Cross-layer design for energy efficient communication in wireless sensor networks

Xiao-Hui Lin¹, Yu-Kwong Kwok²*,¹ and Hui Wang¹

¹Faculty of Information Engineering, Shenzhen University, China
²Department of Electrical and Computer Engineering, Colorado State University, CO, U.S.A.

Summary

There is a plethora of recent research on high performance wireless communications using a cross-layer approach in that adaptive modulation and coding (AMC) schemes at wireless physical layer are used for combating time varying channel fading and enhance link throughput. However, in a wireless sensor network, transmitting packets over deep fading channel can incur excessive energy consumption due to the usage of stronger forwarding error code (FEC) or more robust modulation mode. To avoid such energy inefficient transmission, a straightforward approach is to temporarily buffer packets when the channel is in deep fading, until the channel quality recovers. Unfortunately, packet buffering may lead to communication latency and buffer overflow, which, in turn, can result in severe degradation in communication performance. Specifically, to improve the buffering approach, we need to address two challenging issues: (1) how long should we buffer the packets? and (2) how to choose the optimum channel transmission threshold above which to transmit the buffered packets? In this paper, by using discrete-time queuing model, we analyze the effects of Rayleigh fading over AMC-based communications in a wireless sensor network. We then analytically derive the packet delivery rate and average delay. Guided by these numerical results, we can determine the most energy-efficient operation modes under different transmission environments. Extensive simulation results have validated the analytical results, and indicates that under these modes, we can achieve as much as 40% reduction in energy dissipation. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: wireless sensor networks; cross-layer design; buffering; discrete-time queuing; Rayleigh fading; link adaptation

1. Introduction

Over the last decade, advances in micro-electromechanical technologies, wireless communications, and embedded systems have facilitated the development of small, low-power, and programmable sensor networks, which are designed for task monitoring, battlefield surveillance, intruder detection, and environmental sensing etc., to collect, process, and disseminate wide ranges of complex environmental data. A wireless sensor network consists of hundreds of sensor nodes scattered in the deployment field, and each node is equipped with computation and communication elements. Harmonized by protocol suites at

*Correspondence to: Yu-Kwong Kwok, Department of Electrical and Computer Engineering, Colorado State University, CO, U.S.A.
†E-mail: ricky.kwok@colostate.edu

Copyright © 2008 John Wiley & Sons, Ltd.
all levels, sensor nodes can collaborate together, forming a distributed and autonomous data computing and communication system for automated information gathering and sensing.

While the applications enabled by wireless sensor networks seem attractive, there are still many design challenges to be tackled by researchers. One of these challenges is energy efficient communication. Indeed, for most practical purposes, a sensor node is powered by a battery with limited capacity. In some cases, such power source is expected to sustain for months or even years. Frequent battery recharging or replacement is usually infeasible, if not impossible (e.g., consider the case where sensors are deployed in a battlefield). Thus, wireless communications among sensors must be made highly energy efficient.

Generally speaking, in a wireless sensor node, energy consumptions occur in three domains: sensing, data computation, and communications. Indeed, in an embedded system, energy consumed by the communication component for radio transmission dominates that by the computation and sensing counterparts. For example, the energy expended in a sensor node by Rockwell Inc. for transmitting 1 bit is around 2000 times of that for executing one instruction [1, 2, 3].

Consequently, many proposed approaches work by trading off communication performance for energy efficiency. Specifically, for wireless sensor networks, communication throughput and delay are usually not treated as top priority tasks. Instead, communication for a sensor node should be power-aware, that is, consuming just enough energy to achieve the required level of performance. This idea has been enabled at the circuit level and exploited at algorithm level. For example, in Reference [4] a traffic adaptive technique called dynamic modulation scaling (DMS) is proposed to adaptively change the modulation level to lower the overall energy consumption, according to the number of queued packets in the system, while bounding the packet delay at an acceptable level. In Reference [2], DMS is combined with weighted fair queuing (WFQ) algorithm, creating an energy efficient packet scheduling protocol. As such, the proposed algorithms introduce the notion of energy awareness in the communications.

However, there are a couple of drawbacks in these previous research results: (1) when considering the energy efficiency in wireless sensor networks, the time-varying property of the realistic wireless channel is largely ignored, let alone exploited, leading to inaccuracy in the analytical results; and (2) dynamic transmission power adjustment is mandatory.

Power control under a channel fading environment may entail complicated controlling circuits and algorithms at both the sending and receiving sides, which can incur the increase in circuit complexity and more energy dissipation in computation. This is not affordable for a simple and low-cost sensor node.

Under hostile fading circumstances, reliability of data transmission can be reinforced by either increasing the transmission power level or applying adaptive modulation and coding (AMC) to the raw data [5]. The first method is infeasible because doing this can rapidly deplete the limited sensor energy, which is expected to sustain for months. Moreover, this can also result in the increase in the circuit complexity and more energy consumption. Thus, in this paper we assume constant power transmission and resort to AMC to overcome this unreliable link problem. As the channel quality changes over time, the amount of incorporated error protection should also vary with the instantaneous channel condition to make sure the bit error rate is below the required level. As a result, the poorer the wireless link, the more amount of error protection redundancy in the transmitted packet, and vice versa [6–8]. In overcoming the wireless link quality fluctuation, the introduction of AMC can incur extra energy dissipation, which is unavoidable in combating the adverse channel condition. The power consumption sources include the following two major aspects:

1. From the computation point of view, packet redundancy can lead to additional expended energy that goes into encoding and decoding data at two communication sides. Indeed, this consumption share is not negligible, especially in short distance transmission [9], and thus, it should be taken into consideration in power management.
2. With respect to the packet transmission, extra energy will also be incurred during the message communication, as the length of every frame will increase after the error protection is included. This means that if the raw transmission rate (different from actual link throughput in the latter parts) remains the same, the radio circuits (transceiver, receiver, output amplifier, synthesizer, and PLL/VOC, etc.) will be on for a longer duration, and thus, will consume more energy.

From a practical perspective, a wireless link with worse channel quality can result in more energy expenditure (more error protection redundancy incorporated or lower modulation level adopted). Thus, an
An instinctive approach is to buffer the packet temporarily and let its radio enter sleep state until the channel quality recovers to the required threshold. To implement this basic idea in the real situation, we assume that each sensor can decide the state of its communication component (active/sleep/idle) with respect to the current link condition. Nevertheless, as the packet buffering may lead to communication latency and buffer overflow, this poses a complicated tradeoff problem between energy efficiency and communication quality: given the delivery rate and delay constraints, how long should we buffer the packets? Or equivalently, how to choose the optimum channel transmission threshold above which to transmit the buffered packets? Normally, for an AMC communication system, it is very difficult to achieve the following two design objectives simultaneously: (1) guaranteed packet delivery rate and delay; (2) efficient utilization of battery energy. In our work, we aim at providing desired data delivery rate and bounding the average packet delay within the practical limit, while saving the communication energy to the best effort, thus achieving energy conservation. This motivates us to find the most energy efficient operating mode for an AMC sensor node under a channel fluctuating environment.

