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

Submission Title : Proposal of P-FSK modulation scheme for NG-SUN PHY

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Re : TG4ad Next Generation SUN PHYs

Abstract : This is a proposal of position-based FSK (P-FSK) modulation scheme that enables power-saving transmissions in NG-SUN PHY. The resulting position-based P-FSK modulation enables to decrease the SNR per bit required to achieve a target bit error rate on the minimum increase in complexity.

Purpose: Discussion

Introduction

- **This is a proposal of position-based FSK (P-FSK) modulation scheme that enables power-saving transmissions in NG-SUN PHY.**

- **This document includes**
  - SUN Application Scope
  - Modulation Proposal for NG-SUN PHY
  - Conventional FSK Modulation
  - Concept of P-FSK Modulation
  - P-FSK Transmitter & Receiver
  - Theoretical BER Performance
  - Performance Simulation

SUN Application Scope

- **The IoT industry world has been continuously working to expand the scope of SUN applications**.
  - Early SUN applications focused on wireless metering services for utilities such as electricity, water, and gas.
  - Recently, SUN applications have expanded into smart monitoring services in various industries such as smart cities, smart factories, smart farms, and etc.
- **Monitoring applications in the future IoT industry will require improved performance over existing SUN PHYs.**
  - Ultra-low energy operation that can provide years of battery life
  - Long-range communication in a star topology considering congested environments
  - High reliability and robustness even in harsh environments with severe interference and multi-path effects
  - Low data rate wireless connectivity with simple and low-cost devices

Modulation Proposal for NG-SUN PHY

- **IEEE 802.15.4 SUN PHY standard has adopted FSK modulation that focuses on low complexity and low power consumption**.
  - FSK uses larger bandwidth compare to some other modulation schemes.
  - BER performance of FSK in AWGN channel is worse compare to some other modulation schemes.

- **NG-SUN PHY requires a new modulation scheme that can improve system performance over the conventional FSK modulation.**
  - Propose the position based FSK(P-FSK) modulation that generates 4-dimensional orthogonal signals while the data rate and signal bandwidth intact.
    - ☞ Combine 2-FSK(2-dimensional orthogonal signals in frequency domain) and 2-level PPM(2-dimensional orthogonal signals in time domain)
  - P-FSK modulation enables to decrease the SNR per bit required to achieve a target bit error rate on the minimum increase in complexity.

Conventional FSK Modulation

- **FSK modulation has been used for low-power communication systems because of its simple structure of modulator and demodulator.**
  - Its constant envelope enables to avoid the use of high-linearity power amplifier (PA) which is typically the most power-hungry building block at the transmitter.
  - The continuous waveform of FSK signal entails inevitable transmission power consumption, especially when considering the low date rate system.

- **The k^{th} waveform for a bit stream $b_k \in \{0.1\}$ coming into an FSK transmitter with two equal-energy orthogonal signals is represented as**

$$S_k^{FSK}(t) = \sqrt{\frac{2Eb}{T_s}}\, p(t - kT_s) \cos[2\pi f_c + b_k \Delta f)t]$$

where, p(t) is a rectangular pulse with width T_s equivalent to a symbol duration,

