# Energy-efficient Contact Probing in Opportunistic Mobile Networks

**Huan Zhou[1], Huanyang Zheng[2], Jie Wu[2], and Jiming Chen[1]**

1.State Key Lab. of Industrial Control Technology
Zhejiang University, China
2. Department of Computer and Information Sciences
Temple University, USA

# Outline

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

# Introduction

Opportunistic Mobile Networks (OppNets)

•Intermittent connectivity

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

• General mobile devices

- Smartphones, PDAs, iPads.
- Limited energy supplies

# Motivation

浙江大学

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

↓

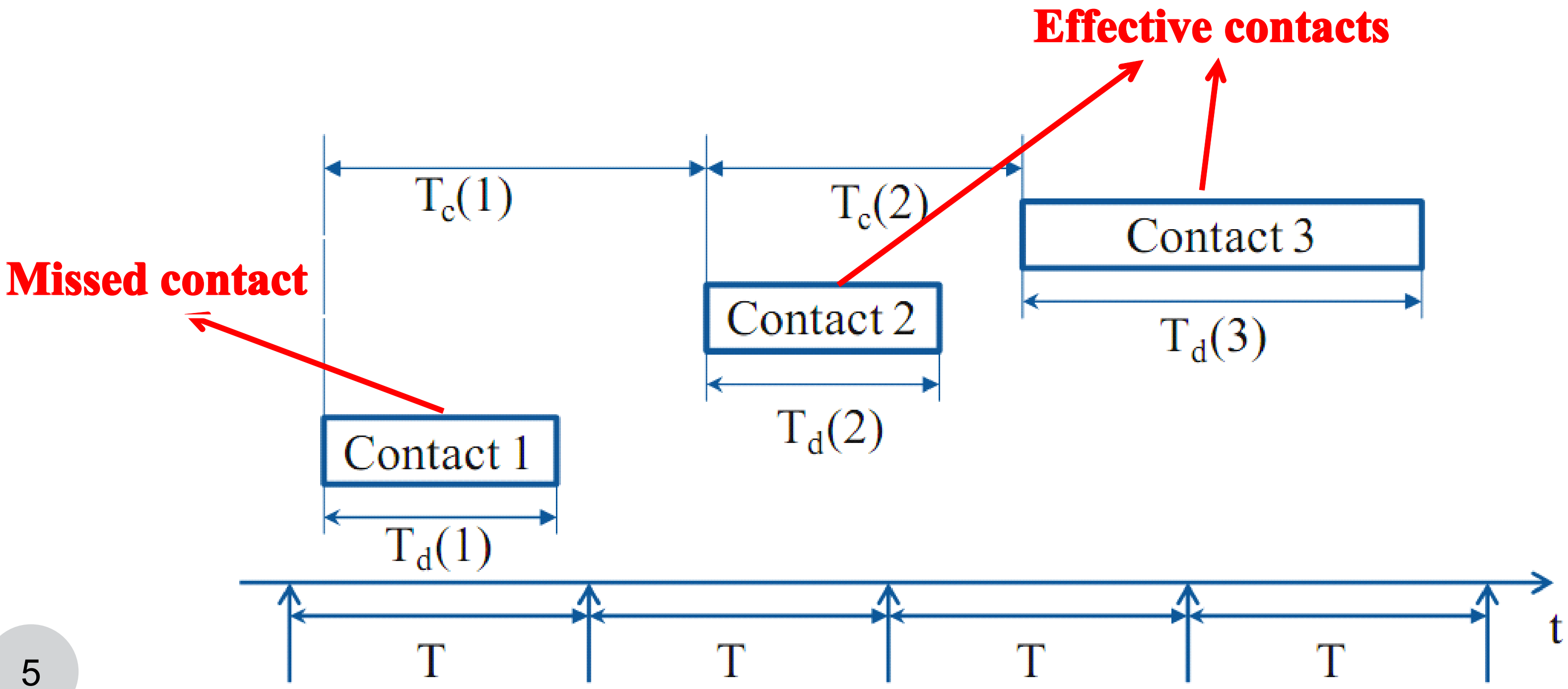
Node discovery process is as energy-intensive as making a phone call!