The rest of this paper is organized as follows. In Section 2, we briefly give some background on the sensor network architecture, and then we present a realistic Rayleigh wireless channel model [7,10]. In Section 3, we use discrete time queuing model to analyze the effects of Rayleigh fading over AMC communication system and derive the packet delivery rate and average delay. Guided by these numerical results, we can then determine the most energy-efficient operating modes for an AMC sensor system under different transmission environments. We also give a sensor network design example to illustrate the dependence of energy consumption on the traffic load and channel attenuation, and quantify the energy-efficiency gain due to optimization. The effect of buffer size on the energy efficiency is also discussed in this section. Finally, we conclude this paper in Section 5.

2. Background

2.1. Sensor Network Architecture

To enable the scalability and energy efficiency in a sensor network comprising hundreds or thousands of sensor nodes, a cluster based hierarchy is usually adopted [11–13]. As the data collected by sensors in vicinity is highly correlated, and the communication between each sensor and end-user can be very energy and bandwidth consuming, the data should be processed locally to get rid of the data redundancy. The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [13] is such an example. In a cluster-based hierarchical sensor network, the whole network is divided into clusters, and in each cluster there exists a cluster head (or base station) to perform local information filtering, data aggregation, and data forwarding for the sensors in that cluster. Consequently, transmitting fused data greatly decreases the bandwidth and energy consumption. The group of cluster heads from the entire network in turn forms a sub-network, among which the traffic load is routed. Thus, a cluster based network organization eases the network management and reduces the energy needed for communicating useful data to the end-user. This idea has been successfully implemented in the ‘FLOWS’ testbed by researchers in Tsinghua University, and, in particular, will be used for the security surveillance in 2008 Olympic Games to be held in Beijing [14].

Figure 1 depicts a cluster based wireless sensor network, which consists of sensor nodes for sensing and data collection, cluster heads for data reception from the sensors and information aggregation, and base station (can be a GPRS base station or any

![Fig. 1. A cluster based wireless sensor network.](image-url)
mobile vehicle or airplane) for the wireless connection to the outside world. In a cluster, time division multiple access (TDMA) can be used to schedule packet transmissions among sensor nodes [13,15,16], just like a cellular network. The fused information is transmitted by the base station to the controlling center through the backbone network, thereby constructing a distributed monitoring and controlling network system.

2.2. Raleigh Fading and Finite-State Markov Channel Model

Using a channel adaptive physical layer is one of major distinctive features of our approach in contrast to existing work in sensor energy saving that uses simple channel model, in which the time-varying nature is neglected. Due to the multipath radio propagation, the combined effects of the signal propagation factors is characterized by the channel state information (CSI), which is the measured signal-to-noise ratio (SNR) of known pilot symbols on a feedback channel [6,17]. In this paper, we assume that the radio propagation model is a non-frequency-selective, slow Rayleigh fading channel, which is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal. With Rayleigh fading, the received signal consists of large number of scattered components that result from multi-path propagation paths, each associating with a different propagation delay and attenuation factor that depend on the obstacles in the path reflecting the wave. Here, the combination of the multi-path effect leads to the time-fluctuation of the received signal envelope that is Rayleigh distributed [7], with the following probability density function given by

\[ p(r) = \begin{cases} \frac{r}{\sigma^2} \exp \left( -\frac{r^2}{2\sigma^2} \right) & 0 \leq r \leq \infty \\ 0 & r < 0 \end{cases} \quad (1) \]

where \( \sigma \) is the root mean square value of the received voltage signal before envelope detection, and \( \sigma^2 \) is the time average power of the received signal before envelope detection. Similarly, with additive Gaussian noise, the received instantaneous SNR \( \gamma \) is distributed exponentially with probability density function

\[ p(\gamma) = \frac{1}{\gamma_0} \exp \left( -\frac{\gamma}{\gamma_0} \right) \quad (2) \]

where \( \gamma \geq 0 \) and \( \gamma_0 \) is the average SNR.

In wireless communication system, the use of received SNR as a measurement of channel quality has been widely accepted when the channel quality is time-varying [6,15]. In this paper, we adopt the adaptive modulation and coding design called ABICM [6,17] in which variable throughput modulation and channel coding are used (see Figure 2). Specifically, when SNR (or CSI) is available at the transmitter (through a feedback channel, or a signaling exchange in this paper), the transmitter performs ‘burst-by-burst’ throughput adaptation [6] with respect to the measured SNR. For instance, when the CSI indicates that the channel is of a good quality, the transmitter employs a high-order modulation and high-rate error correction code (e.g., 64QAM with 5/6 coding rate) so as to boost the instantaneous throughput. On the other hand, when the channel quality is poor, the transmitter employs a lower order modulation and low-rate error protection (e.g., BPSK with 1/2 coding rate) so as to protect the packet transmission at the expense of lower instantaneous throughput. To match the modulation scheme or error correction to the instantaneous CSI, the measured SNR is divided into different threshold levels \( \Omega = [\Gamma_0, \Gamma_1, \ldots, \Gamma_N] \) (with \( \Gamma_0 = -\infty \)). Thus, transmission mode \( q \) is chosen if the feedback CSI \( c \) falls within the adaptation threshold interval \( [\Gamma_q, \Gamma_{q+1}] \). The operation and performance of the AMC scheme are determined by the set of adaptation thresholds \( \Omega \) [15,16]. In our threshold classification, we assume that the AMC scheme is operated in the constant BER mode [6], that is, the adaptation thresholds are set optimally to maintain a target transmission error level over a range of CSI values.
Mathematically, based on the above analysis, we can model the time-varying Rayleigh fading channel with a finite state Markov process. Specifically, if the feedback CSI $c_k$ falls into the adaptation threshold interval $[\Gamma_q, \Gamma_{q+1}]$, we say that the current channel is in state $S_0$ (except for state $S_N$, whose CSI/SNR lies within $[\Gamma_N, \infty]$). Using such a Markov model for the channel variation has been widely accepted and theoretically analyzed. Indeed, the theoretical results accurately accord with simulated values [18]. To theoretically analyze the level crossing rate of $S_0$, we further assume that state transition only happens between adjacent states (this can be satisfied if the channel change is sufficiently slow and observation time is short, e.g., one packet duration), we get

$$t_{j,k} = P(S_{n+1} = s_k|S_n = s_j)$$

(3)

Furthermore, $t_{j,k}$ must satisfy the following condition:

$$\sum_{k=0}^{N} t_{j,k} = 1$$

(4)

for all $j \in \{0, 1, \ldots, N\}$.