E_b is an energy per bit,

f_c is a carrier frequency,

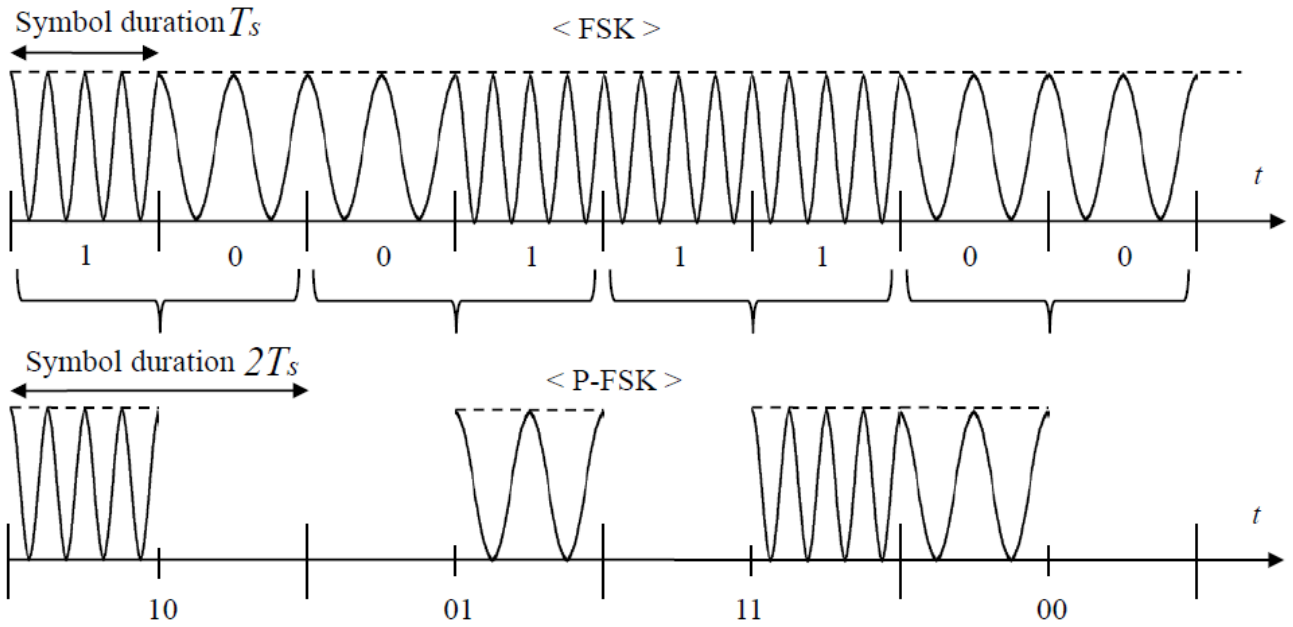
Δf is a frequency deviation

Concept of P-FSK Modulation

- **Modulation using higher-dimension orthogonal signals reduce the SNR per bit required to achieve a target probability of a bit error.**
  - High-level FSK is typically used to increase the number of dimension in the frequency domain.
    - ☞ The higher-level FSK occupies wider signal bandwidth
    - ☞ Difficult to assign the enough number of radio channels for simultaneously operating high -level FSK system in a given frequency band.
    - ☞ Higher-level FSK systems require much more complex receiver architectures to distinguish the increased number of frequencies.
- **P-FSK modulation scheme can generate 4-dimension orthogonal signal without bandwidth expansion and significant increase in complexity**
  - P-FSK modulation scheme combines 2-ary PPM and 2-level FSK
    - ☞ 2-level FSK **:** 2-dimension orthogonal signals (freq. domain)
    - ☞ 2-ary PPM **:** 2-dimension orthogonal signals (time domain)

Concept of P-FSK Modulation - Continued

- **Encodes two bits by transmitting a frequency-modulated signal in one of two possible positions (also known as time-shifts).**
  - 4-dimension orthogonal signaling
    - ☞ 4 waveforms that indicate “00”,”01”,”10”, “11”



Concept of P-FSK Modulation - Continued

- **The proposed P-FSK starts with grouping two incoming bits $b_n=[b_n^0, b_n^1]$ for which the waveform during n^{th} group symbol is expressed as**

$$S_k^{P-FSK}(t) = \sqrt{\frac{2Es}{T_s}}\, G(b_n^0, t) \cos[2\pi(f_c + b_n^1 \Delta f)t]$$

