Toward Robust and Reliable Wireless Personal Area Networks

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WiSeR
Wireless System Research Group

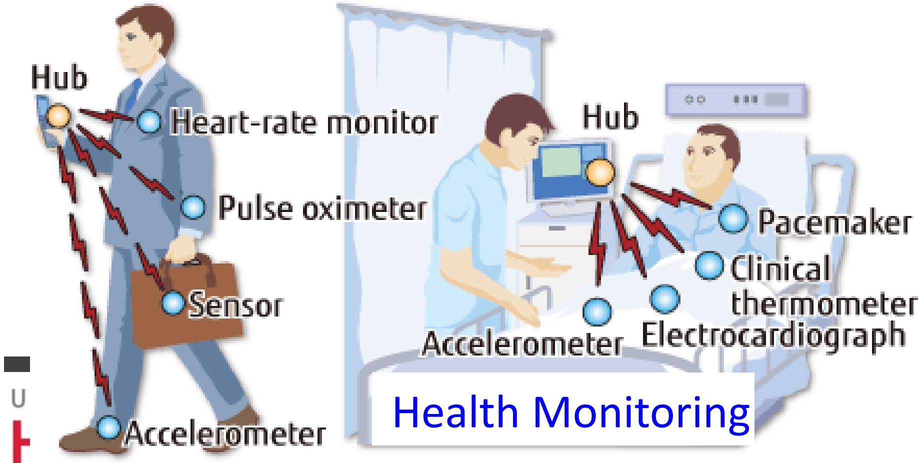
Outline

1. **Background and Motivations**
2. Link Quality Prediction
3. Neighbor Discovery and Contention Graph Inference
    a. A Binary Inference Approach
    b. A Linear Inference Approach
4. Robust Relay Placement and Route Selection
5. Conclusions and Future Work

Wireless Personal Area Network (WPAN)

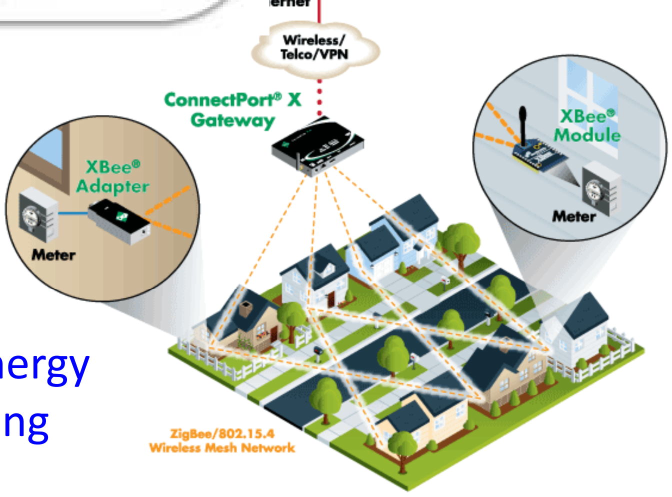
- *WPAN* is a wireless network interconnect wireless devices centered around an individual person.

Bluetooth

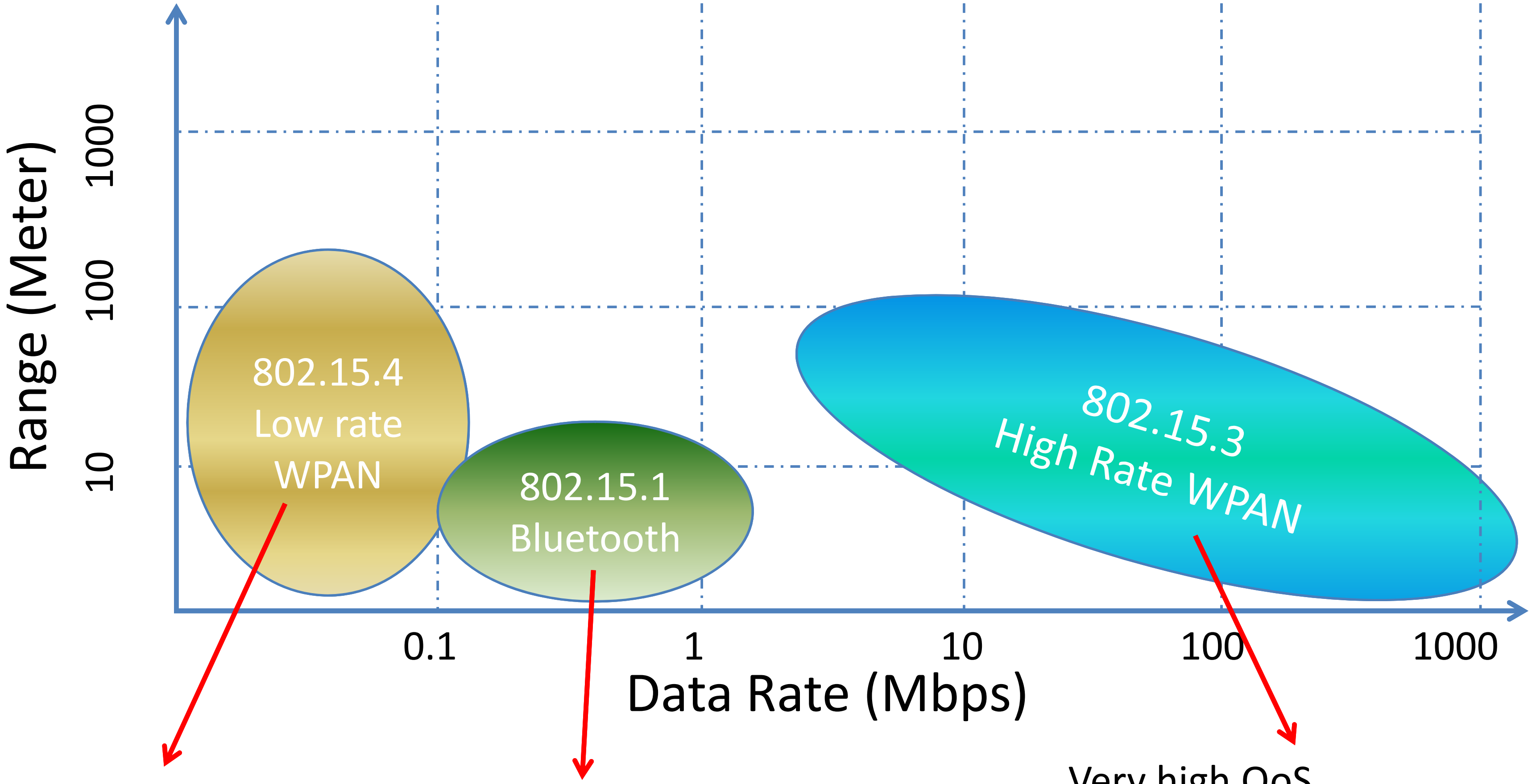


Health Monitoring

- Smart Energy Monitoring



IEEE Standards of WPANs

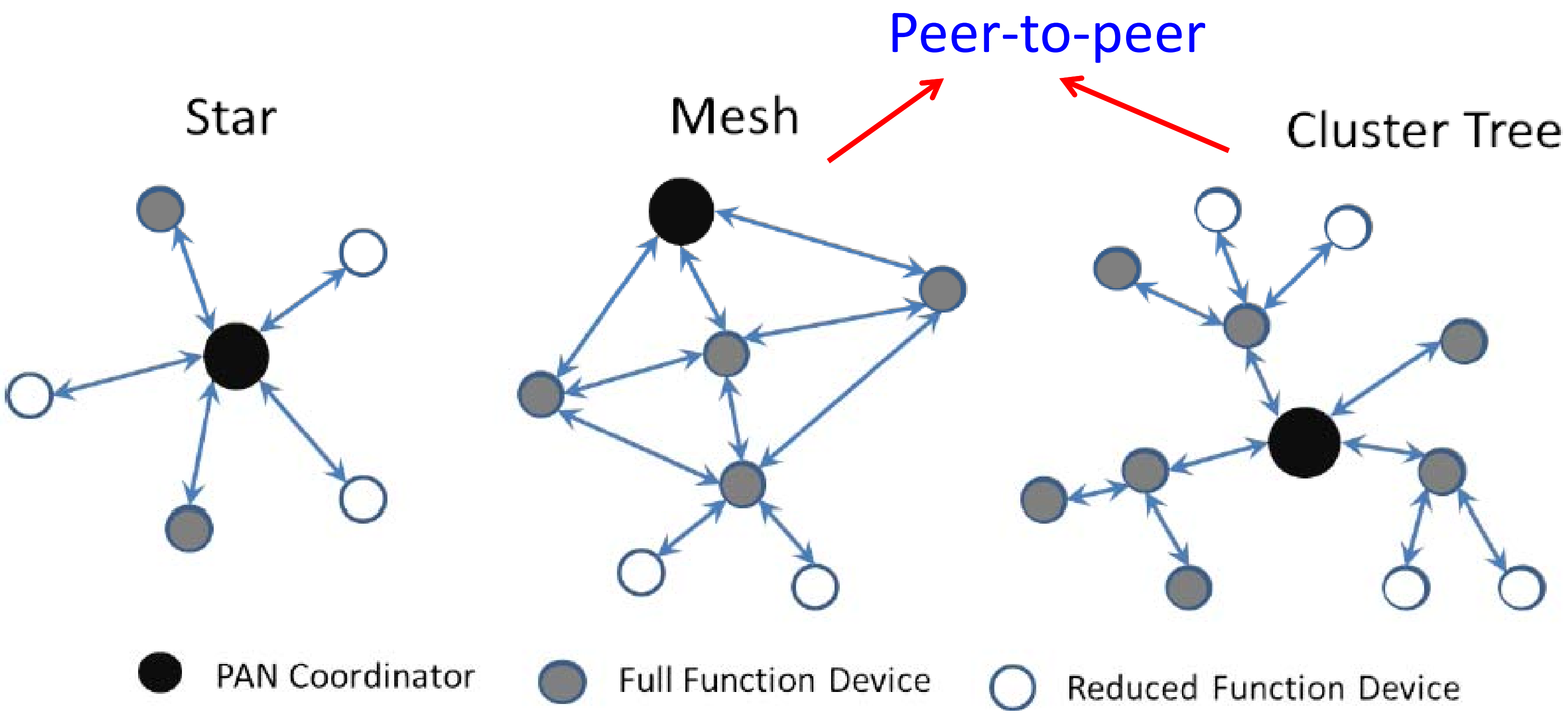


Low QoS

QoS for voice application

Very high QoS
for multimedia streaming

Typical Topologies in WPANs



- Two types: star(coordinated), peer-to-peer(ad-hoc)

Motivations (1)

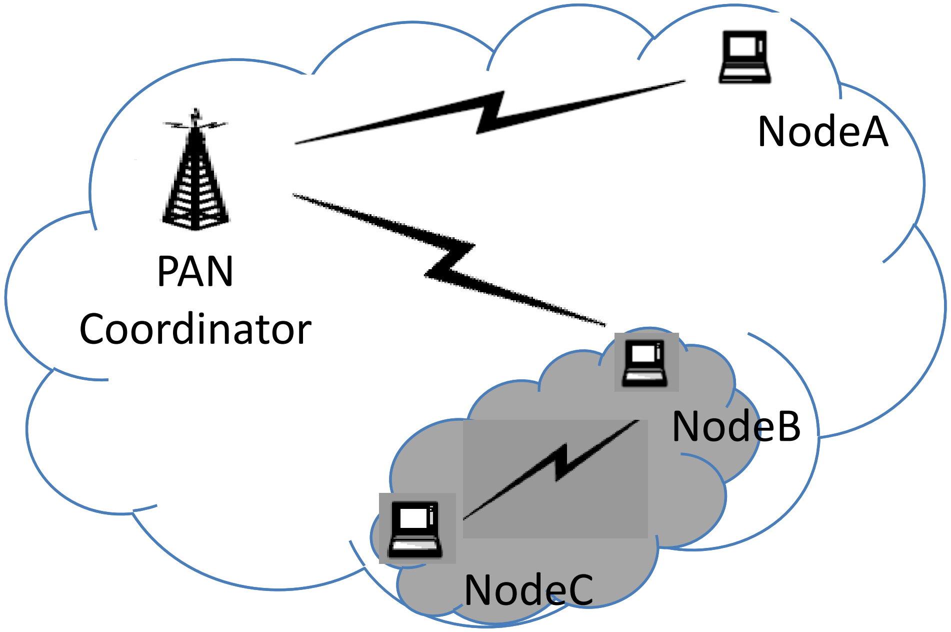
- COTS WPAN devices provides limited PHY information regarding current channel condition.
  - For example, commodity Zigbee only provides:
    - Received signal strength (RSSI)
    - Link quality index (LQI)

Moteiv TelosB Zigbee

- Ask:
  - Are those readings reliable?
  - How to predict the instantaneous link quality? (bit/symbol /packet error rate)

Motivations (2)

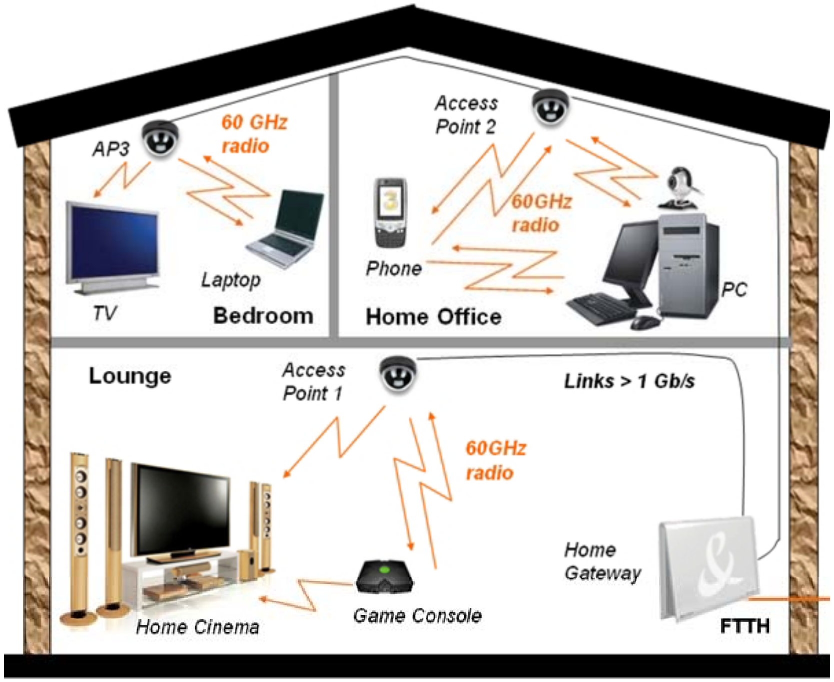
- Coexistence is critical in pervasively deployed WPANs
  - Coexist with other WPANs, and other systems like WiFi.
  - Network topology may change due to node mobility.



→ Need a joint neighbor discovery & contention graph inference approach.

