Design and Evaluation of the Ultra-Reliable Low-Latency Wireless Protocol EchoRing

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Machine-Type Communications: Origins

Autonomous monitoring & metering purpose
- End of 90s: First conceptual research on “sensor networks”
- Mid 2000: First standards (802.15.4, 6LowPAN)
- ~2010: Picked up by cellular networking industry (M2M business)
Closing the Loop …

- Closed-loop control (driven by autonomy trend)
- Dependability becomes the focus: Latency & reliability
  ➔ Critical machine-to-machine communications!
Critical M2M: Challenges

- Smart grid
  \[ T_{\text{max}} < 5 \text{ ms} \quad & \quad P_{\text{out}} < 10^{-5} \]
- Industrial automation
  \[ T_{\text{max}} < 1 \text{ ms} \quad & \quad P_{\text{out}} < 10^{-7} \]
- Traffic safety
  \[ T_{\text{max}} < 10 \text{ ms} \quad & \quad P_{\text{out}} < 10^{-5} \]
- Tactile interaction over a network
  \[ T_{\text{max}} < 10 \text{ ms} \quad & \quad P_{\text{out}} < 10^{-6} \]

Critical M2M possible at all? Efficient system design?
Communication at Finite Blocklength

- Shannon capacity used for principle design of networks
  \[ C_{IBL} = \log_2 (1 + \gamma) \text{ [bits / channel use]} \]

- Low latencies $\Rightarrow$ Shannon capacity inappropriate
  - Assumes infinitely long coding words

- Tight finite blocklength approximation:
  \[ r_{FBL} \approx C_{IBL} - \sqrt{\frac{V}{n}} \cdot Q^{-1} (\epsilon) \text{ [bits / channel use]} \]

  $V$: Channel dispersion, $n$: blocklength, $\epsilon$: block error rate

Y. Polyanskiy, H. Poor, and S. Verdu, “Channel coding rate in the finite blocklength regime,”
Communication at Finite Blocklength

- No error-free communication possible due to “above-average” noise effects
  - The lower the blocklength, the higher the rate reduction

- AWGN Channel
- SNR 10dB
- Target error prob. $10^{-5}$
- Perfect CSI
Design Options for Low-Latency Systems

- Maximize reliability → Exploit diversity:
  - Space & Frequency: Complex transceivers, low diversity degree
  - Multi-terminals (relaying): Simple transceivers, potentially higher diversity degree, but impacts the time budget!
Relaying vs. Direct Transmission

- AWGN channel, blocklength $2m$, perfect CSI, MRC
- Assume always scheduling with rate $r^*$
- Direct transmission:
  \[ \epsilon_{SD}(h_{SD}, r^*, 2m) \Rightarrow T_{DL} = (1 - \epsilon_{SD}) \cdot r^* \]
- Relaying:
  \[ \epsilon_R = \epsilon_{SD} \cdot \epsilon_{SR} + (1 - \epsilon_{SR}) \cdot \epsilon_{MRC} \]
  \[ \Rightarrow T_R = (1 - \epsilon_R) \cdot r^*/2 \]

Trade-off: Slot length vs. channel gain
AWGN Channel

Block Fading Channel

Multi-Terminal Setting

- So far: Relaying beneficial for low latency scenarios
  - FBL loss due to shorter slots overcompensated by better SNR

How does this effect multi-terminal scenarios?

Coordinated Industrial Communication, joint project with Ericsson – www.koi-projekt.de
Multi-terminal System Model

- Single cell TDMA system, $N$ transmitters, Rayleigh fading
System Analysis

- Scheduler selects most efficient path (direct or via relay)
- Consider IBL & FBL regime
- Metric: Packet error probability

1. Frame length is not sufficient (IBL & FBL)

Numerical Analysis – Increasing Load

All links 10 dB av. SNR, 1 ms frame length, 20 MHz bandwidth, perfect CSI at BS
From Theory to Practice

• Cooperation boosts reliability especially for low latencies

• Can this result per confirmed in practice?

