Energy-efficient Contact Probing in Opportunistic Mobile Networks

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Outline

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- Introduction
- Motivation
- Modeling the Contact Process
- Model Validation
- Trade-offs
- Conclusions

Introduction

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Delay Tolerant Networks (DTNs)

• Intermittent connectivity
  - Contact: two nodes within the transmission range of each other
  - Store-carry-forward

• General mobile devices
  - Smart phones, PDAs, iPads.
  - Limited energy supplies

Motivation

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DTN contact is sparse and the inter-contact time is larger than the contact duration.

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Node discovery process is as energy-intensive as making a phone call!

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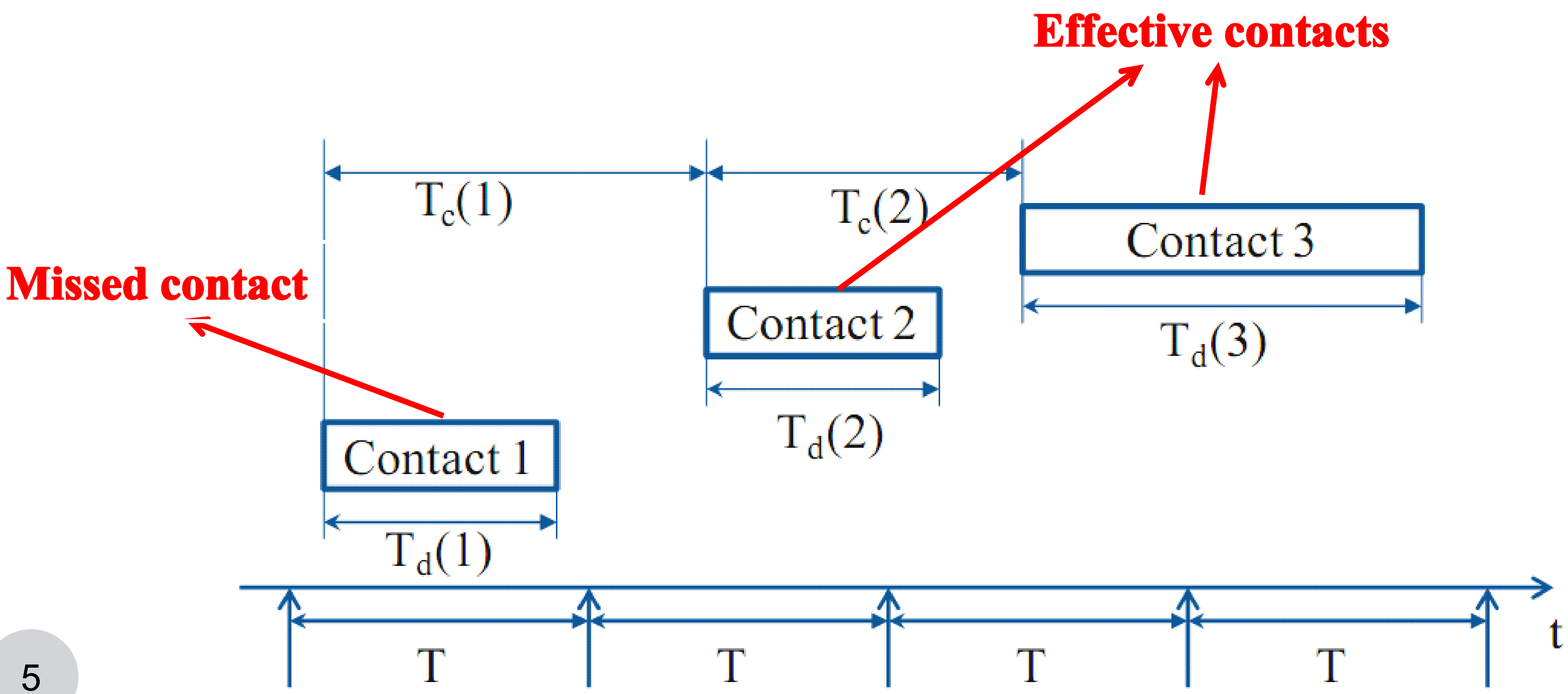
Infrequent contact probing leads to many missed contacts, while frequent contact probing costs energy.