Motivations (3)

- High rate WPANs pose high QoS requirement and are vulnerable to network dynamics and uncertainty.
  - Radio link characteristics
  - Portable devices mobility
  - Moving objects

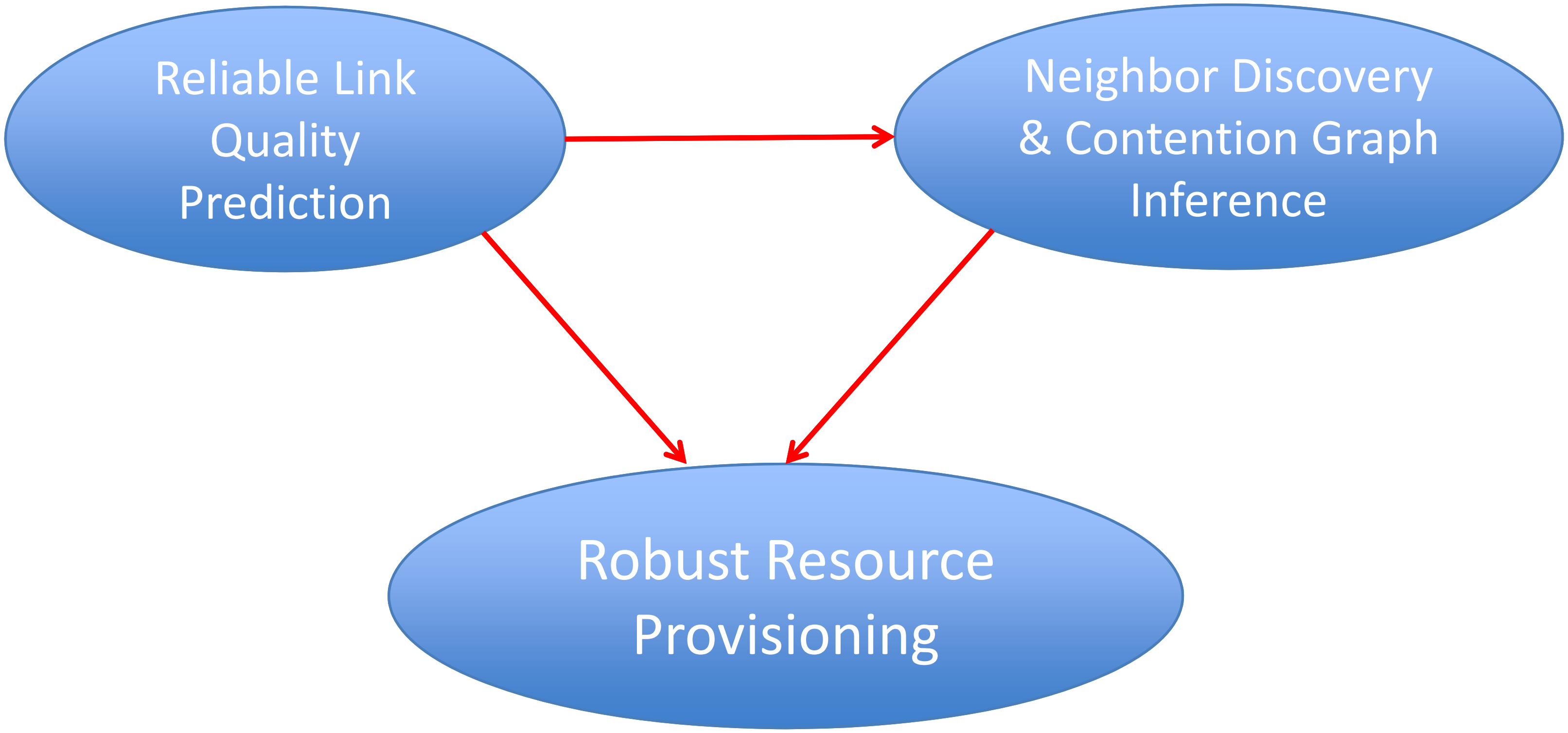


→ Need a *robust* resource provisioning to account for uncertainty.

Main Contributions

- Link quality prediction in 802.15.4 WPANs
  - Decipher RSSI, LQI readings available at commodity Zigbee;
  - Propose a prediction model that predicts the link quality using LQI readings as input.
- Neighbor discovery and contention graph inference in ad-hoc WPANs
  - Propose two solutions to neighbor discovery and contention graph inference, a binary approach and a location based linear approach.
- Relay placement and route selection in 802.15.3c WPANs
  - Propose two robust formulations of relay placement to combat the uncertain link failure.

Structure of This Dissertation



Reliable Link Quality Prediction

Neighbor Discovery & Contention Graph Inference

Robust Resource Provisioning

Our objective is to design reliable and robust WPANs.

Part 1

Link Quality Prediction in 802.15.4 Low Rate WPANs

802.15.4 Compliant Zigbee Sensor

- 802.15.4 Zigbee is a low-rate low-power wireless solution widely used for many applications.
  - 2.4GHz ISM band, bit rate: 250kbps
  - 2MHz bandwidth,
  - Spread Spectrum with 32-chip PN.
  - RF Single Chip: TI CC2420

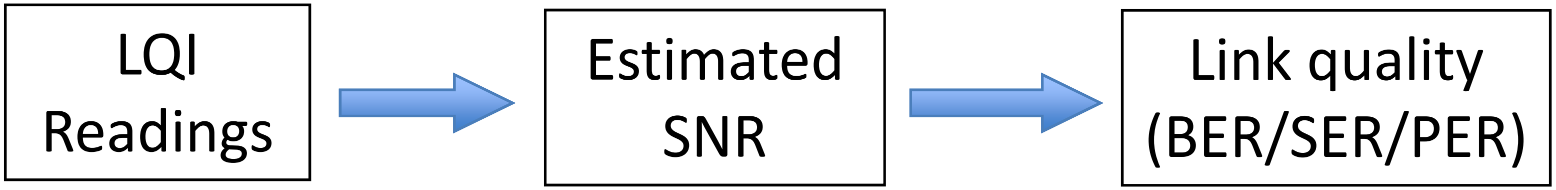
Moteiv TelosB Zigbee

- Provide limited knowledge of physical link
  - Received signal strength indicator (RSSI) readings
  - Link quality index (LQI) readings

Are those readings reliable?

Our Findings

- RSSI is ambiguous and NOT always linear when input power increases.
- LQI truly reflects the SNR at the receiver.
- Formulate SER analytically using SNR under different channel models.
- A link quality prediction model is proposed using LQI.



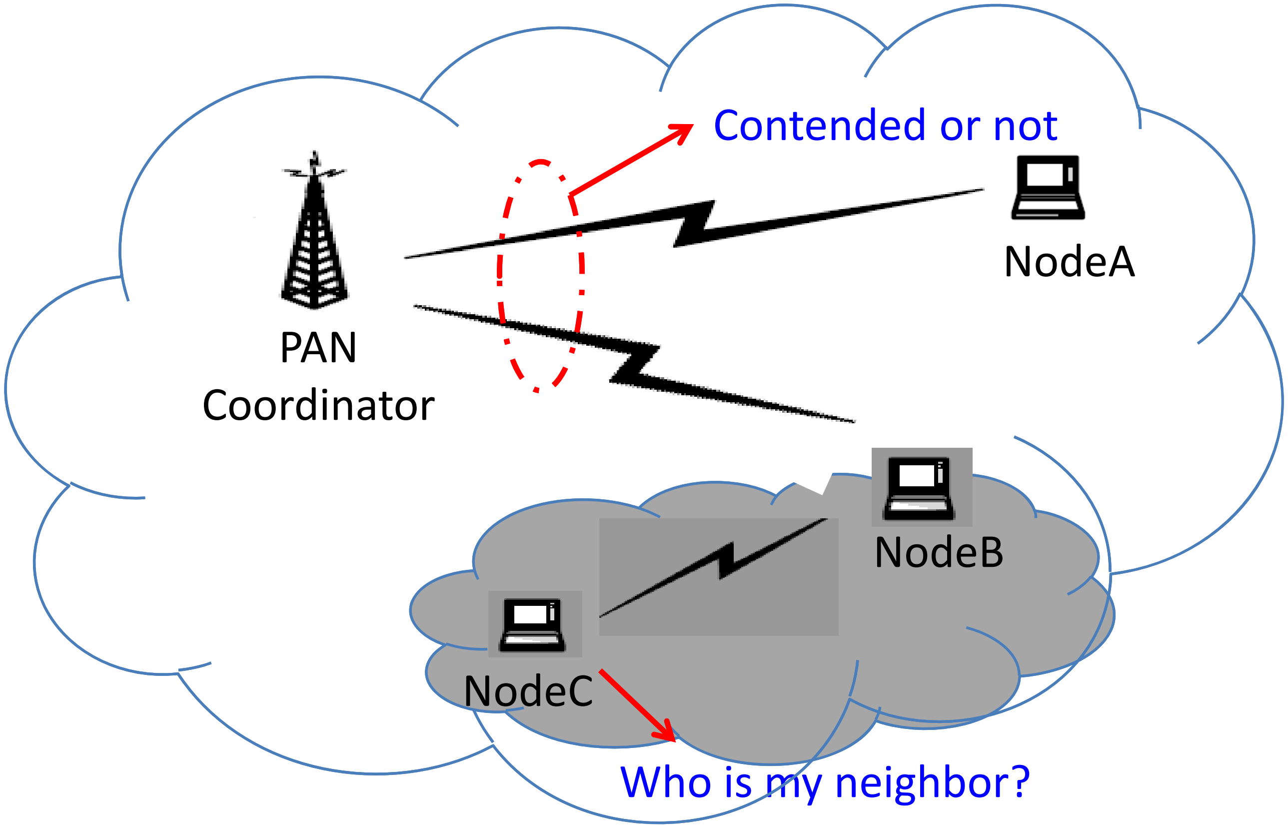
Part 2

Joint Neighbor Discovery and Contention Graph Inference in ad-hoc WPANs

Motivations

- Neighbors are the nodes directly communicable to a given node.
- Neighbor discovery is the procedure of finding and identifying the IDs of all the neighbors.
  - The crucial first step of constructing ad-hoc WPANs.
  - Needed for efficient route selection and topology control.
- Contention graph (or conflict graph)
  - Two concurrent links may end up with failure if they contend with each other.
  - Needed for efficient resource provisioning.

Motivations



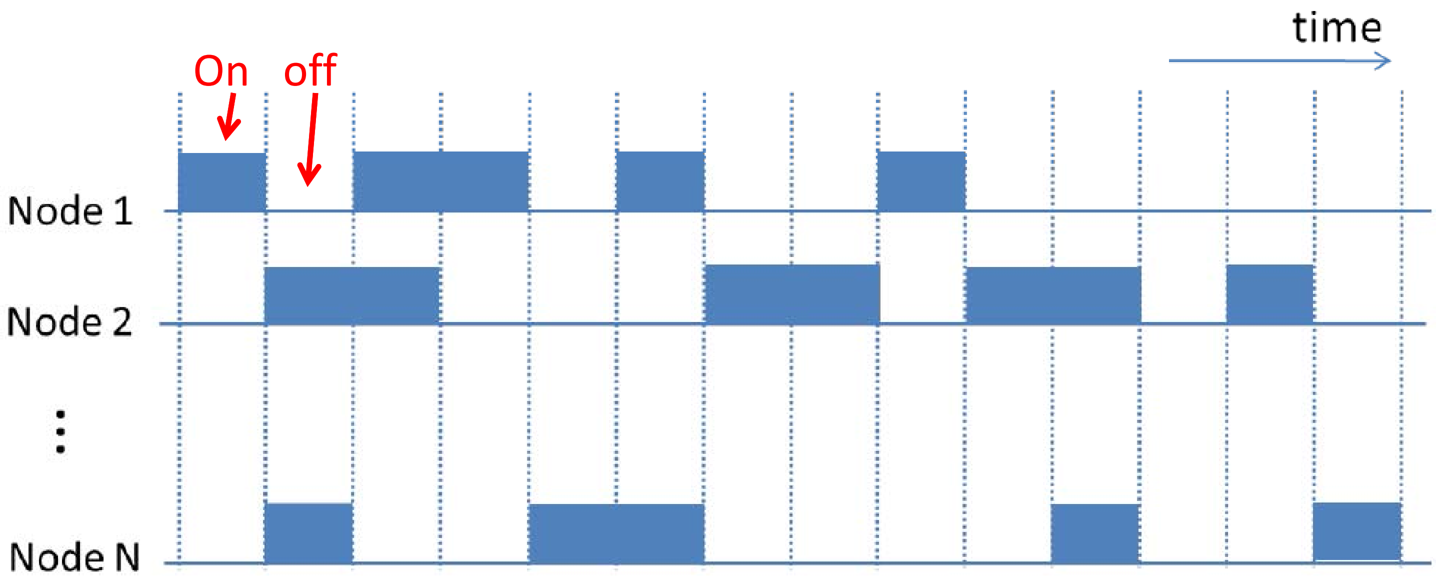
- Especially for dynamic network environment,
  - a fast and accurate inference approach is needed.

Related Work

- Neighbor Discovery
  - [Kesh *et al.*, 04] studied a deterministic approach with centralized scheduling.
  - [Kohvakka *et al.*, 09] studied the randomized scheme in a single packet reception network that discovers when there is only one TX.
  - [Zeng *et al.*, 11] [You *et al.*, 12] extended to multiple packet reception network
  - [Guo *et al.*, 08][Guo *et al.*, 12] explored the group testing algorithm in a multiuser detection based approach.
- Contention Graph Inference
  - [Niculescu *et al.*, 08] studied a per-link active measurement based approach.
  - [Jang *et al.*, 10] proposed a passive interference inference approach.
  - [Zhou *et al.*, 13] built the measurement-calibrated propagation models for determining conflict graph.