↓

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

# Modeling the contact process
## -The detecting probability

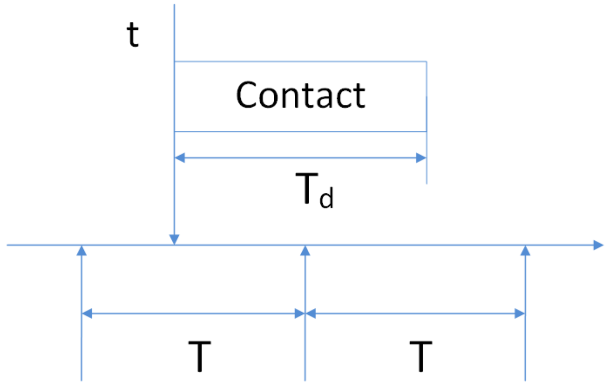
- Node probes for contacts at a constant probing interval of $T$.
- Inter-contact time: $T_c(1)$, $T_c(2)$, ...
- Contact duration: $T_d(1)$, $T_d(2)$, $T_d(3)$, ...
- **Effective contact** and **missed contact**



# 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 at *t* during period (0, T) and its duration is long enough to be detected at time T.

# Modeling the contact process
## -The Random WayPoint model

浙江大学

- 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 contact duration

浙江大學

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

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

(Tsao, WCNC 2006)

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

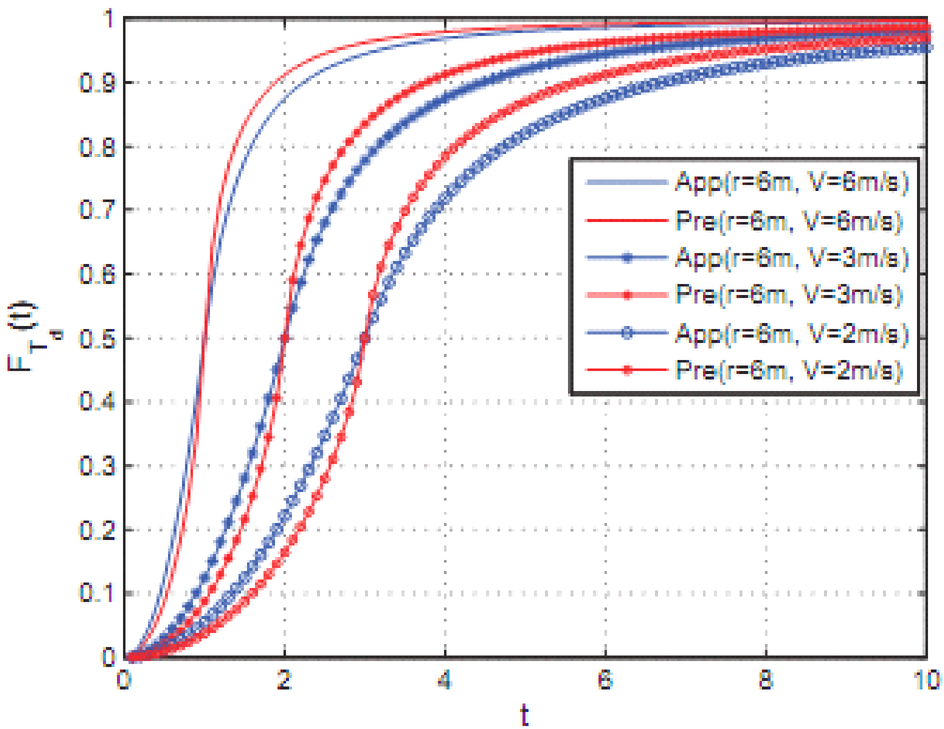
$$\ln\frac{r+Vt}{\sqrt{r^2 - V^2t^2}} = \ln\sqrt{\frac{1+\frac{Vt}{r}}{1-\frac{Vt}{r}}} \approx \ln\sqrt{\left(1+\frac{Vt}{r}\right)^2} = \frac{Vt}{r}$$

