Building Robust Wireless LAN for Industrial Control with DSSS-CDMA Cell Phone Network Paradigm

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The demand for real-time wireless communication is increasing.

Mechanical Freedom / Mobility
Ease of Deployment / Flexibility
The demand for real-time wireless communication is increasing.

Cables for connecting various monitors to anesthesia EMR
The demand for real-time wireless communication is increasing.

Reduce the risk of tripping over wires
What is real-time? Robotic Surgery: each task is a continuous loop of sensing (or actuating) jobs

Each job:
1. Must catch deadline
2. Does not have to be fast
What is real-time? Aviation and Industrial Control: each task is a continuous loop of sensing (or actuating) jobs

Each job:
1. Must catch deadline
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What is real-time? A typical real-time task is a continuous loop of periodic jobs.

Job: (Period, Exe. Time, Deadline)
What is real-time? A typical real-time task is a continuous loop of periodic jobs.

Job: \((\text{Period}, \text{Exe. Time}, \text{Deadline})\)

Real-time = each job catches deadline

Real-time \(\neq\) running fast
Reliability and Robustness is the top concern for real-time wireless communication.

Cannot back off under adverse wireless channel conditions
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Reliability and Robustness is the top concern for real-time wireless communication.

Adverse wireless medium

- Large scale path-loss
- Multipath
- Persistent electric-magnetic interference
- Same-band / adjacent-band RF devices
Nowadays wireless LANs are NOT real-time.
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IEEE 802.11 packet loss rate in an industrial environment [Willig02]
Nowadays wireless LANs are NOT real-time.

IEEE 802.11 packet loss rate in an office environment [Ploplys04]
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IEEE 802.11 packet loss rate in an office environment [Ploplys04]

Why?
Design philosophy mismatch: pursuing large data throughput & short delay
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Send packet fast
Do not spend much time accumulate strength
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Observation: Real-time communications are usually persistent connections with low data rate.

Typical inter-node traffic:
100~200 bit/pkt, 10~1 pkt/sec per connection.
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Information Theory:
Lower data rate $\Rightarrow$ higher robustness.
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Information Theory:
Lower data rate $\Rightarrow$ higher robustness.

Direct Sequence Spread Spectrum (DSSS) Technology:
Lower data rate $\Leftrightarrow$ Higher robustness.
Tutorial on DSSS
Tutorial on DSSS

Data stream, a.k.a. bit stream. Bit rate: \( r_b \).
Tutorial on DSSS


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Definition: Processing Gain
\[ g := \frac{R_c}{r_b} \]
Tutorial on DSSS

Pseudo Noise Sequence (PN) Stream, a.k.a chip stream. Chip rate: $R_c$.

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DSSS Modulated Stream, a.k.a Scrambled Stream
Tutorial on DSSS

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**Tutorial on DSSSS**

**Pseudo Noise Sequence (PN) Stream, a.k.a. chip stream.** Chip rate: \( R_c \).

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**DSSS Modulated Stream, a.k.a. Scrambled Stream**

**Definition:**
Processing Gain \( g := \frac{R_c}{r_b} \).

**Same PN Sequence**

- PN of 100010... (+1 for “1”, -1 for “0”)
- Data bit of 10... (+1 for “1”, -1 for “0”)
- DSSS Modulated chips of 100101...
- RF mod / RF transmission / RF demod
- DSSS Modulated chips of 100101...
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- Original Data

- Decision Logic
- Received bit
Tutorial on DSSS

Pseudo Noise Sequence (PN) Stream, a.k.a chip stream. Chip rate: $R_c$.

Definition: Processing Gain $g := R_c/r_b$.

Same PN Sequence

Integration = $gE_c$ for each bit ($E_c$ is the energy of a chip)

Data stream, a.k.a a bit stream. Bit rate: $r_b$.