If we further assume that state transition only happens between adjacent states (this can be satisfied if the channel change is sufficiently slow and observation time is short, e.g., one packet duration), we get

$$t_{j,k} = 0, \text{ where } |j - k| > 1$$

(5)

With Equation (2), the steady-state probability can be calculated by

$$\pi_k = \int_{\Gamma_k}^{\Gamma_{k+1}} p(\gamma) d\gamma$$

$$= \exp\left( -\frac{\Gamma_k}{\gamma_0} \right) - \exp\left( -\frac{\Gamma_{k+1}}{\gamma_0} \right)$$

(6)

and we have $\sum_{k=0}^{N} \pi_k = 1$.

Let $f_m$ be the maximum Doppler frequency caused by motion at a certain speed. Thus, we have $f_m = v/\lambda$, where $v$ and $\lambda$ denote mobile speed and wavelength, respectively. Now, consider the level crossing rate of the instantaneous SNR $N(\Gamma)$, which is defined as the expected number of times per unit interval the received SNR passes downward across a given level $\Gamma$, and this parameter can be calculated by [10]

$$N(\Gamma) = \sqrt{\frac{2\pi}{\gamma_0}} f_m \exp\left( -\frac{\Gamma}{\gamma_0} \right)$$

(7)

With level cross rate, the channel state transition probability can be approximated by

$$\begin{align*}
  t_{k,k+1} &\approx \frac{N(\Gamma_{k+1})T_f}{\pi_k} & k = 0, 1, \ldots, N - 1 \\
  t_{k,k-1} &\approx \frac{N(\Gamma_k)T_f}{\pi_k} & k = 0, 1, \ldots, N \\
  t_{k,k} &= 1 - t_{k,k-1} - t_{k,k+1} & k \neq 0, N \\
  t_{0,0} &= 1 - t_{0,1} \\
  t_{N,N} &= 1 - t_{N,N-1}
\end{align*}$$

(8)

where $T_f$ is the observation time (which is the frame durations in this paper). Given frequency shift $f_m$ and average received SNR $\gamma_0$, the level cross rate $N(\Gamma)$ can be computed by Equation (7), and steady-state probability can be calculated from Equation (6), thus getting the state transition probability in Equation (8).

2.3. Adaptive Modulation and Coding

Physical Layer

In this paper, we adopt an AMC system called ABICM [6,9], in which variable throughput modulation and channel coding are used (see Figure 2). Specifically, when CSI is available at the transmitter, the transmitter performs ‘burst-by-burst’ throughput adaptation [6,19] by adaptively selecting the modulation-coding pair with respect to the CSI. Coherent demodulation and maximum-likelihood decoding are employed at the receiver for bit stream decoding, which is mapped into user data packet for the higher application layer. The ABICM-based sensor network system is based on the following two assumptions:

1. The channel fading is non-frequency selective, and varies sufficiently slow. For example, at mobile speed of 1 m/s, the coherence time is approximately 122.88 ms for a center frequency of 2.4 GHz [20]. Thus, since a packet or physical frame duration in our system is around several milliseconds, it is justified for us to assume that the CSI remains approximately constant for the duration of at least one frame.

2. The channels between different sending–receiving pairs are independent of each other. In fact, the received signals are correlated only when nodes...
are extremely closed in proximity. For a wireless communication working in a central frequency of 2.4 GHz, this distance is less than 12 cm.

Indeed, the salient concept of adaptive physical layer has been widely deployed in various wireless systems such as 3GPP, 3GPP2, EV-DV, UMTS, HSDPA, and IEEE 802.11a/b/g. Note that using ABICM in our study is just for illustration of AMC only, and other AMC schemes (e.g., the one suggested in References [16,17]) can also be used. For details of the ABICM, scheme, and its applications in MAC protocols, the reader can Refer to [6,7,17]. In our study, we use a 4-mode AMC configuration, and thus, there are four distinct possible data throughput levels: 100 kbps, 400 kbps, 600 kbps, and 1 Mbps, respectively (after adaptive channel coding and modulation), as listed in Table I [9]. Hence these four modes correspond to channel states \([s_1, s_2, s_3, s_4]\). Note that channel state \(s_0\) corresponds to CSI interval \([-\infty, \Gamma]\), within which, channel is in deep fading and no packet is sent (with zero data rate).

### 2.4. Radio Model for Energy Calculation

Due to the fact that power control under a channel fluctuating environment is very complicated for wireless communication system in terms of algorithm and hardware complexity, here we assume a constant power is used for data transmission. The average power consumption of the radio in a sensor node can be described by

\[
E_{\text{radio}} = E_{\text{tx}} + E_{\text{rx}}
\]

\[
= P_{\text{tx}}(T_{\text{on-\text{tx}}} + T_{\text{startup}}) + P_{\text{out}}T_{\text{on-\text{tx}}} + P_{\text{rx}}(T_{\text{on-\text{rx}}} + T_{\text{startup}})
\]

where \(P_{\text{tx}}\) and \(P_{\text{rx}}\) are the power consumption of the transmitter and receiver circuits (frequency synthesizer and PLL/VOC), respectively, and \(P_{\text{out}}\) is the radio output transmit power, \(T_{\text{on-\text{tx}}}\) and \(T_{\text{on-\text{rx}}}\) are the data transmission and reception time, respectively, and \(T_{\text{startup}}\) is the startup time of the transmitter/receiver circuitry. The circuitry startup time is the time needed for the internal phase-locked loop of the transceiver/receiver being locked to the desired carrier frequency. Thus, during circuitry startup time, no data can be sent or received.

We highlight some key points in radio model adopted in the paper:

1. The wireless sensor network is designed to work in short distance monitoring environment, that is, communication range is less than 50 m. Thus, the circuitry power \(P_{\text{tx}}\) and \(P_{\text{rx}}\) dominate the transmit power \(P_{\text{out}}\).

2. An important fact of the wireless radio is that operating in idle mode (radio is on without any packet sent or received) results in significantly high energy consumption comparable to that in transmit and receive modes. Hence, it is necessary to completely shut down the radio to save energy when there is no packet exchange. However, when communication is needed again, radio startup energy overhead can have a great impact on the total energy consumption. A solution is to amortize this fixed overhead by sending as many as possible user data in one transmit to avoid frequent circuitry switching.

3. Channel quality has a great influence on the energy expenditure as

\[
T_{\text{on-\text{tx}}} = \frac{L}{U_n}
\]

where \(L\) is the packet length and \(U_n\) is the user data rate of transmission mode \(n\) listed in Table I. According to the values shown in the table, if the transmit power level is fixed, the energy needed in different transmission modes is 10:2.5:1.67:1, which means a great margin in energy consumption between the highest and the lowest transmission modes. Consequently, to save energy, we should select possibly the highest mode to send packets.

### 2.5. Research Motivation and Problems to be Tackled

To reinforce the reliability of packet transmission over fading channel, stronger forwarding error code (FEC) and more robust modulation scheme are applied to the data communication to decrease the probability of packet corruption. Nevertheless, additional energy
cost is also incurred because time needed to transmit one user data packet is prolonged, as the length of each frame is increased after incorporating more FEC redundancy or the modulation speed is slowed down after lower mode is selected. Therefore, if the raw user data rate of the higher layer remains the same, both the transceiver and output amplifier at the physical layer will be on for a longer duration time as in Equation (10). This, of course, will result in higher energy expenditure.

