ENERGY EFFICIENT MIMO TRANSMISSION WITH HIGH ORDER MODULATIONS FOR WIRELESS SENSOR NETWORK

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ABSTRACT

Energy efficiency emerges as a big concern in wireless sensor networks, where the lifetime of the system depends heavily on energy consumption. In a sensor network, the energy is consumed both by the circuit and the radio link. The radio link performance can be improved by using spatial multiplexing, but the conventional way of spatial multiplexing requires large antenna space and consumes more energy. Thus single RF MIMO transmission is proposed, which maps MIMO symbols on the radiation patterns to reduce power consumption. This paper presents the energy efficiency analysis over different schemes, which extends single RF MIMO capability with 16-QAM constellation though compact ESPAR antenna with only 2 elements. A detailed analysis on the minimal required energy is given, which shows that the proposed single RF MIMO with 16-QAM signaling has similar bit error rate performance with better energy efficiency.

***Index Terms*—** Wireless Sensor Network, Single RF MIMO, Spatial Multiplexing , Energy Efficiency, ESPAR

1. INTRODUCTION

The life time of wireless sensor network draws a lot of attentions both from industry and academia. Since most of sensor nodes are powered by batteries which are not easily replaceable, the energy must be used efficiently in order to maximize the lifetime of the network. The energy consumption can be cataloged into two main parts [1]: the energy consumed by the circuit on the sensor node, and the energy consumed by the transmission in the radio link. In order to have a long life time of the network, those two parts have to be reduced. The transmission energy cost relies on the distance of the radio link, the topology of the network, the channel condition, etc. The circuit energy consumption depends on the amount of circuit blocks that are switched on during a certain period, such period can be reduced by having a higher data rate in transmission.

The spatial multiplexing technique can help the wireless sensor network with a better performance on the radio link [2], such as larger capacity, higher data rate, etc. When the radio link is enhanced, the number of routing/hoping nodes can be reduced [3], which increases energy efficiency of the network. However, the conventional spatial multiplexing needs more RF chains, which increases circuit power consumption. Moreover, the antennas are spaced far away from each other, which makes having multiple antennas on a single sensor node very difficult. Thus the single RF MIMO transmission is introduced, which maps MIMO symbols onto the radiation patterns. By using Electronic Steerable Parasitic Arrays Radiators (ESPAR) antenna [4], the radiation patterns can be modulated by changing the load of the parasitic elements on the antenna, which is equivalent as conventional MIMO symbols faded though independent channel. At the same time, ESPAR antenna has compact size, which can be installed on a sensor node.

The energy efficiency on the radio link depends on the channel diversity, the baseband signaling, etc. Higher modulation schemes has better data rate which can lead to better circuit efficiency, but the total system energy efficiency needs to be reconsidered since the error probability has been changed. This paper proposes a way of improving the radio link in the wireless sensor network as following: Using single RF transmission with 16-QAM modulation over ESPAR antenna with only 2 elements spaced by $d = \lambda/16$. By numerical simulations in terms of system performance, the proposed method has the bit error rate similar as conventional MIMO transmission; while in terms of required energy per bit analysis, it gives better energy efficiency.

The remaining part of this paper is organized as following: section 2 gives the concept and simulation of single RF transmission over ESPAR antenna with 16-QAM signaling; section 3 analysis the energy efficiency over different configuration/constellation in wireless sensor network, also gives a comparison of the energy efficiency over those configurations; a conclusion is given in section 4.