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

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

# Modeling the contact process
## -The contact duration

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



# Modeling the contact process
## -The detecting probability

浙江大學

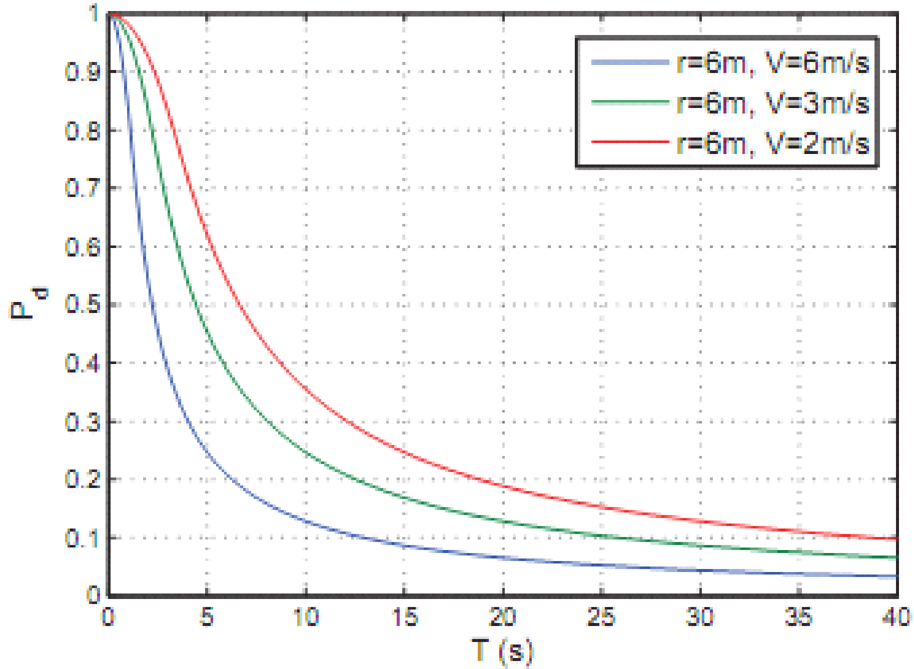
- Substituting Eq. (3) into Eq. (1), we have

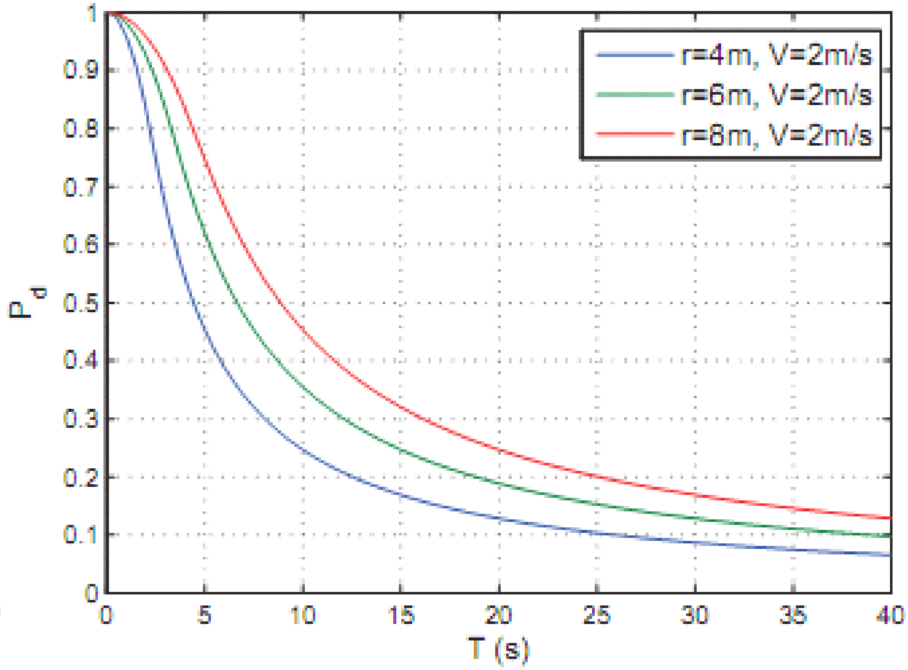
$$P_d = \begin{cases} 1 - \frac{T^2V^2}{6r^2}, & T \le \frac{r}{V}, \\ \frac{4r}{3TV} - \frac{r^2}{2T^2V^2}, & T > \frac{r}{V}, \end{cases} \quad (4)$$