where, E_s is an energy per symbol,

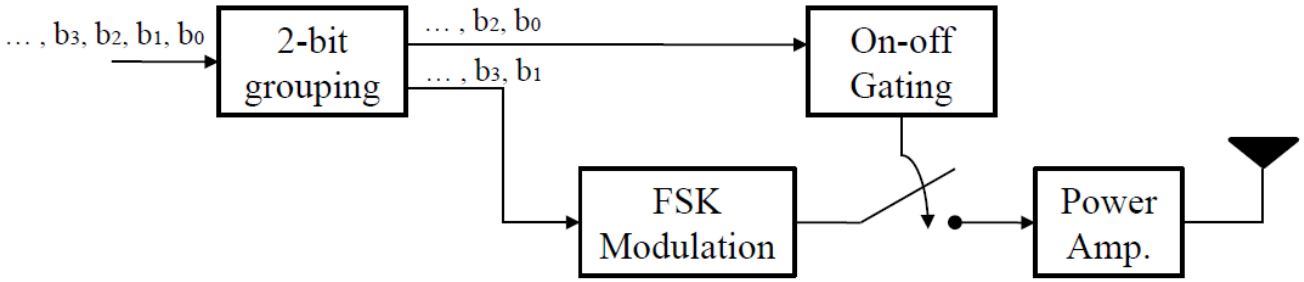
$G(b_n^0, t)$ is a gating function that determines the position of FSK-modulated signal and is given by

$$G(b_n^0, t) = p(t - n2T_s - b_n^0 T_s)$$

– This is conveyed by the conventional FSK-modulated signals and is modulated by the position.

P-FSK Transmitter

- **Two bits are grouped together to be fed into the FSK modulator and on-off gating device to finally yield a P-FSK modulated waveform**
  - A 2-bit group indicates logical
  - The on-off gating device is the only required hardware added to the conventional FSK transmitter
    - ☞ Its implementation overhead is negligible.



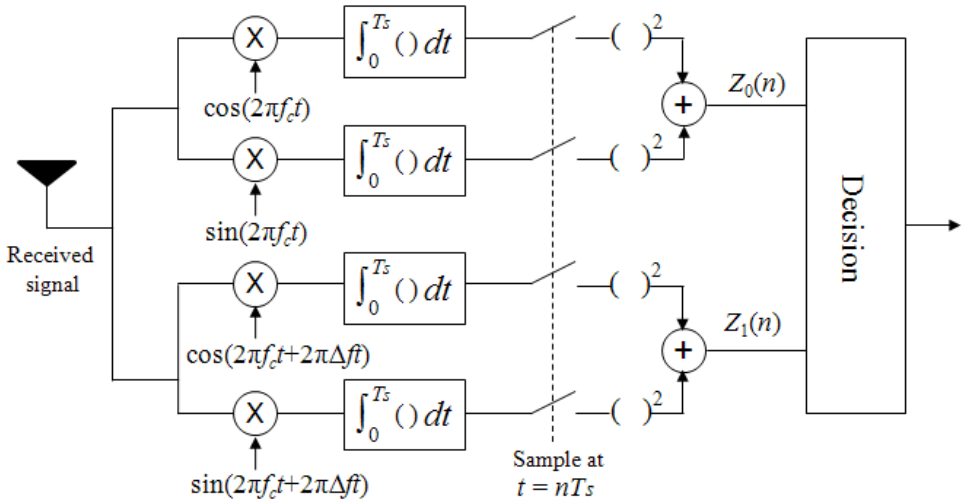
b_1: conveyed by the conventional FSK-modulated signal
b_0: modulated by the position.

P-FSK Receiver

- **Coherent receiver**
  - For 4-dimension orthogonal signals of the P-FSK scheme,
    - ☞ **Correlator based Receiver** : The optimal coherent receiver selects the signal resulting in the largest cross-correlation between the received signal and each of 4 possible transmitted signals, or
    - ☞ **Matched filter based receiver :** The received signal can be passed through a bank of 4 filters matched to the possible transmitted signals and sampled at $t=2T_s$, the end of the symbol interval.
  - The coherent demodulation in the correlator based or matched filter based receiver needs a phase-locked loop (PLL) to track the phase of the carrier.
    - ☞ It is complex and expensive.
  - Consequently, non-coherent demodulation and detection for orthogonal signals(FSK and PPM), have received much attention since the carrier phase irrelevant decision leads to low-power and low-complexity receiver

Proposed P-FSK Receiver - Continued

- **Non-Coherent receiver(1)**
  - The receiver for the proposed P-FSK can be further simplified by employing the conventional non-coherent FSK receiver structure
    - ☞ Same as the conventional FSK non-coherent receiver
    - ☞ **Position bit recovery** : Collect the squared envelops during two times interval and compare the energy



