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

Submission Title: M-ary Code Shift Keying/Binary PPM (MCSK/BPPM) Based Impulse Radio

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Abstract: [Proposed modulation format increases the ranging and location capability of time hopping impulse radios]

Purpose: [Proposal for the IEEE802.15.4a standard]

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Proposal for
IEEE 802.15.4 Alternate PHY

M-ary Code Shift Keying/Binary PPM
(MCSK/BPPM) Based Impulse Radio

SFU, Canada & UWB-ITRC, Inha University
Republic of Korea
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# TG4a Requirements

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<th>802.15.4a PHY</th>
<th>MCSK/BPPM compared to TH-BPPM</th>
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<tr>
<td>scalable information rates</td>
<td><strong>Better BER performance</strong> at the same/higher information rates and lower transmit power</td>
</tr>
<tr>
<td>high precision ranging/location</td>
<td><strong>Improved ranging/location precision</strong> capability</td>
</tr>
<tr>
<td>low power consumption</td>
<td><strong>Lower transmit power</strong> at the same/higher information rates and better BER performance</td>
</tr>
<tr>
<td>low complexity and cost</td>
<td>No new circuit is needed / simple transceiver structure</td>
</tr>
</tbody>
</table>

*MCSK/BPPM: M-ary Code Shift Keying/Binary Pulse Position Modulation*

**TH-BPPM: Time Hopping Binary Pulse Position Modulation**
MCSK/BPPM

TH PPM – user #1

\[ d^{(1)} = [1 \ 1 \ 0 \ 1 \ 0 \ 1 \ldots] \]

1 user specific TH code

MCSK/BPPM – user #1

\[ d^{(1)} = [1 \ 1 \ 0 \ 1 \ 0 \ 1 \ldots] \]

choose a code

\( M = 4 \)

M user specific TH codes

only for multiple access

for multiple access and data modulation

TH-BPPM

\[ 1 \ 1 \ 0 \ 1 \]

\( 0 \ T_b \ 2T_b \ 3T_b \)

\( T_b \) : Bit time

\( T_f \) : Frame time
PHY TX Structure (1/2)

M user specific TH codes

- TH codes are periodic with $N_p$
- each pulse should be repeated $N_s$ times
- $N_p/N_s=k$ is an integer

Example: $M=4, N_p=8, N_s=4$

$d = [1 \ 0 \ 1 \ 1 \ ...]$  \[ TH = \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \end{bmatrix} = \begin{bmatrix} 7 & 8 & 2 & 3 & 6 & 4 & 1 & 5 \\ 3 & 6 & 5 & 2 & 8 & 7 & 4 & 1 \\ 5 & 8 & 7 & 3 & 1 & 4 & 2 & 6 \\ 2 & 4 & 8 & 6 & 3 & 7 & 5 & 1 \end{bmatrix} \]

$C_2 \rightarrow 5 \ 8 \ 7 \ 3 \ T_b \ 1 \ 4 \ 2 \ 6 \ 2T_b$

$t = 0 \ T_f \ 2T_f \ 3T_f \ 4T_f \ 5T_f \ 6T_f \ 7T_f \ 8T_f$

$d = [1 \ 0 \ 1 \ 1 \ ...]$  \[ T_b : \text{Bit time} \]

$T_f : \text{Frame time}$
PHY TX Structure (2/2)

- TH codes are periodic with $N_p$
- each pulse should be repeated $N_s$ times
- $N_p/N_s=k$ is an integer

