# Analysis of Modulation Schemes for Bluetooth-LE Module for Internet-of-Things (IoT) Applications

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***Abstract*-- Bluetooth transceivers have been in the active area of recent research being the key component of physical layer in the Bluetooth technology. The low power consumption of Bluetooth low energy (LE) devices compared to the conventional Bluetooth devices has enhanced its importance in Internet-of-Things (IoT) applications. Therefore, Bluetooth low energy device based solution needs expansion in the IoT network infrastructure. The transceivers in the literature and modulation schemes are compared and summarized. Energy consumption of modulation schemes in Bluetooth communication are analyzed and compared using the model presented in this work. In this approach considering both circuit and signal power consumption, optimum modulation order for minimum energy consumption has been found using numerical calculation and relation between signal to noise ratio (SNR) and channel capacity. Battery life for IoT sensors using Bluetooth LE technology as a wireless link has been analyzed considering multiple transaction times for transmitters having different power consumption. MFSK and more bandwidth-efficient GFSK are identified as low energy solution for all smart devices.**

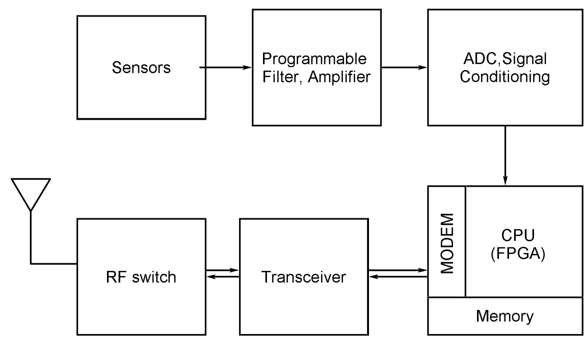
## I. INTRODUCTION

Bluetooth and Wi-Fi technology are common features in today's smartphones that provides additional functionalities to the cellular communication. Although Wi-Fi technology supports long range communication compared to the Bluetooth technology, it consumes more power. In future, billions of smart devices are going to be interconnected resulting to IoT applications [1]. Therefore, low power devices are of interest so that significant amount of energy can be saved for the IoT applications. The smart objects like vehicles, home appliances, wearable devices, mobile devices and smart sensors can be connected to network and hence expanding the network services. The research on low power IoT devices is under progress. The energy of Bluetooth low energy has been measured in [2] and the results suggest that it could be a cheapest and viable solution for IoT applications. The Bluetooth technology can also be used for ECG System [3], home automation [4] that would provide add on facility to the wireless personal area network of user. The key areas are discussed while connecting wearable devices with IoT via Bluetooth smart connection [5].

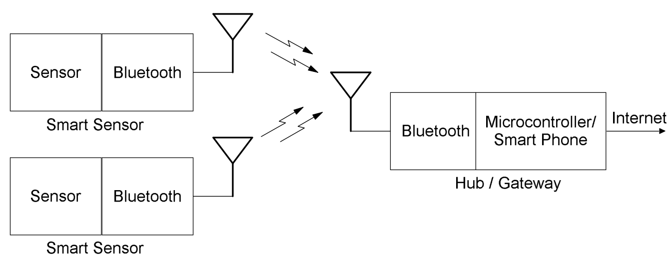
In this work, the low power Bluetooth devices are investigated for IoT applications. The Bluetooth technology for IoT is studied in section 2 along with the literature review of Bluetooth transceivers reported using CMOS technology. Comparative analysis of energy consumption for different modulation schemes used in Bluetooth LE technology is presented in section 3 with computation of battery life for smart sensors used in IoT.

## II. BLUETOOTH TECHNOLOGY FOR IOT

Bluetooth-LE enabled IoT devices connect to Internet through gateway as shown in Fig. 2. A gateway can be a home router having Bluetooth LE connectivity, any microcontroller based internet device or smart phone, which acts as translator between Bluetooth packets to IP packets in application layer and its usage in IoT is detailed in [6].




(a)




(b)

Fig. 2. Architecture of (a) Bluetooth enabled sensor. (b) Internet connectivity for IoT smart sensors.

