Research Article

An Energy-Efficient Adaptive Modulation Suitable for Wireless Sensor Networks with SER and Throughput Constraints

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We consider the problem of minimizing transmission energy in wireless sensor networks by taking into account that every sensor may require a different bit rate and reliability according to its particular application. We propose a cross-layer approach to tackle such a minimization in centralized networks for the total transmission energy consumption of the network: in the physical layer, for each sensor the sink estimates the channel gain and adaptively selects a modulation scheme; in the MAC layer, each sensor is correspondingly assigned a number of time slots. The modulation level and the number of allocated time slots for every sensor are constrained to attain their applications bit rates in a global energy-efficient manner. The signal-to-noise ratio gap approximation is used in our exposition in order to jointly handle required bit rates, transmission energies, and symbol error rates.

1. INTRODUCTION

Wireless sensor networks are susceptible to many different applications in diverse fields such as areas of industry and commerce (i.e., environment monitoring and control), home automation and intelligent buildings (i.e., security, lighting, air conditioning), PC peripherals (i.e., mouse, printer), consumer electronics, medicine and personal health care (i.e., monitors, diagnostics, medical body sensors), and surveillance and maintenance among others [1–6]. Furthermore, the availability of commercial products has fostered potential applications; examples are given in [7–11]. Particularly, wireless devices conforming to IEEE 802.15.4 standard and ZigBee specifications seem to be gaining market due to their characteristics of low power, low cost, and low rate. These features make them very well-suited as well for most WSN applications in the so-called personal area networks (PAN).

Some relevant parameters are usually considered in the context of PANs such as the type and quality of service, scalability, maintainability, and, specially, lifetime of batteries. Therefore, energy-efficient communication schemes have become a main challenge in the design of these networks. One straight approach towards energy efficiency would be the use of long transmission time intervals, however many applications impose hard delay contraints. This energy-efficiency

delay tradeoff has been recently studied in [12]. An other different appproach [13] examines single-hop sensor communications using time division multiple access (TDMA), proposing optimal and suboptimal algorithms to minimize the energy to transmit data with a given capacity in the adequate time. Theoretical energy gains are thus obtained for optimal and suboptimal schemes as compared to the TDMA ideal capacity. Other approaches for multihop networks have been developed in [14, 15].

As for centralized WSN, there exist different works focused on single layer design to tackle the energy minimization problem. Examples of PHY-oriented approaches are given in [16, 17]. Similarly, energy minimization can be accomplished through MAC layer protocols as in [12, 13, 15, 18, 19]. Cross-layer design has been typically focused on MAC and routing layers but does not touch upon the PHY layer [20–23]. Nevertheless, we consider that PHY layer is of paramount importance as to cross layer design when energy efficiency is the aim to tackle. Some recent works on multihop networks follow this same line by using power management [24] or coding [25].

Along with energy-efficient transmission, the reliability of low-power wireless channels is also a challenge in WSN, specially in the heterogeneous case when the requirements for each sensor may be different according to their

implemented services and applications. We will deal with two essential aspects related to reliability in real wireless channels for WSN: path loss and symbol error rate. In this paper, to face the aforementioned problems, we propose a practical and energy-efficient adaptive scheme using cross layer design. It works as follows: firstly, we estimate the channel gains between every node and the sink; then, this information is used by MAC layer to design the time slots lengths in an energy-efficient manner; finally, joint consideration of the calculated time slots lengths and the bit rates determines the suitable modulation level for the PHY layer.

Due to its high energy efficiency, we have selected multilevel quadrature amplitude modulation (MQAM). The modulation level will be adapted to fulfill transmission requirements for each sensor by means of SNR gap approximation. We apply this approximation because it allows to relate a constant application quality (SER) with a constant throughput straightforwardly. In order to show the performance of the proposed scheme, the energy needed for our adaptive modulation scheme will be compared to that of the fixed-slot TDMA scheme within a PAN environment.

IEEE 802.15.4 MAC protocol [26] provides a mode of operation for sensors requiring service guarantees, making use of "guaranteed time slots" (GTS) and slotted CDMA. However, such guaranteed service requests may be rejected by the PAN coordinator, so these guarantees are not assured. Even though GTSs are accepted for a certain sensor, energy minimization could only be implemented by means of power transmission control whilst no power management is considered in the standard. With the TDMA variable-time-slot-length scheme we propose, optimal energy consumption is achieved simply by adjusting the time slots durations, keeping the transmitted power constant.

