Toward Robust and Reliable Wireless Personal Area Networks

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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.
IEEE Standards of WPANs

- **802.15.4 Low rate WPAN**: Low QoS
- **802.15.1 Bluetooth**: QoS for voice application
- **802.15.3 High Rate WPAN**: 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)

- **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.
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

- **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.

![Diagram showing the flow of LQI Readings, Estimated SNR, and Link quality (BER/SER/PER)]
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.

- Contended or not
  - PAN Coordinator
  - NodeA
  - NodeB
  - NodeC
  - Who is my neighbor?
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 $i$,
  
  
  \[
  s_n(i) = \begin{cases} 
  1, & \text{transmitter mode} \\
  0, & \text{receiver mode}
  \end{cases}
  \]

  \[T(i) = \{n : s_n(i) = 1, n \in \{1, ..., N\}\}; \quad R(i) = \{n : s_n(i) = 0, n \in \{1, ..., N\}\}\]

- **$x(n, k)$**: 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 $m \rightarrow n$ is contended by $k \rightarrow n$
  
  \[
  c(n, m; n, k) = \begin{cases} 
  1, & \text{link } m \rightarrow n \text{ is contended by link } k \rightarrow n \\
  0, & \text{link } m \rightarrow n \text{ is not contended by link } k \rightarrow n
  \end{cases}
  \]
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 \( n \) \( \rightarrow x(n, m)=1, x(n, k)=1 \)
  - \( k \rightarrow n \) contends with \( m \rightarrow n \), \( \rightarrow c(n, m; n, k)=1 \)
  - \( m \rightarrow n \) does NOT contend with \( k \rightarrow n \), \( \rightarrow c(n, k; n, m)=0 \)

\[ O(n, m; n, k) = \delta, \quad O(n, k; n, m) = 1, \]
where \( O(n, m; n, k) \) is the outcome of \( m \rightarrow n \) affected by \( k \rightarrow n \).

\[ y_n(i) = 1 \quad \text{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

\[
O(n, m; n, k) = f(x(n, m), x(n, k), c(n, m; n, k))
\]

Then,

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

- For \(|T(i)| \geq 3\):

\[
y_n(i) = \bigcup_{m \in T(i)} \left( \bigcap_{k \in T(i), k \neq m} O(n, m; n, k) \right)
\]
Analysis of Inference

Consider **some examples** where \( n \) is RX, \( m, k \) are TX

- \( x(n, m) = 1 \)
- \( y_n = \delta \)
- Signal observed but undecodable

- \( x(n, k) = 1 \)
- \( y_n = 1 \)
- with ID \( k, m \) decoded

- \( c(n, m; n, k) = 1, c(n, k; n, m) = 1. \)

- \( c(n, m; n, k) = 0, c(n, k; n, m) = 0. \)
Analysis of Inference (Cont’d)

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

<table>
<thead>
<tr>
<th>Cases</th>
<th>$x(n,m)$</th>
<th>$x(n,k)$</th>
<th>$y_n(i)$</th>
<th>ID $c(n,m;n,k)$</th>
<th>$c(n;k;n,m)$</th>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
c(n, m; n, k) = a_{nm}g_{nk}\left(\underbrace{x(n, m) \oplus y_n(i)}_\text{ID}ight) + (1 - a_{nm})d_{nm}g_{nk}
\]

- For $|T(i)|\geq3$, 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 $|T(i)| \geq 2$, 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 \(|T(i)| \geq 2\), 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:

<table>
<thead>
<tr>
<th>PHY parameters</th>
<th>Values</th>
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<tr>
<td>Path Loss</td>
<td>3</td>
</tr>
<tr>
<td>Center Freq</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>20mW (13dBm)</td>
</tr>
<tr>
<td>Noise floor</td>
<td>-100dBm</td>
</tr>
<tr>
<td>Fading channel</td>
<td>AWGN/Rayleigh</td>
</tr>
</tbody>
</table>
Observation Error Rate vs. # of nodes

False positive errors dominate.
Larger network density, lower observation errors.
Smaller threshold pairs, lower observation errors.
Completion Rate vs. # of Tests

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 $SINR_{nmk} = RSS_{nm}/(RSS_{nk} + NF)$.
Mathematical Model

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

$$Y_{K\times1} = (I - S_{K\times K}) U_{K\times K} S_{K\times K} 1_{K\times1} + \varepsilon$$

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

**Flowchart Explanation:**
- **Initialization**
- **Enough independent equations?**
  - **YES:** Start a new trial $i$
    - Get $T(i)$, $R(i)$
    - For $n \in R(i)$, get an equation
    - The equation is independent?
      - **YES:** Save this equation for MSF
      - **NO:** Equations no variables no?
        - **YES:** Solve partial MSE
        - **NO:** Solve MSE to obtain RSS
  - **NO:** Solve the MSE incrementally
- **End**

**Remarks:**
- Keep independently linear equations.
- Solve the MSE incrementally.
Performance of Linear Inference Approach

Completion Rate does NOT depend on thresholds.