To save limited battery energy, a simple solution is to use possibly the highest transmission mode and avoid sending packets when the channel is in deep fading. Hence, if the channel is experiencing deep fading, packets should be kept temporarily in the buffer until the channel quality recovers. However, this approach can cause another problem that should be carefully considered. In many application scenarios of wireless sensor networks such as security surveillance and real-time traffic monitoring, there is quality requirement on the sensing accuracy and delay constraint on information delivery from the sensing site [12]. Specifically, there is a regulation on the sensing quality \([\eta, \tau]\), where \(\eta\) is the packet delivery rate from the monitoring site that can influence the sensing accuracy, and \(\tau\) is the average packet delay from the sensing node which is critical to the sensitivity and reactivity of the system. Packet buffering is then obviously in conflict with sensing quality. Thus, minimizing the communication energy with sensing quality constraints is a complicated problem.

To solve this problem, we need to take the following factors into consideration: (1) dynamic behaviors of the channel and buffer queue; (2) sensing traffic load from the observation site; and (3) allocated channel time slots. Here we formulate the problem to be tackled in this paper as

\[
\min \quad E(\lambda, \gamma_0, f_m, K, b) \\
\text{s.t.} \quad \eta \geq R, \tau \leq T
\]  

(11)

where \(E\) is the communication energy, \(\lambda\) is the traffic load from the sensing node, \(K\) is the buffer size, \(b\) is the number of allocated time slots, \(\gamma_0\) and \(f_m\) are parameters characterizing the dynamics of the channel fluctuation, and \(R\) and \(T\) are the packet delivery rate and delay constraints, respectively.

Minimizing the communication energy in Equation (11) is equivalent to finding the suitable channel quality threshold above which can the packets be transmitted. As the transmission SNR thresholds in Table I are discrete, we need to determine threshold \(\Gamma_n\). Only when the channel quality is above \(\Gamma_n\), can we send the buffered packets; otherwise, we have to wait until the channel recovers. Thus, the optimized sensor communication system only operates above transmission mode \(n\).

### 3. Conserving Communication Energy with Packet Delivery Rate and Delay Guarantees—Discrete Time Queuing Analysis

Minimizing the consumed energy in Equation (11) entails analyzing the influences of traffic load, channel variations, and network resources such as buffer size and allocated time slots on \([\eta, \tau]\). In this paper, we assume that TDMA scheme is used within the cluster, and the time dimension is divided into frames. Each frame is further partitioned into fixed number of slots. A sensor node is allocated a share of these slots, during which it can transmit the buffered packets. On sensing the happening of incident, sensor generates packet describing attributes of the incident, and puts the packet in the buffer which is operated in a first-in-first-out (FIFO) manner. The buffer size is \(K\).

#### 3.1. Discrete Time Queuing Analysis

For a sensor node, we model the packet transmission over the wireless link as a queuing system, that is, treating the arriving packets as ‘customers’ and radio link as a ‘server’. When a packet arrives, it is put in the buffer, and waits for the service. If the buffer is full, the packet is dropped. Each sensor node is a Poisson source, that is, the generated packet follows a Poisson arrival with intensity \(\lambda\)

\[
P(A = n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}
\]

(12)

where \(A\) is the number of packets arrival during period \([0, t]\). This assumption well matches some sensor monitoring applications, such as car traffic in the highway and security guarding on persons entering a specific gate in the airport or gymnasium [14]. We are interested in the evolution of the queuing system with time. However, due to the randomness of packet arrival, and more importantly, to the dynamic
behaviors of the wireless link, the queuing analysis is very challenging. In Reference [15], Liu et al. originally proposed a discrete time queuing analysis method to derive the packet delivery rate and delay \(\eta, \tau\) under a time-varying environment, and applied it to packet scheduling in cellular networks. In this paper, by using this method, we extend the work to the energy efficiency enhancement in wireless sensor networks, under a channel fluctuating environment with some QoS guaranteed.

Without loss of generality, let the frame duration \(T_f\) be one time unit, and the time axis is equally partitioned into adjacent time units indexed by \(\{\ldots, t-1, t, t+1, \ldots\}\) as shown in Figure 3. Let \(A_t\) and \(C_t\) be the number of packet arrivals and number of packets that can be transmitted respectively during time unit \(t\), and \(Q_t\) be the number of packets accumulated in the buffer at the end of unit \(t\). Note that \(A_t\) follows Poisson distribution with \(E(A_t) = \lambda T_f\), while \(C_t\) can vary from unit to unit with transition probability given by Equation (8). Thus, we have \(A_t, t, T = \{0, 1, \ldots, K\}\), \(Q_t, Q = \{0, 1, \ldots, K\}\), \(C_t, C = \{0, u, 0, u, \ldots, u_L\}\) \(\subseteq \{c_0, c_1, \ldots, c_K\}\), where \(K\) and \(L\) are the buffer size and packet length, respectively, while \(U_I\) is the user data rate of transmission mode \(i\) listed in Table I.

To understand how the buffer queue \(Q_t\) evolves with time, according to Reference [15], queue \(Q_t\) and channel capacity \(C_t\) are coupled together to form a state pair. Thus, a finite state Markov chain (FSMC) is constructed. Let \(P(u,v,d)\) be the transition probability from state pair \((Q_{t-1} = u, C_t = c)\) to \((Q_t = v, C_{t+1} = d)\):

\[
P([u,v,d]) = \begin{bmatrix} 0 & \ldots & 0 & 0 \\
\vdots & \ddots & \vdots & \vdots \\
0 & \ldots & 0 & 0 \\
0 & \ldots & 0 & 0 \\
\end{bmatrix}
\]

It can be shown that the stationary distribution of \((Q_{t-1}, C_t)\) exists and can be calculated by solving a linear equation group [16], and thus, we have

\[
P(Q = u, C = c) = \lim_{t \to \infty} P(Q_{t-1} = u, C_t = c) \tag{14}
\]

### 3.1.1. Packet delivery rate and average delay

We can calculate the average number of packets being dropped due to overflow by [16]

\[
E(D) = \sum_{\alpha \in I, \alpha \in \tilde{C}} D \times P(A = \alpha, Q = u, C = c) = \sum_{\alpha \in I, \alpha \in \tilde{C}} \max\{0, \alpha - K + \max(0, u - c)\} P(A = \alpha) P(Q = u, C = c) \tag{15}
\]

From the above equation, we get the average packet delivery rate \(\eta\)

\[
\eta = 1 - \frac{E(D)}{E(A)} = 1 - \frac{E(D)}{\lambda T_f} \tag{16}
\]

The average number of packets in queue and in transmission can be expressed as [11]

\[
N_q = \sum_{u \in \tilde{C}} u P(Q = u, C = c) + \sum_{u \in \tilde{C}} \min(u, c) P(Q = u, C = c) \tag{17}
\]