Since the range of modulation levels in practice is moderate, adaptive schemes can be implemented in a straightforward manner through a parallel hardware architecture. Yet, another recent alternative for adaptive modulation is software radio: its use in the WSN sink can be adopted very easily and, although its implementation in sensors may not seem so immediate, some proposals have already been given in this area [27].

The remaining of the paper is organized as follows. Section 2 reviews SNR gap approximation. In Section 3, we formulate the problem and the system description for the WSN scenario. In Section 4, we present the proposed energy-efficient adaptive modulation scheme while simulations, and results are shown in Section 5. Finally, some conclusions are outlined in Section 6.

2. REVIEW OF SNR GAP APPROXIMATION

SNR gap approximation provides a simple way to relate SNR (signal-to-noise-ratio), bit rate R_b and SER (symbol error Rate) for a given modulation (e.g., M-QAM) and coding scheme [28]. It has been generally used for bit-loading purposes because it makes algorithms easier to implement [29].

Different multilevel modulations can be used for adaptive modulation. M-QAM provides a lower probability symbol error compared to M-PSK for the same SNR. M-FSK is a priori more energy-efficient compared to M-QAM; however, the bandwidth efficiency (bps/Hz) can be a drawback, up to 8 times less than M-QAM ($M = 16$) [30], resulting then that we would need 8 times more bandwidth. As our system is narrowband and, in addition, the bandwidth is constant, our interest falls on an efficient-bandwidth modulation, so M-QAM is more adequate. Additionally, if we consider the distance of the link, energy can be optimized using M-QAM and M-FSK [17]; the energy per bit is lower for M-QAM for distance less than 30 m, which is our range of interest. Other related works consider also M-QAM as the multilevel modulation to be used for energy efficient communications [31, 32].

Then, in this paper we will use M-QAM modulation because of its higher-energy efficiency for centralized WSN with PAN coverage. If M-QAM modulation is used, SNR gap approximation states that the number of bits per symbol Λ may be found as

$$\Lambda = \log_2\left(1 + \frac{\gamma}{\Gamma}\right) = \log_2 M,$$

$$\Gamma = \frac{1}{3}\left(Q^{-1}\left(\frac{SER}{4}\right)\right)^2, \qquad (1)$$

$$Q(x) = \int_x^\infty \frac{e^{-u^2/2}}{\sqrt{2\pi}}\,du,$$

where γ is the SNR, that is, $\gamma = E_S/N_0$, required to convey Λ bits per symbol achieving a given error probability SER in a flat-frequency propagation channel corrupted by AWGN, Γ is the SNR gap [33] and $Q(x)$ is also defined in [33]. In practical applications, Λ and M take real values but have to be discretized. We will use ΔM as the increment between consecutive allowed values of M and we will examine the proposed scheme performance depending on this value.

In real applications, however, the usual way to specify the data-rate is in bits per second (bps), so for our convenience we will use R in these units considering a symbol period T_S:

$$R = \frac{1}{T_S}\log_2\left(1 + \frac{\gamma}{\Gamma}\right) = \frac{1}{T_S}\Lambda. \qquad (2)$$

3. PROBLEM FORMULATION AND SYSTEM DESCRIPTION

3.1. Problem formulation

Let us consider a centralized WSN where a central node or sink needs to collect information from N sensors. Each of these sensors potentially could be implementing a different application or service, resulting in different data-rates R_n and symbol error rates SER_n for each one, where subindex "n" is used to denote different users. Let us assume a total frame duration T, and a time interval of variable length T_n is assigned to sensor n; consequently, the sum of all time intervals equals T:

$$\sum_{n=1}^{N} T_n = T. \qquad (3)$$

For energy minimization purposes, we will calculate the energy E_n associated to nth sensor as the energy used for the transmission in the corresponding nth time slot:

$$E_n = E_{\text{Stx}} \cdot \frac{T_n}{T_S}. \tag{4}$$

We will base then our analysis of energy on the transmitted symbol energy E_{Stx} and the relation T_n/T_S, which determines the number of symbols transmitted during the nth time slot $N_n : N_n = T_n/T_S$. This energy model is a simplified one, since total energy consumption in the sensor encompasses also active-sleep transitions power and circuit power consumption [17, 31]; then, a fully realistic model would take them into account.

It is clear that some entity in the network must coordinate the time assignments, that is, the time-slots duration T_n, and estimate the channel parameters we will need for the adaptive modulation scheme (see Section 3.2). Therefore, some signaling system must be implemented in order to inform the sensors about these assignments. Since the network topology is centralized, these tasks (included channel estimation) are assumed by the sink, because sensors are intended to be as simple as possible and may have limitations in processing; the feedback information can be implemented without significant traffic load [34].