Thre1 = -5dB, Thre2 = -15dB
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.
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

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**.
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: \( Q_u(D, \theta, \phi_u), Q_v(D, \theta, \phi_v) \)

- 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 (\(s_i, d_i\))

- **Direct LOS logical link** (\(s_i\) and \(d_i\) are nodes)
  - \(\delta_1^i = 1\) if physical link \(i\) corresponds to direct LOS logical.

- **1\(^{st}\) hop of NLOS logical link** (\(d_i\) is a relay)
  - \(\delta_2^i = 1\) if physical link \(i\) is the 1\(^{st}\) hop of NLOS logical link.

- **2\(^{nd}\) hop of NLOS logical link** (\(s_i\) is a relay)
  - \(\delta_3^i = 1\) if physical link \(i\) is the 2\(^{nd}\) 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.

\[
r_i = \delta_1^i f_i + \delta_2^i \left[ \sum_{l \in L_{src}(s_i)} \eta_l x_{ld_i} + g_i(y_{di}, f) \right] + \delta_3^i \left[ \sum_{l \in L_{des}(d_i)} \eta_l x_{ls_i} + g_i(y_{si}, f) \right]
\]

- **Protection function**
  - LOS
  - 1\(^{st}\) hop of NLOS
  - 2\(^{nd}\) hop of NLOS

- **TDMA Constraints** for every physical link:

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

- The time of link itself
- By all physical links sharing same \( s_i \)
- By all physical links sharing same \( d_i \)
- 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)

minimize \[ \sum_{k} z_k \]

subject to \[ \sum_{l \in \Omega_k} \eta_{fl} x_{lk} + g_k(y_k, f) \leq z_k, \forall k, \]

\[ \tau_{ik} = \frac{1}{R_{s_{ik}, k}} + \frac{1}{R_{k, d_i}}, \]

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

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

\[ \frac{r_i}{R_{s_i, d_i}} + \sum_{j \in U_{src}(s_i)} \frac{r_j}{R_{s_j, d_j}} + \sum_{j \in U_{des}(d_i)} \frac{r_j}{R_{s_j, d_j}} \]

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

variables \[ x_{ik}, y_{ik}, z_k \in \{0, 1\}, \forall i \in \Omega, k = 1, \ldots, K \]
Robust Maximum Relay Placement (RMURP)

maximize \[ \sum_{i} U_i(r_i) \quad U_i(r_i) = \alpha r_i \] \quad \alpha: \text{the scalar variable}

subject to
\[ \sum_{l \in \Omega_k} \eta_i \alpha^{-1} \pi_k x_{ik} + g_k(y_k, \alpha f) \leq z_k, \forall k, \]
\[ \sum_{k=1}^{K} x_{ik} = \eta_i, \quad \sum_{k=1}^{K} y_{ik} = 1, \forall i \in \Omega. \]
\[ x_{ik} + y_{ik} \leq 1, \forall i \in L_k, \forall k. \]
\[ \frac{r_i}{R_{s_i,d_i}} + \sum_{j \in U_{src}(s_i)} \frac{r_j}{R_{s_j,d_j}} + \sum_{j \in U_{des}(d_i)} \frac{r_j}{R_{s_j,d_j}} \]
\[ + \sum_{j \notin (U_{src}(s_i) \cup U_{des}(d_i))} c_{ji} \frac{r_j}{R_{s_j,d_j}} \leq 1, \forall i, \]
\[ \sum_{k=1}^{K} z_k \leq K \]

variables \[ x_{ik}, y_{ik}, z_k \in \{0, 1\}, \forall i \in \Omega, k = 1, \ldots, K \]
\[ \alpha \geq 0 \]
D-norm Uncertainty Model

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

\[
g_k(y_k, f) = \max_{S_k: S_k \subseteq \Omega_k, \lvert S_k \rvert = \Gamma_k} \sum_{l \in S_k} f_l \tau_{lk} y_{lk}.\]

\[
\begin{align*}
\Gamma_k &= 0, \quad \rightarrow \text{No logical link fails;} \\
\Gamma_k &= |\Omega_k|, \quad \rightarrow \text{All feasible links fail simultaneously.}
\end{align*}
\]

Define robustness index:

\[
\rho \equiv \frac{\Gamma_k}{|\Omega_k|}
\]