Modeling the contact process
-The detecting probability

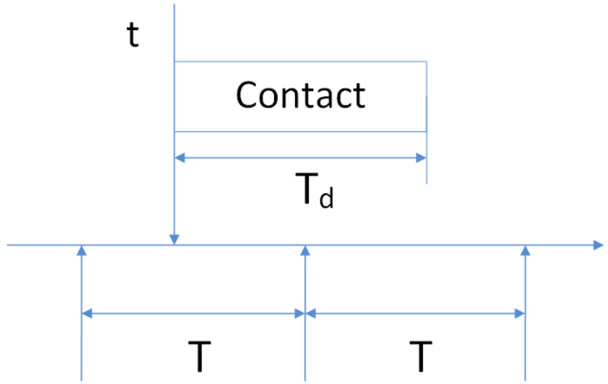
- Node probes for contacts at a constant probing interval of T.
- Inter-contact time: $T_c(1), T_c(2), \ldots$
- Contact duration: $T_d(1), T_d(2), T_d(3), \ldots$
- **Effective contact** and **missed contact**



Modeling the contact process
-The detecting probability

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

$$P_d = \frac{1}{T}\int_0^T Pr\{T_d + t \geq T\}dt = 1 - \frac{1}{T}\int_0^T F_{T_d}(t)dt. \quad (1)$$



Here, F_{Td} (t) is cumulative distribution function (CDF) of T_d.

Proof: B probes its vicinity at time {T, 2T, …}. We consider the period [0, T]. A contact will be detected by B if

- (a) B probes its vicinity at time T.
- (b) The contact happens during period (0, T) and its duration is long enough to be detected at time T.

Modeling the contact process
-The Random WayPoint model

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- Mobility model: Random WayPoint Model (RWP)
  - Consider a two-dimensional system (a square area of width s).
  - Each node selects a target location to reach at a speed of V.
  - Once the target is reached, the node selects another target with another selected speed to reach again.

- Transmission model:
  - N nodes in the network
  - Each node having the same communication range of r

Modeling the contact process
-The Random WayPoint model

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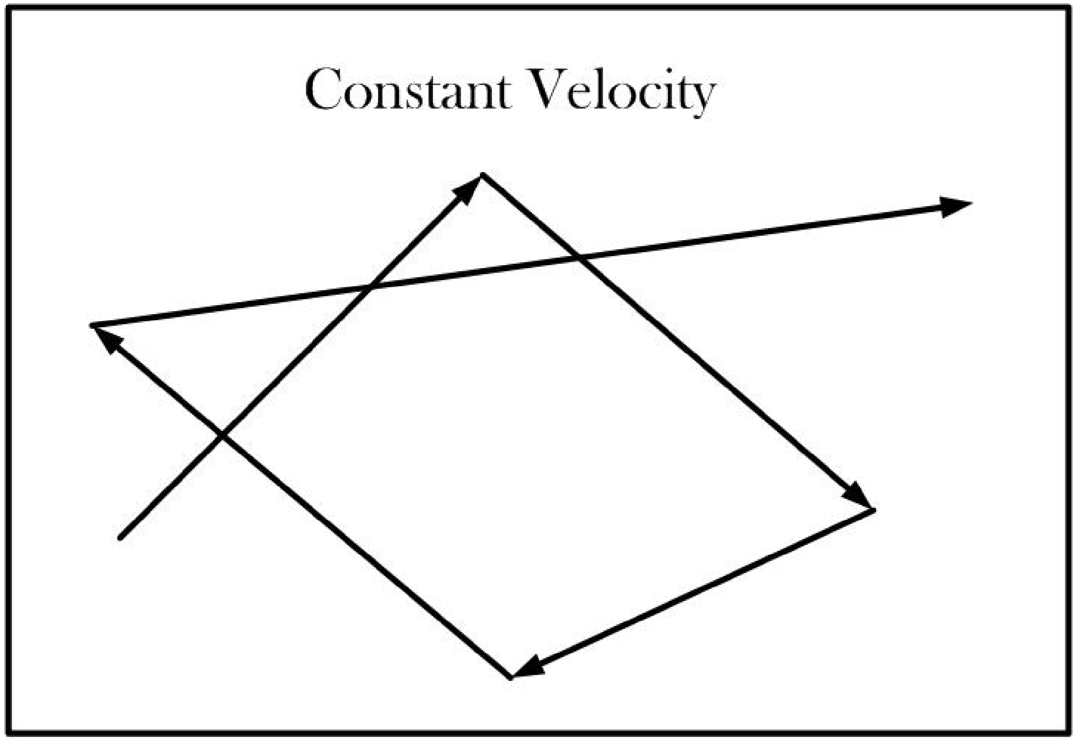
- Mobility model: Random WayPoint Model (RWP)



Modeling the contact process
-The contact duration

- CDF of the contact duration T_d for the RWP model is:

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

- Since the above equation is hard to integrate, here, we simplify the above expression of T_d as follows:

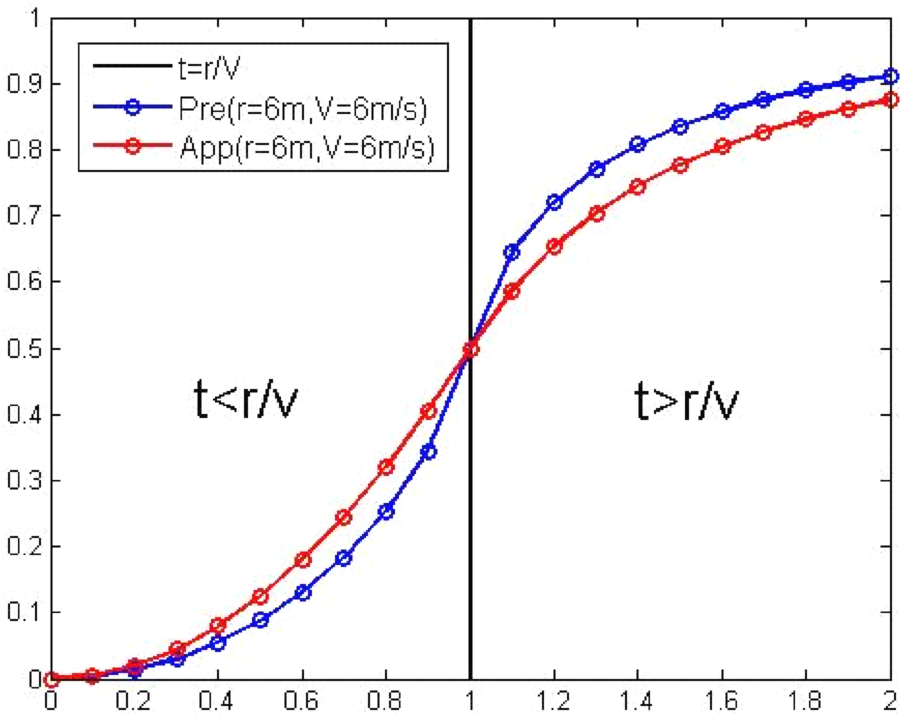
$t \le \frac{r}{V}$ is approximated to be $t \ll \frac{r}{V}$ and thus $\frac{Vt}{r} \ll 1$.

$$\ln\frac{r+Vt}{\sqrt{r^2-V^2t^2}} = \ln\sqrt{\frac{1+\frac{Vt}{r}}{1-\frac{Vt}{r}}} \approx \ln\sqrt{\left(1+\frac{Vt}{r}\right)^2} = \frac{Vt}{r}$$

$$F_{T_d}(t) = \frac{1}{2} - \frac{r^2-V^2t^2}{2rVt}\ln\frac{r+Vt}{\sqrt{r^2-V^2t^2}} \approx \frac{1}{2} - \frac{r^2-V^2t^2}{2rVt}\frac{Vt}{r} = \frac{V^2t^2}{2r^2}$$