In this paper, the function to be minimized is the sum of individual energies needed by each sensor per time interval given by (4); R_n and SER_n will be guaranteed for each sensor despite changes in SNR_n due to channel variations by adapting the modulation and the transmission time. Then, the problem to solve can be formulated as the following constrained minimization problem:

$$\text{minimize} \sum_{n=1}^{N} E_n = \sum_{n=1}^{N} E_{\text{Stx}} \cdot \frac{T_n}{T_S}$$
$$\text{subject to} \sum_{n=1}^{N} T_n = T. \tag{5}$$

3.2. System description

Our system model is a centralized wireless sensor network (Figure 1) made up of sensors whose transmission requirements may differ with respect to each other in bit rate and quality of service, since the implemented applications may be different.

We state our problem from the receiver point of view, so a loss model must be defined to estimate the received energy. The reason for this is that SER is a key parameter in the proposed energy-efficient adaptive modulation scheme and we will formulate it as a function of the received symbol energy (see Section 4). Then, if the energy transmitted by each sensor can be calculated as $E_n = P_n \cdot T_n$, being P_n the nominal transmission power of the device, a path loss needs to be included to estimate the received power. The average path loss $\overline{PL}_n$ can be calculated according to the propagation model described in [35], where distance from each transmitter to
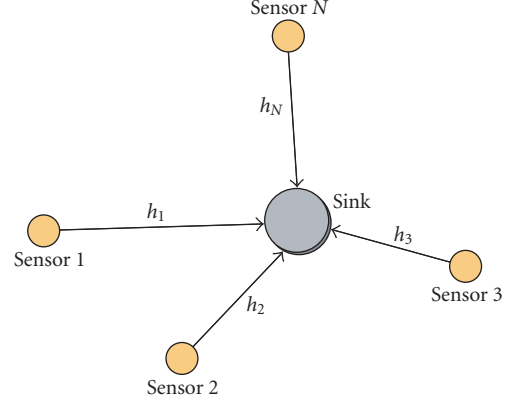

FIGURE 1: Wireless sensor network scheme: a centralized configuration.

the receiver (d_n) is in the order of personal communications range (up to 10 m):

$$\overline{PL}_n = S_0 + 10a \log d_n + b \; (\text{dB}) \tag{6}$$

being in the previous expression S_0 the path loss at 1 m distance, a and b correspond to parameters for LOS (line of sight) scenario in the ISM band (2.4 GHz) in indoor environment. The height of antennas is assumed to be 1 m for the receiver and between 1–3 m for the transmitters.

In addition to path loss, a Rayleigh distribution has been used in order to model small-scale fading for each transceiver. This fading will be represented by the coefficients h_n.

The consideration of both loss factors (path loss and small-scale fading) leads to a modification of the optimization problem (5). The received energy per symbol can be calculated then as $E_{\text{Srx}} = E_{\text{Stx}}/(\alpha_n \cdot |h_n|^2)$, where E_{Stx} denotes the transmitted energy per symbol and $\alpha_n = 10^{\overline{PL}_n/10}$; reformulating (5):

$$\text{minimize} \sum_{n=1}^{N} E_n = \sum_{n=1}^{N} E_{\text{Srx}} \cdot \frac{T_n}{T_s} \cdot |h_n|^2 \alpha_n$$
$$\text{subject to} \sum_{n=1}^{N} T_n = T. \tag{7}$$

4. ADAPTIVE MODULATION WITH SER AND THROUGHPUT CONSTRAINTS

As has been mentioned in the previous sections, the design of the time slots length is performed using SNR gap approximation as a means to relate the quality of service parameters we wish to guarantee (SER and bit rate). In contrast to fixed TDMA, in which all time intervals have the same duration, with the energy-efficient scheme, the length of time intervals T_n will be a function of the required bit rate R_n and the SER_n. The difference between transmission frames can be seen in Figure 2. In this fashion, the defined energy-efficient adaptive modulation scheme ensures fairness: although nodes seem to
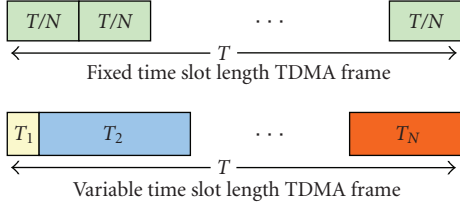
FIGURE 2: Fixed and variable time-slots length TDMA frames.

FIGURE 3: Energy gain with respect to fixed TDMA and variable length TDMA with 16-QAM modulation, $N = 896$ symbol periods.

be "stealing" time for transmission each other, every node is maintaining the required quality specified by R_n and SER_n.