The Bluetooth technologies and their applications are detailed in [7,8]. The total available market for IoT is reported in [8]. The detailed discussion regarding Bluetooth low energy and its applications in [9] suggests its usage in environmental control, security, health and activity monitoring, proximity detection and power conservation. The power consumption in the smart phones due to Bluetooth and Wi-Fi usage is investigated in [10]. The networking solution for Bluetooth low energy devices with IoT with is presented in [6]. The detailed discussions are presented [11] on monitoring the urban traffic conditions using Bluetooth data.

Specifications of Bluetooth transceivers that has been designed, fabricated and tested in recent years are shown in Table I. The popular modulation schemes for Bluetooth modem are GFSK, $\pi/4$ Differential Phase Shift Keying (DPSK) and 8 DPSK. Power consumed in Bluetooth transmitters reported in

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literature are in the range of 9mW to 78mW [12-18].

TABLE I
SPECIFICATIONS OF BLUETOOTH TRANSCEIVERS REPORTED IN LITERATURE

| Ref. | Chip Area ($mm^2$) | Mod. Scheme | Technology (nm) | | Power (mW) | Sensitivity (dbm) |
|---|---|---|---|---|---|---|
| [12] | 1.5 | $\pi$/4 DQPSK GFSK | 65 | Rx. | 63.72 | -89.1 |
| | | | | Tx. | 78.36 | 4 |
| [13] | 10 | GFSK | 180 | Rx. | 99 | -78 |
| | | | | Tx. | 75 | 0 |
| [14] | 4 | 8 DPSK GFSK | 180 | Rx. | 57.6 | -88 |
| | | | | Tx. | 75.6 | NA |
| [15] | 5.7 | $\pi$/4 DQPSK GFSK | 110 | Rx. | 52.5 | -95.5 |
| | | | | Tx. | 72 | 10 |
| [16] | 2.9 | GFSK | 55 | Rx. | 11.2 | -94.5 |
| | | | | Tx. | 10.1 | 0 |
| [17] | 5.9 | $\pi$/4 DQPSK GFSK | 130 | Rx. | 4.8 | -94 |
| | | | | Tx. | 8.9 | 0 |
| [18] | 1.4 | GFSK | 28 | Rx. | 2.75 | -95 |
| | | | | Tx. | 3.6 | 0 |

## III. ENERGY AWARE STUDY OF MODULATION SCHEMES FOR BLUETOOTH LOW ENERGY

An energy consumption model for RF signal processing blocks is proposed in [19] and energy comparison of modulation schemes for individual links in wireless sensor networks is studied in [20]. To model energy consumption per bit for MFSK and MPSK modulation in Bluetooth LE technology, transmitter operation has been divided into three states- active, sleep and transient state. For IoT applications we primarily focus on power consumed by transmitter in its active state, since on receiver side power consumption is not a prime concern. In sleep state, power consumption is very small compared to active state and thus it can be neglected; where as in transient state the transient time is very small compared to active time and thus power consumption in transient state has been neglected in our analysis.

Assuming total L bits to be transmitted in a during active mode, transmitted energy per information bit can be written as

$$E_{IB} = \frac{P_{on}T_{on}}{L} \tag{1}$$

where, $P_{on}$ is power consumed and $T_{on}$ is time spent on active mode and L is number of total information bits. Power in active state $P_{on}$ comprises of transmitted signal power $P_t$, circuit power consumption $P_c$ and power amplifier's (PA) consumption $P_{PA}$. Circuit power consumption $P_c$ is total power consumed by all components of transmitter except power amplifier. Power consumed by PA is related to transmitted power and modulation scheme in use. In general, it is written as

$$P_{PA} = \alpha P_t$$

where $\alpha = \xi/\eta - 1$, $\xi$ is ratio of peak to average power and is equal to unity for MPSK and MFSK, $\eta$ is drain efficiency of PA. The value of $\eta$ is 0.35 for MPSK and 0.75 for MFSK [18] which are typical values for class A and class B PA respectively. Rewriting equation (1) by substituting parameters,

$$E_{IB} = \frac{(1+\alpha)P_t T_{on} + P_c T_{on}}{L} \tag{2}$$

Required signal power of received signal is modelled using relationship of channel capacity and predetection SNR as in [21] for MFSK and in [22] for noncoherent as shown in Fig. 3. Now, to find a set of optimum constellation size and rate of information which minimizes energy consumption per bit for a fixed distance between node and modulation scheme, expression for power received at given SNR in receiver input is written as

$$P_r = \frac{SNR.\, N_o N_f}{T_s} \tag{3}$$

where $P_r$ is received signal power, $N_f$ is noise figure, $N_o/2$ is noise power spectral density, and $T_s$ is time spend in transmitting one symbol.