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

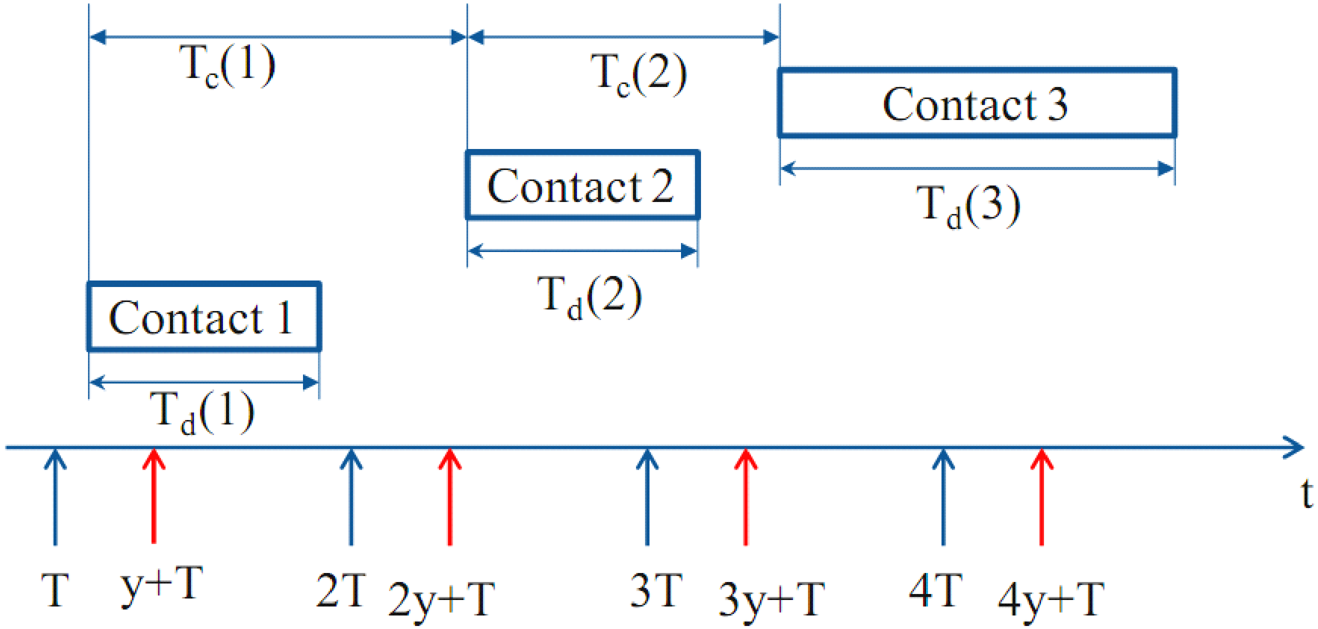
- Relationship between the **detecting probability** $P_d$ and the **contact probing interval** $T$ under different situations.



# 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 $[0, T]$.



# Cont'd

- 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

# Cont'd

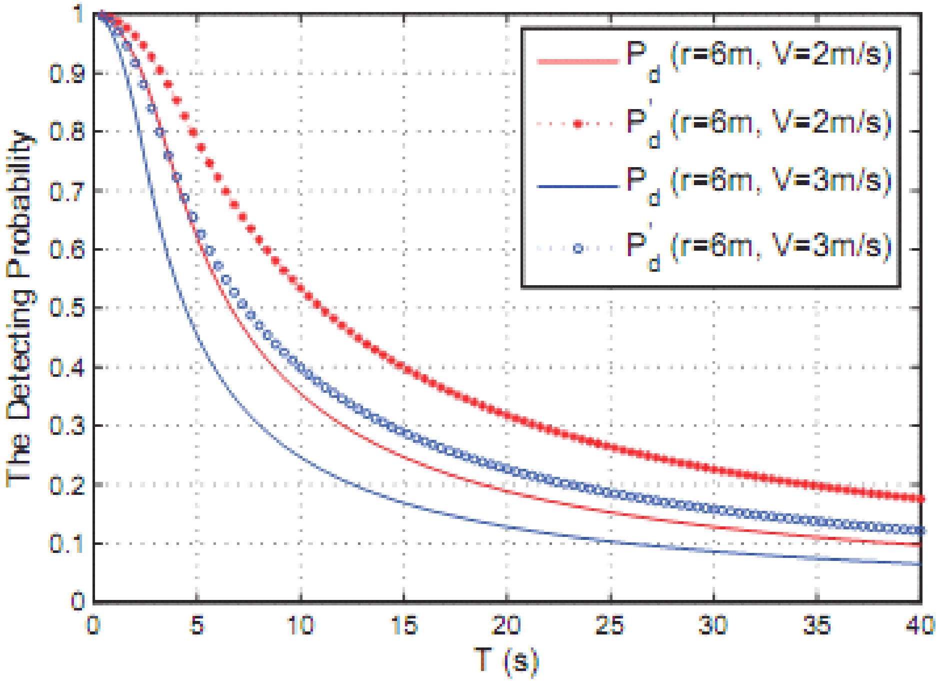
$$P_d' = \frac{1}{T^2}\int_0^T [\int_0^y Pr\{T_d + t \geq y\}dt + \int_y^T Pr\{T_d + t \geq T\}dt]dy$$
$$= \frac{1}{T^2}\int_0^T [T - \int_0^y F_{T_d}(t)dt - \int_0^{T-y} F_{T_d}(t)dt]dy$$
$$= \frac{1}{T^2}\int_0^T [T - 2\int_0^y F_{T_d}(t)dt]dy. \quad (6)$$