Similar conditions for $\mathrm{t} > \frac{\mathrm{r}}{\mathrm{V}}$

Modeling the contact process
-The contact duration

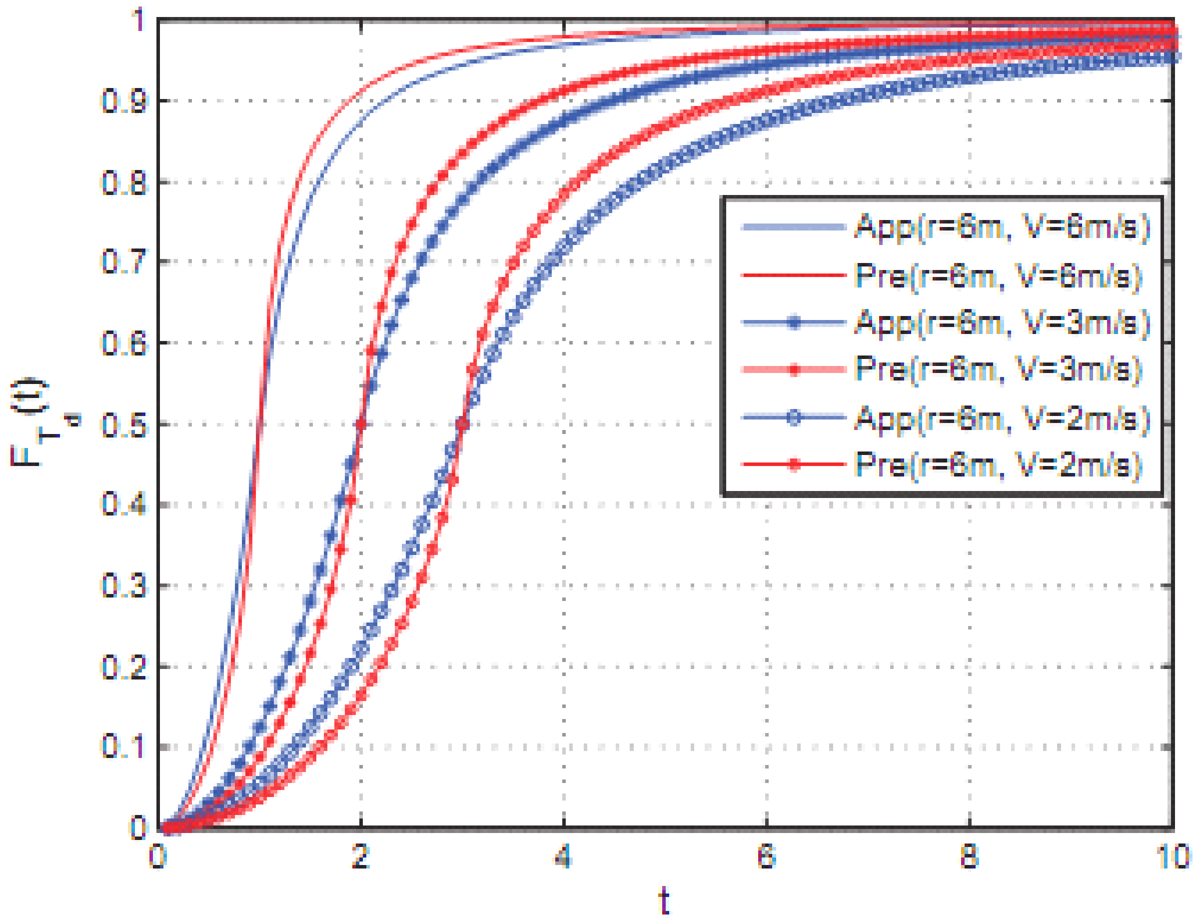


- Approximation result: $$F_{T_d}(t) = \begin{cases} \frac{V^2t^2}{2r^2}, & t \leq \frac{r}{V}, \\ 1 - \frac{r^2}{2V^2t^2}, & t > \frac{r}{V}. \end{cases} \quad (3)$$

Modeling the contact process

-The contact duration

- Comparisons between the approximate value and the precise value of F_{Td} (t) under different situations.



Modeling the contact process
-The detecting probability

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- Substituting Eq. (3) into Eq. (1), we have

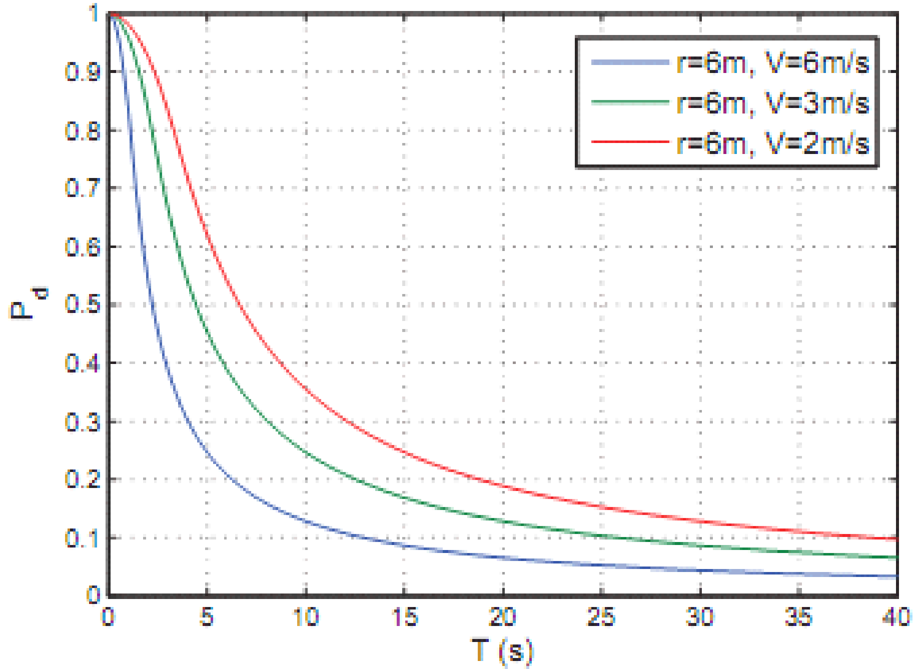
$$P_d = \begin{cases} 1 - \frac{T^2V^2}{6r^2}, & T \le \frac{r}{V}, \\ \frac{4r}{3TV} - \frac{r^2}{2T^2V^2}, & T > \frac{r}{V}, \end{cases} \quad (4)$$