Thus, according to Little Theorem, the average packet delay can be written as

\[
\tau = \frac{N_q}{\lambda} \tag{18}
\]

Here, we give a summary. To derive \(\eta, \tau\) in Equation (11), the crux is to get the steady state probability \(P(Q = u, C = c)\) from Equation (14), which is highly dependent on traffic load \(\lambda\), channel variation characterized by \((\gamma_0, f_m)\), and SNR threshold partition \(\Omega\). Thus, given the channel fluctuation parameters \((\gamma_0, f_m)\) and adaptation threshold partition \(\Omega\) at the physical layer, we can compute the channel state transition probability matrix by Equation (8). With this matrix and the traffic load from the upper MAC layer, we construct queue-channel state pair \((Q_{t-1}, C_t)\), and further get the state pair transition probability matrix \(\bar{P}\) and have steady state probability \(P(Q = u, C = c)\), which is used to calculate packet delivery rate and delay \(\eta, \tau\) in Equations (15)–(18).
Note that the above analysis entails the parameters from both the physical and MAC layers, thus a cross-layer design is necessary and can avail the system performance optimization.

4. Numerical Results and Cross Layer Design

The contention-based channel access schemes such as 802.11 are not suitable for sensor networks due to at least two reasons: (1) packet collision, which has been proved to be one of the major sources of energy waste, is difficult to avoid [21]; and (2) once collision happens, both nodes have to backoff and keep monitoring the channel, which also consumes significant amount of energy. Therefore, to save battery energy, a TDMA-based channel access scheme can be a good solution. When a sensor has packets to send, it just turns on the radio during its allocated time slots, and turns off the radio during other slots, thus avoiding packet collision and unnecessary overhearing. In addition, strict requirement of time synchronization of TDMA is easy to implement in a cluster-based wireless sensor network.

To facilitate rate adaptation, similar to 802.11, at the beginning of the allocated time slots, sensor node transmits a short request to send (RTS) message to the cluster head. On receiving the RTS, the cluster head measures the SNR of this message, which can be used as an indication of the channel quality, then maps this SNR to the appropriate modulation-coding mode and incorporates this mode information in a clear to send (CTS) message which is sent back to the sensor node. Thus, CSI exchange between sensor and cluster head is finished, and the sensor can use the specified transmission mode to send its data packets. Please note that, the RTS and CTS packets are sent via the basic (lowest) modulation-coding mode to ensure the reliability of mode negotiation. After sending out the RTS, there are two cases: (1) the sensor node cannot receive CTS due to the deep channel fading (SNR is below the lowest transmission threshold), and RTS–CTS negotiation is unsuccessful; (2) CTS is received, but the transmission mode incorporated is lower than the optimal (SNR is also below the required transmission threshold). In these two cases, to enhance energy efficiency, the sensor is kept silent by turning off the radio and waits until the channel quality recovers.

4.1. Physical Parameters

In this paper, Rayleigh fading channel is modeled as a 5-state Markov channel, with different data rate of 0, 100 kbps, 400 kbps, 600 kbps, and 1 Mbps, respectively (after adaptive channel coding and modulation). As in wireless sensor network, the sensor is static, and thus, the Doppler frequency is very small, and this small Doppler frequency shift is due to the tiny variations of the surrounding environment, such as small ground vibration, or wavering of the trees in the propagation path. According to the typical field testing values in Reference [12], we let \( f_m \) be 1 Hz. To ensure that the ABICM scheme is operated in the constant BER mode, the adaptation thresholds are set optimally as those values in Reference [6] Radio symbol rate is set to 200 kBaud. The modulation schemes, coding rates, user data rates, and other physical layer adaptation parameters are listed in Table I. The MAC layer and RF parameters are listed in Table II.

4.2. Numerical Results and Performance Analysis

Based on the queuing analysis in Section 3, we present the numerical results of the average packet delivery rate and delay versus channel quality. We also perform extensive simulation to validate the accuracy of these analytical values. The simulated results are plotted in the same figures. In the following sections, to avoid the confusion of ‘sensor operation mode’ with ‘transmission mode,’ according the SNR parameters listed in Table I, we specify that if the SNR transmission threshold is set to \( \Gamma_i \) (only when the channel quality is above \( \Gamma_i \) can sensor transmit packets), the sensor node is said to work under ‘Operation Mode \( i \).’ We adopt this ‘mode’ definition in the following sections.

### Table II. MAC layer and RF parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter/receiver circuit power ( P_{tr}/P_{rx} )</td>
<td>0.2328 W</td>
</tr>
<tr>
<td>Radio output power ( P_{out} )</td>
<td>0.15 W</td>
</tr>
<tr>
<td>Radio sleep power</td>
<td>3.5 mW</td>
</tr>
<tr>
<td>( T_{startup} ) Circuit startup time ( T_{startup} )</td>
<td>20 ( \mu ) s</td>
</tr>
<tr>
<td>Data packet size</td>
<td>100 bit</td>
</tr>
<tr>
<td>Buffer size</td>
<td>50 packet</td>
</tr>
<tr>
<td>Frame duration</td>
<td>5 ms</td>
</tr>
<tr>
<td>Number of slots per frame</td>
<td>20</td>
</tr>
<tr>
<td>Number of slots allocated to sensor per frame</td>
<td>5</td>
</tr>
<tr>
<td>Number of sensors in each cluster</td>
<td>4</td>
</tr>
<tr>
<td>Initial battery energy level</td>
<td>100 Joule</td>
</tr>
<tr>
<td>Sensing delay</td>
<td>8 ( \mu ) s</td>
</tr>
</tbody>
</table>
We firstly consider the point-to-point case, that is, the communication between a single sensor node and cluster head. Note that in one frame unit, a sensor node is allocated 5 slots. Figures 4–6 are the average packet delivery rates versus the received SNR (channel quality), with traffic load varying from 3 packets to 9 packets per frame. In the figures, the analytical results are plotted with lines of different styles, while the simulated results are represented by discrete points. For each point, we have set the virtue simulation time to 20000 s, and repeat simulation 10 times. The final result is the average value of these simulations. It is shown in the figures that the simulated points match quite well with analytical lines, which validates the accuracy of the queuing recursion in Section 3.

We can observe that the improvement in the channel quality avails the packet transmission, in that the packet delivery rate increases with the average received SNR. This is obvious because better channel quality can support higher data transmission rate, which enhances the link capacity. As expected, when adding traffic load from 3 to 9 packets per frame, the traffic delivery rate declines with load in each operation mode, because more traffic incoming can result in buffer overflow more easily. It is also revealed that lower sensor operation mode has higher packet delivery rate. The reason is simple: lower operation mode has lower transmission SNR threshold, thus having more chances (time slots) to transmit the buffered packets. The higher operation mode, however, has higher SNR threshold, which means stricter requirement on the channel quality. Hence, when channel is in fading, sensor operating with higher mode has to give up more time slots, and buffer packets until channel quality recovers, thus causing buffer overflow more easily compared with lower operation mode.