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2. MIMO OVER ESPAR ANTENNA

2.1. System Model

A proposed architecture of Single RF transmission over ESPAR antenna contains 2 closing by elements spaced by $d = \lambda/8$. Two MIMO data streams are mapped to two orthogonal radiation patterns, which gives the total pattern as:

$$P(\theta, \varphi) = \sum_{n=0}^{2-1} w_n \Phi_n(\theta, \varphi) \tag{1}$$

where $\Phi_n(\theta, \phi)$ ($n \in \{0, 1\}$) is the basis pattern, and w_n ($n \in \{0, 1\}$) is the weighting coefficient (which is also corresponding to the transmitted symbol)[5], Mapping of the MIMO symbols onto the radiation pattern is done by changing the parasitic load, given a 2-elements ESPAR antenna parameter Z_{21}, Z_{22}, the load value and the transmitted symbols are linked by [5]:

$$x_1 = -\left(\left[\frac{w_0}{w_1} - \frac{2\pi I_0(jb)}{k_0 k_1}\right] \frac{k_1}{k_0} Z_{21} + Z_{22}\right) \tag{2}$$

where $b = 2\pi d$ and d is the inter-element distance normalized to wavelength, and $I_0(jb)$ is the zero-th order modified Bessel function of the first kind. Assuming an ESPAR antenna is designed as Fig.1, where port 1 is connected to active RF chain and port 2 is connected to adjustable loads. FR4 with E_r=4.3 is used as substrate and metal thickness is 0.0254mm. The self-impedance of the antenna is given by: $Z_{11} = Z_{22} = 48 + j15\Omega$ and $Z_{21} = Z_{22} = 35 + j10\Omega$.

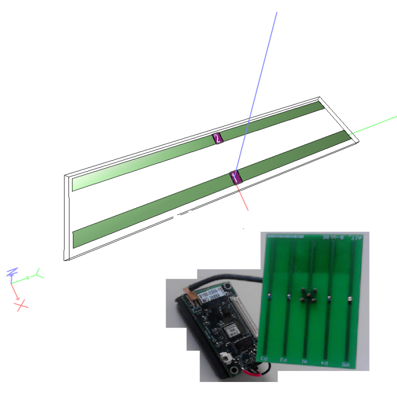

Fig. 1. ESPAR antenna and a sensor node.

Two data streams w_0 and w_1 with 16-QAM signaling are mapped to basis patterns $\Phi_1(\varphi), \Phi_0(\varphi)$. w_0 goes to the conventional RF chain and w_1/w_0 goes to a mapping block that controls the loadings. Combination of two data streams with 16-QAM constellation has 256 numbers, due to symmetric, (e.g. $(1 + j)/(1 - j) = (3 + 3j)/(3 - 3j)$), w_0/w_1 only requires 64 values. Varying all the symbol combinations, the required load in (6) is found to be in the range of $\{-81 \sim +76\} + j\{-56 \sim +69\}\Omega$.

2.2. Circuit for parasitic Load

Complex load is proposed to satisfy system's requirement, and such load should also ranged with both positive and negative values. As mentioned in [6], where CMOS technique was used for load design, the proposed design in this paper uses the similar technique while extending the controllable range on both real part and imaginary part. UMC-0.18μmRF process is used for the load design with the topology shown in Fig.2. Negative load is simulated by inserting a probe though the differential port ({Port+, Port-} in the figure). Transistors M6-M11 work as biasing circuit; M1-M4 work as cross-coupling core which generates negative resistance; M5 works as the main current source of the core circuit. Transistor M12 works as a capacitor to stabilize the biasing.

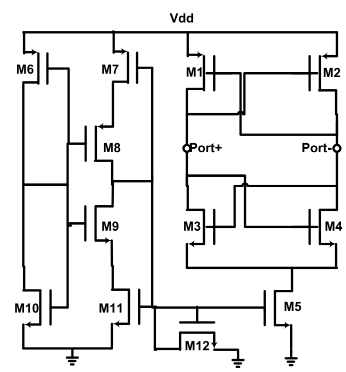

Fig. 2. Active circuit for negative resistance generation.

