SHORT PACKET STRUCTURE FOR ULTRA-RELIABLE MACHINE-TYPE COMMUNICATION: TRADEOFF BETWEEN DETECTION AND DECODING

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Overview

• Machine-type Communications
• Short packet implications
• System model
• Packet structure
• Analysis
• Results and conclusion
Machine-type Communications

eMBB

5G

mMTC

uRLLC
Machine-type Communications

- eMBB
- 5G
- mMTC
- uRLLC

short packets
Machine-type Communications

- eMBB
- mMTC
- uRLLC

- High reliability: >99.999% during 1 ms
- Low latency: Physical layer latency <0.5 ms
- Co-existence

Short packet implications

- Coding limitations in finite blocklength regime
- Non-negligible control information overhead
- Considerable cost of packet detection

System model

Packet

$TX$
System model
System model
System model
System model

System model

• Point to point
• Data and ACK exchange with deadline
• One-shot (no retransmission opportunity)
• Unknown packet arrival time $\tau$
• Constant channel and known by TX & RX
Packet structure

- Zadoff-Chu detection sequences
  \[ R_{Y,\tau-k} = \Re \left[ \sum_{j=0}^{N_t-1} p_j^* Y_{j+\tau-k} \right] > \Delta \]
- Small \( N \) -> finite blocklength regime
- Spherical Gaussian codebook
System model (ctd.)

- Ideal (N)ACK reception and fixed structure
- Sequential receiver operation

\[ P_e = 1 - (1 - \epsilon_d)(1 - \epsilon_D) \]
System model (ctd.)

- Ideal (N)ACK reception and fixed structure
- Sequential receiver operation

\[ P_e = 1 - (1 - \epsilon_d)(1 - \epsilon_D) \]  

Detection errors:
- False alarm
- Misdetection

Decoding error

Diagram showing packet transmission, ACK/NACK reception, and recovery time.
Analysis

• PER upper bound

\[ P_e \leq \Pr[\varepsilon_{FA}] + \Pr[\varepsilon_{MD}] + \Pr[\varepsilon_D] \]
Analysis

- PER upper bound

\[ P_e \leq \Pr[\varepsilon_{FA}] + \Pr[\varepsilon_{MD}] + \Pr[\varepsilon_D] \]

- False alarm

\[ \mathcal{R}_{Y,\tau-k} > \Delta, \forall k \in \{1, ..., t_r - 1\} \]

Diagram:
- Detection window
- Detection sequence
- AWGN
- \( \tau \)
- \( \tau - (t_r - 1) \)
Analysis

- **PER upper bound**

\[ P_e \leq \Pr[\varepsilon_{FA}] + \Pr[\varepsilon_{MD}] + \Pr[\varepsilon_{D}] \]

- **False alarm**

\[ R_{Y,\tau-k} > \Delta, \forall k \in \{1, \ldots, t_r - 1\} \]
Analysis

• PER upper bound

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• False alarm

\[ R_{Y,\tau-k} > \Delta, \forall k \in \{1, \ldots, t_r - 1\} \]

• Misdetection

\[ R_{Y,\tau} \leq \Delta \]
Analysis

• PER upper bound

\[ P_e \leq \Pr[\varepsilon_{\text{FA}}] + \Pr[\varepsilon_{\text{MD}}] + \Pr[\varepsilon_{\text{D}}] \]

• False alarm

\[ \mathcal{R}_{Y,\tau-k} > \Delta, \forall k \in \{1, \ldots, t_r - 1\} \]

• Misdetection

\[ \mathcal{R}_{Y,\tau} \leq \Delta \]

• Decoding error

\[ \epsilon_D(N_c, P) = Q\left(\frac{2N_cC(P) - b + \frac{1}{2}\log_2 2N_c}{\sqrt{2N_cV(P)}}\right) \] [2, 4]

Time-multiplexed preamble

- A false alarm can occur at any \( k \in S_{FA} = \{1, \ldots, t_r - 1\} \).

\[
\Pr[\mathcal{R}_{Y,T-k} > \Delta] = \Phi\left(\frac{\Delta - \mu_{R_{FA}}(k)}{\sigma_{\mathcal{R}_{Y,FA}}(k)}\right)
\]
Time-multiplexed preamble

- A false alarm can occur at any $k \in S_{FA} = \{1, ..., t_r - 1\}$.

\[
\Pr[\mathcal{R}_{Y,\tau-k} > \Delta] = Q \left( \frac{\Delta - \mu_{\mathcal{R}_{Y,FA}}(k)}{\sigma_{\mathcal{R}_{Y,FA}}} \right)
\]

\[
\Pr[\varepsilon_{FA}] = \Pr \left[ \bigcup_{k \in S_{FA}} \{\mathcal{R}_{Y,\tau-k} > \Delta\} \right] \leq \sum_{k=1}^{t_r-1} Q \left( \frac{\Delta - \mu_{\mathcal{R}_{Y,FA}}(k)}{\sigma_{\mathcal{R}_{Y,FA}}} \right).
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\]

