between energy efficiency and the total number of effective contacts in Opp-Nets, while the total number of effective contacts denotes the number of effective contacts over a certain period. Here, we consider that a certain node, e.g., node A, probes its environment over a certain period L (e.g. node A should probe the environment in a 5 hour period), then how to decide the probing interval T, so as to make the contact probing process more energy efficient.

We assume that the random variable $X_{AB}(t)$ denotes the cumulative number of contacts between nodes A and B at time t, and any two contacts between them are independent from each other. Hence, $X_{AB}(t)$ is a stochastic process with independent increments. That is, for any $0 < t_1 < t_2 < ... < t_n$, $X_{AB}(t_2) - X_{AB}(t_1), X_{AB}(t_3) - X_{AB}(t_2), ..., X_{AB}(t_n) -$

$X_{AB}(t_{n-1})$ are all independent random variables. According to [20], [21], the CDF of the inter-contact time T_c in the RWP model is approximating exponential distribution with rate $\lambda = \frac{2rV_{rwp}V}{S}$, where $V_{rwp} \approx 1.75$ is the normalized relative speed for the RWP model, V is moving speed of nodes, and S is the size of the scenario. Thus, $X_{AB}(t)$ can be modeled as a homogeneous poisson process. For any $t > 0$, the number of contacts $X_{AB}(t + \Delta t) - X_{AB}(t)$ between nodes A and B within time Δt follows the Poisson distribution, which can be expressed as:

$$Pr(X_{AB}(t+\Delta t) - X_{AB}(t) = k) = \frac{(\lambda_{AB}\Delta t)^k e^{-\lambda_{AB}\Delta t}}{k!}, \tag{8}$$

where λ_{AB} is the contact rate between nodes A and B.

Since the network in the RWP model is homogenous, which means nodes in the network have the same contact rate λ, then we can obtain the number of effective contacts over period L as:

$$N_{eff} = \lambda(N-1)LP_d, \tag{9}$$

where λ is the contact rate, P_d is the detecting probability, and N is the total number of nodes in the network.

When we substitute Eq. (4) into Eq. (9), then we obtain:

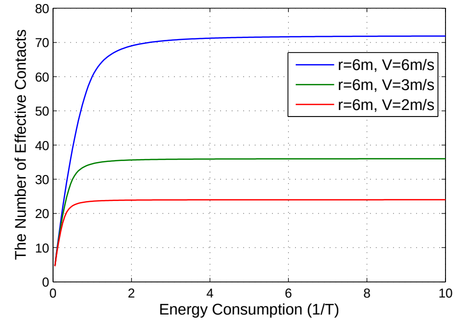
$$N_{eff} = \begin{cases} (1 - \frac{T^2V^2}{6r^2})\frac{2r(N-1)V_{rwp}VL}{S}, & T \le \frac{r}{V}, \\ (\frac{4r}{3T} - \frac{r^2}{2T^2V})\frac{2r(N-1)V_{rwp}L}{S}, & T > \frac{r}{V}, \end{cases} \tag{10}$$

where $V_{rwp} \approx 1.75$ is the normalized relative speed for the RWP model.

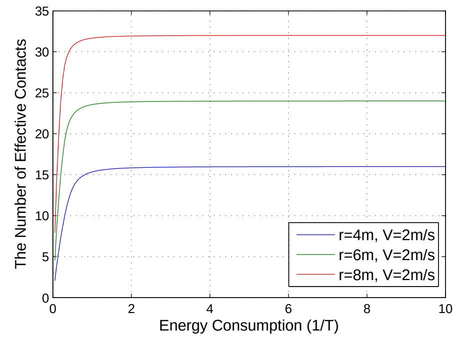
We define energy consumption $E = \frac{1}{T}$, which indicates the probing rate of nodes in the network. If the probing rate is larger, nodes in the network will consume more energy in the contact probing process. Then Eq. (10) will be changed to:

$$N_{eff} = \begin{cases} (1 - \frac{V^2}{6r^2E^2})\frac{2r(N-1)V_{rwp}VL}{S}, & E \ge \frac{V}{r}, \\ (\frac{4rE}{3} - \frac{r^2E^2}{2V})\frac{2r(N-1)V_{rwp}L}{S}, & E < \frac{V}{r}. \end{cases} \tag{11}$$

It is worth noticing that when the energy consumption E is close to ∞, we can obtain that the total number of effective contacts $N_{eff} = \frac{2r(N-1)VL}{S}$, which is the upper-bound of N_{eff}. When E equals 0, we can obtain that $N_{eff} = 0$, which is the lower-bound of N_{eff}. Fig. 7 shows the trade-off between energy efficiency and the total number of effective contacts under different situations. Here, for simplicity, we set $N = 2$, $L = 10,000s$, $S = 10,000m^2$. Therefore, the upper-bound of N_{eff} will be changed to $2rV$. Fig. 7(a) shows the trade-off when the speed V changes, and Fig. 7(b) shows the trade-off when the communication range r changes. It can be found that the total number of effective contacts increases as the energy consumption increases. This is reasonable because more energy consumption means more frequent contact probing, resulting in the increase of the total number of effective contacts. However, when the energy consumption increases to a certain value, the increase rate of N_{eff} will be very small.