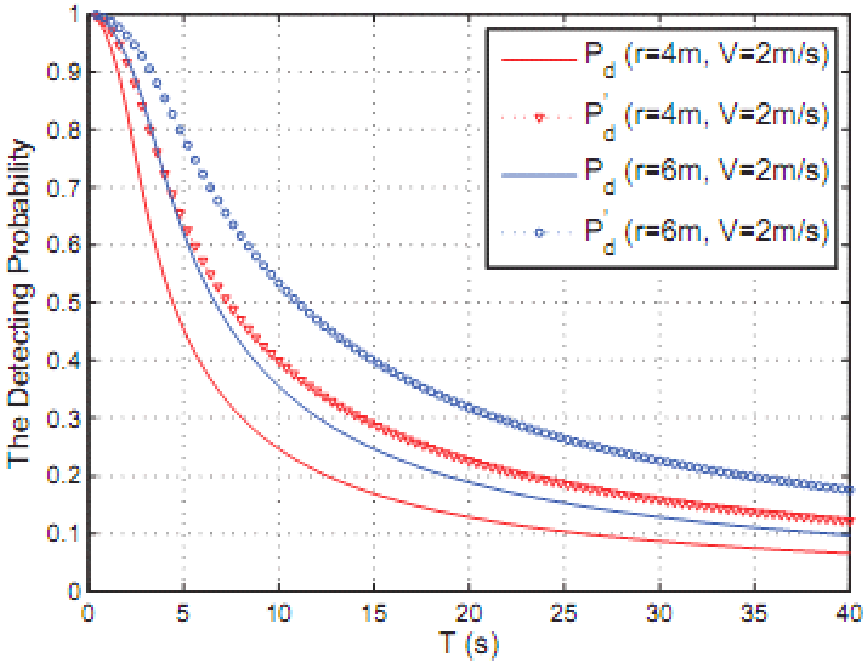
- Substituting Eq. (3) into Eq. (6), we have