Information rate vs. BER performance for fixed $N_s$ and varying $N_p$ and $M$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Time domain illustration</th>
<th>Info. rate</th>
<th>BER performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_p / N_s = 1$</td>
<td>2 bits (MCSK)</td>
<td>$M$ same</td>
<td>$N_p/N_s$ same</td>
</tr>
<tr>
<td>$M = 4$</td>
<td>1 bit (BPPM)</td>
<td>$T_b$</td>
<td>$T_f$ : Frame time</td>
</tr>
<tr>
<td>$N_p / N_s = 1$</td>
<td>3 bits (MCSK)</td>
<td>$M$ increasing</td>
<td></td>
</tr>
<tr>
<td>$M = 8$</td>
<td>1 bit (BPPM)</td>
<td>$T_b$</td>
<td>$T_f$ : Frame time</td>
</tr>
<tr>
<td>$N_p / N_s = 2$</td>
<td>3 bits (MCSK)</td>
<td>$M$ same</td>
<td>$N_p/N_s$ increasing</td>
</tr>
<tr>
<td>$M = 8$</td>
<td>1 bit (BPPM)</td>
<td>$T_b$</td>
<td>$T_f$ : Frame time</td>
</tr>
</tbody>
</table>

$T_b$ : Bit time

$T_f$ : Frame time

1 bit (BPPM)
TH Code Assignment (1/2)

Each user has *M* user specific TH codes $\rightarrow N_u N_p M$ sample-long sequence

**Generation of TH codes – “Case 1: random assignment”**

For $T_f = 100\text{ns}$, $T_c = 1\text{ns}$: 100 slots for multiple access $\rightarrow 2^l \equiv N_h; \ l = 6, \ N_h = 64$

m-sequence: 

\[
\begin{array}{cccccccc}
1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 1 & 1 & 1 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\
\ldots \\
\end{array}
\]

\[
\begin{array}{ccccc}
46 & 20 & 55 & 46 & 31 & 61 & 14 & 56 & 5 & 7 & 24 & 26 & 53 & 45 & 35 & 2 & \ldots \\
\end{array}
\]

$N_p = 4$

\[
\begin{array}{cccc}
46 & 20 & 55 & 17 \\
20 & 13 & 12 & 31 \\
\end{array}
\]

$M = 4$

\[
\begin{array}{cccc}
C_0 & C_2 & C_3 \\
C_1 \\
\end{array}
\]

user #1

\[
\begin{array}{cccc}
46 & 20 & 55 & 17 \\
20 & 13 & 12 & 31 \\
\end{array}
\]

\[
\begin{array}{cccc}
C_0 & C_2 & C_3 \\
C_1 \\
\end{array}
\]

user #2

\[
N_u N_p \Rightarrow N_u \left( N_p + M - 1 \right)
\]
TH Code Assignment (2/2)

Generation of TH codes – “Case 2: no overlapping”

\[
\begin{align*}
N_p &= 4 \\
M &= 4 \\
\text{no collisions allowed within user codes}
\end{align*}
\]

\[
\begin{bmatrix}
46 & 20 & 55 & 17 \\
20 & 55 & 17 & 20 \\
55 & 17 & 20 & 13 \\
17 & 20 & 13 & 12 \\
17 & 13 & 12 & 31
\end{bmatrix}
\]

\[
\begin{bmatrix}
61 & 14 & 56 & 5 \\
7 & 24 & 26 & 53 \\
45 & 35 & 2 & \ldots
\end{bmatrix}
\]

\[
N_u N_p \Rightarrow N_u \left( N_p + M - 1 \right) + n
\]

\( n \): number of overlaps
General Modulation Format

- Extra information
- Random selection of TH codes → Improved spectrum

Binary PPM (BPPM)

$$s(t) = \sum_{j=0}^{\log_2 M} w(t - jT_c - \delta d_j)$$

TH-BPPM

Selection of TH codes
$$\{ c_n^{(i)} \}_{j=0}^{N_p}$$

Fixed signal space
Increased information rate

$$R_s = \left( 1 + \frac{\log_2 M}{N_p / N_s} \right) \cdot R$$

$$T = \{ d_i : i = 1, ..., (N_p / N_s) \}$$

$$C = \{ d_i : i = (N_p / N_s) + \log_2 M \}$$

B = T U C

user k data stream

log_2 M bits

$$(N_p / N_s) \text{ bits}$$

$$(N_p / N_s) \text{ bits}$$
Receiver Structure - MLSE

Template signals: $2M$

Hardware structure:
- 1 correlator

Computation complexity:
$$2^M\left(\frac{N_p}{N_s}\right)M$$
Information Rate (1/3)

\[
R_s = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) \cdot R
\]