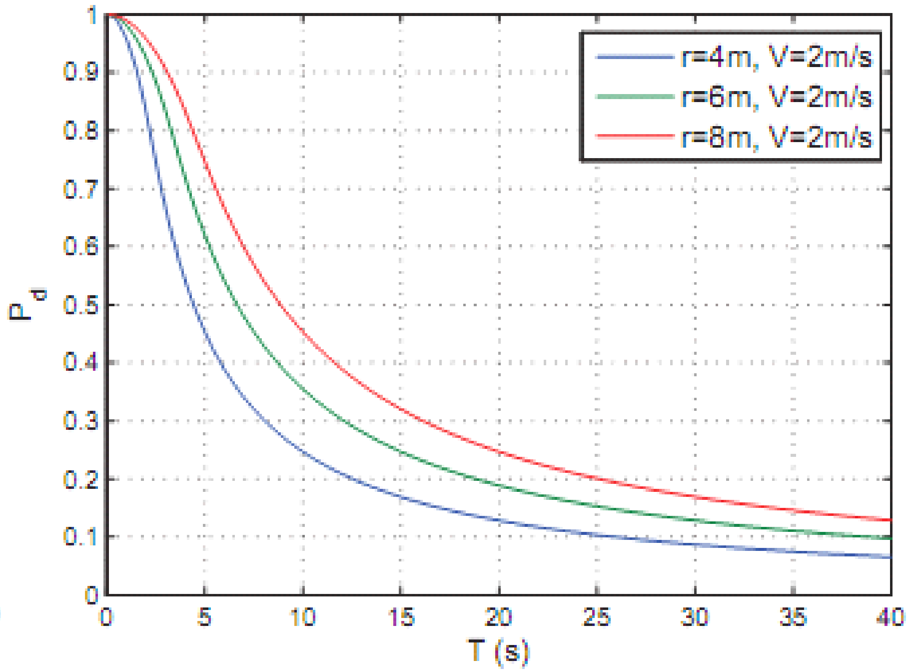
where T is the contact probing interval, r is the communication range, and V is the speed of nodes.

Modeling the contact process

-The detecting probability

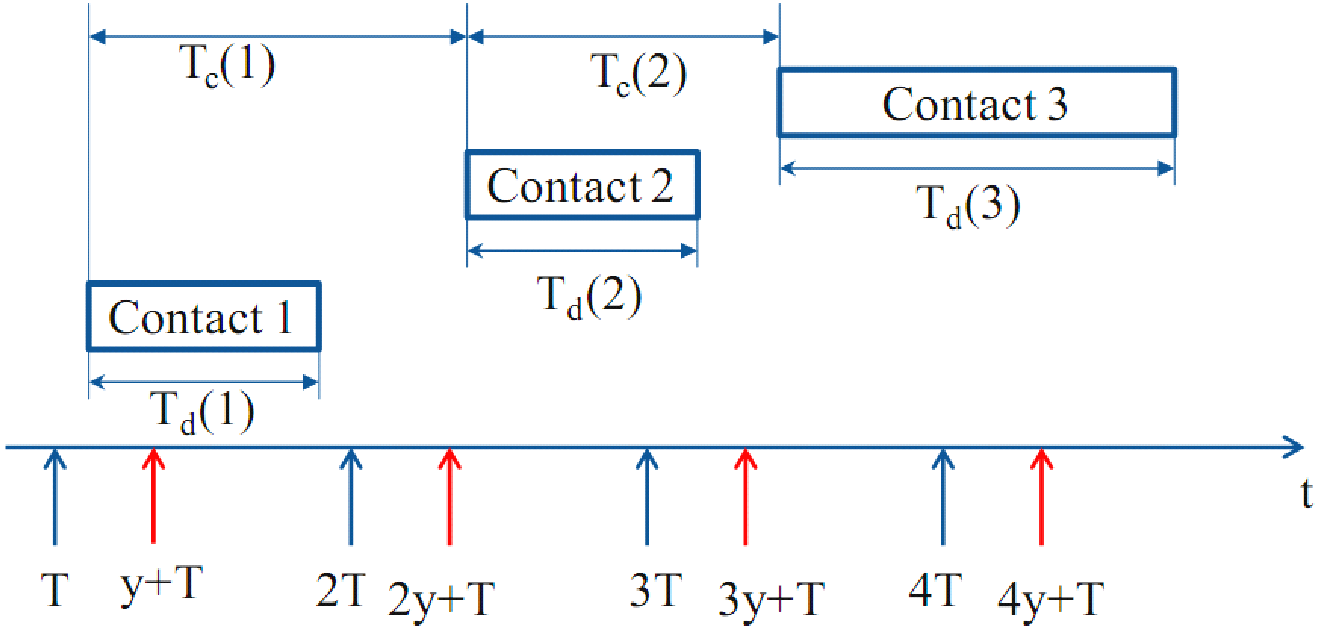
- Relationship between the **detecting probability** P_d and the **contact probing interval** T under different situations.





Modeling the contact process
-Double detection

- A contact between nodes A and B is detected if either node probes its vicinity during their contact.
- Node A probes at times of T, $2T$, . . ., nT, and node B probes at y, $y+T$, . . ., $y+(n-1)T$, y is uniformly distributed in [0, T].



