Wearable networks: A new frontier for device-to-device communication

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Wearable networks

- Multiple communicating devices in and around the body
  - 5 or more devices per person based on market trends trend
- D2D communication between nodes
  - Uncoordinated with another person’s wearable network

Smart phone may be the hub of the D2D wearable network
Galaxy of wearables

- Low-rate fitness monitors to high-rate infotainment devices
- May lead to the high consumption that motivates 5G data rates

Wearable networks will be very heterogeneous

Wearables growth potential

- Significant interest at the Mobile World Congress
  - Smart watches, augmented reality, and other devices
- People may have one smart phone but many wearables
  - New opportunities for semiconductors and software

Wearables becomes a smart phone multiplier

[2] https://medium.com/@iguchiwp/will-telepathy-one-be-able-to-change-the-world-be590c4840b0
### Wearable networks vs. body area networks

<table>
<thead>
<tr>
<th>Narrowband communication</th>
<th>UWB communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Bands (MHz)</td>
<td>Supported data rates (kbps)</td>
</tr>
<tr>
<td>402-405, 420-450, 863-870, 902-928, 950-956, 2360-2400, 2400-2483.5</td>
<td>57.5 – 971.4</td>
</tr>
</tbody>
</table>

- **BANs have been focused low-rate applications:** IEEE 802.15.6
  - Health-care and fitness monitors including implants
  - Man-to-machine communication in workplace
- **Sparse environment and less significant interference**

[1] IEEE 802.15.6 standard, 2012
D2D WEARABLE NETWORKS WITH MMWAVE
PHY / MAC challenges in D2D wearable networks

- Provide a high quality and high bandwidth comm. link
- Support heterogeneous devices
- Co-exist with other networks in dense environments

MmWave as solution for wearable networks

- High bandwidth and reasonable isolation
- Compact antenna arrays to provide array gain and reduced interf.
- Commercial products already available: IEEE 802.11ad, WirelessHD

1 47 CFR 15.255; 2 ARIB STD-T69, ARIB STD-T74; 3 Radiocommunications Class License 2000; 4 CEPT: Official journal of the EU;
PERFORMANCE ANALYSIS IN FINITE MMWAVE WEARABLE NETWORKS

What is different for mmWave wearable networks?

- Finite number of interferers in a finite network region
  - Realistic assumption for the indoor wearable setting w/ mmWave
  - Fixed/random location of interferers (extended in journal version)
- Blockages due to other human bodies (can be extended to pets)
- Both interferer and blockage associated with a user
Related work on interference modeling

◆ Stochastic geometry models for mmWave cellular networks [1]-[3]
  ✦ Infinite spatial extent and number of nodes
  ✦ Did not consider people as a source of blockage

◆ Performance analysis for finite ad-hoc networks [4]
  ✦ Does not include directional antennas or blockage

◆ Self-blockage model for mmWave [5]
  ✦ Considers a 5G cellular system
  ✦ User's own body blocks the signal, not other users

SYSTEM MODEL
Modeling antenna pattern using a sectored antenna

- Use a 2D sectored antenna model to simplify the analysis
  - Parameterize via a uniform planar square array with half-wavelength spacing
- Incorporates omni-directional antennas as a special case
  - \( N = 1 \) → omni-directional antenna, \( G = g = 1 \)
  - Of interest for inexpensive wearable

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of antenna elements</td>
<td>( N )</td>
</tr>
<tr>
<td>Beamwidth ( \theta )</td>
<td>( \frac{2\pi}{\sqrt{N}} )</td>
</tr>
<tr>
<td>Main-lobe gain ( G )</td>
<td>( N )</td>
</tr>
<tr>
<td>Side-lobe gain ( g )</td>
<td>( \frac{1}{\sin^2\left(\frac{3\pi}{2\sqrt{N}}\right)} )</td>
</tr>
</tbody>
</table>
Network topology

- Finite sized network region $\mathcal{A}$, area $|\mathcal{A}|$, $K + 1$ users
- One interferer per user transmits at a time
  - $K$ interferers + reference transmitter-receiver pair
- $X_i = R_i e^{j\phi_i}$, location of transmitters relative to reference receiver
Modeling human body blockages

- Associate diameter $W$ circle with each user – denoted $Y_i$
- Determine **blocking cone** for each $Y_i$
  - $X_i$ blocked if it falls in one of the blocking cones
- Assume $Y_i$ does not block $X_i$, i.e., no self-blocking
SINR and ergodic spectral efficiency

- **SINR is**
  \[ \gamma = \frac{h_0 S_0}{\sigma^2 + \sum_{i=1}^{K} I_i h_i \Omega_i} \]
  
  Noise power normalized by \( P_0 \)

- **Evaluate CCDF of SINR**
- **Derive ergodic spectral efficiency**
Signal from reference transmitter

\[ \gamma = \frac{h_0 S_0}{\sigma^2 + \sum_{i=1}^{K} I_i h_i \Omega_i} \]

- **h_0** – Nakagami fade gain from reference with parameter \( m_0 \)
- Assume that there is **always** LOS communication
- Reference Tx is within the main beam of the reference Rx

\[ S_0 = G_r G_t R_0^{-\alpha_0} \]
Signal from interfering transmitters

\[ \gamma = \frac{h_0 S_0}{\sigma^2 + \sum_{i=1}^{K} I_i h_i \Omega_i} \]

- Reference Rx
- Reference Tx
- Interfering Tx
- Blockage associated with interfering Tx