The nth sensor bit rate R_n is calculated using (2):

$$R_n = \frac{N_n}{T} \log_2 M = \frac{N_n}{T} \log_2 \left(1 + \frac{\gamma}{\Gamma}\right). \quad (8)$$

Analyzing (8), we observe that required R_n is assured performing adaptive modulation: we assume invariant propagation channel during frame T, and if channel conditions get worse from frame to frame, the SNR_n decreases as well as the number of bits per symbol given by $\log_2(1 + \gamma/\Gamma)$. In order to keep R_n constant, the transmission interval must increase via N_n.

Recalling that $\gamma = E_{\text{Srx}}/N_0$, the required energy per user to be minimized of (7) can be expressed as:

$$E_n = E_{\text{Srx}} \cdot \frac{T_n}{T_s} \cdot |h_n|^2 \alpha_n = \gamma \cdot N_0 \cdot N_n \cdot |h_n|^2 \alpha_n$$

$$= \Gamma \cdot N_0 \cdot N_n \cdot |h_n|^2 \alpha_n (2^{R_n \cdot T/N_n} - 1). \quad (9)$$

Without loss of generality, E_n has been normalized with respect to N_0. Written formally, we need to solve the following constrained optimization problem:

$$\text{minimize} \sum_{n=1}^{N} E_n = \sum_{n=1}^{N} \Gamma \cdot N_n \cdot |h_n|^2 \alpha_n (2^{R_n \cdot T/N_n} - 1)$$

$$\text{subject to} \sum_{n=1}^{N} T_n = T. \quad (10)$$

The solution to (10) can be founded using Lagrangean's multipliers method, and the set of $\{N_n\}_{n=1}^{N}$ which optimize the total energy must satisfy

$$\lambda = \Gamma \cdot |h_n|^2 \alpha_n \left(1 + 2^{R_n \cdot T/N_n} \left(\frac{R_n}{N_n} \ln 2 - 1\right)\right), \quad (11)$$

where Lagrangean multiplier λ can be obtained by numerical search. It is straightforward to calculate the time duration of each interval as $T_n = T_S \cdot N_n$.

Furthermore, the corresponding E_n will decrease according to (9), as can be expected since the level of the M-QAM modulation will decrease ($M = 1 + \gamma/\Gamma$) but to preserve the bit rate, the transmission time must increase.

5. SIMULATION SETUP AND RESULTS

The system described has been simulated taking as a reference IEEE 802.15.4 standard in order to make a realistic choice of the simulation parameter values. The band
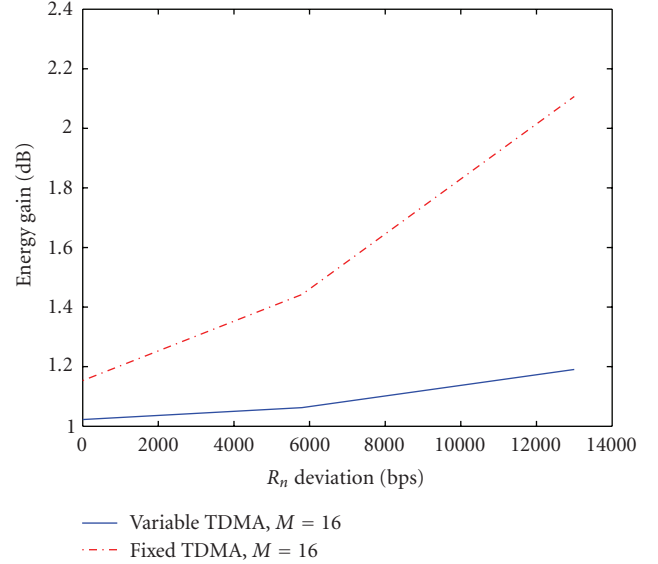
for transmission is the ISM band (2.4 GHz), defined as the primary band for this type of networks. The bandwidth is 62.5 KHz, and the symbol period equals the 802.15.4 symbol period $T_S = 16 \mu$s. In order to consider the channel invariant during a frame transmission, coherence time T_c must be larger than the duration of the frame, and T_c can be calculated as [36] $T_c = 0.423/f_m$, being $f_m = v \cdot f_c/c$, $c = 300000$ m/s, $v = 3$ Km/h (walking velocity), and f_c the carrier frequency 2.4 GHz; then $T_c = 63.45$ ms. The frame length has been chosen considering that 802.15.4 states a length from 15 milliseconds to 250 seconds; according to the value obtained for T_c, we have chosen a duration frame about 15 milliseconds, corresponding to 896 symbols of 16μs (14.336 ms). The rest of parameters have the following values: the total bit rate of the network is 250 Kbps and SER = 10^{-3}.