• Main challenges:
  • Efficient protocol
  • Extremely reliable implementation
Efficient Protocol: EchoRing

- Guarantee medium access
- Distributed cooperative system

Token-passing protocol EchoRing

Distinct features:
- Fast exchange of CSI
- Cooperative ARQ
- Fault-tolerant link layer
- Reliability prediction

Related Work: Wireless token-passing does not work!
EchoRing – Cooperative ARQ

- Piggyback channel state information (CSI) with token
- Full CSI matrix at all stations after one rotation
- Dynamic relay selection primitive = “Echo”
Message Sequence Example

Regular Token Passing

EchoRing
EchoRing – Fault-tolerant Link Layer

- Token-passing protocols susceptible to channel errors
- Introduce *Recovery* state, observe further operation:
  - Recover to *Idle* under certain conditions (link error types)
  - Go *Offline* only if node appears to be permanently down
PTA Model-Checking of EchoRing

- Probabilistic timed automata (PTA):
  - Formal model for stochastic timed systems
  - Finite automaton extended with
    - Finite set of clocks
    - Probabilities on transitions

- Protocol (with stochastic parameters) $\rightarrow$ PTA
- Specification (requirement) $\rightarrow$ PTCTL formula
  - Probabilistic and timed extension of CTL

- Model-checking algorithms available for PTAs
  - Output: Correctness, prob. performance characteristics
  - State-space explosion
PTA Model-Checking II

- (Strongly) simplified token ring protocol for one station
PTA Evaluation Results

- Scenario: 5 station ring, channel error rates 5%
- Evaluate error probability after ten rotations

<table>
<thead>
<tr>
<th>Channel parameters</th>
<th>TkP</th>
<th>Rec</th>
<th>Echo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_s = 5\times10^{-2}$, $p_r = 5\times10^{-2}$, $c = 15%$</td>
<td>2.2E-2</td>
<td>7.2E-3</td>
<td>6.2E-5</td>
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<tr>
<td>$p_s = 1\times10^{-2}$, $p_r = 5\times10^{-2}$, $c = 15%$</td>
<td>3.3E-3</td>
<td>1.5E-3</td>
<td>1.2E-5</td>
</tr>
<tr>
<td>$p_s = 5\times10^{-2}$, $p_r = 5\times10^{-2}$, $c = 1%$</td>
<td>1.1E-2</td>
<td>2.9E-3</td>
<td>2.9E-7</td>
</tr>
<tr>
<td>$p_s = 1\times10^{-2}$, $p_r = 5\times10^{-2}$, $c = 1%$</td>
<td>5.9E-4</td>
<td>2.0E-4</td>
<td>1E-8</td>
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</tbody>
</table>

Prototyping Environment

FPGA-based WARP board
• 2 integrated radios
• 2 & 5 GHz carrier
• .11g compliant stack

• Programming:
  • PHY in Xilinx System Generator
  • Link layer in C
Experimental Evaluation - Settings

Scenario:
• 5 stations
• Indoor, low mobility
• 5 GHz band, no interference
• 100 Byte packet size
• ~10^8 transmitted packets

Schemes:
• Basic ring
• CSMA
• Recovery ring
• EchoRing

~10 x 20 meters
Experimental Evaluation I

Payload PER for Increasing Number of Stations

Experimental Evaluation II

Close-up latency behavior
Cooperative Node Selection – How?

\[
\begin{align*}
\min_{R \in C} p^*_{{SD}}(R) \\
\Leftrightarrow \min_{R \in C} p_{SD} \cdot (p_{SR} + (1 - p_{SR}) \cdot p_{RD}) \\
\Leftrightarrow \min_{R \in C} \frac{1}{\gamma_{SD}} \cdot \frac{1}{\gamma_{RD}} \\
\Leftrightarrow \min_{R \in C} \frac{1}{\gamma_{SD}} + \frac{1}{\gamma_{RD}}
\end{align*}
\]

Quadratic complexity in stations, fast implementation possible

<table>
<thead>
<tr>
<th>(M)</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
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</thead>
<tbody>
<tr>
<td>Duration [(\mu s)]</td>
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<td>29</td>
<td>69</td>
<td>127</td>
<td>202</td>
<td>294</td>
<td>405</td>
</tr>
</tbody>
</table>
What is a “significant” change in CSI?
CSI Report Thresholds - Impact
Conclusions & Future Work

• How to build a critical M2M system?
  • FBL analysis principle tool for system design
  • Relaying/cooperation are promising candidates
  • Rigorous development process required: PMC!
  • Practical experiments validate theoretical analysis
  • Not mentioned: Model vs. experimental performance

• Interesting other areas:
  • Interference
  • Security for low-latency wireless networks
  • Co-design of control loop and communication system