Assumptions

- An ad-hoc WPAN with a peer-to-peer topology
- Non-CSMA (Carrier Sense Multiple Access).
- Random on-off signaling with strictly synchronization in a slotted time domain



Key Notations

- $y_n(i)$: the observation of node n at time slot i,

$$y_n(i) = \begin{cases} 1, & \text{signal observed, TX ID decoded} \\ \delta, & \text{signal observed, but undecodable} \\ 0, & \text{no signal observed} \end{cases}$$

Using two SNR thresholds:
Thre1 and Thre2

- $s_n(i)$: the activity of node n at time slot i,

$$s_n(i) = \begin{cases} 1, & \text{transmitter mode} \\ 0, & \text{receiver mode} \end{cases} \Rightarrow \begin{array}{l} T(i) = \{n : s_n(i) = 1, n \in \{1, ..., N\}\} \\ R(i) = \{n : s_n(i) = 0, n \in \{1, ..., N\}\} \end{array}$$

- $x(n, k)$: node relationship if k is a neighbor node of n.

$$x(n, m) = \begin{cases} 1, & m \text{ is a neighbor of } n \text{ in the decodable range} \\ \delta, & m \text{ is a neighbor of } n \text{ in the undecodable range} \\ 0, & m \text{ is not a neighbor of } n \end{cases}$$

- $c(n, m; n, k)$: link contention if m->n is contended by k->n

$$c(n, m; n, k) = \begin{cases} 1, & \text{link } m \to n \text{ is contended by link } k \to n \\ 0, & \text{link } m \to n \text{ is not contended by link } k \to n \end{cases}$$

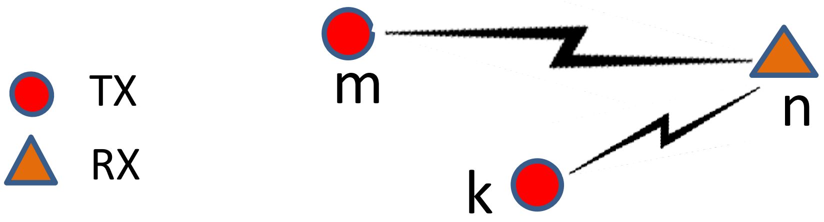
Proposed Binary Inference Approach

- Exploit binary mixture to infer the knowledge of neighbors and contention graph.
- Procedure:
  - First, obtain neighbor relationship using observations and node activity.
  - Then, infer contention graph using observation, node activity and neighbor relationship.
- Two types of error performance:
  - Observation Error
  - Inference Error

(using linear mixture as ground truth)

Analysis of Observation

- Consider an example where *n* is RX, *m, k* are TX
  - both *m* and *k* are neighbors of *n* → x(n, m)=1, x(n, k)=1
  - *k->n* contends with *m->n*, → c(n, m; n, k)=1
  - *m->n* does NOT contend with *k->n*, → c(n, k; n, m)=0



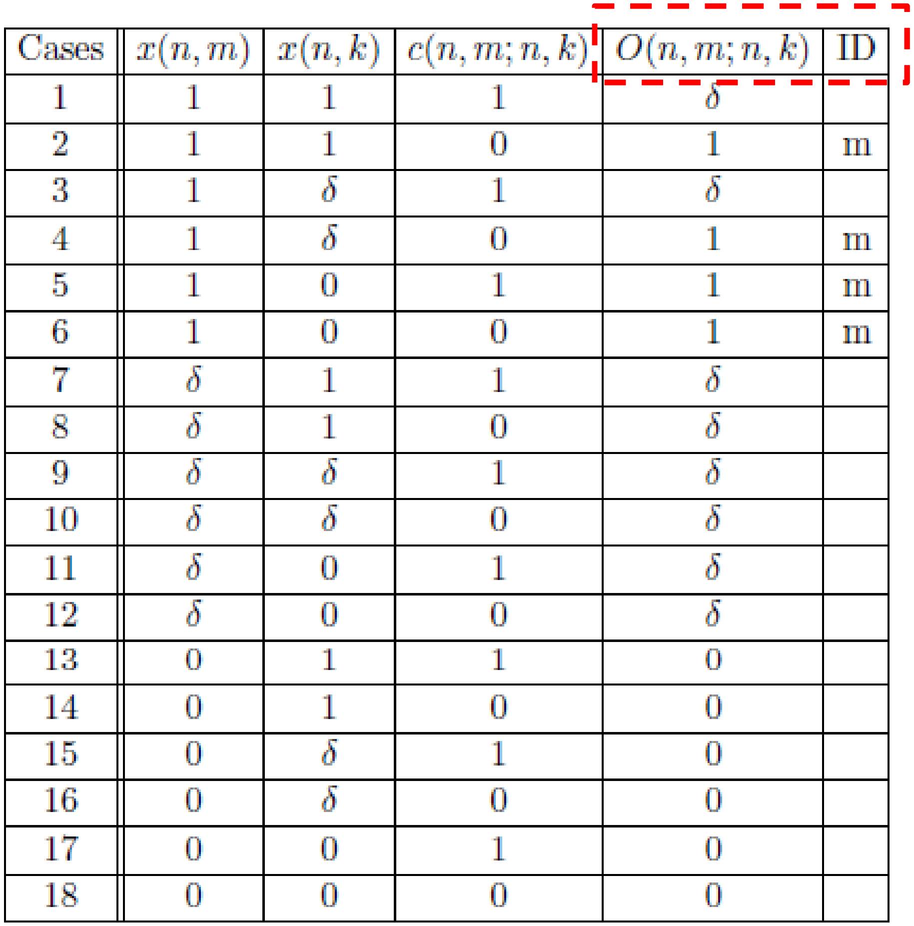
⇒ O(n, m; n, k) = δ, O(n, k; n, m) = 1,

where O(n, m; n, k) is the outcome of *m*→*n* affected by *k*→*n*.

⇒ $y_n(i) = 1$ RX *n* can decode the signal with ID (TX *k*).

Analysis of Observation(Cont'd)

- For a special case (|T(i)|=2), *n* is RX, *m, k* are TX



Cases	$x(n,m)$	$x(n,k)$	$c(n,m;n,k)$	$O(n,m;n,k)$	ID
1	1	1	1	δ	
2	1	1	0	1	m
3	1	δ	1	δ	
4	1	δ	0	1	m
5	1	0	1	1	m
6	1	0	0	1	m
7	δ	1	1	δ	
8	δ	1	0	δ	
9	δ	δ	1	δ	
10	δ	δ	0	δ	
11	δ	0	1	δ	
12	δ	0	0	δ	
13	0	1	1	0	
14	0	1	0	0	
15	0	δ	1	0	
16	0	δ	0	0	
17	0	0	1	0	
18	0	0	0	0	

$$O(n,m;n,k) = f\left(x(n,m), x(n,k), c(n,m;n,k)\right)$$

Then,

$$y_n(i) = O(n,m;n,k) \bigcup O(n,k;n,m)$$

Logical-OR

- For |T(i)|≥3:

$$y_n(i) = \bigcup_{m \in T(i)} \left(\bigcap_{k \in T(i), k \neq m} O(n,m;n,k) \right)$$

$$n \in R(i)$$

Logical-OR

Logical-AND

Analysis of Inference

- Consider some examples where *n* is RX, *m, k* are TX

$x(n, m)=1$

m

n

k

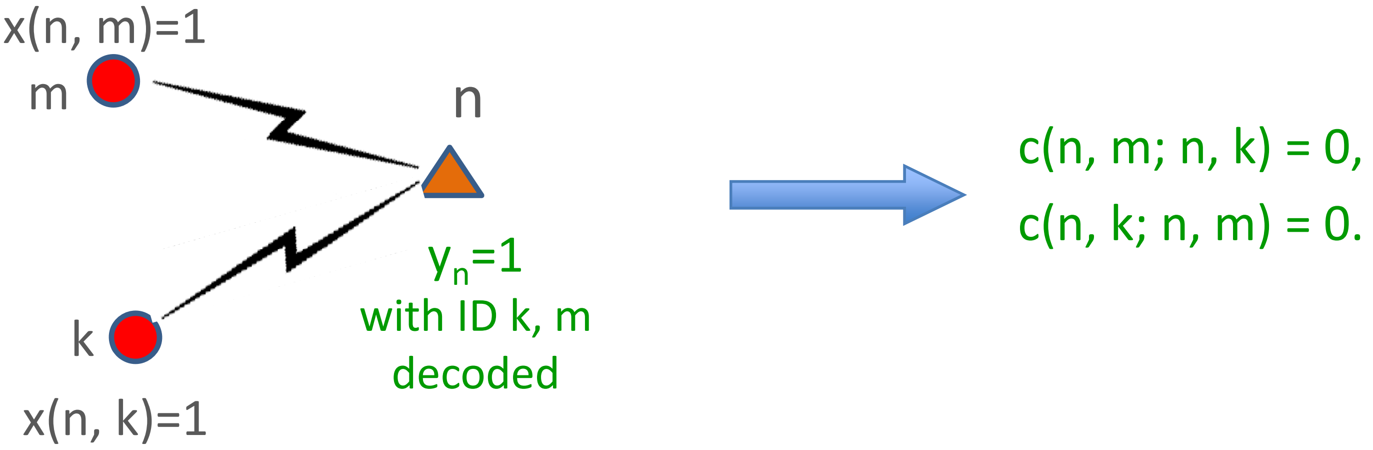
$x(n, k)=1$

$y_n=\delta$

Signal observed but undecodable

$c(n, m; n, k) = 1,$

$c(n, k; n, m) = 1.$



$x(n, m)=1$

m

n

k

$x(n, k)=1$

$y_n=1$

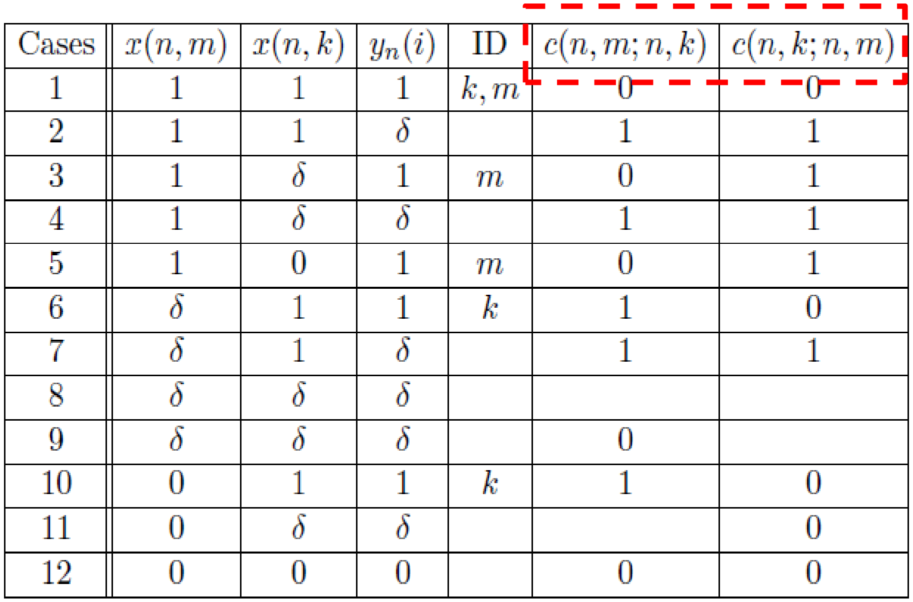
with ID k, m decoded

$c(n, m; n, k) = 0,$

$c(n, k; n, m) = 0.$

Analysis of Inference (Cont'd)

- For a special case (|T(i)|=2), *n* is RX, *m, k* are TX,



Cases	$x(n,m)$	$x(n,k)$	$y_n(i)$	ID	$c(n,m;n,k)$	$c(n,k;n,m)$
1	1	1	1	k,m	0	0
2	1	1	δ		1	1
3	1	δ	1	m	0	1
4	1	δ	δ		1	1
5	1	0	1	m	0	1
6	δ	1	1	k	1	0
7	δ	1	δ		1	1
8	δ	δ	δ			
9	δ	δ	δ		0	
10	0	1	1	k	1	0
11	0	δ	δ			0
12	0	0	0		0	0

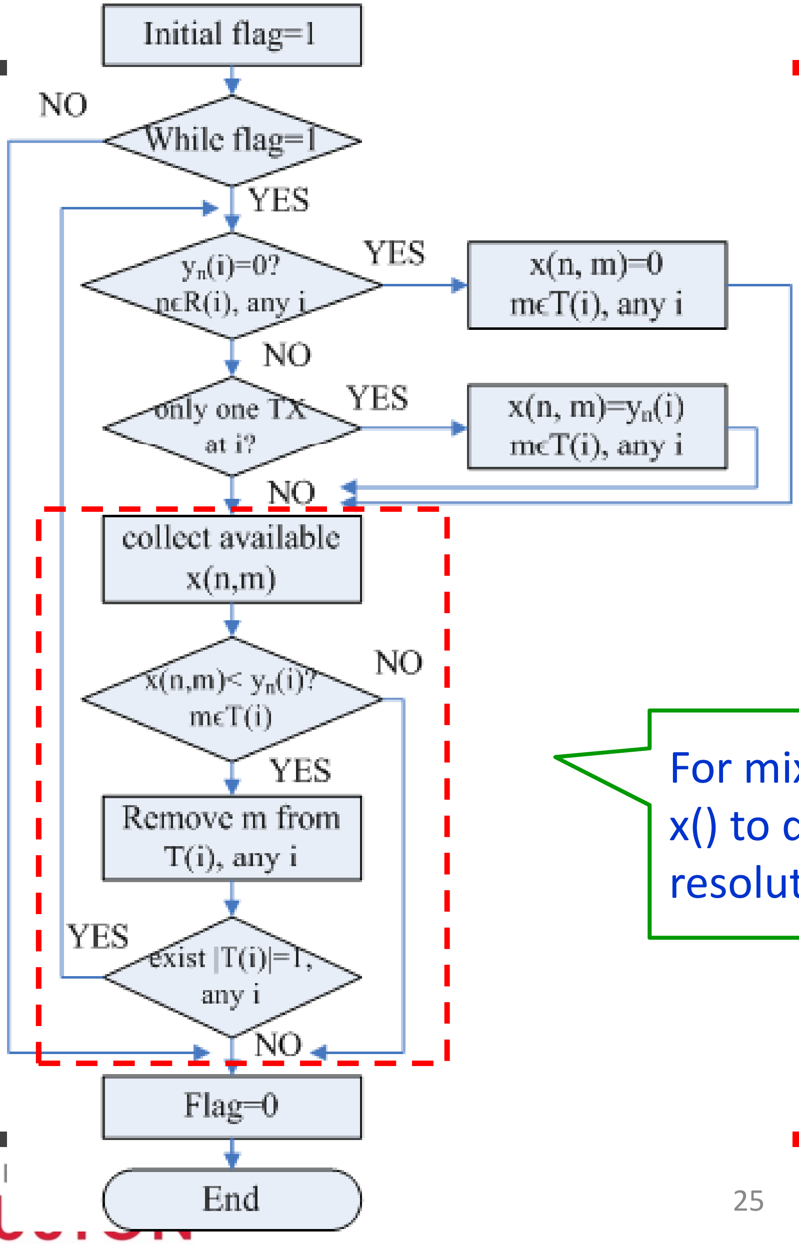
$$c(n,m;n,k) = a_{nm} g_{nk} \left(x(n,m) \oplus y_n(i) \right) + \left(1 - a_{nm}\right) d_{nm} g_{nk}$$

$$a_{nm} = \begin{cases} 1, & x(n,m) = 1 \\ 0, & \text{otherwise} \end{cases}$$

$$d_{nm} = \begin{cases} 1, & x(n,m) = \delta \\ 0, & \text{otherwise} \end{cases} \quad \text{and } g_{nm} = a_{nm} d_{nm}.$$

- For |T(i)|≥3, the observation y() is the result of a mixture, which is very difficult for inference directly.
  - → The mixture decoupling scheme is proposed in the algorithm.