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- Then, the probability that either node discovers the other during a contact is given by:

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

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

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$$P'_d = \frac{1}{T^2}\int_0^T [\int_0^y Pr\{T_d + t \geq y\}dt + \int_y^T Pr\{T_d + t \geq T\}dt]dy$$

$$= \frac{1}{T^2}\int_0^T [T - \int_0^y F_{T_d}(t)dt - \int_0^{T-y} F_{T_d}(t)dt]dy$$

$$= \frac{1}{T^2}\int_0^T [T - 2\int_0^y F_{T_d}(t)dt]dy. \quad (6)$$

- Substituting Eq. (3) into Eq. (6), we have

$$P'_d = 1 - \frac{2}{T^2}\int_0^T [\int_0^y F_{T_d}(t)dt]dy$$

$$= \begin{cases} 1 - \frac{2}{T^2}[\int_0^T \frac{V^2 y^3}{6r^2}dy] & T \leq \frac{r}{V} \\ 1 - \frac{2}{T^2}[\int_0^{\frac{r}{v}} \frac{V^2 y^3}{6r^2}dy + \int_{\frac{r}{v}}^T y + \frac{r^2}{2V^2 y} - \frac{4r}{3V}dy] & T > \frac{r}{V} \end{cases}$$

$$= \begin{cases} 1 - \frac{V^2 T^2}{12r^2} & T \leq \frac{r}{V} \\ \frac{8r}{3VT} - (7 + 4In\frac{TV}{r})\frac{r^2}{4V^2T^2} & T > \frac{r}{V}. \end{cases} \quad (7)$$

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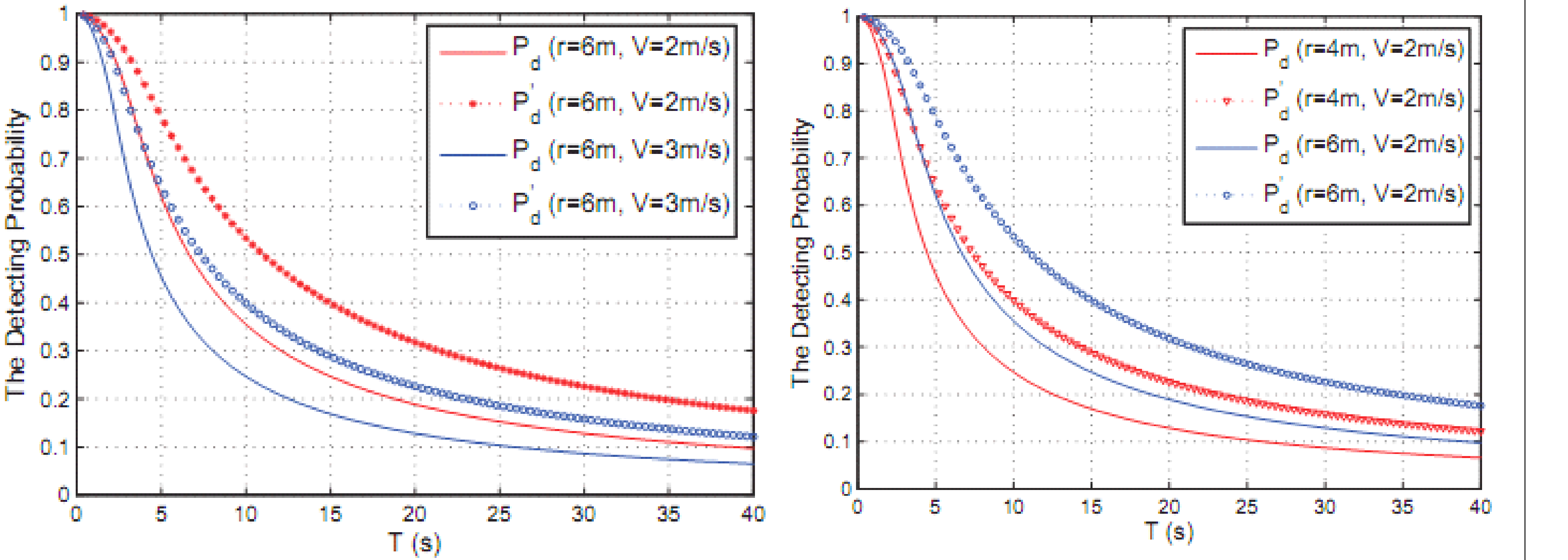
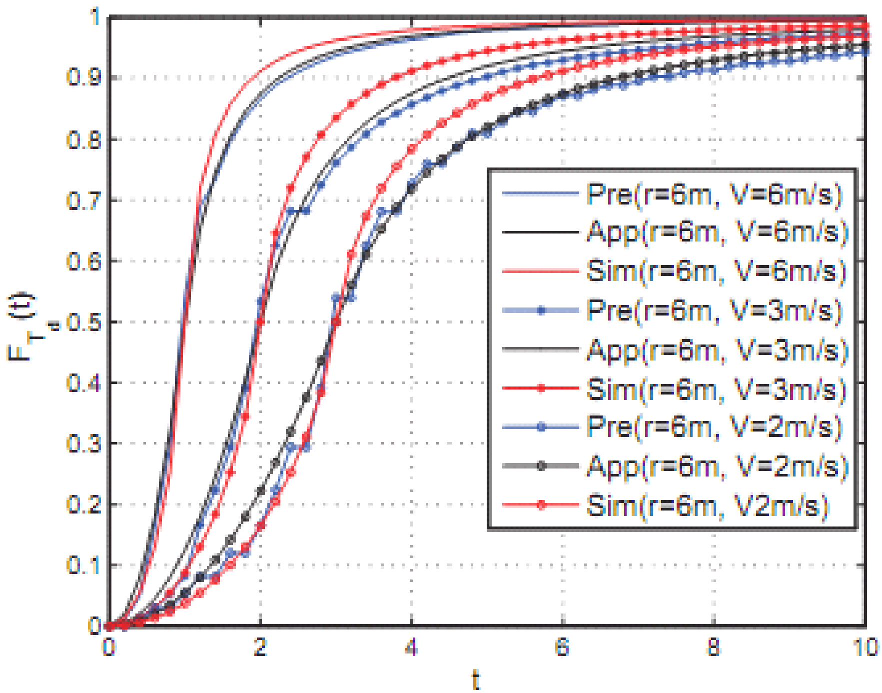
- Comparison between P_d and P_d'