TH-BPPM
Ns = 2, M=1

MCSK/BPPM
“Constant Energy/Bit” Constraint
Ns = 2, Np=2, M=2

MCSK/BPPM
“Constant Power” Constraint
Ns = 2, Np=2, M=2

MCSK/BPPM (same info. rate)
“Constant Power” Constraint
Ns = 2, Np=2, M=2

\[
A' = \left[\sqrt{1 + \frac{\log_2 M}{N_p / N_s}}\right] A
\]

\[
T_f' = \left(1 + \frac{\log_2 M}{N_p / N_s}\right) T_f
\]

can be adjusted to achieve higher information rate at lower transmit power and still maintain better BER performance at the same time
Information Rate (2/3)

Scalable info. rates

\[ A' = 2A \]

\[ A' = 1.58A \]

\[ A' = 1.41A \]

MCSK/BPPM “Constant Power”
Constraint for \( N_s = 1, M=8 \)

BER performance (wrt TH-BPPM)

- increased SNR
- reduced collisions
- no processing gain
- not much improvement

- increased SNR
- reduced collisions
- processing gain
- improved BER
- TX power can be lowered
- info rate can be increased

\[ R_s = \left( 1 + \frac{\log_2 M}{N_p / N_s} \right) R \]

\[ A' = \sqrt{1 + \frac{\log_2 M}{N_p / N_s}} \cdot A \]

\[ T_f' = \left( 1 + \frac{\log_2 M}{N_p / N_s} \right) T_f \]
Information Rate (3/3)

"Constant Power" Constraint

→ Improved performance at the same information rate for $M=8$
# Location Accuracy

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Result</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initial conditions for TH-BPPM</td>
<td>$R_0$ (information rate); $BER_0$ (performance); $TX_0$ (power)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Increase $M$</td>
<td>$R_1 &gt; R_0$; $BER_1 &gt; BER_0$; $TX_1 = TX_0$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Increase $Np/Ns$</td>
<td>$R_1 &gt; R_2 &gt; R_0$; $BER_1 &gt; BER_2$; $TX_2 = TX_0$</td>
<td>$BER_2$ may or may not be less than $BER_0$</td>
</tr>
<tr>
<td>3</td>
<td>Increase $T'f$</td>
<td>$R_1 &gt; R_2 &gt; R_3 &gt; R_0$; $BER_2 &gt; BER_3$; $TX_0 &gt; TX_3$</td>
<td>$BER_3$ may or may not be less than $BER_0$</td>
</tr>
<tr>
<td>4</td>
<td>Increase $A'$</td>
<td>$R_4 = R_3 &gt; R_0$; $BER_3 &gt; BER_4$ &amp; $BER_0 &gt; BER_4$; $TX_0 &gt; TX_4 &gt; TX_3$</td>
<td>Increased frame time with longer observation period, higher information rate, better BER performance and lower transmit power</td>
</tr>
</tbody>
</table>

### MCSK/BPPM

"Constant Power" Constraint

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Accurate Ranging/Location

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Conclusion

- MCSK/BPPM provides:
  - increased information rate
  - lower transmit power
  - better BER performance
  - improved spectral characteristics

- MCSK/BPPM is capable of:
  - information rate scalability
  - location/ranging accuracy

Simultaneously!

IEEE 802.15.4a PHY
Back-up Slides
MCSK/BPPM

“Constant Power” Constraint
MCSK/BPPM

"Constant Energy/Bit" Constraint
Effects of TH Code Design on the Performance

MCSK/BPPM “Constant Power” Constraint

![Graphs showing BER vs. SNR for TH code comparison with Np/Ns=1 and Np/Ns=2]
TH Code Spectrum of:

a) TH-BPPM, $N_p=10$

b) ideal MCSK/BPPM, $N_p \rightarrow \infty$

c) realistic MCSK/BPPM

Fig. a. TH-BPPM

Fig. b. ideal MCSK/BPPM

Fig. c. realistic MCSK/BPPM