Simple Neighbor Discovery Algorithm

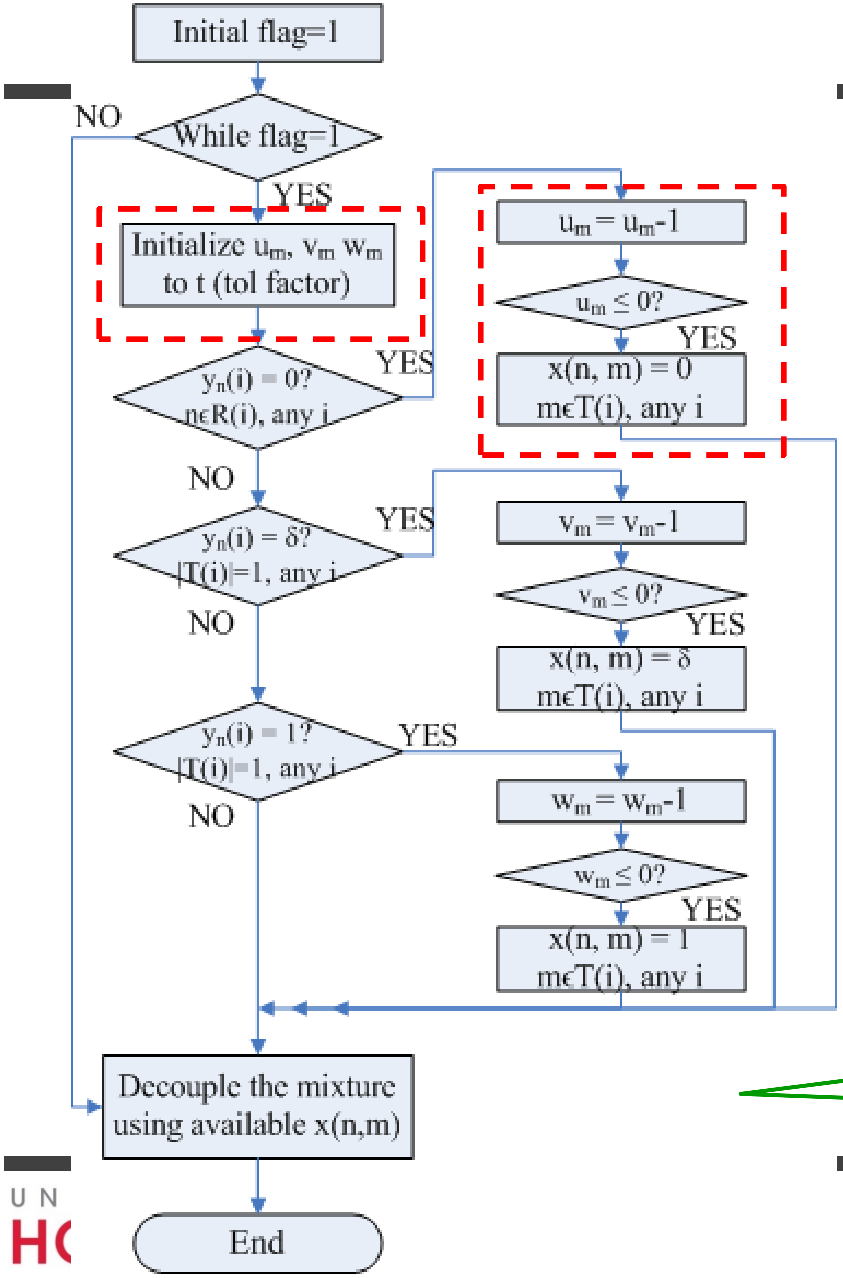


T(i): the transmit nodes set at time t
R(i): the receiver nodes set at time t
$y_n(i)$: the observation of n at time t
x(n, m): neighbor relationship

*Our proposed algorithm is an improved group testing

For mixture |T(i)|>=2, we use available x() to decouple the mixture and find any resolution.

t-tolerance Neighbor Discovery Algorithm

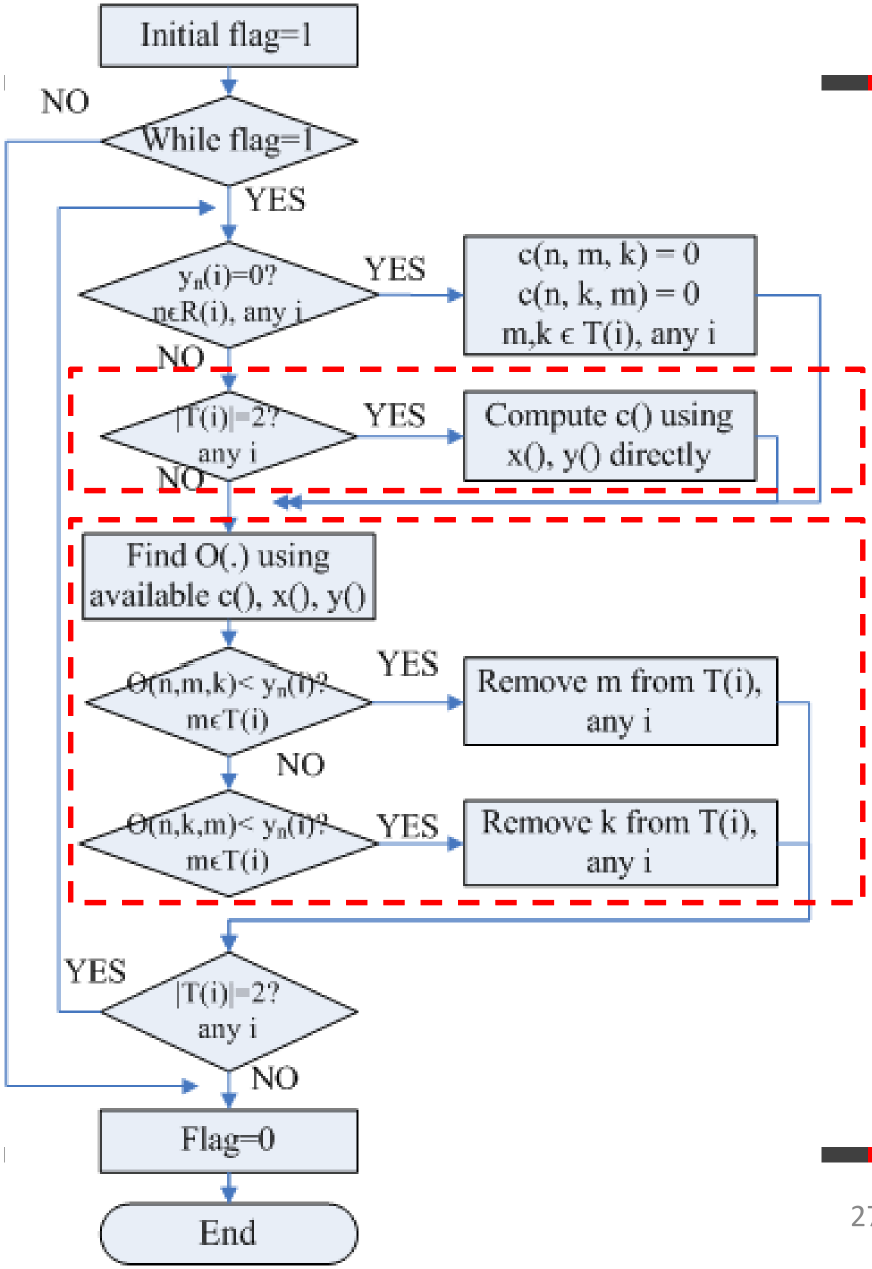


T(i): the transmit nodes set at time t
R(i): the receiver nodes set at time t
$y_n(i)$: the observation of n at time t
x(n, m): the neighbor relationship

We add tolerance factor *t* to add the confidence when making the decision of neighbor discovery.

For mixture |T(i)|>=2, we use the same decoupling scheme.

The Contention Graph Inference Algorithm



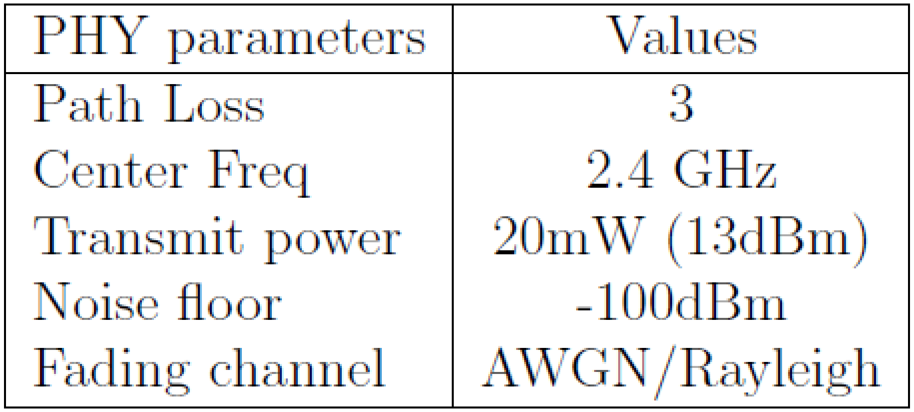
T(i): the transmit nodes set at time t
R(i): the receiver nodes set at time t
$y_n(i)$: the observation of n at time t
x(n, m): the neighbor relationship
c(n,m,n,k): link contention if k->n contends with m->n

For mixture |T(i)|=2 (the special case), we can compute contention graph directly.

For mixture |T(i)|>=3, we use available x(), c() and y() to find O(.), which can be used to decouple the mixture and find any resolution.

Simulation Setup

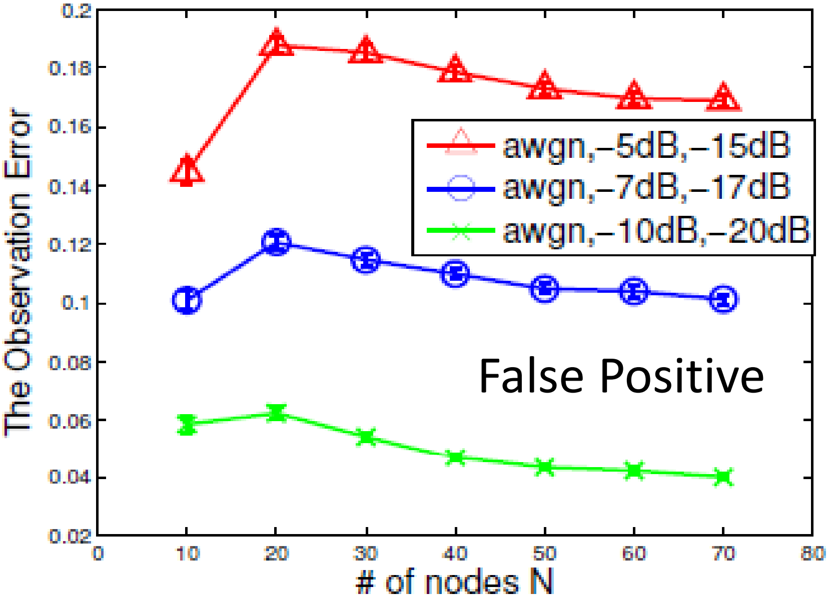
- N nodes are uniformly deployed in a 100X100 room
- Randomly select the sensor activity (TX or RX)
  - Bernoulli distribution with transmitting probability 0.2.
- PHY related parameters:

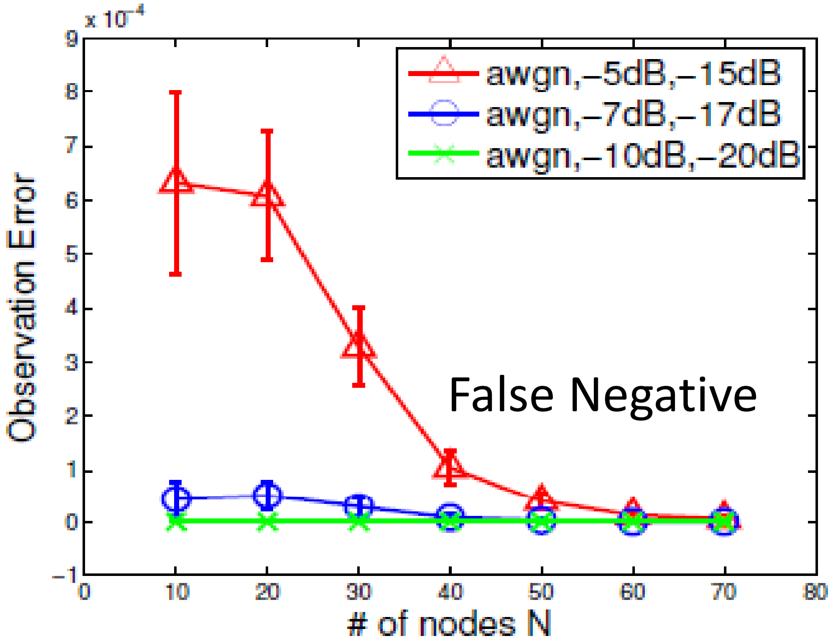


PHY parameters	Values
Path Loss	3
Center Freq	2.4 GHz
Transmit power	20mW (13dBm)
Noise floor	-100dBm
Fading channel	AWGN/Rayleigh

Observation Error Rate vs. # of nodes

95% confidence interval



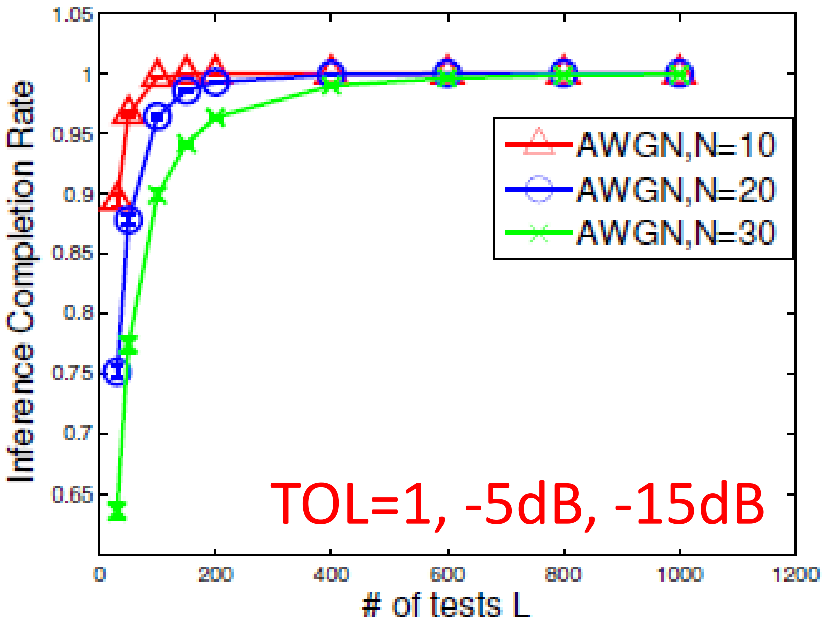


False positive errors dominate.