The energy gain (defined as the ratio of the required energy in each case), when using energy-efficient adaptive modulation compared to conventional TDMA allocation, is the parameter used to compute saving in energy. We distinguish two cases: (a) fixed TDMA with fixed modulation 16-QAM for each sensor and (b) variable length TDMA with fixed modulation ($M = 16$ and 64), which are shown in Figures 3 and 4, and a frame of 896 symbols is considered (802.15.4); abscissa axis represents the deviation among the different 16 sensors bit rates, to account for the heterogeneous nature of the network. Distance between sensors and sink is a random uniformly distributed variable with value in the range 1–10 m. Note that gains up to near 6 dB are obtained, and the heterogeneousness of the network do not have an important influence on the gain, so the performance of the adaptive scheme is able to tackle this situation without degradation. We have considered also interesting to select the parameters for another typical wireless
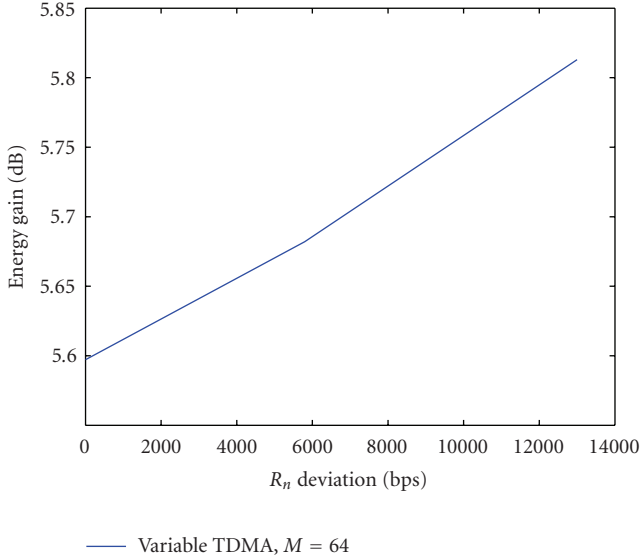
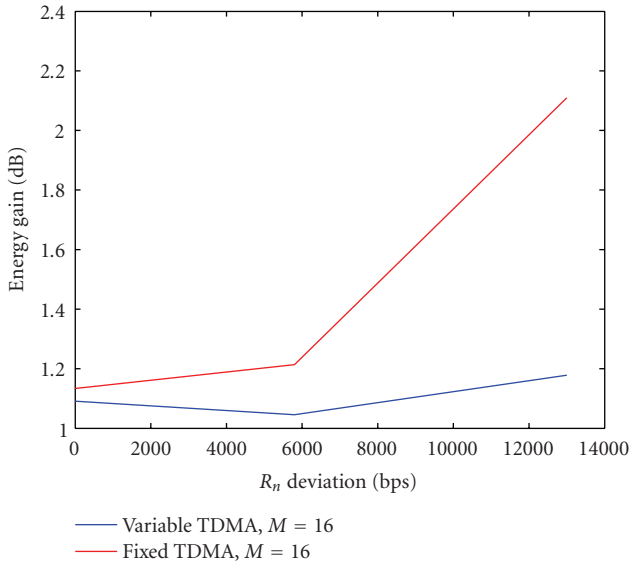Figure 4: Energy gain with respect to variable length TDMA with 64-QAM modulation, $N = 896$ symbol periods.

Figure 5: Energy gain with respect to fixed TDMA and variable length TDMA with 16-QAM modulation, $N = 64$ symbol periods.
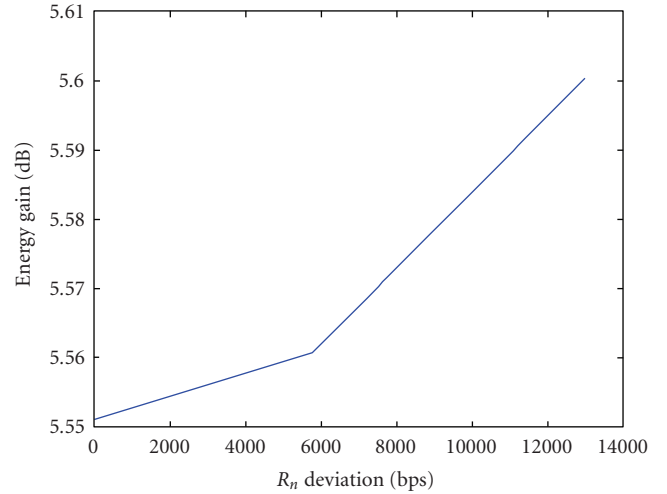

Figure 6: Energy gain with respect to variable length TDMA with 64-QAM modulation, $N = 64$ symbol periods.

