GREEN MODULATION IN DENSE WIRELESS SENSOR NETWORKS

Jamshid Abouei, Konstantinos N. Plataniotis and Subbarayan Pasupathy

The Edward S. Rogers Sr. Dept. of ECE, University of Toronto, Toronto, Canada
Emails: {abouei, kostas, pas}@comm.utoronto.ca

ABSTRACT

Due to unique characteristics of sensor nodes, choosing an energy-efficient modulation scheme with low-complexity implementation (referred to as green modulation) is a critical factor in the physical layer of Wireless Sensor Networks (WSNs). The main goal of this paper is to analyze and compare the energy efficiency of various sinusoidal carrier-based modulation schemes using parameters in the IEEE 802.15.4 standard and state-of-the-art technology to find the best scheme in a dense WSN over frequency-flat Rayleigh fading channel with path-loss. Experimental results show that M-ary Frequency Shift Keying (MFSK) with small order of M has significant energy saving compared to OQPSK and MQAM for short range scenarios, and could be considered as a realistic candidate in dense WSNs. In addition, MFSK has the advantage of less complexity and cost in implementation than the other schemes.

Index Terms— WSN, energy efficiency, green modulation

1. INTRODUCTION

Minimizing the total energy consumption in both circuits and signal transmission is a critical factor in designing a WSN. For typical WSNs, on the other hand, data rates are usually low. Thus, using complicated signal processing techniques are not desirable. Several energy-efficient approaches have been investigated for different layers of a WSN, including the data-link and the physical layers (see e.g., [1]-[3]). Central to the study of energy-efficient techniques in the physical layer of a WSN is modulation. Although, achieving all requirements (e.g., minimum energy consumption, maximum bandwidth efficiency, low signal processing complexity) is a complex task in a WSN, an energy-efficient modulation scheme should be simple enough to be implemented by state-of-the-art low-power technology. In addition, since sensor nodes frequently switch from sleep mode to active mode, modulation circuits should have fast start-up times. We refer to these schemes as green modulations.

Several energy-efficient modulation schemes have been investigated in the physical layer of WSNs [1]-[5]. Reference [2] compares the battery power efficiency of PPM and FSK schemes in a WSN for various wireless channel models. Under the assumption of the non-linear battery model, reference [2] shows that FSK is more power-efficient than PPM in sparse WSNs, while PPM may outperform FSK in dense WSNs. Most of the pioneering works on energy-efficient modulation (e.g. [2], [3]) has focused only on minimizing the average transmitted energy per bit, ignoring the effect of bandwidth and transmission time duration. In a practical WSN however, it is shown that minimizing the total energy consumption depends strongly on the active mode duration and the channel bandwidth. Reference [1] addresses this issue for MFSK and M-ary Quadrature Amplitude Modulation (MQAM) for an AWGN channel with path-loss, and shows that MQAM is more energy-efficient than MFSK.

In this paper, we analyze and compare the energy efficiency of various sinusoidal carrier-based modulation schemes considering the effect of bandwidth and active mode duration to find the green modulation in a point-to-point WSN. Also, new analysis results for comparative evaluation of three popular modulation designs are introduced. The present analysis is based on a frequency-flat Rayleigh fading channel with path-loss which is a feasible model in static WSNs [2], [3]. Experimental results show that among various sinusoidal carrier-based modulation schemes, MFSK is a realistic option in dense WSNs, since it has the advantage of less complexity and cost in implementation than MQAM and Offset Quadrature Phase Shift Keying (OQPSK), and has less total energy consumption. In addition, since for typical energy-constrained WSNs, data rates are usually low, using small order M-ary FSK schemes are desirable.

The rest of the paper is organized as follows. In Section 2, the system model is described. The energy consumption analysis of various sinusoidal carrier-based modulation schemes is presented in Section 3. Section 4 provides some simulation results. Finally in Section 5, an overview of the results and conclusions is presented.

