Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [UWB Direct Chaotic Communications Technology]

Date Submitted: [15 November, 2004]

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Re: [IEEE 802.15.4a Call for Proposals]

Abstract: [This document proposes preliminary proposal for the IEEE 802.15.4a PHY standard based on the UWB direct chaotic communications technology.]

Purpose: [This document proposes preliminary proposal for the IEEE 802.15.4a PHY standard.]

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UWB Direct Chaotic Communications Technology

Presented by:

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Samsung Advanced Institute of Technology (SAIT), Korea
Outline

• Introduction to Chaotic Signal
• Principle of Direct Chaotic Communications (DCC)
• Chaotic Modulation Schemes
• System Performance of DC-OOK
• Conclusion
What is Dynamical Chaos?

- Dynamical chaos is aperiodic long-term behavior in a deterministic system that exhibits sensitive dependence on initial conditions.
- Described by differential equations – dimension $\geq 3$ for chaotic behavior.
Dynamical Chaos

Example Logistic map: \((n+1) = X^2(n) + P\)

\(P = -\frac{3}{4}\)

\(P = -\frac{13}{16}\)

\(P = -1.4015\)

\(P = -1.8\)
Beauty of Dynamical Chaos
Characteristics of Chaotic Signal (1)

- **Simple circuits**
  - Information-carrying chaotic signal can be generated directly into the microwave band by a predefined chaotic generator

- **Low power circuits**
  - The chaotic generator is a non-linear system

- **Large number of codes**
  - Sensitivity to initial conditions – infinite sets of trajectories can be produced in a finite region of *phase space*
  - Possibility of multiple access

- **Multipath resistance**
  - Wideband signal is very immune against multipath fading

- **Self-inherent spread spectrum**
  - Use chaotic basis functions as the spreading signal for spread spectrum system

- **Good spectral properties**
  - Aperiodic with a flat (or tailored) spectrum

- **Security/Confidentiality**
  - Low probability of detection and intercept due to the noise like signal of chaos properties

- **Flexibility**
  - Chaotic radio pulse with different time duration can have the same bandwidth
Characteristics of Chaotic Signal (2)
Characteristics of Chaotic Signal (3)
Methods to Generate Chaos

• Chaotic Masking
• Chaotic Shift Keying
• Non-Linear Masking
• Direct-Chaotic Communication
Direct Chaotic Communication (DCC)

- Chaotic source generates oscillations directly in a specified microwave band.
- Information component is put into the chaotic carrier using the stream chaotic radio pulses.
- Information is retrieved from the chaotic radio pulses without intermediate heterodyning.
- Most simple non-coherent receiver is used.
Direct Chaotic Signal Generation

Direct Chaos Generator

Binary Information

Chaotic Radio Pulse

Time Signal

Frequency Spectrum
Chaotic Generator Model

Oscillator circuit

Experiment device
Chaotic Mathematical Model

- 2nd order differential equation implemented by ODE with 4.5 freedom

System Equations

\[
\begin{align*}
T \dot{x}_1 + x_1 &= mF(x_5) \\
\dot{x}_2 + \alpha_2 x_2 + \omega_2^2 x_2 &= \omega_2^2 x_1 \\
x_3 + \alpha_3 \dot{x}_3 + \omega_3^2 x_3 &= \alpha_3 x_2 \\
x_4 + \alpha_4 \dot{x}_4 + \omega_4^2 x_4 &= \alpha_4 x_3 \\
x_5 + \alpha_5 \dot{x}_5 + \omega_5^2 x_5 &= \alpha_5 x_4
\end{align*}
\]

Runge-Kutta Method

\[
\begin{align*}
y(1) &= \left( mF(x_5) - X1 \right)/T; \\
y(2) &= W1^2 \left( X1 - X3 \right); \\
y(3) &= X2 - A1^2 X3; \\
y(4) &= A2^2 y(3) - W2^2 W2^2 X5; \\
y(5) &= X4 - A2^2 X5; \\
y(6) &= A3^2 y(5) - W3^2 W3^2 X7; \\
y(7) &= X6 - A3^2 X7; \\
y(8) &= A4^2 y(7) - W4^2 W4^2 X9; \\
y(9) &= X8 - A4^2 X9;
\end{align*}
\]

Nonlinearity

\[
F(z) = M \left[ |z + e_1| - |z - e_1| + \frac{|z - e_2| - |z + e_2|}{2} \right]
\]
Frequency Band Plan (1)

FCC Spectrum Mask for UWB

-41.3 dBm/MHz
25 dBm/MHz

GPS 0.96-1.61 GHz
2.4 GHz WLAN, Bluetooth

5 GHz WLAN
Frequency Band Plan (2)

- Operating Frequency: 3.1–5.1 GHz
- Why Lower Band?
  - Limitation in the technical capabilities of integrated circuit implementation at higher frequency.
  - Limit of low cost ICs beyond 6 GHz.
  - Prevent coexistence with 5 GHz WLAN band.
  - Use as much bandwidth as possible to maximize the emitted power and follows FCC rules i.e. >500MHz.
- Can be easily change to use higher band if necessary or when cheap technologies available in the future.
FCC Emission Mask