- The probability of misdetection

\[
\Pr[\varepsilon_{MD}] = Q\left(\frac{\mu_{\mathcal{R}_{Y,\tau}} - \Delta}{\sigma_{\mathcal{R}_{Y,\tau}}}\right)
\]
Superimposed sequence

1. Noise inflicted false alarms when $k \in S_{FA1} = \{N, \ldots, t_r - 1\}$

\[
Pr[\varepsilon_{FA1}] \leq (t_r - N)Q\left(\frac{\Delta}{\sigma_{Y,FA1}}\right), \text{ where } \sigma_{R,Y,FA1}^2 = \frac{N}{2}.
\]
Superimposed sequence

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\]

2. Partial correlation inflicted false alarms when \( k \in S_{FA2} = \{1, ..., N - 1\} \)

\[
\Pr[\varepsilon_{FA2}] = \Pr\left[\bigcup_{k \in S_{FA2}} \{R_{Y,\tau-k} > \Delta\}\right] \approx \sum_{k=1}^{N-1} Q\left(\frac{\Delta - \mu_{R_{Y,FA2}}(k)}{\sigma_{R_{Y,FA2}}(k)}\right).
\]

\( \tau - (t_r - 1) \)

\( \tau \)

\( \tau - (N - 1) \)
Superimposed sequence

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and $\sigma_{R_Y,FA2}^2(k) = \frac{N}{2} + \frac{N-k}{2} (1 - \alpha)P$
Superimposed sequence

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and $\sigma_{R,Y,FA2}^2(k) = \frac{N}{2} + \frac{N-k}{2} (1 - \alpha)P$.  

$\tau - (t_r - 1)$  

$\tau - (N - 1)$  

$\tau - 1$  

$\tau$  

$\tau$  

$\tau$  

$\tau$
Superimposed sequence

1. Noise inflicted false alarms when \( k \in S_{FA1} = \{N, ..., t_r - 1\} \)

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\Pr[\varepsilon_{FA1}] \leq (t_r - N) Q \left( \frac{\Delta}{\sigma_{R_Y,FA1}} \right), \text{ where } \sigma^2_{R_Y,FA1} = \frac{N}{2}.
\]

2. Partial correlation inflicted false alarms when \( k \in S_{FA2} = \{1, ..., N - 1\} \)

\[
\Pr[\varepsilon_{FA2}] = \Pr \left[ \bigcup_{k \in S_{FA2}} \{R_{Y,\tau-k} > \Delta\} \right] \approx \sum_{k=1}^{N-1} Q \left( \frac{\Delta - \mu_{R_Y,FA2}(k)}{\sigma_{R_Y,FA2}(k)} \right).
\]

and \( \sigma^2_{R_Y,FA2}(k) = \frac{N}{2} + \frac{N-k}{2} (1 - \alpha) P \)

3. Misdetection probability

\[
\Pr[\varepsilon_{MD}] \approx Q \left( \frac{\mu_{R_Y,\tau} - \Delta}{\sigma_{R_Y,\tau}} \right)
\]
Packet structure optimization

- Formulate the problem as a minimization of the upper bounds on the PER

\[ P_e \leq \Pr[\varepsilon_{FA}] + \Pr[\varepsilon_{MD}] + \Pr[\varepsilon_{D}] \]
Packet structure optimization

- Formulate the problem as a minimization of the upper bounds on the PER

\[ P_e \leq Pr[\varepsilon_{FA}] + Pr[\varepsilon_{MD}] + Pr[\varepsilon_D] \]

Preamble case:

\[ \min_{N_p \in \{1, \ldots, N-1\}} \min_{\Delta \geq 0} P_e^{pre}(\Delta, N_p, N, P) \]
Packet structure optimization

- Formulate the problem as a minimization of the upper bounds on the PER

\[ P_e \leq \Pr[\varepsilon_{FA}] + \Pr[\varepsilon_{MD}] + \Pr[\varepsilon_D] \]

Preamble case:

\[ \min_{N_p \in \{1, \ldots, N-1\}} \Delta \geq 0 \quad P_{e\text{pre}}^N (\Delta, N_p, N, P) \]

Superimposed case:

\[ \min_{\alpha \in (0,1)} \Delta \geq 0 \quad P_{e\text{SI}}^N (\Delta, \alpha, N, P) \]
Numerical results

\[ b = 128, \quad N = 257, \quad t_r = 1.1N \]
Optimal vs. pragmatic approach

- Optimal SI
- Optimal preamble
- Pragmatic preamble

\[ b = 128, R_{\text{eff}} = \frac{b}{N}, t_r = 1.1N \]
Conclusion and further work

- Showcase the importance of considering overhead when transmitting short packets
- Compared two packet structures
- Provided an upper bound and an approximation for evaluating short packet error probability
- Include ACK error probability and ACK structure
- Improve detection metric to take into account the received signal energy