2. SYSTEM MODEL AND ASSUMPTIONS

In this work, we consider a wireless sensor system, in which a sensor node transmits data to a designated sink node in a time-based process as follows. During active mode duration $T_{ac}$, the sensed signal is first digitized by an Analog-to-Digital Converter (ADC), and an N-bit message $(a_1, ..., a_N)$ is generated. The bit stream is then modulated using a pre-determined modulation scheme and is transmitted to the sink node. Finally, sensor node returns to sleep mode, and all the circuits of the transceiver are shutdown for sleep mode duration $T_{sl}$ for energy saving. We denote $T_{ac}$ as the transient mode duration consisting of the switching time from sleep mode to active mode (i.e., $T_{sl} \rightarrow T_{ac}$) plus the switching time from active mode to sleep mode (i.e., $T_{ac} \rightarrow T_{sl}$), where $T_{ac} \rightarrow T_{sl}$ is short enough compared to $T_{sl} \rightarrow T_{ac}$ to be negligible. Also, we define $T_X \triangleq T_{tr} + T_{ac} + T_{sl}$ with $T_{tr} \approx T_{sl} \rightarrow T_{ac}$. We denote the total circuit power consumption as $P_e \triangleq P_{sl} + P_{tr}$, where $P_{sl}$ and $P_{tr}$ represent the circuit power consumptions for sensor and sink nodes, respectively. In addition, the RF transmit power consumption of the sensor node is denoted by $P_e$. In this case, the total energy consumption in $T_{ac}$, denoted by $E_{ac}$, is given by $E_{ac} = (P_e + P_r)T_{ac}$. Also, the energy consumption in the sleep mode period is given by $E_{sl} = P_{sl}T_{sl}$, where $P_{sl}$ is the corresponding power consumption. Present state-of-the-art technology aims to keep $P_{sl}$ much smaller than the power consumption in active mode. For this reason, we assume that $P_{sl} \approx 0$. As a result, the energy efficiency can be measured by the total energy consumption in each period $T_X$ corresponding to $N$-bit message $E_X \approx (P_e + P_r)T_{ac} + P_{tr}T_{tr}$, where $P_{tr}$ is the circuit power consumption during $T_{tr}$.

The channel model between the sensor and sink nodes is as-
sumed to be Rayleigh flat fading with path-loss. We denote the fading channel coefficient corresponding to the transmitted symbol $i$ as $h_i$, where the amplitude $|h_i|$ is Rayleigh distributed with probability density function (pdf) $f_{h_i}(r) = \frac{r}{\Omega} e^{-\frac{r}{\Omega}}$ with $\Omega \triangleq \mathbb{E}[|h_i|^2]$. This results in $|h_i|^2$ being chi-square distributed with 2 degrees of freedom. In addition, for a $\gamma^\text{HL}$-power path-loss channel between the sensor and sink nodes with distance $d$, the channel gain factor is given by $L_d \triangleq \frac{f_{L_d}}{d^\ell} = M d^\ell L_1$, where $P_t$ and $P_r$ are the transmitted and the received powers, $M_1$ is the gain margin which accounts for the effects of hardware process variations and background noise, and $L_1 \triangleq \frac{(4\pi)^2}{\Omega d^2 N_0}$ is the gain factor at $d=1$ meter which is specified by the transmitter and receiver antenna gains $G_t$ and $G_r$, and wavelength $\lambda$. As a result, when both fading and path-loss are considered, the instantaneous channel coefficient becomes $G_i \triangleq \frac{h_i}{\sqrt{L_d}}$.