- \( h_i \) - Nakagami fading with parameter \( m_i \) from \( X_i \)
- Link is NLOS if \textbf{blocked} and LOS otherwise

\[ m_i = m_N \quad \quad m_i = m_L \]
Path-loss model and power gains

\[ \gamma = \frac{h_0 S_0}{\sigma^2 + \sum_{i=1}^{K} I_i h_i \Omega_i} \]

- Reference Rx
- Reference Tx
- Interfering Tx

- \( \alpha_i \)- path-loss exponent from \( X_i \): \( \alpha_L \) for LOS, \( \alpha_N \) for NLOS
- Define normalized power gain from \( X_i \)

\[ \Omega_i = \begin{cases} \frac{P_i}{P_0} G_r R_i^{-\alpha_i} & \text{if } -\frac{\theta_r}{2} \leq \phi_i - \phi_0 \leq \frac{\theta_r}{2} \\ \frac{P_i}{P_0} g_r R_i^{-\alpha_i} & \text{otherwise} \end{cases} \]

Ref. receiver’s main-lobe points towards \( X_i \)

Captures path loss and Rx orientation
Relative transmit power

\[ \gamma = \frac{h_0 S_0}{\sigma^2 + \sum_{i=1}^{K} I_i h_i \Omega_i} \]

Gain \( G_t \) w.p. \((\theta_t/2\pi)\)

Gain \( g_t \) w.p. \((1 - \theta_t/2\pi)\)

- \( X_i \) transmits with probability \( p_t \) (Aloha-like medium access)
- \( X_i \) points its main-lobe in a (uniform) random direction

\[ I_i = \begin{cases} 
0 & \text{w.p. } (1 - p_t) \\
G_t & \text{w.p. } p_t \left( \frac{\theta_t}{2\pi} \right) \\
g_t & \text{w.p. } p_t \left( 1 - \frac{\theta_t}{2\pi} \right) 
\end{cases} \]

Captures \( p_t \) and random Tx orientation

Probability that ref. receiver is within main-lobe of \( X_i \)
CCDF of SINR

- SINR coverage probability for a given $\Omega = [\Omega_0, ..., \Omega_K]$

$$P_c(\beta) = \mathbb{P}[\gamma > \beta | \Omega]$$

Theorem 1

$$P_c(\beta) = \mathbb{P} \left[ S > \sigma^2 + \sum_{i=1}^{K} Y_i \mathrel{|} \Omega \right],$$

where

$$S = \beta^{-1} h_0 \Omega_0, \quad Y_i = I_i h_i \Omega_i.$$
CCDF of SINR

- SINR coverage probability for a given $\Omega = [\Omega_0, ..., \Omega_K]$

$$P_c(\beta) = \mathbb{P} [\gamma > \beta | \Omega]$$

$$P_c(\beta) = e^{-\beta_0 \sigma^2} \sum_{t=0}^{m_0-1} \frac{(\beta_0 \sigma^2)^t}{t!} \sum_{t=0}^{t} \left( \frac{t!}{\sigma^{2t}} \right) \sum_{t_i \geq 0} \left( \prod_{i=1}^{K} G_{t_i}(\Omega_i) \right),$$

where

$$G_{t_i}(\Omega_i) = p_t \left( \frac{\Omega_i}{m_i} \right)^{t_i} \frac{\Gamma(m_i + t_i)}{t_i! \Gamma(m_i)} \left[ \frac{\theta_t}{2\pi} \psi_{t_i}(G_t) + \left( 1 - \frac{\theta_t}{2\pi} \right) \psi_{t_i}(g_t) \right] + (1 - p_t) \delta[t_i],$$

$$\delta[t_i] = \begin{cases} 1 & \text{if } t_i = 0 \\ 0 & \text{if } t_i \neq 0 \end{cases},$$

$$\psi_{t_i}(x) = x^{t_i} \left( 1 + \frac{\beta_0 x \Omega_i}{m_i} \right)^{-(m_i + t_i)}$$
NUMERICAL RESULTS
Setting

- 5 X 9 rectangular grid
- Separation between nodes = 2R₀
- No reflection from boundaries
- All nodes transmit with same Pᵢ

Parameter | Value
---|---
R₀ | 1
m_L | 4
m_N | 2
α_L | 2
α_N | 4
W | 1
σ² | -20 dB
K | 44
Spectral efficiency for different antenna configurations

$p_t = 0.1$

Receiver at the center

Significant benefits to beamforming
Effect of receive antenna orientation

Receiver at the center

Receiver at a corner

Orientation of RX is more important in the corner

$p_t = 0.7$

$N_t = N_r = 16$
## Rate trends with $N_t$ and $N_r$

Assume 2.16 GHz BW of IEEE 802.11ad

<table>
<thead>
<tr>
<th>$N_t$</th>
<th>$N_r$</th>
<th>Ergodic spectral efficiency (bits/s/Hz)</th>
<th>Rate (Gb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Receiver at center</td>
<td>Receiver at a corner</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.499</td>
<td>1.063</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0.797</td>
<td>1.405</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>1.757</td>
<td>2.087</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.449</td>
<td>4.046</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3.210</td>
<td>5.072</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>5.437</td>
<td>7.078</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>3.618</td>
<td>5.027</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>4.635</td>
<td>6.396</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>6.952</td>
<td>8.434</td>
</tr>
</tbody>
</table>

$\rho_t = 1$

Gigabit throughputs are achieved even with a single transmit and receive antenna
Concluding remarks

- Wearable networks are the next frontier for D2D
  - MmWave can provide Gbps data rates to wearables
    - Substantial variation as a function of location

- Many issues remain to be studied
  - Protocols for wearables to support multi-band and het. devices
  - Channel models including self-body blocking
  - Performance analysis

QUESTIONS?