Proposed P-FSK Receiver - Continued

- **Non-Coherent receiver(2)**
  - At the correlator outputs, obtain the squared envelopes $Z_0(n)$ and $Z_1(n)$, at sampling time $t = nT_s$
    - ☞ For the conventional FSK receiver, comparing with the decision threshold 0 accomplishes non-coherent detection process of the n^{th} transmitted symbol
    - ☞ For our P-FSK demodulation, collect the squared envelopes during two times intervals to obtain $\{Z_0(2n),\ Z_1(2n)\}$ and $\{Z_0(2n+1),\ Z_1(2n+1)\}$
  - First, recover the position bit by comparing the energy between two time slots, where the energy at each time interval is defined as:

$$\Delta Z(2n) \coloneqq Z_0(2n) + z_1(2n)$$

$$\Delta Z(2n+1) \coloneqq Z_0(2n+1) + z_1(2n+1)$$

  - Then, comparing with the $\Delta Z(n) \coloneqq \Delta Z(2n) - \Delta Z(2n)$ with the decision threshold 0 gives the position bit as follows;

$$\boldsymbol{b_n^0} = \begin{cases} 0, & if\ \Delta Z(n) \geq 0 \\ 1, & if\ \Delta Z(n) < 0 \end{cases}$$

Proposed P-FSK Receiver - Continued

- **Non-Coherent receiver(3)**
  - Once the position bit is determined, the next step is to draw the frequency-modulated bit $\boldsymbol{b_n^1}$ by the exact same process of FSK demodulation
    - ☞ The squared envelopes are selected and calculated based on restored position bit $\boldsymbol{b_n^0}$ as:

$$\begin{cases} Z_0(2n) - Z_1(2n), & if\ \boldsymbol{b_n^0} = 0 \\ Z_0(2n+1) - Z_1 + 1, & if\ \boldsymbol{b_n^0} = 1 \end{cases}$$

    - ☞ Consequently, comparing with the decision threshold 0 finalizes our non-coherent P-FSK demodulation

Theoretical BER Performance

- **Evaluate the probability of a bit error for the conventional FSK and the proposed P-FSK, assuming the coherent receiver.**
  - The probability of error for 2-level FSK signal is presented as follows

$$P_b^{FSK} = \mathrm{Q}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

  - P-FSK transmits one of 4-dimension orthogonal signals for 2-bit transmission which is equivalent to the general M-ary orthogonal modulation with M=4.
    - ☞ As a result, the probability of a bit error for the P-FSK scheme is same as the case of 4-level FSK and it is derived as:

$$P_b^{P-FSK} \leq 2\,\mathrm{Q}\left(\sqrt{\frac{E_s}{N_0}}\right) = 2\,\mathrm{Q}\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

    where $E_s = 2E_b$ since the P-FSK signal contains two bits.

Theoretical BER Performance - Continued

- **P-FSK scheme with 4-dimension orthogonal signaling renders better performance than the conventional FSK by approximately 2.7dB SNR gain at BER 10^{-5}.**
  - In other words, our P-FSK system keeping the same SNR per bit (E_b/N_0) with the conventional FSK system can lower the probability of a bit error at the receiver or extend the communication range.