- Frequency, GHz
- UWB EIRP Emission Level in dBm

Graph showing the FCC Emission Mask with frequency on the x-axis and UWB EIRP Emission Level in dBm on the y-axis.
# Types of Chaotic Modulation Schemes

<table>
<thead>
<tr>
<th>Class</th>
<th>System</th>
<th>Correlator type detection applicable</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog</td>
<td>Chaotic masking</td>
<td>No</td>
<td>Kocarev et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cuomo and Oppenhiem.</td>
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<td></td>
<td></td>
<td></td>
<td>Milonovic and Zaghloul</td>
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<tr>
<td>Coherent</td>
<td>Generic:</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chaos shift keying (CSK)</td>
<td>Yes</td>
<td>Kolumban et al.</td>
</tr>
<tr>
<td></td>
<td>CSK (correlation)</td>
<td>Yes</td>
<td>Sushchick et al.</td>
</tr>
<tr>
<td></td>
<td>Symmetric CSK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>DS spread spectrum:</td>
<td>Yes</td>
<td>Heidari-Bateni and McGillem.</td>
</tr>
<tr>
<td></td>
<td>Chaotic spreading sequence</td>
<td>Yes</td>
<td>Yang and Chua</td>
</tr>
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<td></td>
<td>Chaotic digital CDMA</td>
<td>Yes</td>
<td>Mazzini et al.</td>
</tr>
<tr>
<td></td>
<td>Quantized chaotic spreading sequence</td>
<td></td>
<td></td>
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<tr>
<td>Non-Coherent</td>
<td>Analog</td>
<td>No</td>
<td>Itoh-Murakami</td>
</tr>
<tr>
<td></td>
<td>Signal reconstruction based system</td>
<td>No</td>
<td>Feng and Tse</td>
</tr>
<tr>
<td>Digital</td>
<td>Differential CSK (DCSK)</td>
<td>Yes</td>
<td></td>
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<tr>
<td></td>
<td>FM-DCSK</td>
<td>Yes</td>
<td>Kolumban et al.</td>
</tr>
<tr>
<td></td>
<td>Chaotic On-Off Keying (COOK)</td>
<td>No</td>
<td>Kolumban et al.</td>
</tr>
<tr>
<td></td>
<td>CSK (bit-energy)</td>
<td>No</td>
<td>Kolumban et al.</td>
</tr>
<tr>
<td></td>
<td>CSK (optimal)</td>
<td>No</td>
<td>Kolumban et al.</td>
</tr>
<tr>
<td></td>
<td>CSK (regression)</td>
<td>No</td>
<td>Hasler and Schimming</td>
</tr>
<tr>
<td></td>
<td>Correlation delay shift keying</td>
<td>Yes</td>
<td>Tse et al.</td>
</tr>
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<td></td>
<td>Quadrature CSK</td>
<td>Yes</td>
<td>Sushchick et al.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Galias and Maggio</td>
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</table>
DC-OOK Transmitter & Receiver

Transmitter

Direct Chaos Generator

…1001011

Receiver

Multipath Channel

Envelope detector

\((\ldots)^2\)

Threshold decision
DC-OOK Transceiver Architecture

- Very simple modulation scheme: on-off power supply is used for modulation (OOK)
- Additional power saving
Signal Waveforms and Spectrum

Signal of chaotic generator

Modulated signal
PHY Frame Structure

PHY Packet Fields

- Preamble (32 bits) – synchronization
- SFD (Start of Frame Delimiter) (8 bits) – specifies frame type
- PHR (PHY Header) (8 bits) – Sync Burst flag, PSDU length
- PSDU (PHY Service Data Unit) (0 to 127 bytes) – Data field

\[ T_s = 100 \text{ ns} : \text{Pulse emission time} \]
\[ T_m = 200 \text{ ns} : \text{Pulse bin width} \]
System Performance

Signal structure (COOK)

$T_s = 100 \text{ ns, } T_m = 200 \text{ ns}$

$T_s = 50 \text{ ns, } T_m = 100 \text{ ns}$

AWGN channel

$E_b/N_0 \text{ [dB]}$
UWB-DCC System
Test Bed (3.1–5.1 GHz)
UWB-DCC Experiments: 3.1–5.1 GHz
Conclusions

• Chaotic communications meet the low power, low cost & low complexity requirements.
• Proposed UWB-DCC-COOK compliant with FCC PSD regulation.
• The implemented test bed demonstrated that the feasibility of DCC technology.
• Current investigation issues:
  – UWB-DCSK modulation scheme for more robust performance.
  – Suitable location awareness techniques.
  – Multiple access solution for simultaneous operating piconets (SOP).