Denoting $x_i(t)$ as the transmitted signal with energy $E_i$, the received signal at the sink node is given by $y_i(t) = G_i x_i(t) + n_i(t)$, where $n_i(t)$ is Additive White Gaussian Noise (AWGN) with two-sided power spectral density $N_0/2$. Thus, the instantaneous Signal-to-Noise Ratio (SNR) can be computed as $\gamma_i = \frac{|G_i|^2 E_i}{N_0}$. In this case, $\gamma_i$ has the same distributed as $|h_i|^2$ with pdf $f_{\gamma_i}(\gamma_i) = \frac{1}{\pi} e^{-\frac{\gamma_i}{\Omega}}$, where $\gamma \triangleq \mathbb{E}[|G_i|^2] \frac{E_i}{N_0}$ denotes the average received SNR.

### 3. ENERGY CONSUMPTION ANALYSIS

Pass-band modulation schemes such as MFSK and MQAM use sinusoidal carrier signals for modulation. In the following, we investigate three popular sinusoidal carrier-based modulation schemes from energy and bandwidth efficiency points of view\(^1\).

**M-ary FSK:** Let assume $(a_1, \ldots, a_N)$ is considered as modulating signals in an $M$-ary FSK modulation scheme, where $M$ orthogonal carriers can be mapped into $b \triangleq \log_2 M$ bits. An MFSK modulator is a direct digital modulation approach, i.e., it does not need a mixer and a Digital-to-Analog Converter (DAC), and modulation is implemented digitally inside the frequency synthesizer. Thus, MFSK has a faster start-up time than other pass-band schemes. The modulated signal is filtered, amplified by the power amplifier, and finally transmitted to the wireless channel. Denoting $E^{FS}_i$ as the energy of an MFSK transmitted symbol $x^{FS}_i(t)$, we have $E^{FS}_i(t) = \sqrt{\frac{2E_i}{T_{FS}}} \cos(2\pi f_0 + i\Delta f) t_i$, where $i = 0, 1, \ldots, M-1$, $f_0$ is the first carrier frequency, $\Delta f = \frac{1}{T_{FS}}$ is the carrier separation and $T_{FS}$ is the MFSK symbol duration. Thus, the channel bandwidth is obtained as $B \approx M \times \Delta f = \frac{M}{T_{FS}}$, where $B$ is assumed to be fixed for all the pass-band modulation schemes. Since the rate of the sensor is given by $R = \frac{E_i}{T_{FS}}$ (bits/sec), the bandwidth efficiency of MFSK modulation is obtained as $B_e^{FS} = \frac{R}{\Delta f} = \frac{\log_2 M}{M} (\text{bits/Hz})$. It is observed that increasing $M$ leads to decrease in the bandwidth efficiency in MFSK. However, the effect of increasing $M$ on the energy efficiency should be considered as well. To address this problem, we first derive the relationship between $M$ and the active mode duration. Since we have $b$ bits during $T_{FS}$, we can write $T_{FS} = \frac{b}{M} T_{FS} = \frac{bN}{\log_2 M}$. Recalling that $B$ and $N$ are fixed, an increase $M$ results in an increase in $T_{FS}$. However, the maximum value for $T_{FS}^\text{acc}$ is equal to $T_N - T_{FS}^*$. Thus, the maximum constellation size $M$, denoted by $M_{\text{max}}$, is $2^{b_{\text{max}}}$, for MFSK is calculated by $\frac{\log_2 M_{\text{max}}}{b_{\text{max}}} = \frac{1}{2} (T_N - T_{FS}^*)$. Now, we are ready to derive the total energy consumption with MFSK scheme. We first derive $E_i^{FS}$ in terms of a given average Symbol Error Rate (SER) denoted by $P_s$. The average SER of a non-coherent MFSK is given by $P_s = \int_0^\infty P_s(\gamma_i) f_{\gamma_i}(\gamma_i) d\gamma_i$, where $P_s(\gamma_i)$, namely the SER conditioned upon $\gamma_i$, is obtained as $\gamma_i = \frac{E_i^{FS}}{T_{FS}}$.

\[
E_i^{FS} = \log_2 M \left(1 - (1 - P_s)^{M-1} \right) \frac{1}{M - 1} - \frac{2}{\Omega} \log_2 M + \frac{1.75 P_{\text{FS Amp}} T_{\text{tr}}}{N}.
\]

where $I_0(x)$ is the zeroth order modified Bessel function. It is shown in [2] that $P_s$ is upper bounded by $P_s \leq 1 - \left(\frac{1}{2\sqrt{\pi} f_{\gamma_i}}\right)^{-1}$.