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

# Cont'd

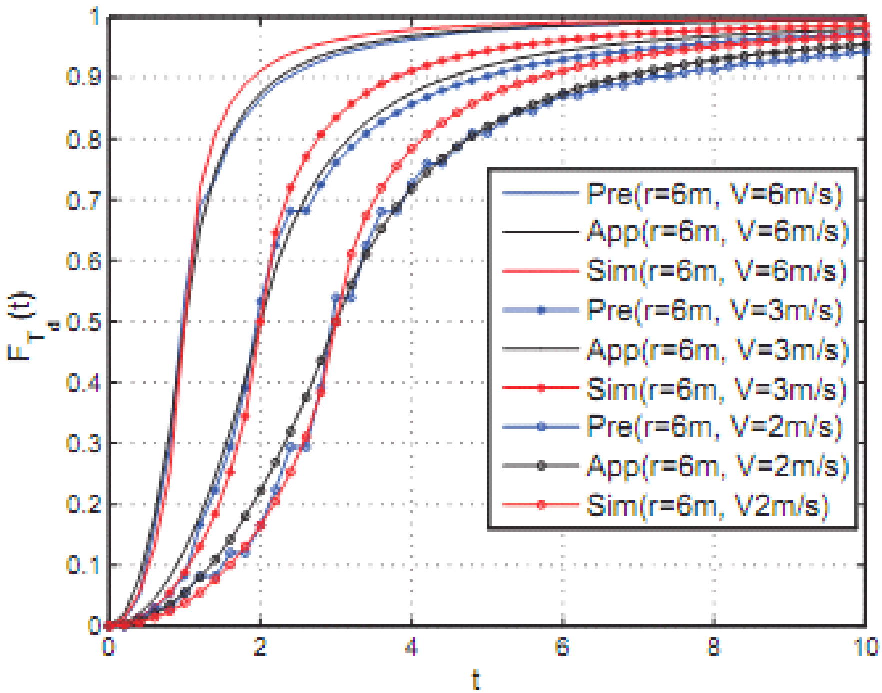
- Comparison between $P_d$ and $P_d'$



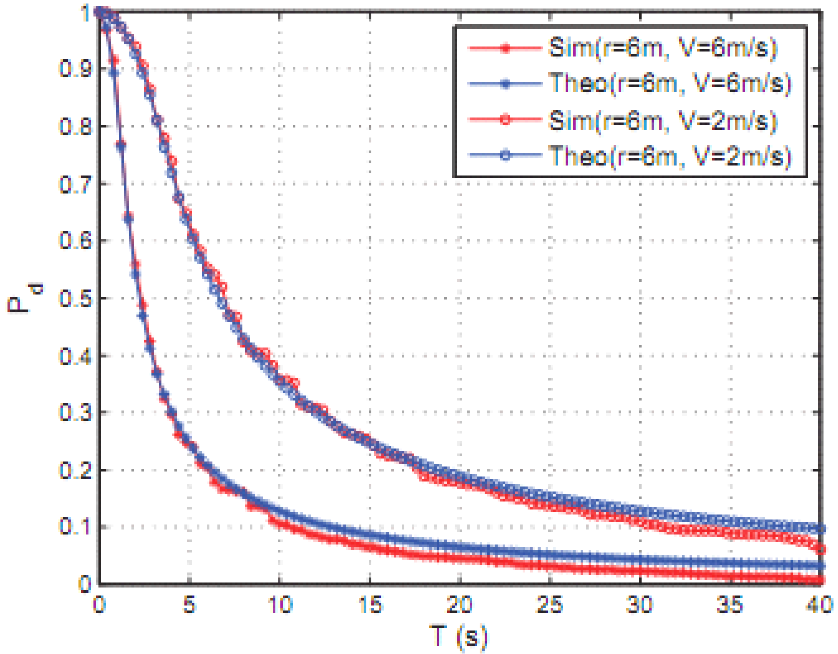
# Model Validation

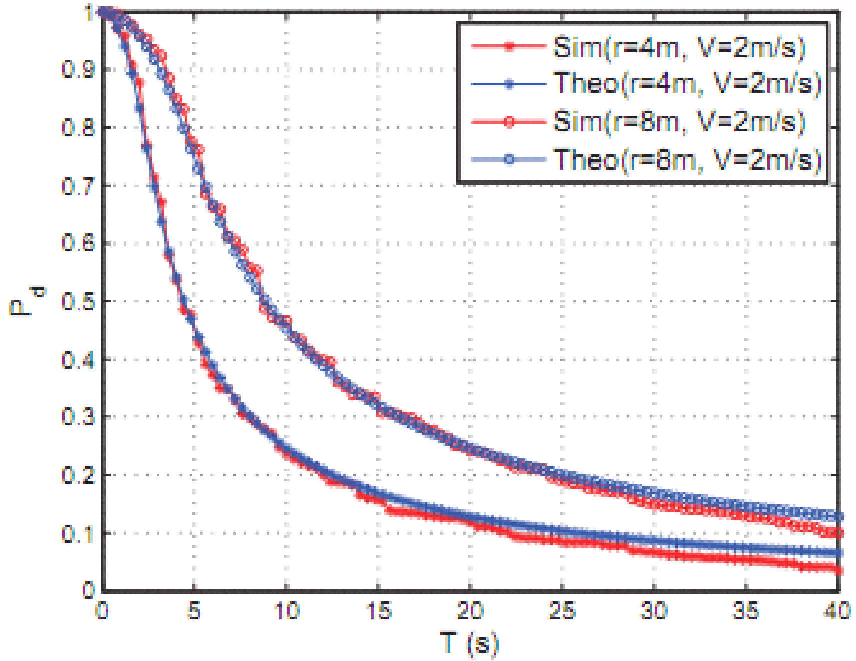
- A network with 20 nodes distributed over 400 x 400 $m^2$
- Nodes moving around according to the RWP model
- Comparison among precise, approximation, and simulation results on the CDF of contact durations, $F_{Td}$ (t)