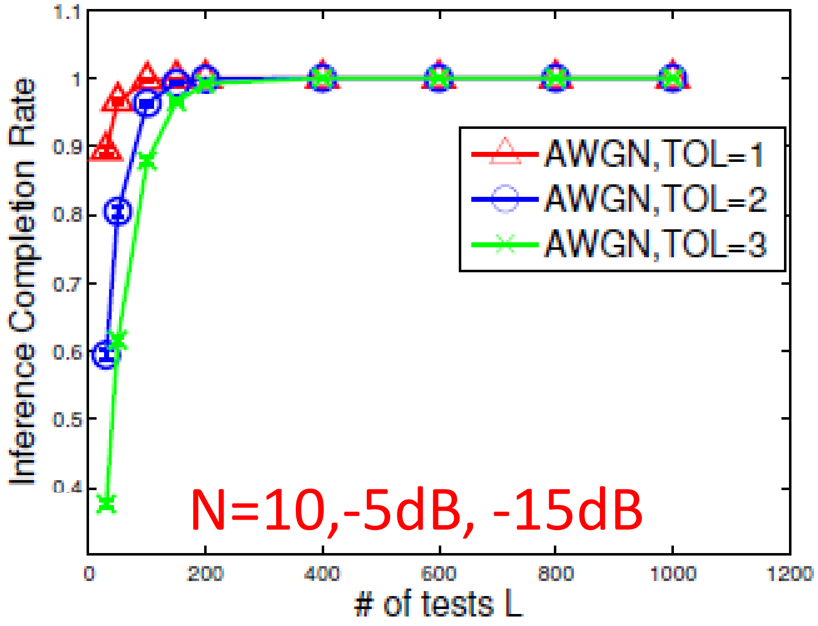
Larger network density, lower observation errors.

Smaller threshold pairs, lower observation errors.

Completion Rate vs. # of Tests



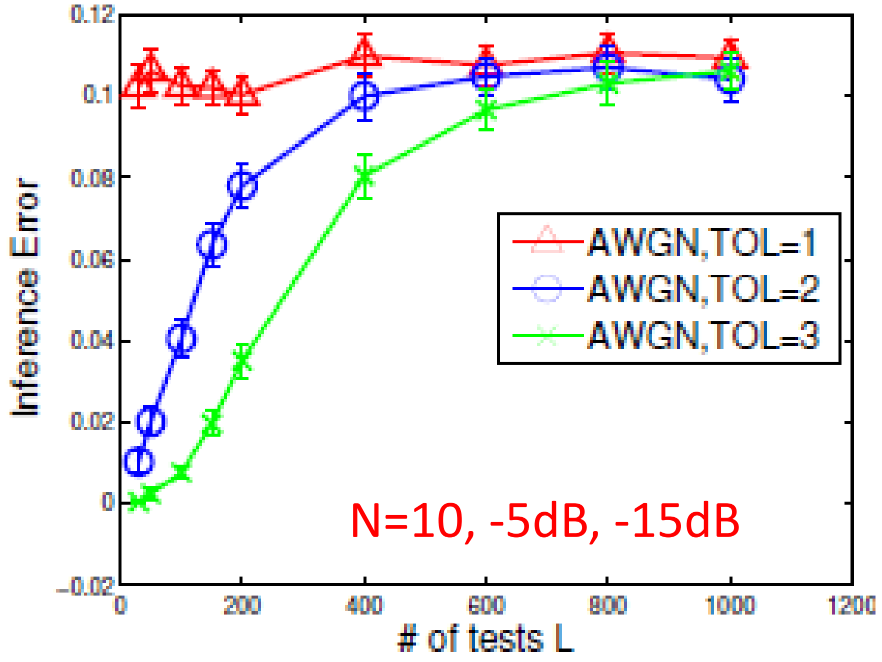
TOL=1, -5dB, -15dB

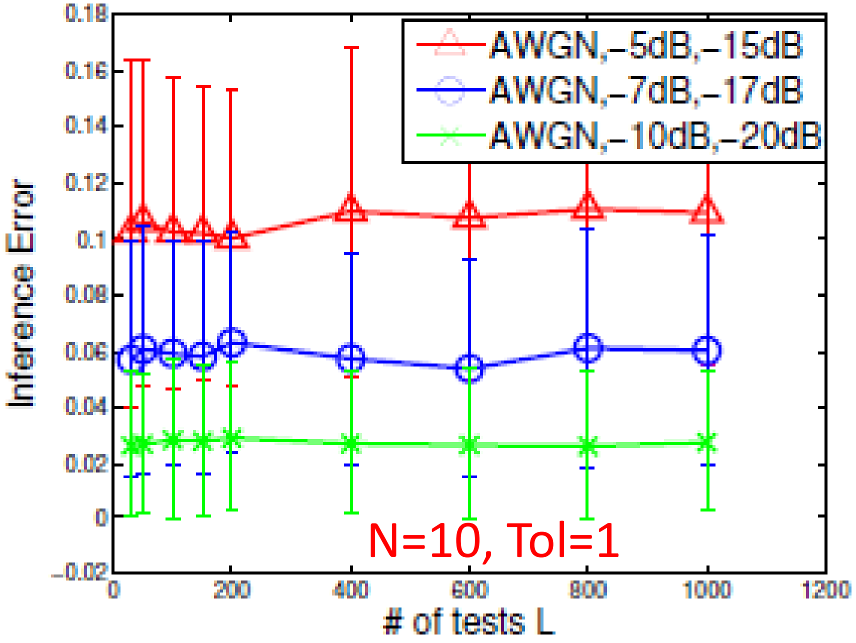


N=10,-5dB, -15dB

Larger network density, slower completion rate.
More tolerance employed, slower completion rate.

Inference Error Rate vs. # of Tests





More tolerance employed, lower inference error.
Smaller threshold pairs, lower inference error.

The Location Based Linear Approach

- Consider a network with *K* target nodes (half duplex) at unknown locations in an isotropic area (divided into a discrete grid with *N* grid points)

- The Objective:
  - Find the relative locations between any two nodes simultaneously, by exploiting the linear RSS mixture from concurrent transmitting nodes.
  - Compute pairwise RSS using relative locations
  - Infer neighbor relationship *x(.)* using $SNR_{nm} = RSS_{nm}/NF$
  - Infer contention graph *c(.)* using $SINR_{nmk}$ as $RSS_{nm}/\left(RSS_{nk} + NF\right)$;

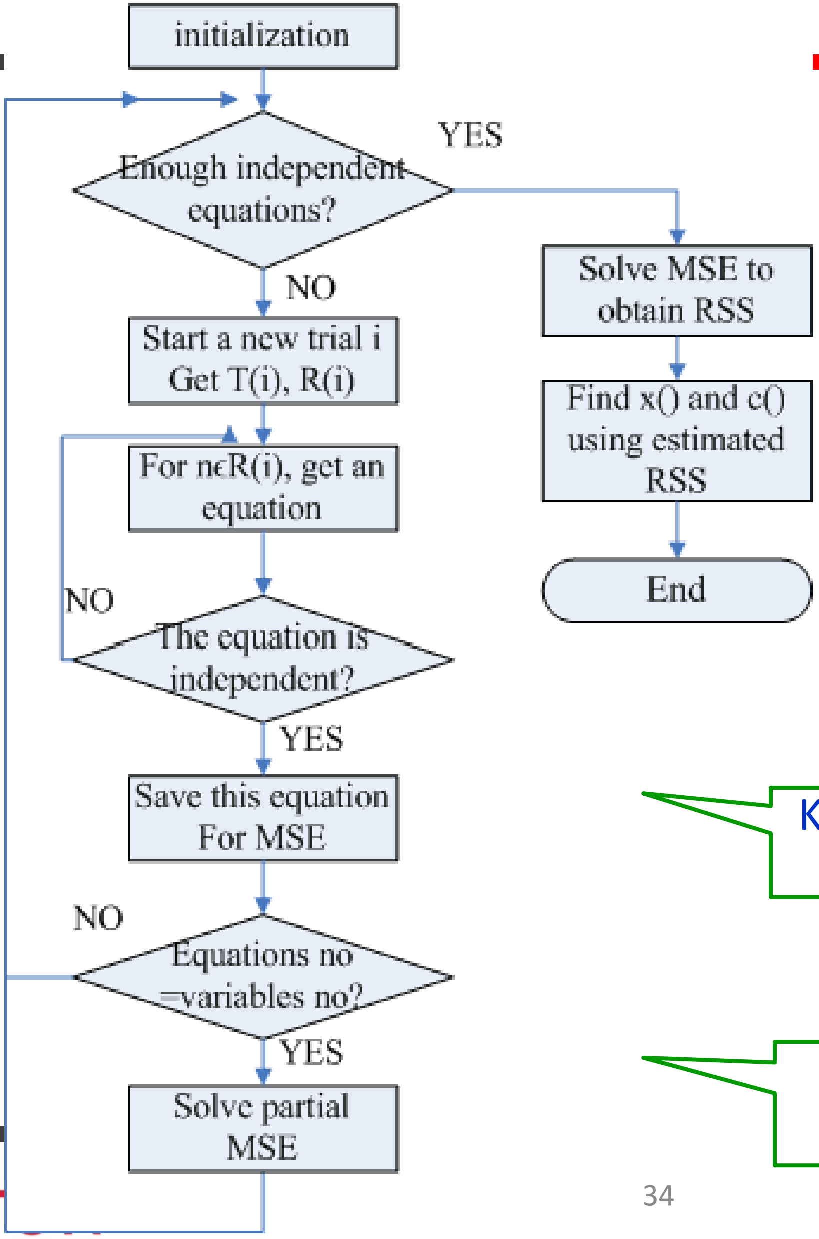
Mathematical Model

- Denote U as the pairwise RSS matrix between any two target nodes, u_{ij}=RSS(d_{ij}).
- The observation can be rewritten as:

$$Y_{K\times 1} = (\underbrace{I - S_{K\times K}}_{\text{RX activity matrix}})U_{K\times K}\underbrace{S_{K\times K}}_{\text{TX activity matrix}}1_{K\times 1} + \underset{\searrow\ \text{noise}}{\varepsilon}$$

➡ Given Y() and S() over enough # of trials,
we can solve U (K^2 variables) by using minimum square error (MSE) estimator.

Location based Incremental Inference Algorithm

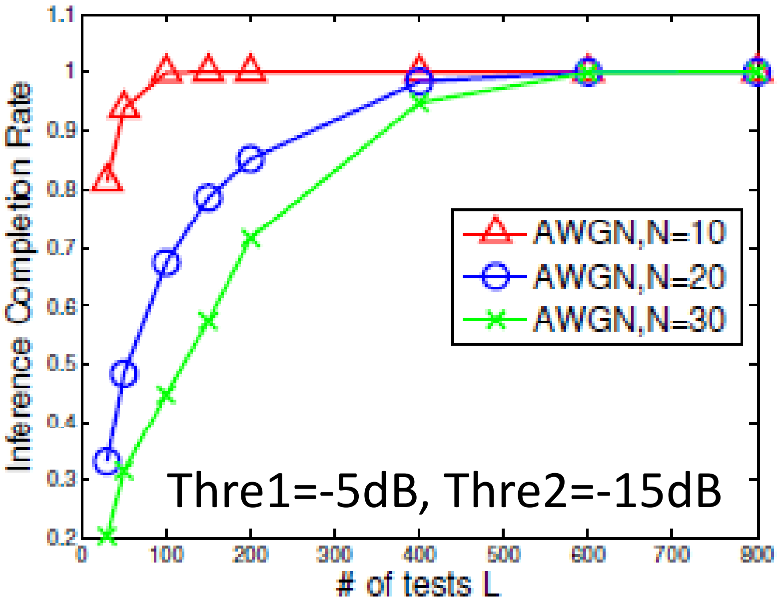


T(i): the TX nodes set at time t
R(i): the RX nodes set at time t
x(n, m): neighbor relationship
c(n,m; n,k): link contention

Keep independently linear equations.

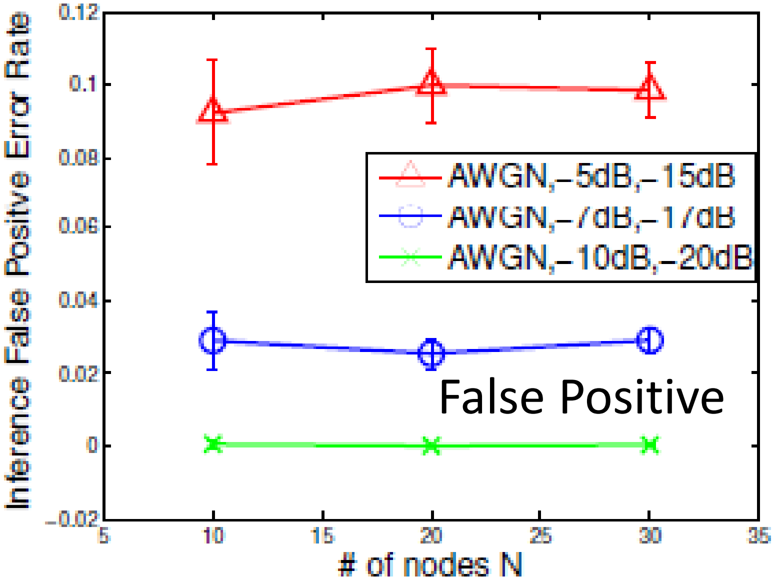
Solve the MSE incrementally

Performance of Linear Inference Approach

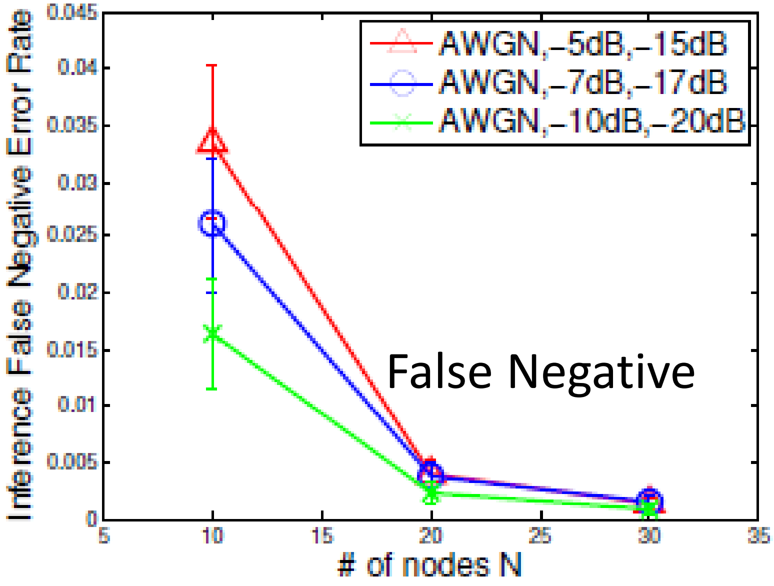


Thre1=-5dB, Thre2=-15dB

Completion Rate does NOT depend on thresholds.



False Positive



False Negative

Discussion

- The binary approach has the advantage of small computation complexity, which can achieve the inference completion faster.
- The linear approach outperforms the binary one with lower inference error rate but longer completion time.
- As a future work, we are interested in reducing the number of tests in current linear approach.