The variations of average packet delay versus received SNR under different loads are plotted in Figures 7–9. Again, the accordance of simulated values with the analytical lines confirms the accuracy of the queuing analysis. Similarly, the increase in the SNR can improve the data transmission, thus decreasing the packet delay. Figures also depict that lower operation mode has shorter packet delay because sensor with lower mode has more time slots to transmit packets, thus decreasing the packet queuing time. In each operation mode, when the traffic load increases from 3 to 9 packets per frame, the average delay keeps rising as link gets more saturated (9 packets per frame).

The above performance results illustrate that low operation mode outperforms high mode in communication performance, in that packet delivery rate is higher and delay is shorter. However, we must see the other side of the coin: sensor working under lower...
mode achieves this at the expense of more energy consumption, as more frequently, it has to work under adverse channel condition, while sensor of higher mode is prohibited from transmitting when channel quality is below the SNR threshold. Thus, naturally, people may ask: given sensing quality requirement \( [R, T] \) in Equation (11), which operation mode should we choose? Our design criterion is: consume just enough energy to achieve the required level of performance or more specifically, to save energy, select possibly the highest mode that can just satisfy the delivery and delay requirement.

4.3. Cross Layer Energy Consumption Optimization

Different from conventional cellular or ad hoc networks, in which, provision of high QoS (high network throughput, low packet delay) is of the first priority, we are more concerned about the sensor lifetime in the network (here we define the sensor lifetime as the sustaining time of its battery energy). A major reason is that in cellular/ad hoc networks, the terminals battery can be recharged whenever needed. However, energy replenishment is infeasible for a sensor terminal working in distant or hostile areas. The depletion of the battery energy means the failure of the node and partial partition of the network, resulting in the blind area of the corresponding location. Therefore, given the desired delivery rate and delay constraints \( [R, T] \) in Equation (11), it is a waste to spend extra energy on achieving communication performance than needed. Thus, although lower operation mode has better communication performance, it is more energy consuming and unsuitable in view of energy efficiency, hence, we should select possibly the highest mode with the delivery rate and delay just satisfying the requirements.

Due to the characteristics of wireless sensor network, in the same location, there could be multiple sensors monitoring the area. Hence, there is significant redundancy in data collected by the cluster head. Therefore, sensor network is more tolerant to packet loss than cellular or ad hoc networks, and we only need to provide the minimum required delivery rate. This provides us exploration room for energy conservation. Let us see an example. A sensor node communicates with its cluster head, and the set of working parameters is fixed as follows: average received SNR \( \gamma_0 = 20 \text{ dB} \), and traffic load \( \lambda T = 3 \). The desired sensing sensitivity is \( [R, T] = [0.7, 100 \text{ ms}] \), that is, the needed packet delivery rate is 70%, and the average delay must be less than 100 ms. From Figures 4 and 7, we get the analytical delivery rate and packet delay pairs for the four modes (from the lowest to the highest) as follows: [0.7816, 21.78 ms], [0.7643, 22.28 ms], [0.7062, 24.42 ms], and [0.5880, 30.05 ms],
respectively. Obviously, except Mode 4 whose packet delivery rate cannot satisfy the requirement, all the other three operation modes can provide the desired sensing quality. According to the design criterion, to save communication energy, we should select the highest operation mode, that is, Mode 3 in this example. In Figure 10, through simulation, we give the energy consumption speed versus elapsed time of these three modes. It is illustrated that Mode 3 is the most energy conserving operation mode, in that its communication energy consumption is the least. This is due to the fact that SNR transmission threshold of Mode 3 is the highest, thus, the average link throughput (average link bandwidth used to transmit packets) is also the highest, which should shorten the communication time and save energy. The related battery life, average link throughput and average energy consumed per received bit of these three modes are shown in Figure 11. Here, we can see that Mode 1 consumes the most amount of energy for both communication sides because it has not taken the channel quality into consideration and set the SNR transmission threshold to the lowest, thus, its energy management has not been optimized. Due to this reason, we use Mode 1 as reference, comparing it with optimized mode (Mode 3 in this example) to see how much gain we can achieve. In Figure 11, it is shown by using Mode 1 as reference, we can save as much as 27% of energy for each received bit, and extend the sensor lifetime about 33%.

From this example, we can see that, to conserve energy, a joint cross layer design across the MAC layer and physical layer is necessary. The joint integration of MAC and physical layers is illustrated in Figure 12, where, the physical parameters such as instantaneous CSI, channel fluctuation \((\gamma_0, f_m)\), and MAC traffic load \(\lambda\), together with the performance requirements \([R, T]\) are fed into the mode selection unit, which performs queuing recursion as in Section 3 and selects the most energy-efficient operation mode. The output (SNR threshold) of this unit and the instantaneous CSI from the physical layer are provided to the MAC layer for packet scheduling: if the instantaneous channel quality is above the threshold, send the packet, otherwise, buffer them until channel recovers. At the physical layer, the transmitter is under the control of MAC layer scheduler and performs a ‘burst-by-burst’ throughput adaptation according to the current channel quality.

According to the energy-efficient cross layer design described above, a three-dimensioned histogram illustrating how sensor optimized operation mode varies with the traffic load and average received SNR is given in Figure 13 (with sensing quality \([R, T] = [0.7,\]

![Fig. 10. Rate of energy consumption versus elapsed time.](image)

![Fig. 11. Average link throughput and average energy consumed per received bit.](image)

![Fig. 12. The interaction between MAC and physical layers.](image)
100 ms). We get these values through analytical computations that have been validated with simulations. From this figure, it is observed that mode increases with average received SNR $\gamma_0$, while decreases with traffic load $\lambda$. This is because when traffic load is increased, to satisfy the performance requirements $[R, T]$, sensor has to lower the transmission threshold to get more slots to send packets, resulting in a lower mode value. However, when the channel quality improves, more frequently, sensor can transmit packets through link of high quality. Thus even threshold (mode value) is increased, performance requirements $[R, T]$ can still be fulfilled. Note that in this figure, mode zero (zero point) means that performance requirements can never be satisfied, even transmission requirements has been degraded to $\Gamma_1$, because the channel condition is too harsh or the traffic load is too heavy. The corresponding simulated sensor lifetime under these analytical optimized mode is given in Figure 14.

To analyze the gain that can be achieved through cross layer design, we use Mode 1 as reference, which has not taken the channel fluctuations into account, comparing its energy consumption with that of optimized modes as illustrated in Figure 13. The percentage of energy saved versus traffic load and average received SNR is presented in Figure 15. The results are achieved through extensive simulations, and the percentage energy saved equals to the difference between the average energy consumed to send one packet in Mode 1 (reference) and the optimized mode divided by energy consumed in Mode 1. It is observed that after optimization, we can save up to 40% of the energy. This gain decreases with traffic load because the increase of load forces the sensor to lower the threshold to satisfy performance constraints, reducing the gain achieved. Energy saving can also extend the sensor lifetime, and the corresponding gain in lifetime is shown in Figure 16. Normalized lifetime in this figure means the sensor lifetime under optimized modes given in Figure 13 normalized by the lifetime of Mode 1. We observe that using the cross layer design can extend sensor lifetime up to 110%. This illustrates the effectiveness of a channel dependent cross layer design.