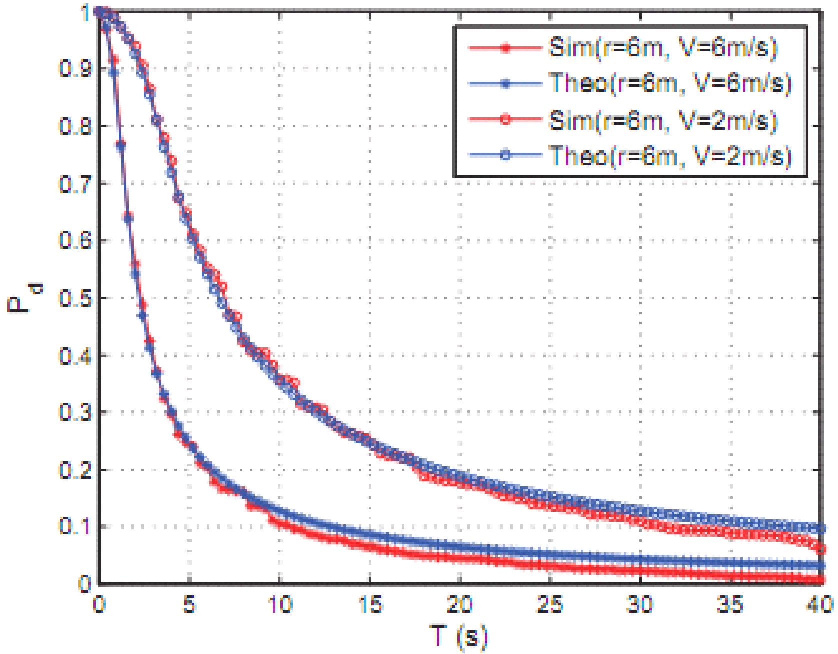
Model Validation

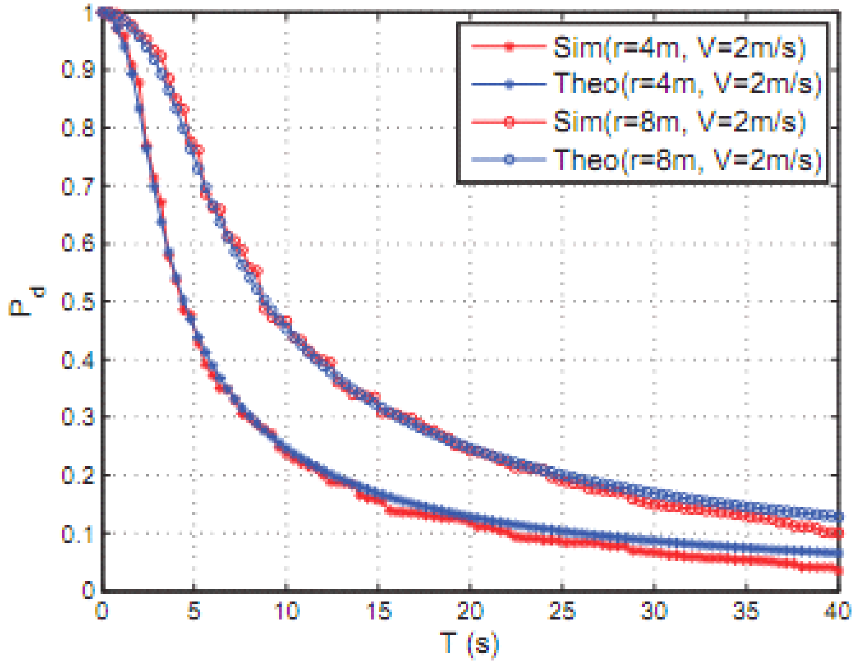
- A network with 20 nodes distributed over 400 * 400m^2
- Nodes moving around according to the RWP model
- Comparison among precise, approximation, and simulation results on the CDF of contact durations, F_{Td} (t)



Model Validation

- Comparison between simulation and approximation results of detection probability P_d under different situations





Trade-off s: Energy Efficiency vs. The Total Number of Effective Contacts

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- CDF of the inter-contact time T_c in RWP is approximated as **exponential distribution** with rate

$$\lambda = 2rV_{rwp}V/S$$

where $V_{rwp} \approx 1.75$ and S is the size of the area.