- Reformulation:

\[
\max_{\{0 \leq \beta_{lk} \leq 1\}_{l \in \Omega_k}} \sum_{l \in \Omega_k} f_l \tau_{lk} y_{lk} \beta_{lk},
\]

\[
\text{s.t.} \quad \sum_{l \in \Omega_k} \beta_{lk} \leq \Gamma_k,
\]

\[
\beta_{lk} \in \{0, 1\}, \quad \forall l \in \Omega_k
\]

\[
\min_{\{\mu_{lk} \geq 0\}_{l \in \Omega_k}, \nu_k \geq 0} \nu_k \Gamma_k + \sum_{l \in \Omega_k} \mu_{lk},
\]

\[
\text{s.t.} \quad \nu_k + \mu_{lk} \geq f_l \tau_{lk} y_{lk},
\]

LP Relaxation & Lagrangian Dual
Equivalent Formulation of RMRP

- A mixed integer linear programming problem (MILP)

\[
\min_{x, y, z, \mu, \nu, p, q} \sum_{k} z_k \\
\text{s.t.} \quad \sum_{i \in \Omega_k} \eta_i x_{lk} f_i \tau_{lk} + \nu_k \Gamma_k + \sum_{i \in \Omega_k} \mu_{lk} \leq z_k, \forall k, \\
\nu_k + \mu_{lk} \geq f_i \tau_{lk} y_{lk}, \forall i \in \Omega_k, \forall k, \\
r_i = \delta^i_1 f_i + \delta^i_2 \left[ \sum_{l \in L_{src}(s_i)} (\eta_l f_i x_{ld_i} + p_{ld_i}) + q_{di} \Gamma_i \right] \\
+ \delta^i_3 \left[ \sum_{l \in L_{des}(d_i)} (\eta_l f_i x_{ls_i} + p_{ls_i}) + q_{si} \Gamma_i \right] \\
q_{di} + p_{ld_i} \geq f_i y_{ld_i}, \forall l \in L_{src}(s_i), \forall i \\
q_{si} + p_{ls_i} \geq f_i y_{ls_i}, \forall l \in L_{des}(d_i), \forall i \\
\text{variables} \quad x_{lk}, y_{lk}, z_k \in \{0, 1\}, \\
\mu_{lk} \geq 0, \nu_k \geq 0, p_{lk} \geq 0, q_k \geq 0
\]

NP-hard

*MILP can be solved directly using IBM CPLEX solver.
Equivalent Formulation of RMURP

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

\[
\begin{align*}
\text{Maximize} \quad & \sum_l \alpha f_i \\
\text{s.t.} \quad & \sum_{l \in \Omega_k} \eta_i \alpha f_i \tau_{lk} x_{lk} + \nu_k \Gamma_k + \sum_{l \in \Omega_k} \mu_{lk} \leq z_k, \quad \forall k, \\
& \nu_k + \mu_{lk} \geq \alpha f_i \tau_{lk} y_{lk}, \quad \forall l \in \Omega_k, \forall k, \\
& r_i = \delta_1^i \alpha f_i + \delta_2^i \left[ \sum_{l \in L_{\text{src}}(s_i)} (\eta_i \alpha f_i x_{ldi} + p_{ldi}) + q_{di} \Gamma_i \right] \\
& \quad + \delta_3^i \left[ \sum_{l \in L_{\text{des}}(d_i)} (\eta_i \alpha f_i x_{lsi} + p_{lsi}) + q_{si} \Gamma_i \right] \\
& q_{di} + p_{ldi} \geq \alpha f_i y_{ldi}, \quad \forall l \in L_{\text{src}}(s_i), \forall i \\
& q_{si} + p_{lsi} \geq \alpha f_i y_{lsi}, \quad \forall l \in L_{\text{des}}(d_i), \forall i \\
\text{variables} \quad & x_{lk}, y_{lk}, z_k \in \{0, 1\}, \\
& \mu_{lk} \geq 0, \nu_k \geq 0, p_{lk} \geq 0, q_k \geq 0, \alpha \geq 0.
\end{align*}
\]

*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 \((b-a)/2 < \text{TOL}\).

- In our RMURP,
  - Given \(\alpha\), the problem becomes MILP.
  - If \(\alpha\) is large, \(\rightarrow\) RMURP infeasible
  - If \(\alpha=0\), \(\rightarrow\) RMURP feasible

Find \(\alpha_{\text{max}}\) 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 \( f_i \): \( 1/3 \) of channel capacity of the slowest path.
  - Transmission radii of all nodes/relays: 6 meters.