Since our goal is to obtain the maximum energy consumption, we approximate the upper bound (1) as an equality. Thus, the energy consumption of transmitting $N$ bits during $T_{FS}^*$ is computed as $P_{FS} = \frac{R}{\Delta f} \frac{N}{\log_2 M}$. In addition, the energy consumption of the sensor and the sink circuitry during $T_{FS}^*$ is computed as $(P_{FS}^S + P_{FS}^T) T_{FS}^*$.

\[
E_{\text{MFSK}} = P_{FS}^S + P_{FS}^T + P_{FS}^\text{Filt} + P_{FS}^\text{AMP} + P_{FS}^\text{AMP}.
\]

It is shown that the relationship between $P_{FS}^\text{AMP}$ and $P_{FS}^S$ is $P_{FS}^\text{AMP} = \alpha_{FS} P_{FS}^S$, where $\alpha_{FS} = 0.33$ for a class B power amplifier [1], [2]. For the power consumption of the sink circuitry, we use the fact that most practical MFSK receivers use non-coherent detectors. The optimal non-coherent MFSK consists of a bank of $M$ matched filters, each followed by an envelope detector, but the sampling times $i = \ell T_{FS}^*$, a Maximum-Likelihood (ML) decision is based on the largest filter output. Also, we assume that the sink node uses a Low-Noise Amplifier (LNA) which is generally placed at the front-end of a RF receiver, an Intermediate-Frequency Amplifier (IFA), and an ADC unit, regardless of type of deployed pass-band modulation scheme. Thus, denoting $P_{FS}^\text{LNA}, P_{FS}^\text{Filt}, P_{FS}^\text{IQA}, P_{FS}^\text{AMP} + P_{FS}^\text{AMP}$ as the power consumption of LNA, filters, envelop detector, IF Amplifier, and ADC, respectively, the power consumption of the sink circuitry can be obtained as $P_{FS} = P_{FS}^\text{LNA} = \frac{1}{M} \frac{N}{\log_2 M}$. In addition, it is shown that the power consumption during transition mode period $T_{FS}^*$ is governed by the frequency synthesizer, and is obtained as $P_{FS} = 1.75 P_{FS}^S T_{FS}^*$. As a result, the total energy consumption of a non-coherent MFSK scheme for transmitting $N$ bits in $T_N$ under $M \leq M_{\text{max}}$, and for a given $P_s$ is obtained as

\[
E_{\text{NCS}} = \left(1 + \alpha_{FS}\right) \left[\left(1 - (1 - P_s)^{M-1}\right)^{-1} - 2\right] \frac{N \log_2 M}{\Omega} + \frac{M N}{B log_2 M} + 1.75 P_{FS}^S T_{FS}^*.
\]