- Nodes in RWP have the same contact rate λ, then the number of effective contacts over period L is

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

Trade-off s: Energy Efficiency vs. The Total Number of Effective Contacts

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- Substituting Eq. (4) into Eq. (9), we have

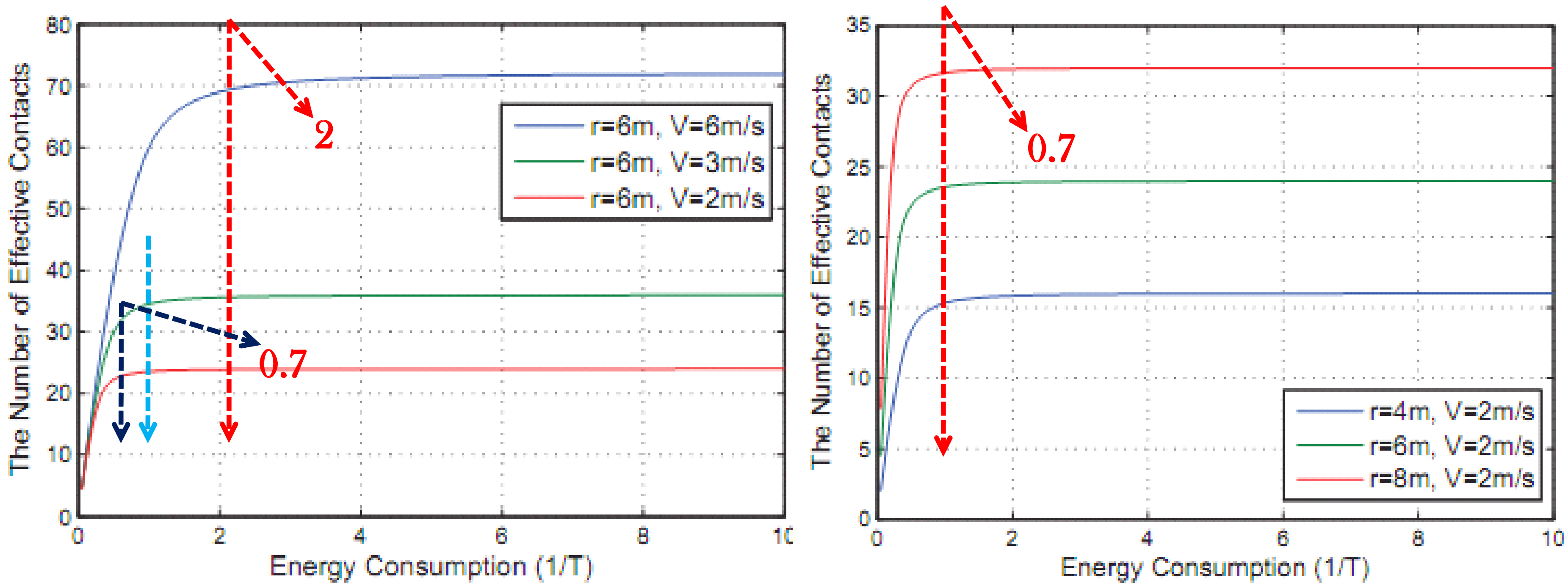
$$N_{eff} = \begin{cases} (1 - \frac{T^2V^2}{6r^2})\frac{2r(N-1)V_{rwp}VL}{S}, & T \leq \frac{r}{V}, \\ (\frac{4r}{3T} - \frac{r^2}{2T^2V})\frac{2r(N-1)V_{rwp}L}{S}, & T > \frac{r}{V}, \end{cases} \quad (10)$$

- We define a simple **energy consumption** *E = 1/T*, which indicates the probing rate of nodes in the network. Then,

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

Trade-off s: Energy Efficiency vs. The Total Number of Effective Contacts

- When E is close to ∞ , we have the total number of effective contacts as $N_{eff}=2r(N-1)VL/S$, which is the upper-bound.
- When E equals 0, we can obtain that $N_{eff}=0$, which is the lower-bound.
- Simulation: N=2, L=10,000s, and S = 100 x 100 m^2



Conclusions

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- We model the contact process under RWP and analytically obtain the detecting probability P_d.
- We conduct simulations to validate the correctness of the proposed model.
- We study trade-offs between the detecting probability and the energy efficiency under different situations are analyzed.
- Out future work includes in-depth analysis of trade-offs under a more sophisticate and accurate energy model.

Questions?