Table 1: Energy gain for energy-efficient adaptive modulation compared to conventional TDMA with different correlations between channels (σ^2), $N = 896$ symbols.

M	Deviation (Kbps)	σ^2	G fixed (dB)	G variable (dB)
16	0	1	1,15	1,02
16	0	20	1,24	1,06
16	5.8	1	1,44	1,07
16	5.8	20	1,34	1,07
16	13	1	2,11	1,19
16	13	20	2,12	1,23
64	0	1	—	5,6
64	0	20	—	5,62
64	5.8	1	—	5,68
64	5.8	20	—	5,7
64	13	1	—	5,81
64	13	20	—	5,93

sensors environment, as Bluetooth; in this case, the possibilities for duration frame are. 0.625/1.875/3.125 milliseconds, so we have selected a frame of 64 symbols, corresponding to 1.024 millisecond. Figures 5 and 6 shows the energy gain in the mentioned (a) and (b) situations with the new parameters.

The effect of correlation among the propagation small-scale (Rayleigh) channels sensor-sink h_n, is taken into account. Parameter σ indicates the correlation among channels. The energy gain is shown in Table 1 for frame duration $N = 896$ symbols, and it could be expected a significant dif-

ference favourable to the uncorrelated case that in practice does not occur. The explanation to this is that the path loss coefficients (α_n) are much larger than the Rayleigh fading coefficients (h_n) and, as can be observed in (9), the optimized energy E_n is strongly dominated by path loss effect. Related to this, sensors in the lowest distance ($d = 1$ m) use a very low number of time slots (3, 4, 5 symbols per time slot), and consequently the level of modulation M is high. Similar results and conclusions apply for the case of $N = 64$ symbols.

In simulations, discrete bit-loading has been addressed in order to preserve practicality; we have used $\Delta M = 1$ ensuring always a bit rate higher than the searched R_n, taking into account that any integer value of M can be achieved using an appropriate coding. Additionally, we have explored the energy consumption of the uncoded case with the restriction $M = 2^k$ (being k an integer) with respect to $\Delta M = 1$, and we found that the former choice implies an increment in energy that can be up to 7 dB for high-level modulations.

It is important to consider power limitations that are generally and worldwide imposed by regulating agencies to radiofrequency transmissions. In IEEE 802.15.4 applications, the maximum allowed transmit power is 100 mW, but in practical 802.15.4 networks usual values of about 1 mW are very common. In the simulations carried out using the proposed energy-efficient scheme, the needed power was checked to be below this practical limit value. The result is that the maximum transmit power obtained is slightly larger than 1 mW and usual values are a few hundreds of microwatts.

6. CONCLUSIONS

Energy efficiency is critical to lifetime and performance of wireless sensor networks. In this work, we have developed an energy-efficient cross layer adaptive modulation scheme that minimizes the total energy utilized by the network. This scheme is based on bit rate and reliability: SER is maintained for the required bit rate of the implemented application adapting the M-QAM modulation. As a consequence, the design of WSN can be realized assuring the quality of service for the different implemented applications.

It must be noted that although we have chosen M-QAM as the modulation scheme, M-PSK modulation can be a possibility to be considered [37]. The choice of M-QAM has been made because of its higher-energy efficiency, since this is the parameter we are focusing our interest on. Nevertheless, M-PSK may be useful for other reasons: it can offer advantages in some other situations due to its behavior in terms of Peak-to-average power ratio (PAR); this possibility remains to be explored.

Another important topic to consider is mobility in this type of networks: the channel model we have considered assumes that sensors are static (or restricted to very slow movement). Our system model and the energy-efficient scheme developed in this paper may be suitable for the case of mobile sensors. However, the gain in this case should be evaluated with the inclusion of an appropriate channel model; this scenario could be of great interest for a wide range of different applications, such as mobile body sensors, mobile home personal devices, image transmission in surveillance systems, and mobile security sensors, always considering not high speeds.

ACKNOWLEDGMENTS

REFERENCES

[1] C. Sharp, S. Schaffert, A. Woo, et al., "Design and implementation of a sensor network system for vehicle tracking and autonomous interception," in *Proceedings of the 2nd European Workshop on Wireless Sensor Networks (EWSN '05)*, pp. 93–107, Istanbul, Turkey, January-February 2005.