# 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

- 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 (Sypropoulos, MobiHoc 2006).

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

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

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

浙江大學

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

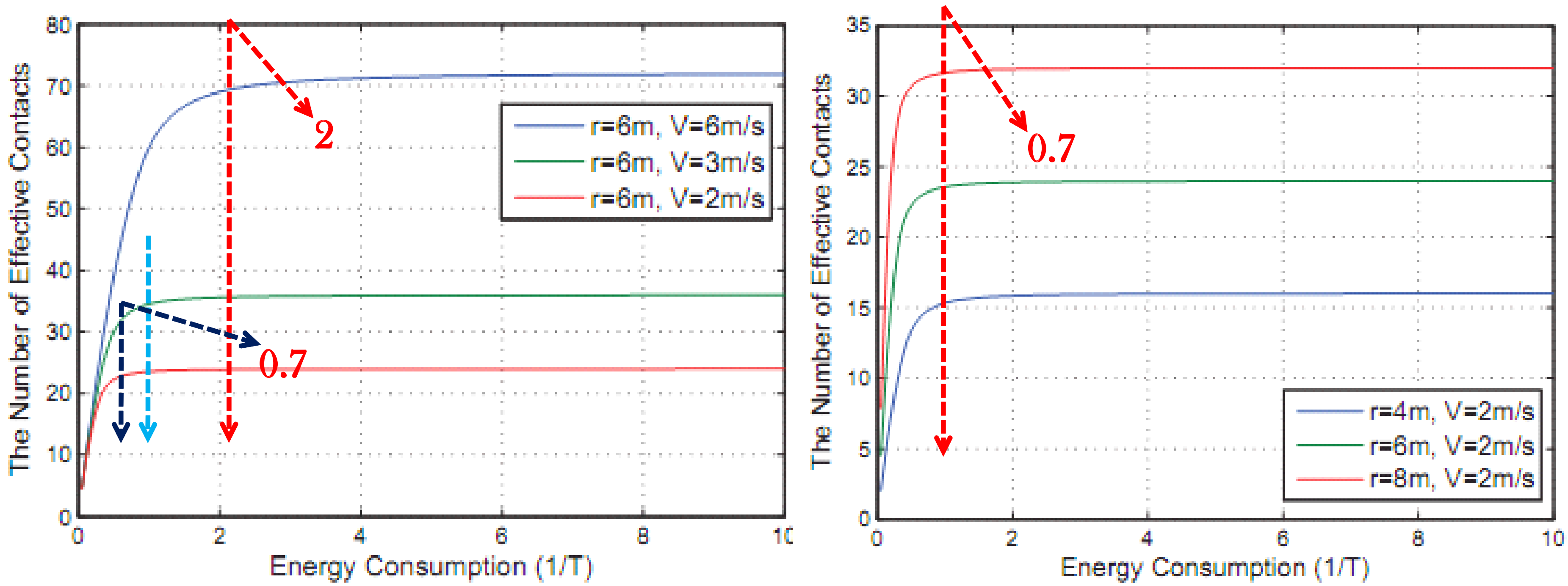
$$N_{eff} = \begin{cases} (1 - \frac{T^2V^2}{6r^2})\frac{2r(N-1)V_{rwp}VL}{S}, & T \leq \frac{r}{V}, \\ (\frac{4r}{3T} - \frac{r^2}{2T^2V})\frac{2r(N-1)V_{rwp}L}{S}, & T > \frac{r}{V}, \end{cases} \quad (10)$$

- 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 the energy consumption $E$ is close to $\infty$, 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.



# Conclusions

- We model the contact process of OppNets 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?