\(^1\)In the sequel, we use the superscripts ‘FS’, ‘QA’ and ‘OQ’ for MFSK, MQAM and OQPSK, respectively.
M-ary QAM: For an M-ary QAM scheme with square constellation, each \( b = \log_2 M \) bits is mapped to a complex symbol \( S_i, i = 0, 1, \ldots, M - 1 \). Unlike MFSK, an MQAM modulator uses a mixer and an DAC. Assuming raised-cosine filter is used for pulse shaping, the channel bandwidth of MQAM is \( B \approx \frac{1}{2T^Q_{ac}} \), where \( T^Q_{ac} \) represents the MQAM symbol duration. Using the data rate \( R^Q_{ac} = \frac{b}{2T^Q_{ac}} \) (bits/sec), the bandwidth efficiency of MQAM is obtained as \( B_{QAM}^M \approx \frac{R^Q_{ac}}{B} = 2 \log_2 M \) (bits/Hz). It is observed that \( B_{QAM}^M \) is a logarithmically increasing function of \( M \). With a similar argument as MFSK, the active mode duration for MQAM is obtained as \( T^Q_{ac} = N \frac{T^Q_{ac} = N T^Q_{ac}}{2T^n_{log2 M}} \). Assuming the fixed bandwidth \( B \), increasing \( M \) results in decreasing in \( T^Q_{ac} \). To obtain the transmit energy consumption \( P^Q_{ac} T^Q_{ac} \), we use the SER conditioned upon \( \gamma_t \) of a coherent MQAM by
\[
P_s = \sqrt{\frac{d^2 \theta}{d^2 2\pi}} \exp \left( -\frac{3}{2(2M-1)} \right) \]
with \( \gamma_t = \frac{v^{QAM}}{d^2 N_0} \). As a result,
\[
\varepsilon_t^{QAM} \triangleq P^Q_{ac} T^Q_{ac} \leq \frac{2(M-1)}{3} \left[ \frac{1 - \frac{1}{\sqrt{M}}} {P_t} \right] L_d N_0 \frac{N}{\Omega \log_2 M}.
\]
Approximating the above upper bound as an equality, the energy consumption of transmitting \( N \) bits during active mode period is computed as
\[
P^Q_{ac} T^Q_{ac} \approx \frac{2(M-1)}{3} \left[ \frac{1 - \frac{1}{\sqrt{M}}} {P_t} \right] L_d N_0 \frac{N}{\Omega \log_2 M}.
\]
The energy consumption of the sensor and the sink circuitry during active mode period \( T^Q_{ac} \) for MQAM scheme is computed as \((P^Q_{ac} + P^Q_{cr}) T^Q_{ac}\). For the sensor node with MQAM,
\[
P^Q_{ac} = P^Q_{DAC} + P^Q_{FS} + P^Q_{Mix} + P^Q_{Filt} + P^Q_{Amp}.
\]
where \( P^Q_{DAC} \) and \( P^Q_{Mix} \) denote the power consumption of DAC and mixer. It is shown that the relationship between \( P^Q_{Amp} \) and \( P^Q_{cr} \) of MQAM is given by \( P^Q_{Amp} = \alpha_{QAM} P^Q_{cr}, \) where \( \alpha_{QAM} = 2 - 1 \) with \( \alpha = 2 - 1 \) and \( \theta = 0.35 \) [1]. In addition, the power consumption of the sink circuitry with coherent MQAM can be obtained as
\[
P^Q_{cr} = P^Q_{LNA} + P^Q_{Mix} + P^Q_{Sy} + P^Q_{Filt} + P^Q_{Amp} + P^Q_{ADC}.
\]
As a result, the total energy consumption of a coherent MQAM system for transmitting \( N \) bits in each period \( T^Q_{ac} \) is obtained as
\[
\epsilon^Q_N = \frac{2(M-1)}{3} \left[ \frac{1 - \frac{1}{\sqrt{M}}} {P_t} \right] L_d N_0 \frac{N}{\Omega \log_2 M} + N \frac{(P^Q_{DAC} + P^Q_{Amp})}{2B \log_2 M} + \beta P^Q_{Sy} T^Q_{ac}.
\]
where \( \beta = 2 \) for MQAM scheme [1].