Assuming $K^{th}$ path power loss model for communicating devices separated by distance d, transmission power is expressed as

$$P_t = P_r G_d = P_r G_1 d^k M_l \tag{4}$$

where, $G_d = G_1 d^k M_l$ is power gain factor, $G_1$ is gain factor at distance d = 1m and link margin $M_l$ is used to compensate hardware process variations and other background noise.

To relate $T_{ON}$ with information rate, Information rate per symbol, R can be written as

$$R = \frac{L}{T_{on}/T_s} \tag{5}$$

rewriting equation (5),

$$T_{on} = \frac{LT_s}{R} \tag{6}$$

substituting equations (3) (4) and (6) in (2),

$$E_{IB} = \frac{(1+\alpha)\, SNR\; N_o N_f G_d + P_c T_s}{R} \tag{7}$$

For simplicity, we assume square pulses as input for all modulation. Average power ratio will be unity for all constellation sizes for MPSK due to use to square pulses.

For MPSK assuming signal occupy bandwidth of B Hz and with $T_s = 1/B$, rewriting equation (7) for MPSK signals

$$E_{IB} = \frac{(1+\alpha)\, SNR\; N_o N_f G_d}{R} + \frac{P_c}{RB} \tag{8}$$

For MFSK signals average power ratio always remains unity irrespective of constellation size. For non-coherent receiver, $M = 2T_s B$ [20].

Substituting this value in equation (7) and rewriting for MFSK signals,

$$E_{IB} = \frac{(1+\alpha)\, SNR\; N_o N_f G_d}{R} + \frac{1}{2}\frac{P_c M}{RB} \tag{9}$$

The relation between information rate (R) and SNR is obtained and plotted for each constellation size and modulation scheme using relationship between SNR and capacity as given in [21] for MFSK and in [22] for MPSK over Additive White Gaussian Noise (AWGN) channel, for fixed distance between transmitting and receiving end. The results for MFSK and MPSK are shown in Fig. 3 for $1 \le \log_2 M \le 12$ and $2\le$

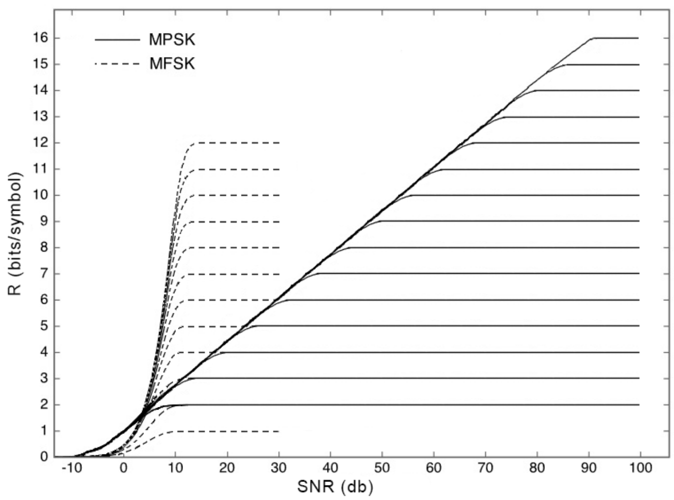


Fig. 3. Channel capacity of MFSK and MPSK versus predetection SNR in AWGN channel

$\log_2 M \leq 16$ respectively, where M represents constellation size. From these curves, optimum information rate for minimized energy and its linked constellation size is solved by using equations (8) and (9) for MPSK and MFSK respectively and minimum energy per bit is obtained through numerical search. It is then substituted in equation (6) with R to get optimum $T_{on}$. Other parameters used in calculation are listed in Table II. Bandwidth efficiency of MFSK is less as compared to MPSK. For a given constellation size M for any modulation scheme, maximum bandwidth efficiency can be achieved by $B_{eff} = b/(T_s B)$, where $b = \log_2 M$ is total number of bits per symbol. Maximum attainable bandwidth efficiency for MPSK constellation considering $T_s \approx 1/B$ is approximately b bits/s/Hz and for MFSK constellation, it is $b/2^{n-1}$ bits/s/Hz, since $M = 2BT_s$ .