The generated load is given by (9) , such load is valid under DC biasing, at high frequency the value will change.

$$R_{neg} = -\frac{L}{uC_{ox}W(V_{gs} - V_{th})} = -\frac{1}{2}\sqrt{\frac{2n}{uC_{ox}} \frac{L}{W} \frac{1}{I_{ds}}} \tag{3}$$

uC_{ox} is CMOS process related coefficient; W/L is the ratio of width and length of the transistor; I_{ds} is the *biasing* current controlled by M5. V_{gs} is the *gate-source* voltage, V_{th} is the threshold voltage, g_m is the *trans-conductance* of (M1-M4). n is the ratio of *drain-source* voltage V_{ds} and *gate-source* voltage V_{gs}. According to the simulation, the load of such circuit block is -113+76jΩ at 2.5GHz.

2.3. Load Switching Circuit

The CMOS load can be changed by changing the currentI_{ds}, but the side effects on the imaginary part is nonpredictable. In order to have a stable design, the proposed system uses a fixed CMOS load and adds a switching stage for generating the 64 variable loads.

The switching stage is composed of passive element, and connects between the CMOS load and parasitic antenna element, which is shown in Fig.3. It is an 8×8 array that contains 8 vertical beams and 8 horizontal beams. 64 cells are

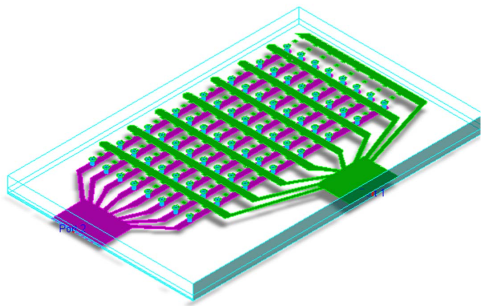

Fig. 3. Loading array for 16-QAM MIMO mapping.

formed between the cross point of the beams, each cell contains a resistor and inductor with fixed values. By selecting the appropriate combination of array beams (the vertical and horizontal), one of the cells can be chosen, which gives the compensated loading value for parasitic antenna. One indica-

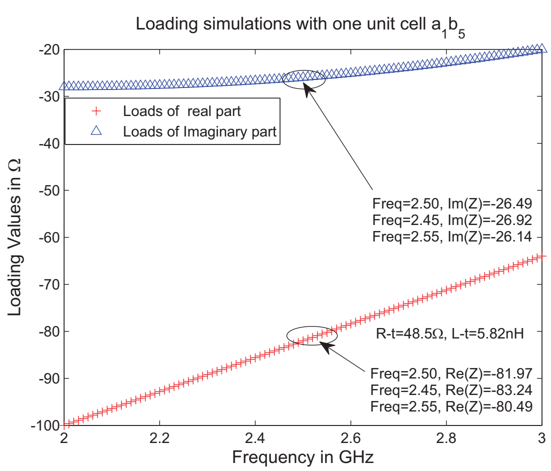

Fig. 4. Simulated loading with variations.

tive example is given by selecting the first horizontal and 5th vertical beams, where$a_1b_5$is selected, thus the CMOS Load combines with the compensation load inside unit a_1b_5 to form a load with -83.24-26.92jΩ for parasitic antenna, the corresponding resistor and inductor value are 4.85Ω and 5.82 nH respectively. It can also be concluded from Fig.4, The load value varies little over 90MHz frequency band.

2.4. System Performance

The performance of Single RF MIMO is evaluated by comparing bit error rate with conventional MIMO, the result is shown in Fig.5. It can be seen that, in the ideal case, there's no big difference between single RF MIMO and conventional MIMO.

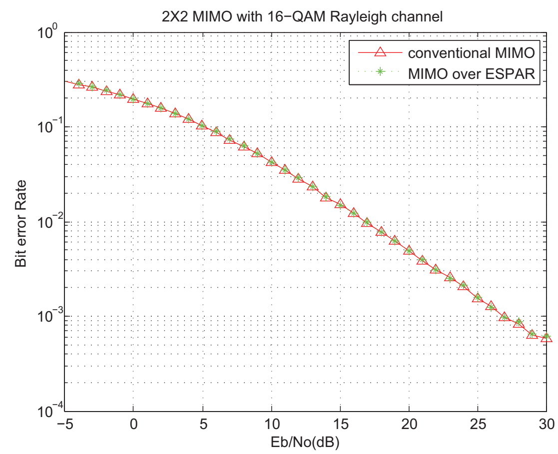

Fig. 5. Simulated bit error rate performance.