<table>
<thead>
<tr>
<th>PHY parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>AWGN with gain 1</td>
</tr>
<tr>
<td>Path Loss</td>
<td>free space, exponent 2</td>
</tr>
<tr>
<td>Transmission power</td>
<td>20mW (13dBm)</td>
</tr>
<tr>
<td>Noise floor</td>
<td>-100dBm</td>
</tr>
</tbody>
</table>
Performance of RMRP

Antenna beamwidth, robustness index

- Graph showing the relationship between the number of reflectors used and the number of mmWave nodes.
- Graph showing the percentage of link blockage with respect to the number of moving human objects.
Performance of RMURP

- Graph 1: Max Utility vs. # of mmWave nodes N
  - Graph 2: Max Utility vs. # of candidate relays m
  - Graph 3: Percentage of link blockage vs. # of moving human objects M

- Legend:
  - 0 degree, ρ=0
  - π/8 degree, ρ=0
  - π/4 degree, ρ=0
  - 0 degree, ρ=1
  - π/8 degree, ρ=1
  - π/4 degree, ρ=1
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


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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>the number of tests</td>
</tr>
<tr>
<td>$N$</td>
<td>the number of nodes in the network</td>
</tr>
<tr>
<td>$i$</td>
<td>the $i$-th time slot, where $i \in {1,\ldots,L}$</td>
</tr>
<tr>
<td>$n, m, k$</td>
<td>the $n$-th/$m$-th/$k$-th node, where $n, m, k \in {1,\ldots,N}$</td>
</tr>
<tr>
<td>$s_n(i)$</td>
<td>the activity of node $n$ at time $i$</td>
</tr>
<tr>
<td>$y_n(i)$</td>
<td>the observation at node $n$ at time $i$</td>
</tr>
<tr>
<td>$x(n, m)$</td>
<td>the neighbor relationship if $m$ is a neighbor node of $n$</td>
</tr>
<tr>
<td>$c(n, m; n, k)$</td>
<td>the link contention relationship if $m \rightarrow n$ is contended by link $k \rightarrow n$</td>
</tr>
<tr>
<td>$O(n, m; n, k)$</td>
<td>the outcome of $m \rightarrow n$ interfered by link $k \rightarrow n$</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>the SNR threshold corresponding to the receiver sensitivity</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>the SNR threshold corresponding to the interference sensitivity</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$l$</td>
<td>a logical mmWave link $l$, where $s_l, d_l$ are sender and receiver</td>
</tr>
<tr>
<td>$i$</td>
<td>a physical mmWave link $i$</td>
</tr>
<tr>
<td>$k$</td>
<td>a relay device $k$</td>
</tr>
<tr>
<td>$f_l$</td>
<td>the traffic demand of logical link $l$</td>
</tr>
<tr>
<td>$r_i$</td>
<td>the flow rate of physical link $i$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>the set of all feasible logical links in the network</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>the set of feasible logical links that can use $k$ as relay</td>
</tr>
<tr>
<td>$Q$</td>
<td>the radiation pattern of transmit antenna</td>
</tr>
<tr>
<td>$D$</td>
<td>the transmission radii of mmWave devices</td>
</tr>
<tr>
<td>$\theta$</td>
<td>the beamwidth of transmit antenna</td>
</tr>
<tr>
<td>$\phi$</td>
<td>the transmit antenna direction</td>
</tr>
<tr>
<td>$K$</td>
<td>the number of candidate relays</td>
</tr>
<tr>
<td>$O$</td>
<td>the number of obstacles</td>
</tr>
<tr>
<td>$N$</td>
<td>the number of mmWave devices</td>
</tr>
<tr>
<td>$M$</td>
<td>the number of moving human objects</td>
</tr>
<tr>
<td>$c_{uv}$</td>
<td>a binary indicator for spatial contention of $u$ and $v$</td>
</tr>
<tr>
<td>$x_{lk}$</td>
<td>a binary variable of logical link $l$ selecting relay $k$ in its primary path</td>
</tr>
<tr>
<td>$y_{lk}$</td>
<td>a binary variable of logical link $l$ selecting relay $k$ in its secondary path</td>
</tr>
<tr>
<td>$z_k$</td>
<td>a binary variable of relay $k$ being selected</td>
</tr>
<tr>
<td>$\eta_l$</td>
<td>a binary indicator for NLOS of logical link $l$</td>
</tr>
<tr>
<td>$\tau_{lk}$</td>
<td>the unit data relay time of $l$ via $k$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>the scaling factor for traffic demand</td>
</tr>
<tr>
<td>$U$</td>
<td>total network utility</td>
</tr>
<tr>
<td>$d_0$</td>
<td>the grid spacing for relay placement</td>
</tr>
<tr>
<td>$m$</td>
<td>the maximum number of relays to be used</td>
</tr>
<tr>
<td>$\rho$</td>
<td>the robustness index</td>
</tr>
</tbody>
</table>