Part 3

Robust Relay Placement and Route Selection in 802.15.3c WPANs

60GHz Radio & 802.15.3c

- Plentiful free spectrum resource (7GHz, unlicensed)
- Much faster transmit speed (Gigabit)
- 802.15.3c targets at short-range, super-high data rate wireless networking, includes:
  - HD streamed multimedia
  - Wireless Gigabit Ethernet
  - Data center and …

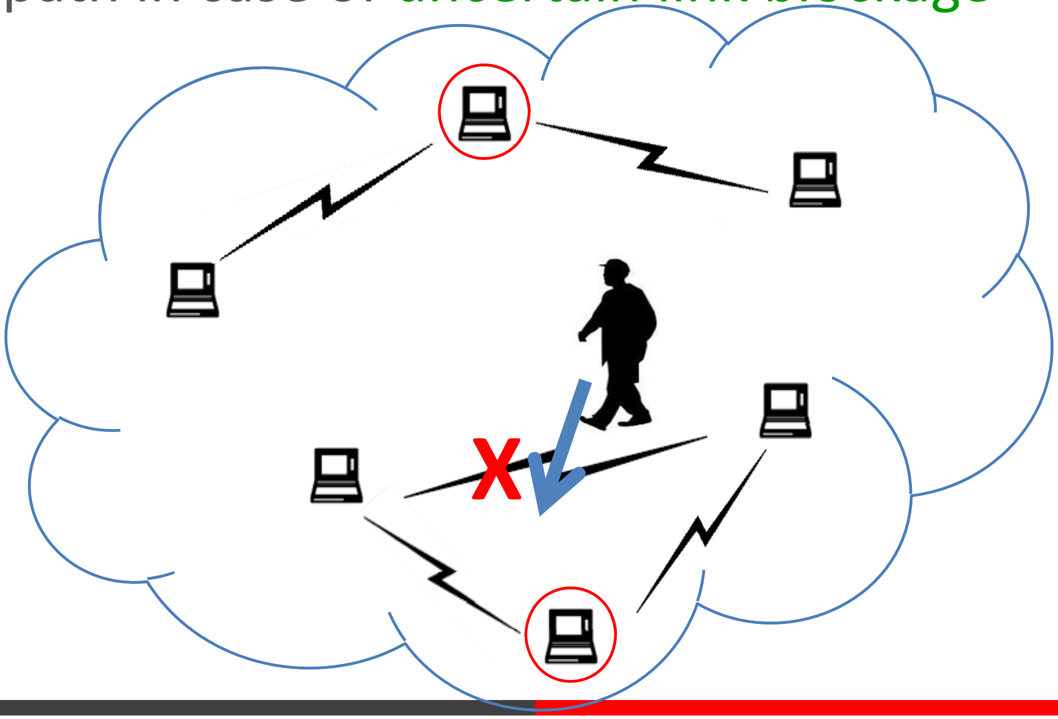
60GHz Characteristics

- Large Propagation loss
  - 22dB larger than free space on 5GHz;
- Large Penetration loss
  - by extremely small wavelength
  - Human body: 15dB~25dB
- Need directional PHY/MAC and beam-forming
  - To combat attenuation;
  - Interference-limit environment.

looks like wired links

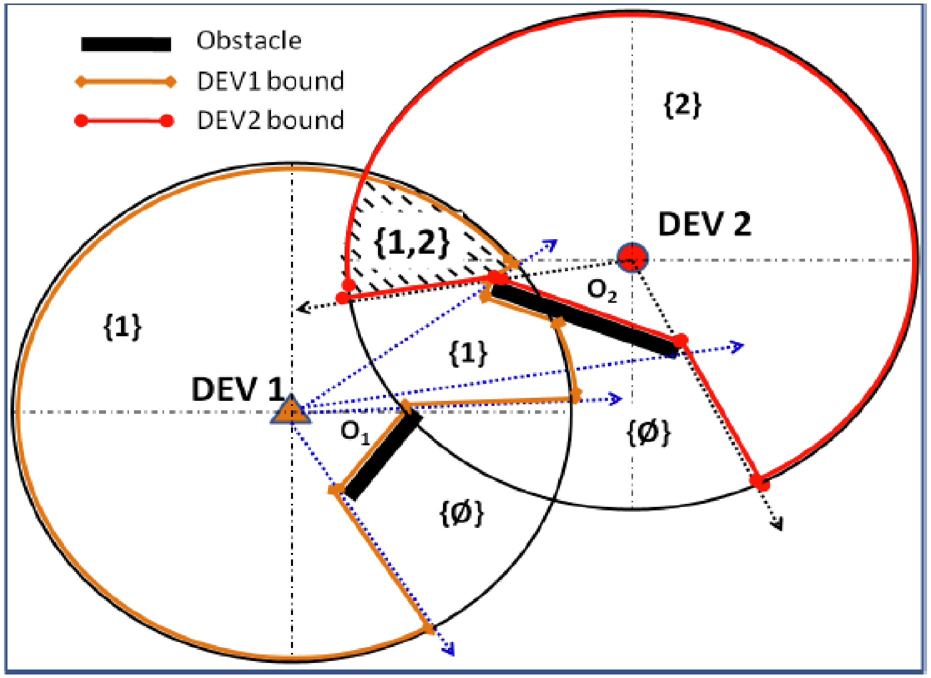
Why Relay Placement?

- For non-line-of-sight (NLOS) link, relays manage to forward traffic from TX to RX that does not have direct connectivity.
- For line-of-sight (LOS) link, relays provide a secondary (backup) path in case of uncertain link blockage



Geometric Model of Link Connectivity

- (Overlapped) Visibility Region



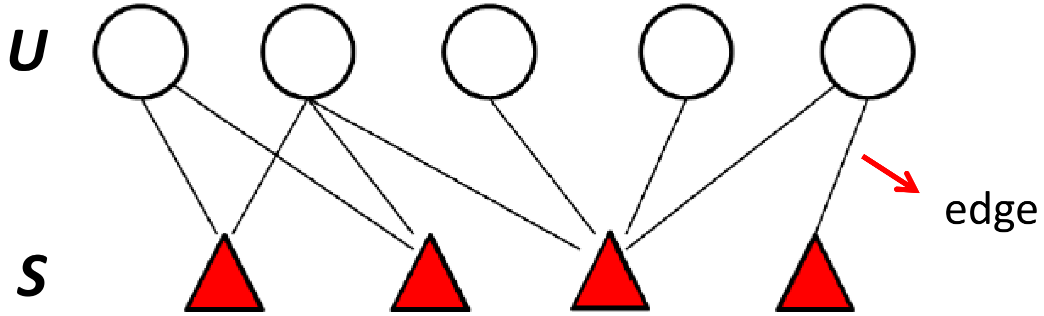
$$\lambda(a,b) = \begin{cases} 1, & \text{iff } V(a) \cap V(b) \neq \emptyset \\ 0, & \text{otherwise} \end{cases}$$

- The set of feasible mmWave links is:

$$\Omega = \{i \mid \lambda(s_i, d_i) = 1, \forall i \in S_0\},$$

Network Model

- Consider an mmWave WPANs with N links,
  - Each link $i \in N$ is associated with s_i, d_i and a flow rate f_i.
  - M obstacles with known locations.
  - K candidate locations for relay placement.
- The relationship btw mmWave links (U) and relays(S) is an undirected bi-partite graph.



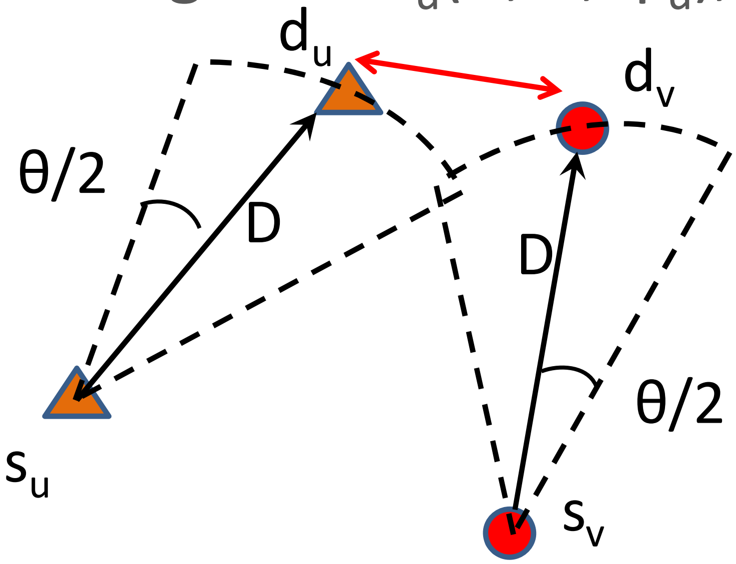
$$G(U, S, E)$$

Assumptions

- At most 2-hop paths (via relay)
  - TX → RX, TX → Relay → RX (delay sensitive QoS)
- Relays can be shared by multiple links using TDMA.
- TXs know the direction of RXs and tune the beam direction immediately without any additional switching overhead.
- A classic interference model with directional antenna is adopted.

Spatial Contention Between Two Physical Links

- The covered regions: $Q_u(D, \theta, \phi_u)$, $Q_v(D, \theta, \phi_v)$



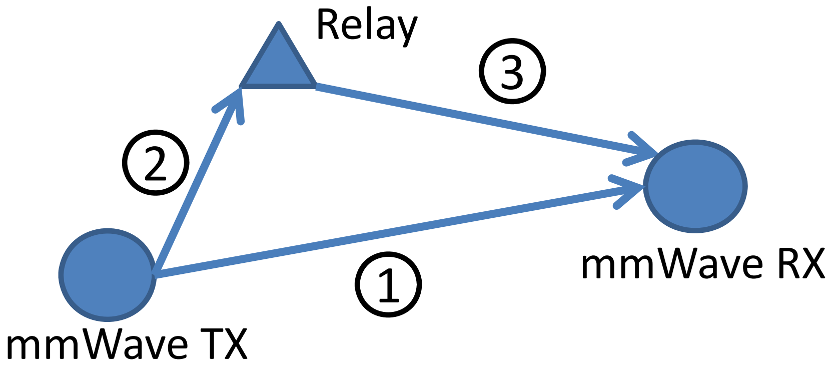
$$c_{uv} \neq c_{vu}$$

- The contention relationship is denoted as:

$$c_{uv} = \begin{cases} 0, & \text{if } d_v \notin Q_u \cap \text{Min}(\|d_v - d_u\|, \|d_v - s_u\|) > 0.635 \\ 1, & \text{otherwise,} \end{cases}$$

From an experiment work at 60GHz [Ref]

Three kinds of physical link i (s_i, d_i)



- Direct LOS logical link (s_i and d_i are nodes)
  - $\delta_1^i = 1$ if physical link i corresponds to direct LOS logical.
- 1st hop of NLOS logical link (d_i is a relay)
  - $\delta_2^i = 1$ if physical link i is the 1st hop of NLOS logical link.
- 2nd hop of NLOS logical link (s_i is a relay)
  - $\delta_3^i = 1$ if physical link i is the 2nd hop of NLOS logical link.

Flow Rate of physical link i (s_i, d_i)

- Flow rate of a physical link is the sum of traffic demands of all logical links passing through it.

Protection function

$$r_i = \delta_1^i f_i + \delta_2^i \left[\sum_{l\in L_{src}(s_i)} \eta_l f_l x_{ld_i} + \boxed{g_i(\mathbf{y}_{\mathbf{d}_i}, \mathbf{f})} \right] + \delta_3^i \left[\sum_{l\in L_{des}(d_i)} \eta_l f_l x_{ls_i} + \boxed{g_i(\mathbf{y}_{\mathbf{s}_i}, \mathbf{f})} \right]$$

LOS

1st hop of NLOS

2nd hop of NLOS

- TDMA Constraints for every physical link:

$$\frac{r_i}{R_{s_i,d_i}} + \sum_{j\in U_{src}(s_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j\in U_{des}(d_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j\notin (U_{src}(s_i)\cup U_{des}(d_i))} c_{ji} \frac{r_j}{R_{s_j,d_j}} \le 1, \forall i,$$

The time of link itself

By all physical links sharing same Si

By all physical links sharing same di

By all physical links with spatial contention

Problem Statements

- Given an mmWave WPAN with *N* feasible logical links, *M* obstacles, *K* candidate relay locations,
- Robust Minimum Relay Placement (RMRP):
  - What is the minimum number of relays and their locations to satisfy the connectivity, and bandwidth and robustness constraints?
- Robust Maximum Relay Placement (RMURP):
  - What is the maximum network utility that scaled from base rates by placing at most *m* relays such that robustness constraints?

Robust Minimum Relay Placement (RMRP)

x_{lk}: l select k as primary path
y_{lk}: l select k as secondary path
z_k: relay k is selected
η_l: NLOS indicator
f_l : traffic demand of logical link l
R: AWGN channel capacity

$$\underset{\mathbf{x},\mathbf{y},\mathbf{z}}{\text{minimize}} \quad \sum_k z_k$$

Protection function

$$\text{subject to} \quad \sum_{l\in\Omega_k} \eta_l f_l \tau_{lk} x_{lk} + \boxed{g_k(\mathbf{y}_\mathbf{k}, \mathbf{f})} \le z_k, \forall k,$$

relay bandwidth constraint

$$\tau_{ik} = \frac{1}{R_{s_i,k}} + \frac{1}{R_{k,d_i}},$$

The time of unit data at link i over relay k

$$\sum_{k=1}^{K} x_{ik} = \eta_i, \qquad \sum_{k=1}^{K} y_{ik} = 1, \forall i \in \Omega.$$

at most one relay for a link

$$x_{ik} + y_{ik} \le 1, \forall i \in L_k, \forall k.$$

The disjoint paths

$$\frac{r_i}{R_{s_i,d_i}} + \sum_{j\in U_{src}(s_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j\in U_{des}(d_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j\notin(U_{src}(s_i)\cup U_{des}(d_i))} c_{ji}\frac{r_j}{R_{s_j,d_j}} \le 1, \forall i,$$

TDMA constraint for every physical link.

$$\text{variables} \quad x_{ik}, y_{ik}, z_k \in \{0,1\}, \forall i \in \Omega, k = 1, \ldots, K$$

Robust Maximum Relay Placement (RMURP)

$$\underset{\mathbf{x},\mathbf{y},\mathbf{z},\alpha}{\text{maximize}} \quad \sum_i U_i(r_i) \qquad U_i(r_i) = \alpha r_i$$

α: the scalar variable

$$\text{subject to} \quad \sum_{l \in \Omega_k} \eta_l \underline{\alpha f_l} \tau_{lk} x_{lk} + \boxed{g_k(\mathbf{y_k}, \alpha\mathbf{f})} \leq z_k, \forall k,$$

relay bandwidth constraint

$$\sum_{k=1}^{K} x_{ik} = \eta_i, \quad \sum_{k=1}^{K} y_{ik} = 1, \forall i \in \Omega.$$

at most one relay for a link

$$x_{ik} + y_{ik} \leq 1, \forall i \in L_k, \forall k.$$

The disjoint paths

$$\frac{r_i}{R_{s_i,d_i}} + \sum_{j \in U_{src}(s_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j \in U_{des}(d_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j \notin (U_{src}(s_i) \cup U_{des}(d_i))} c_{ji} \frac{r_j}{R_{s_j,d_j}} \leq 1, \forall i,$$

TDMA constraint for every physical link.

$$\boxed{\sum_k z_k \leq K}$$

Relay number limit

$$\text{variables} \quad x_{ik}, y_{ik}, z_k \in \{0,1\}, \forall i \in \Omega, k = 1, \ldots, K \qquad \alpha \geq 0$$

D-norm Uncertainty Model

- The protection function in D-norm is given by:

$$g_k(\mathbf{y_k}, \mathbf{f}) = \max_{S_k : S_k \subseteq \Omega_k, |S_k| = \Gamma_k} \sum_{l \in S_k} f_l \tau_{lk} y_{lk}.$$

$\Gamma_k = 0,$ → No logical link fails;
$\Gamma_k = |\Omega_k|,$ → All feasible links fail simultaneously.