The aforementioned system performance is simulated only with consideration of baseband signal power, which is noted by Eb/No. In order to transmit such amount of signal bits into the air, radio frequency circuits are required, which involve mixers, power amplifiers, frequency synthesizers,etc. Conventional MIMO system needs M_t number of such RF Chain for transmission, while Single RF MIMO transmission just uses one. Thus it is expected with less power requirement, a detailed energy efficiency is analysed in the next section.

3. ENERGY EFFICIENCY ANALYSIS

3.1. Energy for the Transmission Link

The total energy consumption in a wireless sensor network depends both on the radio link and circuit consumption on the sensor nodes. Without losing of generality, we assume G_t is the antenna gain of a transmitter, and G_r is the antenna gain of the receiver for a single link; for a MIMO radio link, we assume there are M_t number of transmit antennas and M_r number of receiving antennas. The power consumed by the radio transmission is noted as P_T, while the power consumed by the circuit is noted as P_C. Assuming the data rate of such a link is given by R_b, Thus the energy efficiency (required energy for one bit) is defined as [1]:

$$E_{bt} = (P_T + P_C)/R_b \tag{4}$$

Which is defined by joule per bit (J/bit). (4) indicates that, for a given data rate, system energy efficiency linearly follows the total power consumption.

A typical circuit power consumption of a radio link includes mixers (P_{mix}), frequency synthesizers (P_{sys}) and power amplifier (P_A) (transmission), low noise amplifier P_{lna}(receiving), as well as analog to digital converter (P_{adc}) and digital to analog converter (P_{dac}). The power amplifier is the last stage on the transmission chain, and its efficiency and linearity influence the output power, which are considered in the power for transmission P_T. Assuming P_T relates to the actual power amplifier consumption P_A by $P_T = (1+\alpha)P_A$, where α is given by $\alpha = \xi/\eta - 1$, and ξ, η are linearity factor and drain efficiency respectively. For a M-arry signaling, ξ is related to the Peak to Average Power Ratio (PAPR) given by $\xi = 3(M - 2\sqrt{M} + 1)/(M - 1)$.

The circuit power consumption P_C is modeled with minimal circuit blocks required in sensor communication, as shown in(5), where for a SISO link, M_t, M_r is assumed to be 1.

$$P_C = M_t(P_{adc}+P_{mix}+P_{sys})+M_r(P_{mix}+P_{sys}+P_{lna}+P_{dac}) \tag{5}$$

The required transmission power from the power amplifier P_A can be calculated though the radio link budget. The channel $\boldsymbol{H}$ among the transmitters and receivers is modeled as following: the distance d_{ij} among the i^{th}transmitter and j^{th}receiver is assumed to be d; the attenuation coefficient κ is assumed to represent the fading (with κ ranged from 2 to 4 according to the fading condition). according to [1], The energy budget is shown as following:

$$P_A = \overline{E}_b \times R_b \times \left(\frac{4\pi}{\lambda}\right)^2 \times \frac{U_{link}N_F}{G_tG_r} \times d^\kappa \tag{6}$$

where $\overline{E}_b$ is the required energy per bit for a given error probability $\overline{P}_b$, and R_b is the data rate noted by bit/s, U_{link} is the link compensation due to the hardware variation and system interferences. N_F is the noise figure given by $N_F = N_r/N_o$. Thus the energy required for a single radio link with data rate R_b is given by [7]:

$$P_T = (1+\alpha) \times \overline{E}_b \times R_b \times \left(\frac{4\pi}{\lambda}\right)^2 \times \frac{U_{link}N_F}{G_tG_r} \times d^\kappa \tag{7}$$