4.4. A Cluster Design Example

We take a look at a cluster design example, in which there are four sensors communicating with the cluster head. The four sensors indexed with 1, 2, 3, 4, have different attenuation distance to the cluster head, resulting in different signal strength with average received SNR 16 dB, 18 dB, 21 dB, and 24 dB, respectively. The time slots in a frame are equally allocated within cluster, that is, each sensor has five slots in one
frame to transmit packets. We investigate how the channel quality and traffic load influence the energy consumption. The communication performance constraints are still fixed at \([R, T] = [0.7, 100 \text{ ms}]\).

Figure 17 is the variation of sensor optimized operation mode with increased traffic load. Under heavy traffic condition, to satisfy the performance requirement, a sensor has to adopt lower operation mode by degrading the transmission SNR threshold. Only Sensor 4, which has the best channel quality can maintain the highest mode. Note that for Sensor 1 and Sensor 2, when the load is above 10 packets per frame, they cannot provide required communication quality anymore, even working with Mode 1. Therefore, this load area is infeasible zone for the two sensors.

Corresponding to the operation mode given in the above figure, the sensor lifetime versus traffic load of four sensors is depicted in Figure 18. The increase in traffic load adds communication burden to sensor and at the same time, forces sensor to lower the transmission threshold, resulting in more energy consumption, thus shortening the sensor lifetime. Again, Sensor 4, which has the best channel quality, can keep the highest operation mode, and thus having the longest battery life. We are also interested in the energy efficiency, which is defined as the average energy consumed at both communication sides to send a packet. The energy efficiency of four sensors under their respective optimized modes is plotted in Figure 19. It is observed that Sensor 1 consumes nearly two times of energy used by Sensor 4 in one packet transmission, due to a harsher communication channel. The average energy expended decreases with traffic load, as sending more packets per transmission can amortize the radio startup energy overhead, thus enhancing the energy efficiency.

Finally, we fix the traffic load at 7 packets per frame, and according to the operation modes given in the Figure 17, four sensors (from Sensor 1 to 4) work at Mode 1, 2, 3, 4, respectively. Through simulations,
the rate of energy consumption is plotted in Figure 20. Again, Sensor 1 consumes the most amount of energy to transmit packets, because on average, to satisfy the same communication performance requirement, it has to use more time to transmit one packet due to lower modulation-coding mode adopted to compensate the distance attenuation.

4.5. The Effect of Buffer Size on the Energy Efficiency

In this paper, packet buffering approach is used to combat channel fading. However, the tiny size of sensor poses a physical limitation on the buffer capacity, which means that a sensor node cannot cache large volume of data as in a mobile laptop. Nevertheless, if the buffer size is too small, packets have to be dropped due to overflow. Consequently the operation mode has to be scaled down, rendering more energy consumption. On the other hand, large buffer size means increase in the hardware complexity and might be unaffordable for a sensor. Thus, this is a tradeoff between hardware complexity and energy efficiency. In our simulation, we set the buffer size to 50 (6.25 Kbyte) and this value is suitable for a tiny sensor. We are interested in the effect of buffer size on the energy efficiency in data communication.

We consider how the buffer size can be further minimized when the QoS requirements have been fulfilled (that is, \([R, T] = [0.7, 100 \text{ ms}]\)). We configure the buffer size as such: (1) in Setting 1, we calculate the minimum buffer size, without the consideration of operation mode, and set the buffer size with this value; and (2) in Setting 2, we calculate the minimum buffer size, when the sensor is working at the highest operation mode, and set the buffer size to the value. That means, in Setting 1, the buffer sized is minimized without the consideration of energy efficiency, while in Setting 2, the size is minimized when the sensor operates in the most energy efficient mode. The results are listed in Tables III and IV.

In Table III, the minimum buffer sizes of sensor with Setting 1 and Setting 2 under different working environments are listed on the right and right sides of symbol ‘/’ respectively. It is shown that the minimum size of Setting 1 is smaller. The reason is that sensor of Setting 1 only considers how to reduce the buffer size, and energy efficiency is not taken into consideration. While sensor with Setting 2 takes both buffer size and energy efficiency into account. Naturally, larger buffer size allows longer packet buffering time and higher operation mode as well. The operation modes of both settings are given in Table IV. The life gain with Setting 2 is depicted in Figure 21. We can see that some little increase in the buffer size (less than 50) can result considerable gain in sensor lifetime. Thus, we

<table>
<thead>
<tr>
<th>Average received SNR (decibel)</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic load (packet/frame time)</td>
<td>1</td>
<td>2/3</td>
<td>2/2</td>
<td>2/19</td>
<td>2/5</td>
<td>2/3</td>
<td>2/29</td>
<td>2/12</td>
<td>2/3</td>
<td>2/3</td>
<td>2/2</td>
</tr>
<tr>
<td>5</td>
<td>6/6</td>
<td>6/8</td>
<td>5/6</td>
<td>5/31</td>
<td>5/8</td>
<td>5/6</td>
<td>5/6</td>
<td>5/6</td>
<td>5/7</td>
<td>5/5</td>
<td>5/6</td>
</tr>
<tr>
<td>6</td>
<td>18/18</td>
<td>18/29</td>
<td>7/8</td>
<td>6/7</td>
<td>6/7</td>
<td>6/7</td>
<td>6/7</td>
<td>5/10</td>
<td>5/8</td>
<td>5/7</td>
<td>5/6</td>
</tr>
<tr>
<td>7</td>
<td>×</td>
<td>×</td>
<td>9/26</td>
<td>8/9</td>
<td>7/13</td>
<td>7/9</td>
<td>6/8</td>
<td>6/12</td>
<td>6/9</td>
<td>6/8</td>
<td>6/7</td>
</tr>
<tr>
<td>8</td>
<td>×</td>
<td>×</td>
<td>10/15</td>
<td>9/9</td>
<td>8/10</td>
<td>7/9</td>
<td>7/9</td>
<td>10/13</td>
<td>9/10</td>
<td>8/10</td>
<td>8/9</td>
</tr>
<tr>
<td>9</td>
<td>×</td>
<td>×</td>
<td>28/28</td>
<td>11/13</td>
<td>9/14</td>
<td>9/10</td>
<td>8/17</td>
<td>8/11</td>
<td>9/10</td>
<td>8/10</td>
<td>8/9</td>
</tr>
<tr>
<td>10</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>20/20</td>
<td>11/13</td>
<td>10/13</td>
<td>9/42</td>
<td>9/13</td>
<td>9/10</td>
<td>9/10</td>
<td>8/10</td>
</tr>
<tr>
<td>11</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>12/14</td>
<td>10/13</td>
<td>10/10</td>
<td>10/10</td>
<td>9/13</td>
<td>9/10</td>
<td>9/10</td>
</tr>
</tbody>
</table>

The symbol ‘×’ means no feasible operation mode under such working environment. The value on the left of ‘/’ is the minimum buffer size with Setting 1, and value on the right of ‘/’ is the minimum buffer size with Setting 2.
think that such increase in hardware complexity is deserved.