Define robustness index:

$$\rho \equiv \Gamma_k / |\Omega_k|$$

- Reformulation:

$$\max_{\{0 \le \beta_{lk} \le 1\}_{\forall l \in \Omega_k}} \sum_{l \in \Omega_k} f_l \tau_{lk} y_{lk} \beta_{lk},$$

$$\text{s.t.} \sum_{l \in \Omega_k} \beta_{lk} \le \Gamma_k,$$

$$\beta_{lk} \in \{0, 1\}, \forall l \in \Omega_k$$

LP Relaxation &
Lagrangian Dual

$$\min_{\{\mu_{lk} \ge 0\}_{\forall l \in \Omega_k}, \nu_k \ge 0} \nu_k \Gamma_k + \sum_{l \in \Omega_k} \mu_{lk},$$

$$\text{s.t.} \ \nu_k + \mu_{lk} \ge f_l \tau_{lk} y_{lk},$$

Equivalent Formulation of RMRP

- A mixed integer linear programming problem (MILP)

$$\min_{\mathbf{x},\mathbf{y},\mathbf{z},\mu,\nu,\mathbf{p},\mathbf{q}} \quad \sum_k z_k$$

$$\text{s.t.} \quad \sum_{l\in\Omega_k} \eta_l x_{lk} f_l \tau_{lk} + \nu_k \Gamma_k + \sum_{l\in\Omega_k} \mu_{lk} \le z_k, \ \forall k,$$

$$\nu_k + \mu_{lk} \ge f_l \tau_{lk} y_{lk}, \ \forall l \in \Omega_k, \forall k,$$

$$r_i = \delta_1^i f_i + \delta_2^i \left[\sum_{l\in L_{src}(s_i)} (\eta_l f_l x_{ld_i} + p_{ld_i}) + q_{d_i}\Gamma_i \right] + \delta_3^i \left[\sum_{l\in L_{des}(d_i)} (\eta_l f_l x_{ls_i} + p_{ls_i}) + q_{s_i}\Gamma_i \right]$$

$$q_{d_i} + p_{ld_i} \ge f_l y_{ld_i}, \ \forall l \in L_{src}(s_i), \forall i$$

$$q_{s_i} + p_{ls_i} \ge f_l y_{ls_i}, \ \forall l \in L_{des}(d_i), \forall i$$

All other constraints in original problem.

$$\text{variables} \quad x_{lk}, y_{lk}, z_k \in \{0,1\},$$
$$\mu_{lk} \ge 0, \nu_k \ge 0, p_{lk} \ge 0, q_k \ge 0$$

NP-hard

*MILP can be solved directly using IBM CPLEX solver.

Equivalent Formulation of RMURP

- A mixed integer non-linear programming problem (MINLP)

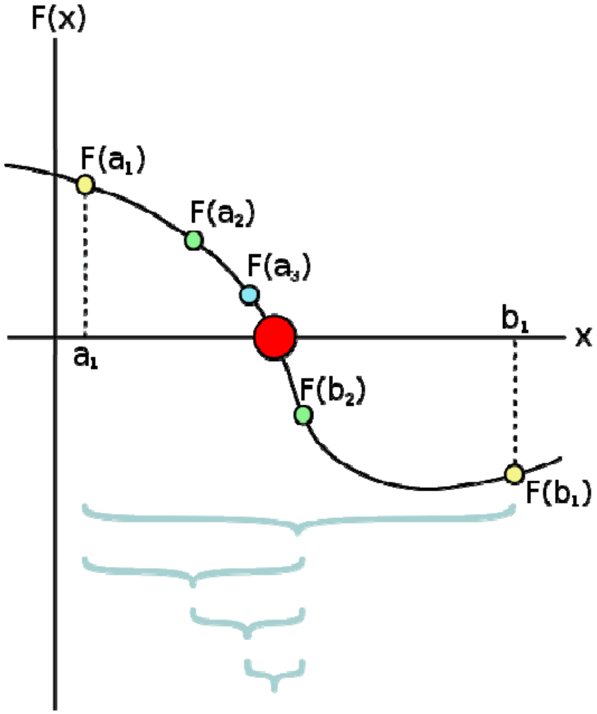
$$
\begin{aligned}
\underset{\mathbf{x},\mathbf{y},\mathbf{z},\mu,\nu,\mathbf{p},\mathbf{q},\alpha}{\text{Maximize}} \quad & \sum_{l} \alpha f_l \\
\text{s.t.} \quad & \sum_{l\in\Omega_k} \eta_l \alpha f_l \tau_{lk} x_{lk} + \nu_k \Gamma_k + \sum_{l\in\Omega_k} \mu_{lk} \le z_k, \ \forall k, \\
& \nu_k + \mu_{lk} \ge \alpha f_l \tau_{lk} y_{lk}, \ \forall l \in \Omega_k, \forall k, \\
& r_i = \delta_1^i \alpha f_i + \delta_2^i \left[\sum_{l\in L_{src}(s_i)} (\eta_l \alpha f_l x_{ld_i} + p_{ld_i}) + q_{d_i} \Gamma_i \right] \\
& \quad + \delta_3^i \left[\sum_{l\in L_{des}(d_i)} (\eta_l \alpha f_l x_{ls_i} + p_{ls_i}) + q_{s_i} \Gamma_i \right] \\
& q_{d_i} + p_{ld_i} \ge \alpha f_l y_{ld_i}, \ \forall l \in L_{src}(s_i), \forall i \\
& q_{s_i} + p_{ls_i} \ge \alpha f_l y_{ls_i}, \ \forall l \in L_{des}(d_i), \forall i \\
\text{variables} \quad & x_{lk}, y_{lk}, z_k \in \{0,1\}, \\
& \mu_{lk} \ge 0, \nu_k \ge 0, p_{lk} \ge 0, q_k \ge 0, \alpha \ge 0
\end{aligned}
$$

NP-hard

*MINLP can't be solved directly

The Bisection Search Algorithm for RMURP

- Principle:
  - F is continuous on [a, b],
  - F(a) and F(b) have opposite signs.
  - The algorithm starts from [a, b], and stops when (b-a)/2 < TOL.

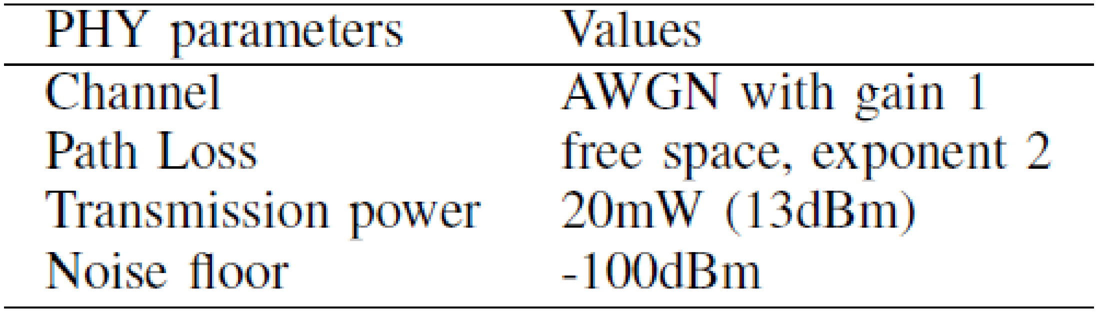


- In our RMURP,
  - Given α, the problem becomes MILP.
  - If α is large, → RMURP infeasible
  - If α=0, → RMURP feasible

→ Find α_{max} that makes RMURP feasible

Simulation Setup

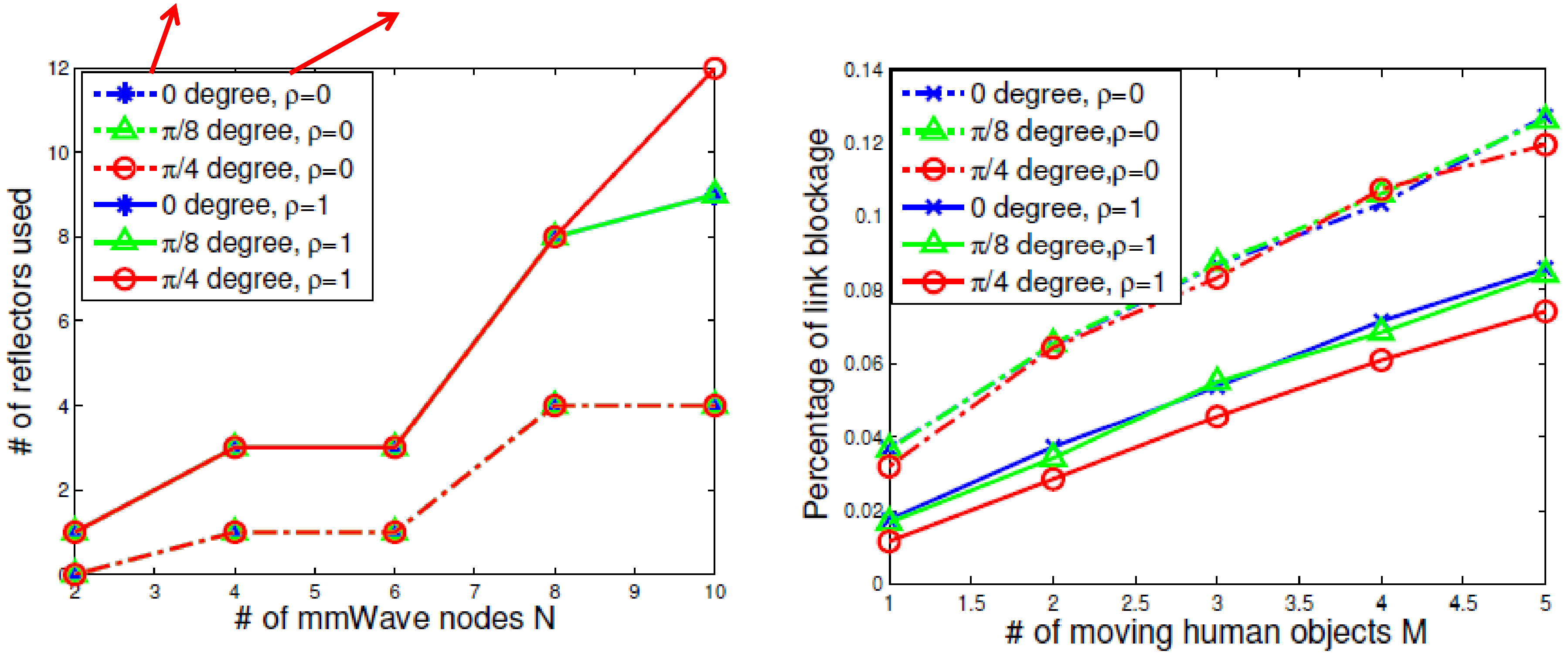
- Parameters:
  - A 10mX10m room with *N* mmWave links, 10 obstacles.
  - Grid point separation distance: d_0=2.
  - Base traffic demand f_l: 1/3 of channel capacity of the slowest path.
  - Transmission radii of all nodes/relays: 6 meters.



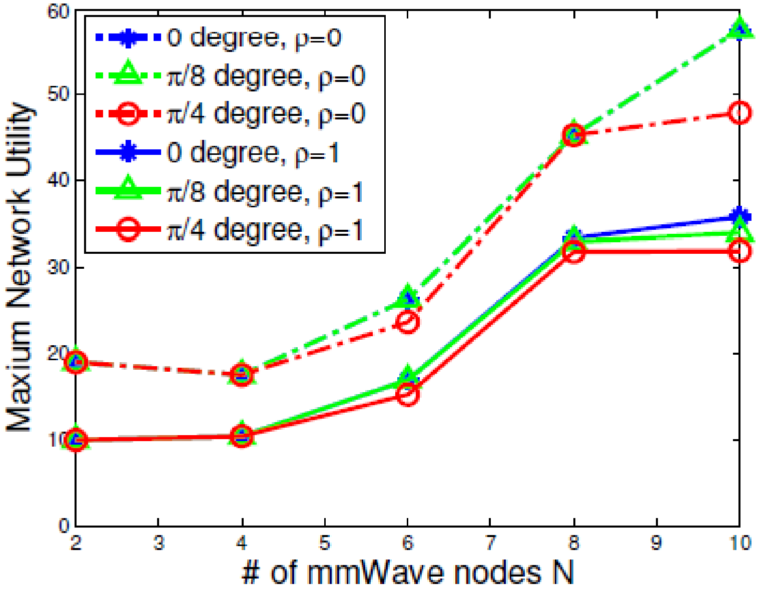
PHY parameters	Values
Channel	AWGN with gain 1
Path Loss	free space, exponent 2
Transmission power	20mW (13dBm)
Noise floor	-100dBm