Offset-QPSK: Offset QPSK is a typical modulation scheme used in the IEEE 802.15.4 standard. The structure of an OQPSK modulator is the same as an QPSK modulator except that the in-phase and the quadrature-phase pulse trains are staggered. Since for OQPSK, the information is carried in the phase of the carrier, and noting that non-coherent receivers are designed to ignore this phase, non-coherent detection can not be employed with OQPSK modulation. A popular technique which surpasses this problem is to use differential encoding before classical OQPSK modulator. This is called Differential Offset QPSK (DOQPSK). In this case, the sensed data stream \( (a_1, \ldots, a_N) \) is first differentially encoded twice at the sensor node such that it is the change from one bit to the next using \( \bar{a}_n = a_n \oplus \bar{a}_{n-1}, \) where \( \oplus \) denotes addition modulo 2. Then, the encoded bit stream is entered to the classical OQPSK modulator. For the above configuration, the channel bandwidth and the data rate are determined by \( B \approx \frac{1}{2T^Q_{ac}} \) and \( R^Q = \frac{Q}{2T^Q_{ac}} \) (bits/sec), respectively, where \( T^Q_{ac} \) is the OQPSK symbol duration. As a result, the bandwidth efficiency of OQPSK is obtained as \( B_{QPSK}^O \approx \frac{R^Q}{B} \approx 2 \log_2 M \). Since during \( T^Q_{ac} \), we have 2 bits, \( T^Q_{ac} = \frac{N}{2} T^Q_{ac} = \frac{N}{2} T^Q_{ac} \). Also, compared to MFSK and MQAM, we have \( T^Q_{ac} \leq T^Q_{ac} < T^Q_{ac} \). To determine the transmit energy consumption of the differential OQPSK scheme, denoted by \( P^Q_{QPSK} T^Q_{ac} \), one would derive \( \varepsilon_t^{QPSK} \) in terms of SER. The SER conditioned upon \( \gamma_t \) of differential OQPSK for two-bits observation interval is upper bounded by \( P_s(\gamma_t) \leq \sqrt{\frac{15N^2}{4} e^{-2\gamma_t^O}} \). Thus, the average SER of differential OQPSK is upper bounded by
\[
P_s \leq \sqrt{\frac{15N^2}{4} e^{-2\gamma_t^O}} \quad \text{with} \quad \gamma_t^O = \frac{2 \log_2 N_0}.\]

Approximating the above upper bound as an equality, the energy consumption per each symbol is given for a existing by
\[
P^Q_{QPSK} T^Q_{ac} \approx \frac{1}{2} \left[ 4 \frac{(1 + \sqrt{2})}{2} - 4 \right] L_d N_0 \frac{N}{\Omega}.\]

Thus, the energy consumption of transmitting \( N \) bits during \( T^Q_{ac} \) is computed as \((P^Q_{QPSK} + P^Q_{cr}) T^Q_{ac}\). With a similar argument, for the sensor node with differential QPSK, \( P^Q_{cr} = P^Q_{DAC} + P^Q_{FS} + P^Q_{mix} + P^Q_{Filt} + P^Q_{Amp} \), where we assume that \( P^Q_{Amp} = \alpha_{QPSK} P^Q_{cr}, \) with \( \alpha_{QPSK} = 0.33 \). In addition, the power consumption of the sink circuitry with differential detection OQPSK can be obtained as \( P^Q_{cr} = P^Q_{LNA} + P^Q_{Mix} + P^Q_{Sy} + P^Q_{Filt} + P^Q_{Amp} + P^Q_{ADC} \). As a result, the total energy consumption of a differential OQPSK system for transmitting \( N \) bits in each period \( T^Q_{ac} \) is obtained as
\[
\epsilon^Q_N = \frac{1 + \alpha_{QPSK}}{2} \left[ 4 \frac{(1 + \sqrt{2})}{2} - 4 \right] L_d N_0 \frac{N}{\Omega} + \frac{(P^Q_{DAC} + P^Q_{Amp})}{2B} \frac{N}{2B} + 2P^Q_{Sy} T^Q_{ac}.
\]