4.6. Some Remarks on the Sensor Network Design

**Remark 1:** A cross layer design is effective for energy efficiency in wireless sensor network. However, it entails intensive computational complexity involved in getting the steady state distribution $\pi_{(u,c)}$ in linear equation group (20), and this can consume a significant amount of energy and time at CPU, which may not be viable for a computation and energy limited sensor. An efficient approach to this problem is to pre-compute the operation modes under different working environments, then store them in a file, and thus they can be retrieved whenever needed. This solution is fast and energy efficient, hence, can be applied in sensor network. Another solution is to let the sensor transmit channel fluctuation ($\gamma_{0,f_m}$), MAC traffic load $\lambda$, number of time slots in each frame, together with the performance requirements $[R, T]$ to the network controlling center that has more powerful ability to perform such complicated calculation.

**Remark 2:** In the above design example, we have only 4 sensors accommodated in a cluster, and we call them QoS guaranteed sensors in that their packet delivery rate and delay can be ensured by fixed number of time slots allocated to them in each frame. However, when the channel is in deep fading, they will give up the allocated slots. We can allocate these discarded slots to those ‘best effort’ sensors that do not have such strict communication performance constraints, and thus, maximizing the channel resource utilization.

**Remark 3:** In each frame, there is a RTS–CTS signaling handshake between sensor and cluster head for channel adaptation. However, usually, channel fading can last for 10–60 frames, thus to avoid unnecessary RTS–CTS exchanges and frequent radio switch on/off during this period, in case channel fading happens, the radio should power off and keep silent for expected fading duration. The determination of this fading coherence time is an interesting problem, and overestimation of this value can forfeit sensor multiple slots. Thus we should adopt a conservative estimation and this is beyond our discussion.

**Remark 4:** In the above design example, we note that worse channel quality can lead to higher energy consumption level (e.g., Sensor 1). Therefore, to

<table>
<thead>
<tr>
<th>Average received SNR (decibel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 16 17 18 19 20 21 22 23 24 25</td>
</tr>
</tbody>
</table>

The symbol ‘×’ means no feasible operation mode under such working environment. The value on the left of ‘/’ is the operation mode with Setting 1, and value on the right of ‘/’ is the operation mode with Setting 2.

![Fig. 21. Life gain with more buffer size in Setting 2.](image-url)
save energy, a sensor should select a cluster head between which it can set up the least attenuated wireless link.

**Remark 5:** In the cluster, we allocate each sensor node equal number of time slots, and we call this ‘channel access fairness’. However, this results in different energy consumption speeds within cluster, further leading to partial partitioning of the network. Hence, it may be ideal for each sensor node to have the same energy consumption rate, and we call this ‘energy fairness’. Nevertheless, given the energy efficiency and performance requirement, to make sensors of same traffic load but different channel quality have identical energy expenditure speed, sensor with low channel quality must be allocated more slots. This might render inadequacy of time slots allocated to other sensors. Therefore, how to achieve a balance between ‘channel access fairness’ and ‘energy fairness’ is very challenging, and has become a complicated optimization problem that has multiple optimization objectives—energy efficiency, fairness, communication performance, and network capacity etc., depending on the real application scenario. Thus, it can still provide us large room for further exploitation.

5. **Concluding Remarks and Future Work**

In summary, we have presented a cross layer approach which can improve the energy efficiency of the wireless sensor network. Specifically, by sharing the channel fluctuation information with MAC layer, we derive the most energy efficient operation modes under different working environments, while ensuring the communication performance above the acceptable level. Through extensive simulations, this approach has shown its effectiveness in energy conservation, and has the merits of low complexity and compatibility with separate layer design, and thus, can be easily implemented in sensor networks.

Our work at this stage has only considered how to extend lifetime of single sensor, and ignored the network life time as a whole. In some cases, for the ease of network maintenance, people may prefer an equal energy consumption speed within the network, while achieving energy saving at the same time. This entails much more complicated analysis of the relationship among energy efficiency, fairness, QoS guarantee, and channel resource allocation. Thus, more research work needs to be done in the future to find a good solution to the problem, with all the related factors taken into consideration.

**Acknowledgement**

The authors thank the reviewers for their constructive comments on earlier version of the paper. The research was jointly supported by research grant from National Science Foundation of China under project number 60602066 and 60773203, and grant from Guangdong Natural Science Foundation under project number 5010494. The work has also got support from Foundation of Shenzhen City under project number QK200601.

**References**

15. Liu Q, Zhou S, Giannakis GB. Queuing with adaptive modulation and coding over wireless links: cross-layer analysis and


Authors’ Biographies

**Xiao-Hui Lin** received his B.S. and M.S. degrees in Electronics and Information Science from the Lanzhou University, in 1997 and 2000, respectively. He got his Ph.D. degree in Electrical and Electronic Engineering from the University of Hong Kong in 2003. He is now an Associate Professor in the Faculty of Information Engineering, Shenzhen University in Guangdong, China. His research interests include mobile computing, wireless networking, and multimedia communication. In these fields, he has published more than 20 papers in international leading journals and refereed conferences.

**Yu-Kwong Kwok** is an associate professor in the Electrical and Computer Engineering Department at the Colorado State University. Prior to joining CSU in August 2007, he was an associate professor at the University of Hong Kong. He received his Ph.D. in computer science from the Hong Kong University of Science and Technology in 1997. In the areas of distributed systems and wireless networking, he has co-authored over 170 technical papers and two textbooks. Dr. Kwok currently serves on the Editorial Board of the *Journal of Parallel and Distributed Computing* for the subject area Peer-to-Peer (P2P) Computing, and the *International Journal of Sensor Networks*. His current research endeavors are mainly related to game theoretic security and incentive issues for wireless systems, and resource management for dynamically reconfigurable chip multiprocessor systems. Dr. Kwok received the Outstanding Young Researcher Award from the University of Hong Kong in November 2004. He is a senior member of the ACM and the IEEE.

**Hui Wang** received his B.S., M.S., and Ph.D. degrees from Xi’an Jiaotong University, in 1990, 1993, and 1996, respectively, all in telecommunication. He is now a Professor and Dean of the Faculty of Information Engineering, Shenzhen University. His research interests include wireless communication, signal processing, and distributed computing systems, in which, he is author or co-author of more than 50 international leading journals, conferences and book chapters. He is member of IEEE.