DSSS Modulated Stream, a.k.a Scrambled Stream

Original Data

Data bit of 10... (+1 for "1", -1 for "0")

PN of 100010... (+1 for "1", -1 for "0")

RF mod / RF transmission / RF demod

DSSS Modulated chips of 100101...

+1 -1 +1 -1 +1...

-1 -1 -1 -1 -1...

DSSS Modulated chips of 100101...

-1 +1 -1 +1 -1...

+1 -1 -1 -1 -1...

Decision Logic

+1

-1

-1

...
Tutorial on DSSS

If a different PN Sequence is applied
If a different PN Sequence is applied

Another scrambled sequence
Tutorial on DSSS

If a different PN Sequence is applied

Integration = Gaussian Noise

Another scrambled sequence
Observation

\[ P_{ber} \leq \exp \left( - \frac{g P_u}{J + \sum_{i=1, i \neq u}^{\Xi} P_i + \sum_{h=1}^{H} A_h + P_u} \right) \]

- DSSS Technology:
  
  Larger Processing Gain \( g \) \( \iff \) Lower data rate \( \iff \) Lower Bit Error Rate (Higher robustness)
Observation: DSSS can exploit low data rate to achieve higher robustness

\[ P_{BER} \leq \exp(-gK) = \exp\left(-\frac{K}{r_b}\right) \]

DSSS BER Upper Bound
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DSSS BER Upper Bound
Lower data rate \( r_b \)
Observation: DSSS can exploit low data rate to achieve higher robustness

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DSSS BER Upper Bound

Lower data rate \( r_b \overset{\leftrightarrow}{=} \) Larger Processing Gain \( g \)
Observation: DSSS can exploit low data rate to achieve higher robustness

\[
P_{BER} \leq \exp(-gK) = \exp\left(-\frac{K}{r_b}\right)
\]

DSSS BER Upper Bound
- Lower data rate \( r_b \) \( \leftrightarrow \) Larger Processing Gain \( g \) \( \leftrightarrow \)
- Lower Bit Error Rate \( P_{BER} \) (higher robustness)
Key Idea: How to configure for max robustness for adverse wireless medium?
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Answer: Use DSSS, deploy as slow data rate $r_b$ (i.e., as large processing gain $g$) as the application allows.

\[
P_{BER} \leq \exp(-gK) = \exp\left(-\frac{K}{r_b}\right)
\]
Solution Heuristics

DSSS with low data rate for high robustness

PHY:DSSS
Observation: Centralized, last-hop wireless scheme is preferred

Centralized: Economical & Simple

PHY: DSSS
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Centralized: Economical & Simple

Last-Hop: reuse legacy wired backbone

PHY: DSSS
Solution Heuristics

DSSS with low data rate for high robustness

Centralized WLAN paradigm
Observation: CDMA is better than TDMA (e.g., IEEE 802.11 PCF).
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Smaller overhead under adverse channel conditions.
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- Smaller overhead under adverse channel conditions
- Easier to schedule
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- Smaller overhead under adverse channel conditions
- Easier to schedule
- Better overrun isolation
Centralized WLAN paradigm

DSSS with low data rate for high robustness

CDMA instead of TDMA
Solution Heuristics ➔ Choose DSSS-CDMA cell phone network paradigm!

- DSSS with low data rate for high robustness
- Centralized WLAN paradigm
- CDMA instead of TDMA
Simulation and Comparisons

Wireless medium model complies with typical settings for industrial environments [Rappaport02]:

<table>
<thead>
<tr>
<th>Table 1. Wireless Medium Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale path loss model</td>
</tr>
<tr>
<td>Small-scale fading model</td>
</tr>
<tr>
<td>Multipath max excess delay</td>
</tr>
<tr>
<td>Additive White Gaussian Noise†</td>
</tr>
</tbody>
</table>

* $\beta$ is the path loss exponent, $\sigma$ is the log-normal standard deviation.
† Typically refers to thermal noise.
A simulated demo showing DSSS-CDMA tolerates RF jamming, while IEEE 802.11b cannot