TABLE II
PARAMETERS USED IN MODEL

| | | | |
|---|---|---|---|
| $P_c = 75\,mW$ | $M_l = 40db$ | $k = 3.5$ | $N_o/2 = -174$ dbm/Hz |
| $B = 1\,MHz$ | $N_f = 10db$ | $G = 30db$ | $\eta =$ 0.35 ($for\ MPSK$) |
| $f_c = 2.4\,GHz$ | $T = 3\,ms$ | $L = 1\,KB$ | $\eta =$ 0.75 ($for\ MFSK$) |

Fig. 4 compares minimum energy consumption for MPSK and MFSK modulation schemes for various transmission distance. Optimum information rate, minimum energy consumption per information bit and corresponding bits per symbol for different transmission distances for both MPSK and MFSK are shown in Table III and Fig. 5.

MFSK needs lower SNR than MPSK for any information rate as shown in Fig. 3 but energy consumption is higher in MFSK than its counterpart, since it needs more time to transmit any given information due to lower bandwidth efficiency. Energy performance of MFSK is poor for short distance transmission when consumption of circuit energy is dominant, but when consumption of signal energy is dominant, MFSK outperforms MPSK in terms of energy efficiency. By converting input signal to Non-Return to Zero (NRZ) stream and passing it to Gaussian filter before MFSK modulation, which is also known as GFSK modulation, more bandwidth efficiency can be achieved. Since Gaussian filter smooth out abrupt transitions of input signal, it limits spectrum width of modulated signal and further reduces power consumption in transmitter and becomes good choice for IoT applications where short distance signal transmission is required and RF circuitry is designed to consume very less power.

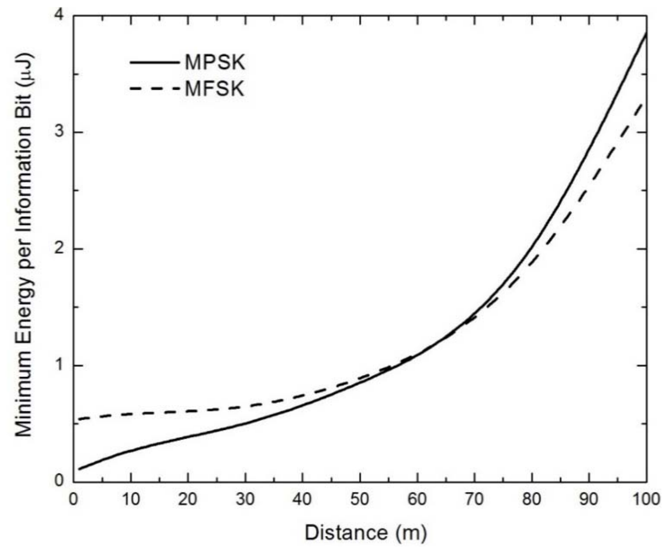


Fig. 4. Minimum energy consumption for various transmission distance for MPSK and MFSK modulation.

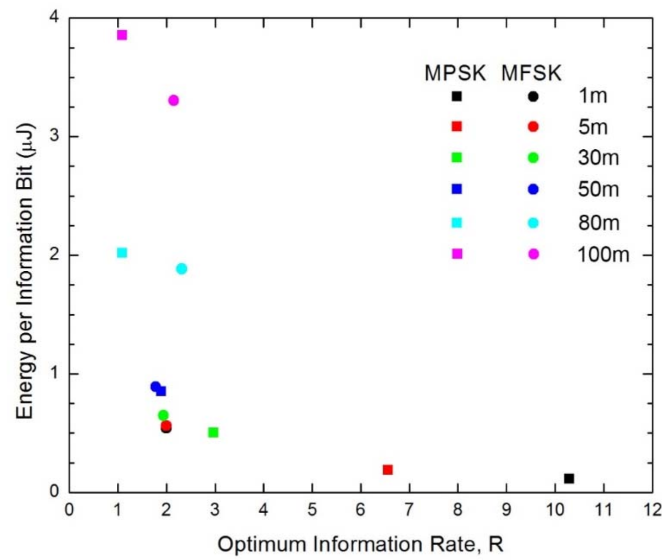


Fig. 5. Energy per Information Bit versus Optimum Information Rate for MPSK and MFSK modulation at various transmission distance.