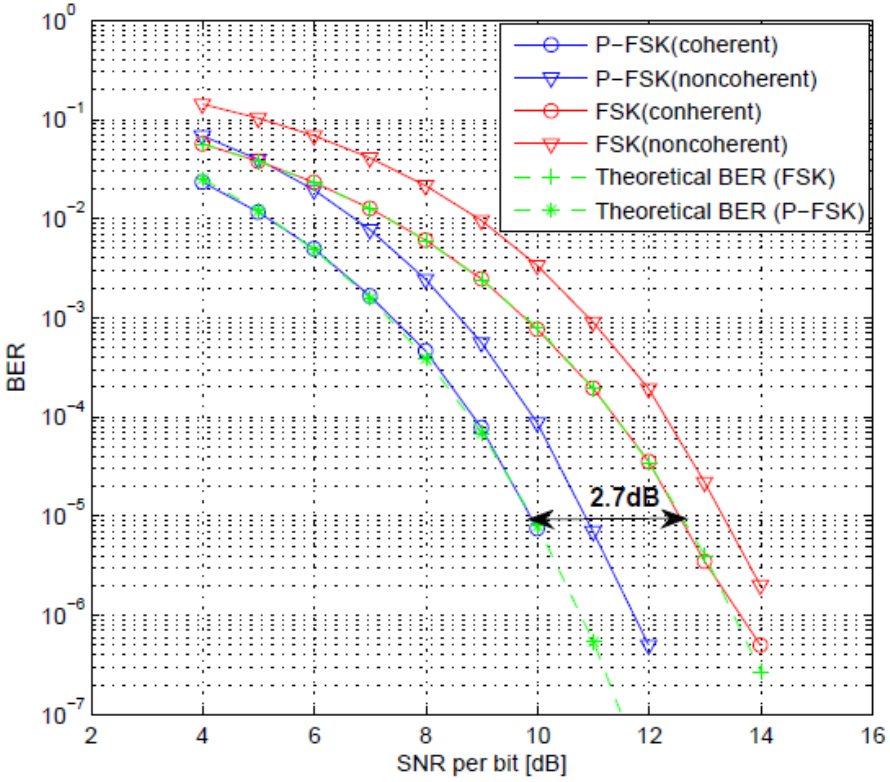
- **Leveraging this 2.7 dB gain for power-saving transmission in NG-SUN's battery-powered endpoint devices is very attractive.**
  - Higher dimension orthogonal signaling enhances the BER performance
  - It reduces the SNR per bit required to achieve a target BER
  - It leads to the reduced transmission power.

Performance Simulation

- **To verify the performance of the proposed P-FSK scheme, simulations were conducted**
  - For experiments, For a NG-SUN packet,
    - ☞ FSK-modulated preamble sequence of multiple ‘01010101’s
    - ☞ P-FSK modulated payload with length 127 bytes that contains information bits
  - Assuming that the clock recovery loop at the receiver can successfully perform synchronization during the preamble period,
    - ☞ Here focus on the BER performance rather than the synchronization performance.
  - The bit rate is 1/Ts=40KHz and the frequency deviation is $\Delta f = 40KHz$
  - The typical urban 6-ray model with COST 207 is used for NG-SUN multi-path channel, where the delay spreads up to 5 μs.

Simulation Results

- **Both coherent and non-coherent demodulation are considered for FSK and P-FSK schemes**



BER performance as a function of the SNR per bit

- ☞ P-FSK with coherent demodulator outperforms the conventional FSK by 2.7dB at BER in AWGN channel, which is the identical result of the theoretical BERs
- ☞ Non-coherent demodulation of FSK and P-FSK exhibits roughly 1 dB performance degradation compared with the optimal coherent demodulation.
- ☞ The BER performance in multi-path channel shows 2dB degradation compared with AWGN case.

Conclusion

- **IEEE 802.15.4 SUN PHY standard has adopted FSK modulation that focuses on low complexity and low power consumption**.
  - FSK uses larger bandwidth compare to some other modulation schemes.
  - BER performance of FSK in AWGN channel is worse compare to some other modulation schemes.
- **Propose to generate the P-FSK modulation scheme that generates 4-dimensional orthogonal signal by combining FSK and PPM while the data rate and signal bandwidth intact.**
  - The resulting position-based P-FSK modulation enables to decrease the SNR per bit required to achieve a target bit error rate on the minimum increase in complexity.
  - Relying on judiciously designed 4-dimension orthogonal signals as the combination of FSK and PPM, the resulting P-FSK scheme can save 2.7 dB transmission power at the receiver, which makes it attractive for NG-SUN PHY.

Reference

- Mi-Kyung Oh, Sangsung Choi, and Young-Hyoun Kwon, Position-Based FSK Scheme Toward Power-Saving Transmission in LECIM Networks, IEEE Communications Letters, Vol. 16, No. 2, February 2012

Thanks for Listening !
Q&A