3.2. Energy and Error Probability

The theoretical error probability for a BPSK signaling is given by:

$$\overline{P}_b = Q(\sqrt{2\gamma_b}) \tag{8}$$

where γ_b is given by $\gamma_b = \overline{E}_b/N_o$ in a SISO link, for MIMO system, $\gamma_b = (|\mathrm{H}|_F^2 \cdot \overline{E}_b)/(M_t \cdot N_o)$, where $|\mathrm{H}|$ is the channel matrix. According to chernoff bound, the error probability is approximately given by:

$$\overline{P}_b = \varepsilon_{\mathrm{H}}(Q(\sqrt{2\gamma_b})) \le (\frac{|\mathrm{H}|_F^2 \cdot \overline{E}_b}{M_t \cdot N_o})^{-M_t} \tag{9}$$

Where M_t is the number of transmission antennas, the required energy per bit $\overline{E}_b$ (J/bit) can be derived as :

$$\overline{E}_b \ge \frac{M_t \cdot N_o}{|\mathrm{H}|_F^2 \, \overline{P}_b{}^{\frac{1}{M_t}}} \tag{10}$$

Thus, the required power for transmission (7) can be derived as:

$$P_T = (1+\alpha)\frac{M_t \cdot N_o}{|\mathrm{H}|_F^2 \, \overline{P}_b{}^{\frac{1}{M_t}}} R_b \left(\frac{4\pi}{\lambda}\right)^2 \frac{U_{link}N_F}{G_tG_r} d^\kappa \tag{11}$$

It is noticed that in (11), the power for transmission is related to data rate, when considering the energy efficiency, such data rate should be divided as in (4). Thus the energy per bit for transmission is independent of data rate, while the energy per bit for circuit consumption depends on the data rate, which can be expressed as:

$$E_{bt} = \frac{(1+\alpha)M_t \cdot N_o}{|\mathrm{H}|_F^2 \, \overline{P}_b{}^{1/M_t}} \left(\frac{4\pi}{\lambda}\right)^2 \frac{U_{link}N_F d^\kappa}{G_tG_r} + \frac{Pc}{Rb} \tag{12}$$

For higher order signaling, e.g., M-arry signaling (16-QAM is used in this paper), the error probability [2] is given by:

$$\overline{P}_b \approx \varepsilon_H \left(\frac{4}{b}(1 - 1\big/2^{b/2})Q(\sqrt{\frac{3b}{M-1}\gamma_b})\right) \tag{13}$$

Where $M = 2^b$ and b is the constellation size. M-arry signaling has better data rate than BPSK within a same bandwidth, and such ratio is represented by the constellation size b. Error probability (13) can be approximated as following under chernoff bound.

$$\overline{P}_b \le \frac{4}{b}(1 - 1\big/2^{b/2})\left(\frac{3\overline{E}_b b\,|\mathrm{H}|_F^2}{2M_t \cdot N_o(2^b - 1)}\right)^{-M_t} \tag{14}$$

And the required energy per bit for M-arry signaling with constellation size b is given by:

$$\overline{E}_b \ge \frac{2}{3}\left(\frac{4\left(1 - 1/2^{b/2}\right)}{b\overline{P}_b}\right)^{1/M_t} \frac{M_t \cdot N_o}{|\mathrm{H}|_F^2}\frac{(2^b - 1)}{b} \tag{15}$$

Thus the energy per bit of the M-arry signaling system within same bandwidth as BPSK can be derived as:

$$E_{bt} = \frac{2M_tN_o(1+\alpha)U_{link}N_F d^\kappa 4^2\pi^2}{3\,|\mathrm{H}|_F^2\,(2^b-1)^{-1}b^{1/M_t}G_tG_r\lambda^2}\left(\frac{4}{\overline{P}_b}\right)^{\frac{1}{M_t}} + \frac{Pc}{b \cdot Rb} \tag{16}$$

Where an assumption is made as $\left(1 - 1\big/2^{b/2}\right) \simeq 1$. From (4),(12),(16) It can be concluded that, for a fixed amount of data, the circuit power consumption can be reduced by a scheme with better data rate; the transmission power consumption per bit is independent of data rate but depends on the error probability; for higher signaling, the error probability is different from that of a lower constellation. The energy efficiency of the single RF MIMO is modeled as following: Only one RF amplifier is used while the channel matrix H is considered as the same as that in conventional MIMO. The Circuit power consumption P_C only considers one mixer, one frequency synthesizer is used at transmitter.

