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
Motivation

- MCSK/BPPM increases the location/ranging capability of existing Time Hopping (TH) Impulse Radios (IRs)
- H/W complexity is not increased
- Same signal space with respect to TH-BPPM
- “MCSK” can be applied to other TH-IRs; eg. MCSK/BPSK
Contents

• TG4a Requirements
• MCSK/BPPM
• PHY TX Structure
• TH Code Assignment
• Transceiver Architecture
• Information Rate
• Location Accuracy
• Conclusion
## TG4a Requirements

<table>
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<th>802.15.4a PHY</th>
<th>MCSK/BPPM compared to TH-BPPM</th>
</tr>
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<tbody>
<tr>
<td>scalable information rates</td>
<td>Better BER performance at the same/higher information rates and lower transmit power</td>
</tr>
<tr>
<td>high precision ranging/ location</td>
<td>Improved ranging/location precision capability</td>
</tr>
<tr>
<td>low power consumption</td>
<td>Lower transmit power 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

only for multiple access

MCSK/BPPM – user #1

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

choose a code

M user specific TH codes

for multiple access and data modulation

\[110 \ 101 \ldots\]

TX

\[0 \ T_b \ 2T_b \ 3T_b\]

\[1 \ 1 \ 0 \ 1\]

\[0 \ T_b \ 2T_b \ 3T_b\]

\[T_b : \text{Bit time}\]

\[T_f : \text{Frame time}\]
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: $M=4, N_p=8, N_s=4$

$$d = [1 \ 0 \ 1 \ 1 \ldots]$$

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

$$c_2 \rightarrow \begin{array}{ccccccccc} 0 & 5 & 8 & 7 & 3 & 1 & 4 & 2 & 6 \end{array}$$

$$d = [1 \ 0 \ 1 \ 1 \ldots]$$

$T_b$ : Bit time
$T_f$ : 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>
</table>
| $N_p / N_s = 1$ | 2 bits (MCSK) | ↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑↑∪
TH Code Assignment (1/2)

Each user has M user specific TH codes → $N_u N_p M$ 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 → $2^l \equiv N_h$; $l = 6$, $N_h = 64$

m-sequence: $[1 0 1 1 1 0 0 1 0 1 0 0 1 1 0 1 1 1 0 1 0 0 0 1 0 1 0 1 0 0 ...]$

$N_p = 4$

$M = 4$

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

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

\[ \begin{align*}
N_{p} &= 4 \\
M &= 4
\end{align*} \]

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

no collisions allowed within user codes

\[ N_u N_{p} \Rightarrow N_u (N_{p} + M - 1) + n \]

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

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

Fixed signal space
- Increased information rate

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

Hardware structure
1 correlator

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

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

TH-BPPM
\( N_s = 2, M=1 \)

MCSK/BPPM
“Constant Energy/Bit” Constraint
\( N_s = 2, N_p=2, M=2 \)

MCSK/BPPM
“Constant Power” Constraint
\( N_s = 2, N_p=2, M=2 \)

MCSK/BPPM (same info. rate)
“Constant Power” Constraint
\( N_s = 2, N_p=2, M=2 \)

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)**

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

**Scalable info. rates**

- **4R \( \rightarrow \) R**

\[
\begin{align*}
\frac{N_p}{N_s} = 1 & \\
A' &= 2A \\
T_f &= 0, T_f, 2T_f, 3T_f, 4T_f, 2T_f' = 4T_f
\end{align*}
\]

- **2.5R \( \rightarrow \) R**

\[
\begin{align*}
\frac{N_p}{N_s} = 2 & \\
A' &= 1.58A \\
T_f &= 0, T_f, 2T_f, T_f', 3T_f, 4T_f, 2T_f' = 5T_f
\end{align*}
\]

- **2R \( \rightarrow \) R**

\[
\begin{align*}
\frac{N_p}{N_s} = 3 & \\
A' &= 1.41A \\
T_f &= 0, T_f, 2T_f, T_f', 3T_f, 4T_f, 5T_f, 6T_f
\end{align*}
\]

**BER performance** (wrt TH-BPPM)

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

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

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

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

“Constant Power” Constraint

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

<table>
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<tr>
<th>Step 0</th>
<th>Initial conditions for TH-BPPM</th>
<th>$R_0$ (information rate); $BER_0$ (performance); $TX_0$ (power)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 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>Step 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>Step 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>Step 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
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!
Back-up Slides
MCSK/BPPM

“Constant Power” Constraint

![Graphs showing Power Const. BER for Np/Ns = 1, 2, and 4 (TH code set-1)]
MCSK/BPPM

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

MCSK/BPPM “Constant Power” Constraint

![Np/Ns=1, TH code comparison](image1)

![Np/Ns=2, TH code comparison](image2)
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