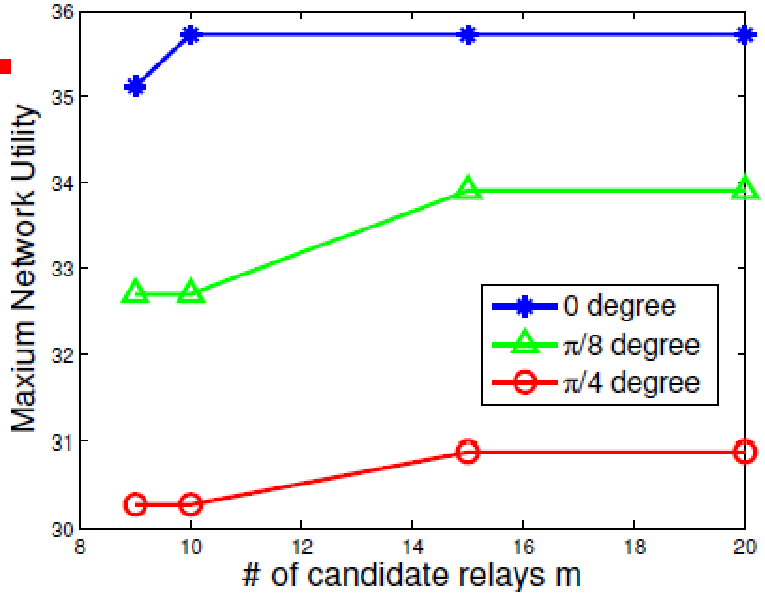
Performance of RMRP

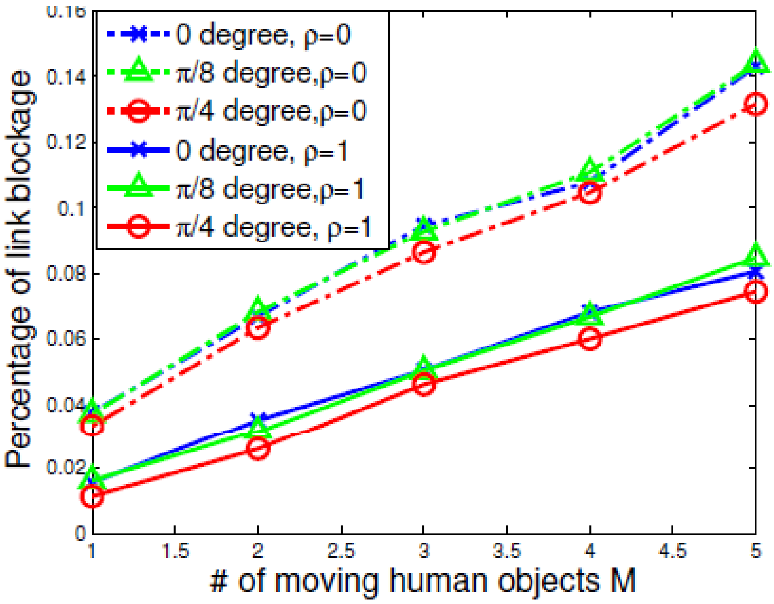
Antenna beamwidth, robustness index



Performance of RMURP







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Outline

1. Motivation and Background
2. Link Quality Prediction
3. Neighbor Discovery and Contention Graph Inference
    a. A Binary Inference Approach
    b. A Linear Inference Approach
4. Robust Relay Placement and Routing Selection
5. **Conclusions and Future Work**

Conclusions

- Link quality prediction in 802.15.4 LR-WPANs
  - Decipher RSSI, LQI readings available at commodity Zigbee nodes.
  - Propose a prediction model that predicts the instantaneous link quality using LQI readings.
- Joint neighbor discovery and contention graph inference in ad-hoc WPANs
  - Propose two solutions to joint neighbor discovery and contention graph inference, a binary approach and a location based linear approach.
- Robust relay placement and route selection in mmWave WPANs
  - Proposed two robust formulations to combat the uncertain link failure.
  - The proposed solution is a joint optimization of the relay placement and 2-hop routing through relays.

Future Work

- Channel Profiling for link quality prediction
  - Current approach assumes the knowledge of channel.
  - A channel profiling is needed not only to classify channel models but also obtain the key parameters.
- Efficient Location Estimation in linear inference approach
  - Current approach simply solves a full-rank MSE problem.
  - An efficient estimation method is needed to solve for locations using as few tests as possible.
- Passive Relay Placement in 60GHz WPANs
  - Current approach utilizes active relays to forward the signal from TX to any intended direction.
  - Passive relay may introduce additional challenges on controlling unwanted interference.

Publications

[J1] **Guanbo Zheng**, C. Hua, R. Zheng and Q. Wang, "*Toward a Robust Relay Placement in mmWave Wireless Personal Area Networks*", submitted to IEEE Transactions on Wireless Communications (**TWC**), 2013. (Under review).

[J2] Y. Wang, Q. Wang, **Guanbo Zheng**, Z. Zeng and R. Zheng, "*WiCop: Engineering WiFi Temporal White-Spaces for Safe Operations of Wireless Personal Area Networks in Medical Applications*", IEEE Transactions on Mobile Computing (**TMC**), 2013. (Accepted for publication)

[J3] H. Nguyen, **Guanbo Zheng**, Z. Han, and R. Zheng, "*Binary Inference for Primary User Separation in Cognitive Radio Networks*", In IEEE Transactions on Wireless Communications (**TWC**), Vol. 12, Issue. 4, pp. 1532-1542, April. 2013.

[C1] **Guanbo Zheng**, C. Hua, R. Zheng and Q. Wang, "*A Robust Relay Placement Framework for 60GHz mmWave Wireless Personal Area Networks*", in Proc. of IEEE Global Communication Conf. (**GLOBECOM**), Atlanta, Dec. 2013. (To appear)

[C2] **Guanbo Zheng**, C. Hua, K, Vu, R. Zheng and Q. Wang, "*Robust Reflector Placement in 60GHz mmWave Wireless Personal Area Networks*", In Proc. of Real-Time and Embedded Technology and Applications Symposium (**RTAS**), Work-in-Progress, 2012.

[C3] H. Nguyen, N. Nguyen, **Guanbo Zheng**, Z. Han, and R. Zheng, "*Binary Blind Identification of Wireless Transmission Technologies for Wideband Spectrum Monitoring*", In Proc. of IEEE Global Communication Conf. (**GLOBECOM**), Houston, Dec. 2011.

[C4] **Guanbo Zheng,** D. Han, R. Zheng, C. Schmitz and X. Yuan, "*A Link Quality Inference Model for IEEE 802.15. 4 Low-Rate WPANs*", In Proc. of IEEE Global Communication Conf. (**GLOBECOM**), Houston, Dec. 2011.

[C5] Y. Wang, Q. Wang, Z. Zeng, **Guanbo Zheng** and R. Zheng, "*WiCop: Engineering WiFi Temporal White-Spaces for Safe Operations of Wireless Body Area Networks in Medical Applications*", In Proc. of Real-Time Systems Symposium (**RTSS**), Nov. 2011.

[C6] N. Nguyen, **Guanbo Zheng**, Z. Han, and R. Zheng, "*Device fingerprinting to enhance wireless security using nonparametric Bayesian method*", In Proc. of IEEE International Conference on Computer Communications (**INFOCOM**), Apr. 2011.

Thank you for your attention

Questions?

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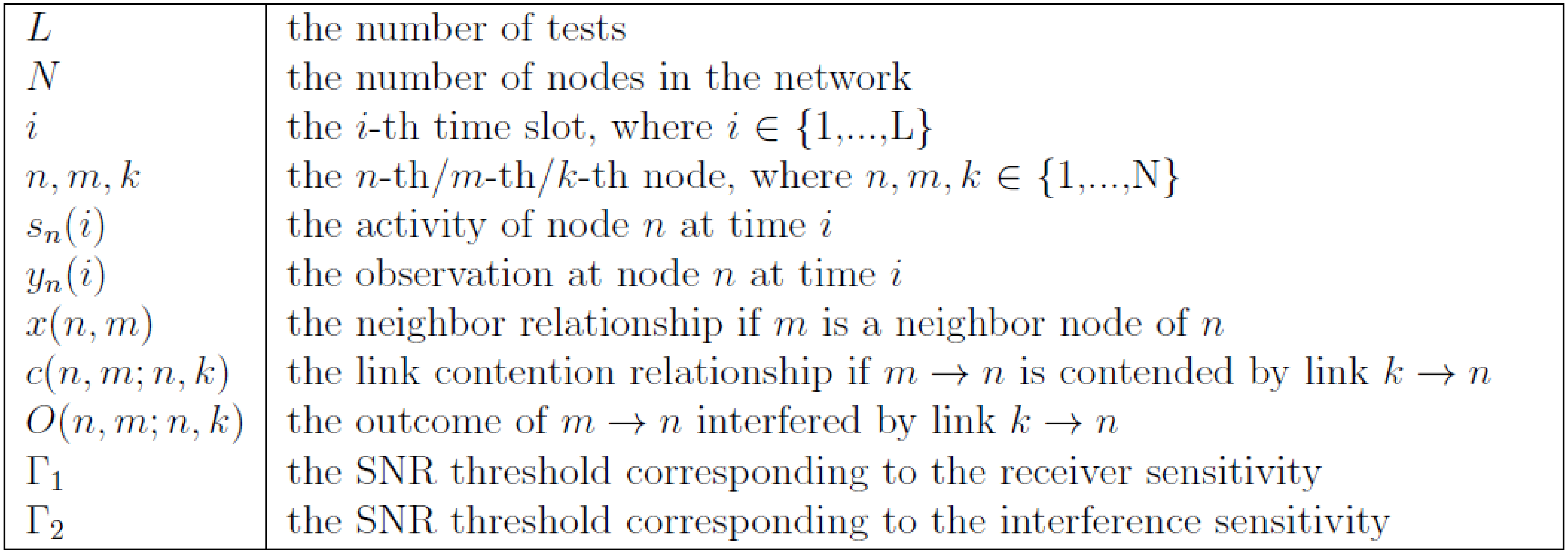
Part 1 - Terms Definition

- 802.15: IEEE standards Working Group for WPANs
- Zigbee: The spec of a low-cost low-power wireless comm. solution
- COTS: Commercial-of-the-shelf devices
- PHY: Physical Layer
- MAC: Media Access Control Layer
- RSSI: Received signal strength indicator
- LQI: Link quality index
- SNR: Signal-to-noise ratio
- BER/SER/PER: Bit/Symbol/Packet error rate
- CC2420: 2.4GHz IEEE 802.15.4 compliant RF transceiver chip
- USRP: Universal Software Radio Peripheral
- SDR: Software-defined radio
- GNU Radio: a free software toolkit for SDR
- TinyOS: An open source OS targeting wireless sensor networks

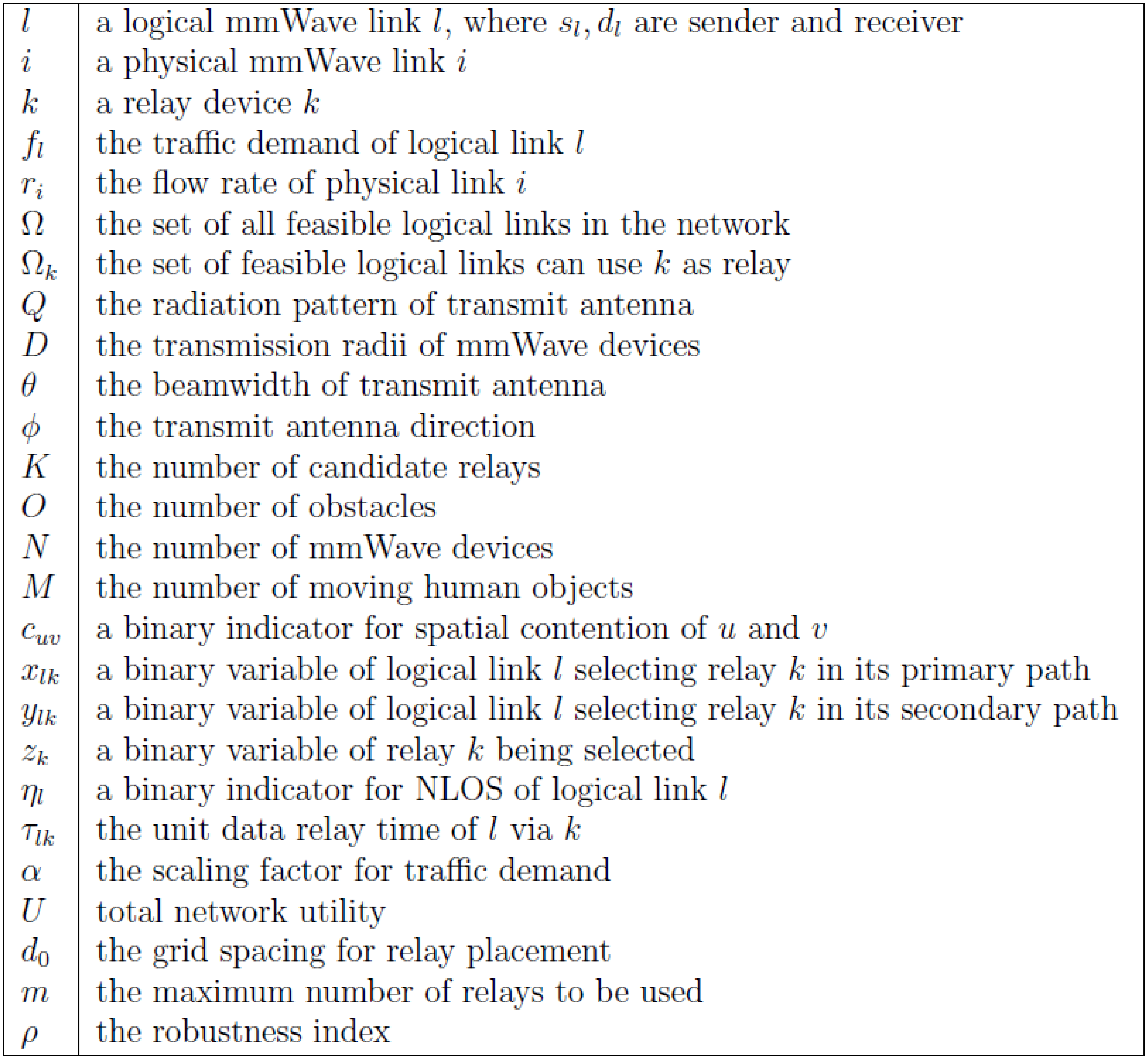
Part 2 - Terms and Notations

- CSMA: Carrier Sense Multiple Access, which is a probabilistic medium access protocol.
- CDMA: Code Division Multiple Access



L	the number of tests
N	the number of nodes in the network
i	the i-th time slot, where $i \in \{1,...,L\}$
n, m, k	the n-th/m-th/k-th node, where $n, m, k \in \{1,...,N\}$
$s_n(i)$	the activity of node n at time i
$y_n(i)$	the observation at node n at time i
$x(n, m)$	the neighbor relationship if m is a neighbor node of n
$c(n, m; n, k)$	the link contention relationship if $m \rightarrow n$ is contended by link $k \rightarrow n$
$O(n, m; n, k)$	the outcome of $m \rightarrow n$ interfered by link $k \rightarrow n$
Γ_1	the SNR threshold corresponding to the receiver sensitivity
Γ_2	the SNR threshold corresponding to the interference sensitivity

Part 3 notations



l	a logical mmWave link l, where s_l, d_l are sender and receiver
i	a physical mmWave link i
k	a relay device k
f_l	the traffic demand of logical link l
r_i	the flow rate of physical link i
Ω	the set of all feasible logical links in the network
Ω_k	the set of feasible logical links can use k as relay
Q	the radiation pattern of transmit antenna
D	the transmission radii of mmWave devices
θ	the beamwidth of transmit antenna
ϕ	the transmit antenna direction
K	the number of candidate relays
O	the number of obstacles
N	the number of mmWave devices
M	the number of moving human objects
c_{uv}	a binary indicator for spatial contention of u and v
x_{lk}	a binary variable of logical link l selecting relay k in its primary path
y_{lk}	a binary variable of logical link l selecting relay k in its secondary path
z_k	a binary variable of relay k being selected
η_l	a binary indicator for NLOS of logical link l
τ_{lk}	the unit data relay time of l via k
α	the scaling factor for traffic demand
U	total network utility
d_0	the grid spacing for relay placement
m	the maximum number of relays to be used
ρ	the robustness index