3.3. Energy efficiency Comparison

An energy efficiency comparison between conventional SISO transmission and single RF MIMO is given with the aforementioned assumptions. The system parameters are defined as following: The channel fading factor κ is assumed to be 2, the carrier frequency of the sensor network is 2.5GHz (which is also the ESPAR antenna center frequency), the antenna gain on the SISO radio link with conventional architecture is given by G_t=3dBi and G_r=3dBi, for ESPAR antenna G_t=2.5dBi, for conventional MOMO, the channel matrix H is considered as 2×2 with diversity order of 4. M_t is considered to be 2 and M_r is considered as 2, $U_{link} = 40dB$, $NF = 10dB$, $N_0 = -174dBm/Hz$, the system bandwidth is considered as 10KHz, where for BPSK signaling, the data rate is R_b=10Kb/s, for 16-QAM, the data rate is considered as $4\times R_b$.

The circuit power consumption model is based on the parameters mentioned in [1], where the mixer power is assumed to be 30mW, the frequency synthesizer is considered as 50mW, the low noise amplifier is considered as 20mW. the drain efficiency η of power amplifier is conspired as 0.35, the analog to digital converter and digital to analog converter is considered 10mw and 12mw respectively.

An indicative comparison is given in Fig.6, where the minimal required energy per bit to reach error probability of $P_b = 10^{-3}$ is plotted over the transmission distance. It indicates that, by using QAM modulation with MIMO, the power efficiency is better than the conventional BPSK in SISO with distance less than 20 meters (which is a reasonable distance for inter-sensor communication), while using sinlge RF MIMO transmission with higher order constellation, e.g., 16-QAM as mentioned in this paper, the required energy per bit is further reduced.

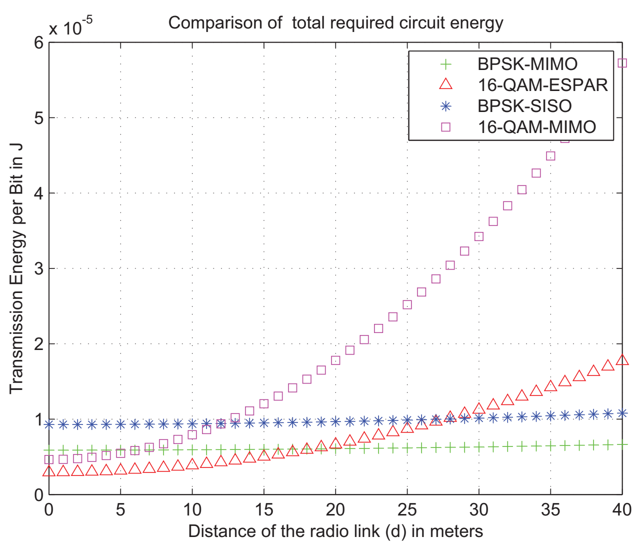

Fig. 6. Comparison of minimal required energy.

4. CONCLUSION

Energy efficiency influences the lifetime of the wireless sensor network, while most of the energy in WSN is consumed by the radio link as well as circuit cost. With the help of spatial multiplexing, a better efficiency can be achieved. However, it is not easy to implement conventional MIMO on a sensor node, thus single RF MIMO transmission with 16-QAM signaling is proposed in this paper, which uses an ESPAR antenna with 2 elements spaced by $\lambda/16$ on the sensor node. A detailed energy analysis and indicative system performance evaluation is given. It shows that the proposed architecture has a better energy efficiency than the conventional MIMO; for the inter-sensor distance less than 20 meters, it requires less energy than other signaling.

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