TABLE III
OPTIMUM INFORMATION RATE (R), ENERGY/BIT AND BITS/SYMBOL (b)

| Distance[1] | MPSK | | | MFSK | | |
|---|---|---|---|---|---|---|
| | R | Energy/Bit[2] | b[3] | R | Energy/Bit[2] | b[3] |
| 1 | 10.3 | 0.112 | 11 | 2 | 0.541 | 2 |
| 5 | 6.57 | 0.189 | 8 | 2 | 0.564 | 2 |
| 30 | 2.97 | 0.503 | 4 | 1.94 | 0.649 | 2 |
| 50 | 1.9 | 0.853 | 3 | 1.78 | 0.891 | 2 |
| 80 | 1.1 | 2.017 | 2 | 2.32 | 1.884 | 3 |
| 100 | 1.1 | 3.854 | 2 | 2.15 | 3.304 | 3 |

[1] Distance in Meters, [2] Energy/Bit in $\mu$J, [3] $b = \log_2 M$

### A. Battery Life

The purpose of IoT is to connect all remote and tiny sensors altogether to collect data for several applications. These sensors are mainly battery powered and are anticipated to run unattended for years. For these sensors, battery life is shown in Fig. 6 assuming sensor report every minute with upper bound of 3ms, 6ms and 10ms per transaction [9] for transmitter power of 15mW, 45mW, 65mw and 75mW. A generally available $Li/MnO_2$ coin cell Energizer CR2032 battery is used for calculation which have typical capacity of 240 mAH and service life of 10 to 15 years [23]. For most 65nm devices, transmitting power is 15mW and battery life for 3ms, 6ms and 10ms transaction time is approx. 55, 27.5, 16.5 years respectively which is far beyond sensors and battery service life.

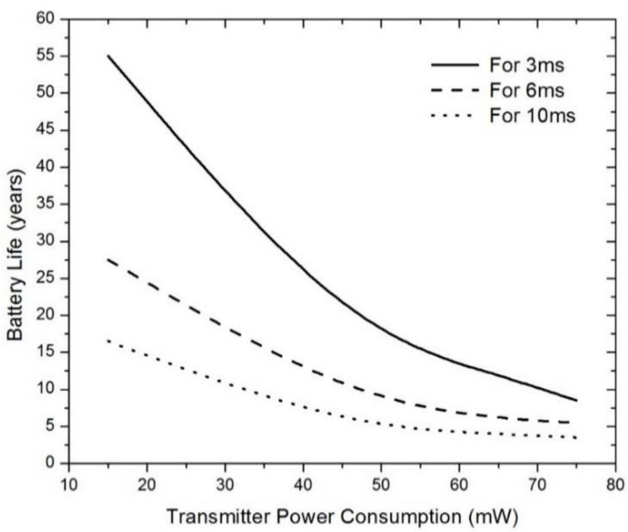


Fig. 6. Battery life in years and transmitter power consumption in mW

## IV. Conclusion

Energy consumption of two widely used modulation schemes MFSK and MPSK are evaluated and compared over AWGN channel. For fixed range of communication the transmitted power of the system will be independent of semiconductor technologies. Only circuit power which includes receiver, transmitter and power management circuit, can be minimized by using better VLSI technologies (14 nm / 22 nm SOI CMOS). The Battery life for IoT sensors using Bluetooth LE technology has been investigated for multiple transaction times for transmitters having different power consumption and result shows that the incremental change in transmitter power consumption and device active time affects the battery life significantly. The result can be used to choose energy efficient modulation scheme for IoT devices having Bluetooth capabilities.

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