4. NUMERICAL RESULTS

In this section, we present some numerical results to evaluate the energy efficiency of the pass-band modulation schemes mentioned in Sections 3. For this purpose, we assume that all modulation schemes operate in B=10 KHz and the \( f_0 = 2.4 \) GHz Industrial Scientist and Medical (ISM) band utilized in IEEE 802.15.4 for WSNs. According to the FCC 15.247 RSS-210 standard for United States/Canada, the maximum allowed antenna gain is 6 dBi. In this work, we assume that \( g_r = g_r = 5 \) dBi. Thus, \( L_1 \) (dB) \( \leq 10 \log_{10} \left( \frac{4\pi^2}{g_r g_r} \right) \approx 30 \) dB. Table 1 summarizes the system parameters for simulation.
Table 1. System Evaluation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>2000</td>
</tr>
<tr>
<td>N0</td>
<td>-180 dB</td>
</tr>
<tr>
<td>η</td>
<td>3.5</td>
</tr>
<tr>
<td>Ml</td>
<td>40 dB</td>
</tr>
<tr>
<td>TN</td>
<td>1.07 sec</td>
</tr>
<tr>
<td>Ti</td>
<td>20 μs</td>
</tr>
<tr>
<td>PDAC</td>
<td>7 mw</td>
</tr>
<tr>
<td>PFilt</td>
<td>7 mw</td>
</tr>
<tr>
<td>PADC</td>
<td>2.5 mw</td>
</tr>
<tr>
<td>Pfilt</td>
<td>2.5 mw</td>
</tr>
<tr>
<td>PNA</td>
<td>9 mw</td>
</tr>
<tr>
<td>P2y</td>
<td>10 mw</td>
</tr>
<tr>
<td>PFA</td>
<td>3 mw</td>
</tr>
</tbody>
</table>

Fig. 1. Total Energy consumption of different modulation schemes vs. M for \( P_s = 10^{-3} \) and \( d = 10 \) m.

Fig. 1 compares the energy efficiency of various modulation schemes versus \( M \) for \( P_s = 10^{-3} \) and \( d = 10 \) m. It is seen that for \( M < 50 \), MFSK is more energy efficient than MQAM and OQPSK for \( d = 10 \) m. In addition, the MFSK with small \( M \) benefits from low complexity and cost in implementation over MQAM. Also, we obtain the same results for different values of \( 10 \leq d \leq 150 \) m. The above results are in contrast to [1], where the authors consider modulation schemes over an AWGN channel. While, we considered a Rayleigh fading channel which is a general model in practical WSNs. Fig. 2 shows the total energy consumption of 4FSK, 4QAM and differential OQPSK in terms of \( d \) for \( P_s = 10^{-3} \). As shown in this figure, 4FSK performs better than the other schemes from energy consumption points of view, for every distance \( d \). In addition, it can be seen that 4FSK scheme consumes much less energy than the other schemes in short ranges of \( d \). The sacrifice, however, is the bandwidth efficiency of MFSK (when \( M \) increases) which is a critical factor in band-limited WSN. But in the unlicensed band where large bandwidth is available, MFSK can be considered a realistic option in dense WSNs. We also plot the total energy consumption of MFSK as a function of bandwidth efficiency for different values of \( M \) and \( d \) in Fig. 3. In all cases, we observe that the minimum \( E_s^F \) is achieved at low values of distance \( d \) and for \( M = 2 \), which corresponds to the maximum bandwidth efficiency \( B_{eff}^{FS} = 1 \).

5. CONCLUSION

In this paper, we have analyzed the energy efficiency of various modulation schemes to find the best scheme in a WSN over frequency-flat Rayleigh fading channel with path-loss. The experimental results show that MFSK is attractive for using in WSNs, in particular for short-range applications, since MFSK already has the advantage of less complexity and cost in implementation than MQAM and differential OQPSK, and has less total energy consumption. In addition, since for typical energy-constrained WSNs, data transmission rates are usually low, using small order M-ary FSK schemes are desirable.

6. REFERENCES