(a) When the speed V changes



(b) When the communication range r changes

Fig. 7. Trade-off between energy efficiency and the total number of effective contacts.

For example, when $r = 6m$, $V = 2m/s$, the total number of effective contacts nearly reaches the upper-bound when energy consumption is 0.7, and the corresponding value is 2 when $r = 6m$, $V = 6m/s$, which are good trade-off points between energy efficiency and the total number of effective contacts. It is worth noticing that good trade-off points also change as the speed V or the communication range r changes. When the speed V is smaller, the total number of effective contacts reaches the upper-bound more quickly. Therefore, the good trade-off points are obviously different when $V = 2, 3$, and $6m/s$. When the communication range r changes, the good trade-off points are nearly the same, because the total number of effective contacts nearly reaches the upper-bound when the energy consumption is 0.7.

Similar to the results in Fig. 3(b), the total number of effective contacts also increases as the communication range r increases. The main reason is that P_d increases as r increases, resulting in the increase of the total number of effective contacts. It is worth noticing that different from the results in Fig. 3(a), the total number of effective contacts increases as the speed V increases. The main reason is that although the detecting probability decreases as V increases, the contact rate λ increases as V increases, and the contact rate λ increases more quickly, resulting in the increase of the total number of effective contacts.

To summarize, we have obtained the expression of the number of effective contacts over a certain period, and analyzed the trade-off between energy efficiency and the total number of effective contacts in this section. Our results show that the total number of effective contacts has a lower-bound and a upper-bound, and the good trade-off points are obviously different when the speed of nodes is different. Our results also show that the detecting probability increases as the speed of nodes decreases, while the total number of effective contacts increases as the speed of nodes increases.

VII. Conclusions

In this paper, we proposed a model to investigate the contact probing process in OppNets, using the RWP model, and derived the detecting probability. Then, we conduct extensive simulations to validate the correctness of proposed model. Our results show that the simulation results are quite close to the theoretical results. These close results validate the correctness of our proposed model. At last, based on the proposed model, we analyzed the trade-off between energy efficiency and the total number of effective contacts under different situations. Our results show that the good trade-off points are obviously different when the speed of nodes is different. Moreover, the detecting probability increases as the speed of nodes decreases, while the total number of effective contacts increases as the speed of nodes increases. In the future, we will focus on analyzing the trade-off between energy efficiency and data transmission in OppNets.

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Appendix

According to Eq. (2), we have:

$$F_{T_d}(t) = \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\sqrt{\frac{\frac{r}{V}+t}{|\frac{r}{V}-t|}}). \tag{12}$$

If $t \ll \frac{r}{V}$, we have:

$$\begin{aligned} F_{T_d}(t) &= \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\sqrt{\frac{\frac{r}{V}+t}{\frac{r}{V}-t}}) \\ &\approx \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\sqrt{[\frac{r}{V}+t]^2}) \\ &= \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\frac{r}{V}+t) \\ &\approx \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} \frac{Vt}{r} \\ &= \frac{V^2t^2}{2r^2}. \end{aligned} \tag{13}$$

If $t \gg \frac{r}{V}$, we have:

$$\begin{aligned} F_{T_d}(t) &= \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\sqrt{\frac{t+\frac{r}{V}}{t-\frac{r}{V}}}) \\ &\approx \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(\sqrt{[t+\frac{r}{V}]^2}) \\ &= \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} In(t+\frac{r}{V}) \\ &\approx \frac{1}{2} - \frac{r^2 - V^2t^2}{2rVt} \frac{r}{Vt} \\ &= 1 - \frac{r^2}{2V^2t^2}. \end{aligned} \tag{14}$$

Therefore, we obtain the approximation of Eq. (2) as:

$$F_{T_d}(t) = \begin{cases} \frac{V^2t^2}{2r^2} & t \le \frac{r}{V} \\ 1 - \frac{r^2}{2V^2t^2} & t > \frac{r}{V}. \end{cases} \tag{15}$$