[2] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, and M. Welsh, "Monitoring volcanic eruptions with a wireless sensor network," in *Proceedings of the 2nd European Workshop on Wireless Sensor Networks (EWSN '05)*, pp. 108–120, Istanbul, Turkey, January-February 2005.

[3] M. M. Nordman and M. Lehtonen, "A wireless sensor concept for managing electrical distribution networks," in *Proceedings of IEEE PES Power Systems Conference and Exposition (PSCE '04)*, vol. 2, pp. 1198–1206, New York, NY, USA, October 2004.

[4] H. Bai, M. Atiquzzaman, and D. Lilja, "Wireless sensor network for aircraft health monitoring," in *Proceedings of the 1st International Conference on Broadband Networks (BroadNets '04)*, pp. 748–750, San Jose, Calif, USA, October 2004.

[5] Y. Li, S. S. Panwar, and S. Burugupalli, "A mobile sensor network using autonomously controlled animals," in *Proceedings of the 1st International Conference on Broadband Networks (BroadNets '04)*, pp. 742–744, San Jose, Calif, USA, October 2004.

[6] V. Rajaravivarma, Y. Yi, and Y. Teng, "An overview of wireless sensor network and applications," in *Proceedings of the 35th Southeastern Symposium on System Theory*, pp. 432–436, Morgantown, WVa, USA, March 2003.

[7] L.-J. Hwang, S.-T. Sheu, Y.-Y. Shih, and Y.-C. Cheng, "Grouping strategy for solving hidden node problem in IEEE 802.15.4 LR-WPAN," in *Proceedings of the 1st International Conference on Wireless Internet (WICON '05)*, pp. 26–32, Budapest, Hungary, July 2005.

[8] G. Pekhteryev, Z. Sahinoglu, P. Orlik, and G. Bhatti, "Image transmission over IEEE 802.15.4 and ZigBee networks," in *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS '05)*, vol. 4, pp. 3539–3542, Kobe, Japan, May 2005.

[9] J. A. Gutierrez and D. B. Durocher, "On the use of IEEE 802.15.4 to enable wireless sensor networks in pulp and paper industrys," in *Proceedings of Annual Pulp and Paper Industry Technical Conference*, pp. 105–110, Jacksonville, Fla, USA, June 2005.

[10] S. Hara, D. Zhao, K. Yanagihara, et al., "Propagation characteristics of IEEE 802.15.4 radio signal and their application for location estimation," in *Proceedings of the 61st IEEE Vehicular Technology Conference (VTC '05)*, vol. 1, pp. 97–101, Stockholm, Sweden, May-June 2005.

[11] N. F. Timmons and W. G. Scanlon, "Analysis of the performance of IEEE 802.15.4 for medical sensor body area networking," in *Proceedings of the 1st Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON '04)*, pp. 16–24, Santa Clara, Calif, USA, October 2004.

[12] Y. Yu, B. Krishnamachari, and V. K. Prasanna, "Energy-latency tradeoffs for data gathering in wireless sensor networks," in *Proceedings the 23rd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '04)*, vol. 1, pp. 244–255, Hong kong, March 2004.

[13] Y. Yao and G. B. Giannakis, "Energy-efficient scheduling for wireless sensor networks," *IEEE Transactions on Communications*, vol. 53, no. 8, pp. 1333–1342, 2005.

[14] J. Haapola, Z. Shelby, C. Pomalaza-Raez, and P. Mahonen, "Cross-layer energy analysis of multihop wireless sensor

networks," in *Proceeedings of the 2nd European Workshop on Wireless Sensor Networks (EWSN '05)*, pp. 33–44, Istanbul, Turkey, January-Feburary 2005.

[15] Z. Shelby, C. Pomalaza-Raez, and J. Haapola, "Energy optimization in multihop wireless embedded and sensor networks," in *Proceedings of the 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '04)*, vol. 1, pp. 221–225, Barcelona, Spain, September 2004.

[16] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 6, pp. 1089–1098, 2004.

[17] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 2349–2360, 2005.

[18] R. Jurdak, P. Baldi, and C. V. Lopes, "State-driven energy optimization in wireless sensor networks," in *Proceedings of IEEE Systems Communications (ICW '05)*, pp. 356–363, Montreal, Canada, August 2005.

[19] S. C. Evans, N. Van Stralen, J. Hershey, and H. Tomlinson, "Energy minimization in wireless sensor networks through an adaptive connectionless scheduling protocol (adaptive CSP)," in *Proceedings of IEEE Military Communications Conference (MILCOM '05)*, vol. 5, pp. 2990–2996, Atlatnic City, NJ, USA, October 2005.