IP2 at (-3, 2)

IP1 at (4, 0)

Base station at (0, 0)
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Typical industrial environment wireless medium model

IP2 at \((-3, 2)\)

Base station at \((0, 0)\)

IP1 at \((4, 0)\)
A simulated demo showing DSSS-CDMA tolerates RF jamming, while IEEE 802.11b cannot

Typical industrial environment wireless medium model

Basetation at (0, 0)  BS  Basestation at (0, 0)

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external RF interference source at (7, 0)
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Comparison:
DSSS-CDMA: lowest data rate
IEEE 802.11b: keep retransmitting

Base Station at (0, 0) [BS]

IP1 at (4, 0)

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External RF interference source at (7, 0)
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A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

Monte-Carlo simulation setup
- 20m x 20m room, base station at the center
- \( n (n = 1, \ldots, 100) \) remote stations, random layout
- 200 trails for each \( n \)
- Typical industrial environment wireless medium model

Robustness Method:
- DSSS-CDMA: lowest data rate
- IEEE 802.11a/b: keep retransmitting
A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

802.11:
- Use the most robust mode:
  - 802.11b (DSSS): 1, 2, 5.5, 11Mbps
  - 802.11a (OFDM): 6, 9, 12, 18, 24, 36, 48, 54Mbps
- Under adverse channel conditions, 802.11 keeps retransmitting (PCF).

DSSS-CDMA
- Deploy as slow data rate as (i.e., as large processing gain $g$ as) the application allows (proposition 1).
- Keep transmitting even under adverse channel conditions.
Table 2. Physical Layer Settings for Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Max trans power*</th>
<th>RF band†</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSS-CDMA vs. IEEE 802.11b comparison</td>
<td>1watt</td>
<td>2.425 ~</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.449GHz</td>
</tr>
<tr>
<td>DSSS-CDMA vs. IEEE 802.11a comparison</td>
<td>800mw</td>
<td>5.735 ~</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.795GHz</td>
</tr>
</tbody>
</table>

* According to FCC regulation.
† According to IEEE 802.11 specification. Note RF bandwidth also decides baseband bandwidth (i.e. chip rate for DSSS and bit rate for OFDM).
A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b

(a) Comparison with IEEE 802.11b
A Monte-Carlo simulation showing DSSS-CDMA is more robust than IEEE 802.11a/b
Monte Carlo comparison with IEEE 802.15.4
Monte Carlo comparison with IEEE 802.15.4
Monte Carlo comparison with IEEE 802.15.4

![Graph showing comparison between DS–CDMA and 802.15.4iii]

- DS–CDMA, $f_{\text{min}} = 1\text{Hz}$, $g = 3289$
- 802.15.4iii, $f_{\text{min}} = 1\text{Hz}$
- DS–CDMA, $f_{\text{min}} = 10\text{Hz}$, $g = 329$
- 802.15.4iii, $f_{\text{min}} = 10\text{Hz}$
Feasibility of Convolutional Coding

$k$ input bits, $m$ shift registers
Conclusion

“DSSS-CDMA Cell Phone Paradigm + Slowest Data Rate” is more robust than “IEEE 802.11 + Retransmission”.
"DSSS-CDMA Cell Phone Paradigm + Slowest Data Rate" is more robust than "IEEE 802.11 + Retransmission".

For real-time wireless LAN, change philosophy from pursuing throughput/delay to pursuing reliability/robustness.
Thank You!
Publications

Journal Publications:

Conference, Workshop and Other Publications:
6. **[HCMDSS07a]** Mu Sun, Qixin Wang, and Lui Sha, "Building Safe and Reliable MD PnP Systems", in Joint Workshop on High Confidence Medical Devices, Software, and Systems (HCMDSS) and Medical Devices Plug-and-Play (MD PnP), June, 2007.