[20] C.-F. Chou and K.-T. Chuang, "CoLaNet: a cross-layer design of energy-efficient wireless sensor networks," in *Proceedings of IEEE Systems Communications (ICW '05)*, pp. 364–369, Montreal, Canada, August 2005.

[21] Q. Liang, "Fault-tolerant and energy efficient wireless sensor networks: a cross-layer approach," in *Proceedings of IEEE Military Communications Conference (MILCOM '05)*, vol. 3, pp. 1862–1868, Atlatnic City, NJ, USA, October 2005.

[22] X. Lu, Y. Sun, J. Yu, and W. Yan, "An energy efficient cross-layer routing algorithm for wireless sensor networks," in *Proceedings of the 1st IEEE Conference on Industrial Electronics and Applications (ICIEA '06)*, pp. 1–5, Singapore, May 2006.

[23] I.-Y. Kong and W.-J. Hwang, "Lifetime maximization by cross-layer interaction in wireless sensor networks," in *Proceedings of the 8th International Conference Advanced Communication Technology (ICACT '06)*, vol. 3, pp. 2055–2060, Phoenix Park, Korea, February 2006.

[24] H. Kwon, T. H. Kim, S. Choi, and B. G. Lee, "A cross-layer strategy for energy-efficient reliable delivery in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 5, no. 12, pp. 3689–3699, 2006.

[25] H. Karvonen and C. Pomalaza-Raez, "A cross layer design of coding and awake/sleep periods in WSNS," in *Proceedings of the 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '06)*, pp. 1–5, Helsinki, Finland, September 2006.

[26] IEEE Std 802.15.4-2003, IEEE Standard for Information technology—telecommunications and information exchange between systems—local and metropolitan area networks—specific requirements—part 15.4: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANS).

[27] J. Shen, X. Yuan, L. Shen, D. Yao, and H. Liu, "An energy-efficient node for wireless sensor networks using software radio," in *Proceedings of the 6th IEEE International Conference on Electro/Information Technology (EIT '06)*, pp. 245–249, East Lansing, Mich, USA, May 2006.

[28] J. M. Cioffi, G. P. Dudevoir, M. V. Eyuboglu, and G. D. Forney Jr., "MMSE decision-feedback equalizers and coding—part II: coding results," *IEEE Transactions on Communications*, vol. 43, no. 10, pp. 2595–2604, 1995.

[29] A. G. Armada, "A simple multiuser bit loading algorithm for multicarrier WLAN," in *Proceedings of IEEE International Conference on Communications (ICC '01)*, vol. 4, pp. 1168–1171, Helsinki, Finland, June 2001.

[30] A. Y. Wang, S.-H. Cho, C. G. Sodini, and A. P. Chandrakasan, "Energy efficient modulation and MAC for asymmetric RF microsensor systems," in *Proceedings of the International Symposium on Low Power Electronics and Design (ISLPED '01)*, pp. 106–111, Huntington Beach, Calif, USA, August 2001.

[31] E. Shih, S.-H. Cho, N. Ickes, et al., "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MOBICOM '01)*, pp. 272–287, Rome, Italy, July 2001.

[32] C. Schurgers, O. Aberthorne, and M. B. Srivastava, "Modulation scaling for energy aware communication systems," in *Proceedings of the International Symposium on Low Power Electronics and Design (ISLPED '01)*, pp. 96–99, Huntington Beach, Calif, USA, August 2001.

[33] T. Starr, J. M. Cioffi, and P. J. Silverman, *Understanding Digital Subscriber Line Technology*, Prentice Hall PTR, Upper Saddle River, NJ, USA, 1999.

[34] M. Johansson, "Diversity-enhanced equal access-considerable throughput gains with 1-bit feedback," in *Proceedings of the 5th IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC '04)*, pp. 6–10, Lisbon, Portugal, July 2004.

[35] G. J. M. Janssen, P. A. Stitger, and R. Prasad, "Wideband indoor channel measurements and BER analysis of frecuency selective multipath channels at 2.4, 4.75 and 11.5 GHz," *IEEE Transactions on Communications*, vol. 44, no. 10, pp. 1272–1288, 1996.

[36] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall PTR, Upper Saddle River, NJ, USA, 2nd edition, 2002.

[37] A. G. Armada, "SNR gap approximation for M-PSK-based bit loading," *IEEE Transactions on Wireless Communications*, vol. 5, no. 1, pp. 57–60, 2006.