Research Article

Mixed Cooperation MAC Protocol with Sleep Mechanism for Data Acquisition in Wireless Machine-to-Machine Networks

Yulei Zhao, Bing Du, and Ning Ge

State Key Laboratory on Microwave and Digital Communications, Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

Correspondence should be addressed to Yulei Zhao; sunstone2222@163.com

By exploring the idle state of each sensor node, a mixed sleep-cooperative time division multiple access (TDMA) media access control (MAC) protocol (MS-CTDMA) is proposed for the wireless data gathering network in wireless machine-to-machine (M2M) networks. The basic idea is that in the idle state, each sensor node dynamically goes into sleep state or cooperative state to maximize the network lifetime. A single-hop network delay model of MS-CTDMA is established by the $M^X/G/1$ N-policy queue with multiple exhaustive vacations, which provides a way to balance energy consumption in network and the delay of each node with the delay sensitive traffic constraint. Furthermore, based on some reasonable assumptions, the proposed MS-CTDMA analysis model can be extended to the whole M2M network. Consequently, we propose an optimal source node selection strategy from the perspective of the relay node during its idle time, regarding the traffic load, residual energy, and channel state. Numerical results reveal that with proper tradeoff between delays and energy conservations, MS-CTDMA can significantly prolong the network lifetime in Rayleigh fading channels compared to pure sleep scheme.

1. Introduction

Machine-to-Machine (M2M) technology is widely used to gather information, and the machines are small and low-power. Cooperative communications enhance the link quality of the wireless network in a distributed fashion. The peer terminals in wireless M2M networks can achieve the diversity gain via mutual cooperation realized by the prevalent cooperative relay protocols, such as amplify-and-forward (AF) and decode-and-forward (DF) in [1]. In fact, the source and the relay form the virtual antenna array which brings benefits of the spatial diversity. For data acquisition system in wireless networks, a node receives transmission signals sent by its neighbors due to the wireless broadcast nature. Reference [2] proposed iterative collaborative relay beamforming strategies based on AF to maximize the received signal-to-interference-and-noise ratio (SINR) in wireless M2M networks. Time division multiple address (TDMA) is adopted to guarantee the quality of service (QoS) of the traffic data. More important, TDMA system can save energy by permitting the nodes to work with sleep mode in wireless data acquisition

network [3]. Recently, several cooperative retransmission media access control (MAC) protocols have been investigated for TDMA systems. In [4], a Cooperative TDMA (C-TDMA) protocol was proposed to improve the throughput of the wireless network. Reference [5] extended the previous work to the dynamic slot assignment scheme for TDMA systems.

However, cooperations introduce delay to the system. In order to investigate the delay character of the cooperative relay network, the researchers first established a delay model of the single source and single-relay cooperative automatic-repeat request (ARQ) protocols for failure transmission [6], in which the Poisson arrival model of frames is assumed to estimate the delay caused by the cooperative relay when error frame triggers the retransmission.

For the consideration of saving energy in wireless sensor networks, [7] demonstrated that the network lifetime of wireless sensor network is more important for data collection network. Reference [8] established the energy model of single-hop wireless sensor networks. The transceiver of each sensor node uses energy when sending, receiving, or listening, and the ratio energy consumption is about $1.5 : 1 : 1$ [9, 10]. Energy

efficiency and power allocation of cooperation transmission in wireless data gathering network were investigated in [11]. Reference [11] adopted the minimum energy consumption (MIE) policy and maximum residual energy (MARE) policy to allocate transmit power between the relay and the source node. Based on the control message of RTS-CTS, the proposed transmission scheme could decrease the signaling overhead. Reference [12] extended MARE policy to pricing strategy to maximize the network lifetime. The proposed energy pricing strategy could balance each node's energy consumption. Besides, [13] proposed the improved power allocation scheme based on communication distance for each group to maximize the lifetime of the whole sensor network. The priority queuing model combined with the vacation queuing model [14] is used to analyze the energy-aware MAC for differentiated services in wireless packet networks.

Only in sleep state, the energy consumption is very low. The microprocessor embedded in sensor node can go to the sleep state automatically when there is no task. So it is essential to introduce sleep mode to wireless sensor MAC protocol to save power [9]. Reference [15] adopted the vacation queue model, depicted extensively in [16], to study the sleep mode in the 802.16e system, which increased the energy efficiency and prolonged the lifetime of the wireless network.

However, it seems that the above cooperative transmission protocols cannot consider the incurred overhead extensively, which includes energy consumption of the relay node, additional delay of the relay traffic, and signaling for cooperating nodes selection [17]. Furthermore, if a terminal is in its idle state (here, we define, idle state is that the incoming buffer length of one node is less than the predefined threshold), it can become a relay node or sleep node according to its residual energy, traffic load, and received signal strength. When the node selects cooperative target during its idle state, many-to-one cooperative communication topology is established, and [18, 19] used game theory to analyze power allocation problem for this topology. When the node selects sleep scheme during its idle state, intuitively it saves power for itself, but if adopting random or independent sleep scheme, the network lifetime of sensor network cannot be maximized, because the network lifetime is attributed to the shortest duration time of the sensor node. Thus, in idle state we combined the sleep mode with the cooperative transmission, which is able to average energy cost over several sensor nodes. Both cooperative scheme and sleep scheme incur the transmit delay.

To deal with both energy and delay challenges, we propose a mixed cooperation MAC protocol with sleep mechanism (MS-CTDMA) for data acquisition system. And a queue model for MS-CTDMA protocol is given to measure the pros and cons of the proposed transmission. The contributions of this research are mainly at the following three points.

(1) MS-CTDMA protocol is introduced by fully utilizing the idle time of each node to save power. During idle state each node can select sleep scheme or cooperative transmission.

(2) We establish a $M^X/G/1$ N-policy vacation queue model for MS-CTDMA to carry out the performance analysis. The vacation time in $M^X/G/1$ is equivalent to the idle time in MS-CTDMA.

(3) Considering many-to-one cooperation communication topology, we give the optimal node selection strategy from the perspective of the relay naming source node selection, which is more efficient to average energy over the whole network.

The rest of the paper is organized as follows. Section 2 describes MS-CTDMA protocol elaborately. In Section 3, we establish the $M^X/G/1$ N-policy multiple vacation queue model for MS-CTDMA. Section 4 derives the system performance extensively. The optimal source node selection strategy is also depicted in this section. Numerical results and discussions are given in Section 5. And finally Section 6 draws the conclusions and the future work.

2. System Model with MS-CTDMA Protocol

2.1. Network Model. The research in this paper considers the wireless data acquisition network with sensor nodes and a sink node. In this network, each node only transfers collected data to the sink node. We focus on single-hop wireless network which means that all nodes are within one-hop transmit range. Moreover, each node can obtain spatial diversity through 2-hop cooperative transmission. This wireless packet system adopts TDMA scheduling protocol. Each node has its own allocated time slot and only has the chance to access the channel in its time slot. All nodes are synchronized and the MAC frames have equal length. Without loss of generality, this study concentrates on single relay cooperative scheme which incurs less overhead. As depicted in Figure 1, this data acquisition system contains M sensor nodes and one sink node. Each node alternatively acts as source node during its busy state or as relay node within its idle state. A frame time is divided into two fields: a control time slot (CT) and a data time slot (DT). CT conveys the scheduling information for each node. DT contains the time slots reserved for data transmission. Each node coordinates the cooperative transmission mechanism through CT.

An Rayleigh fading channel [20] is considered between two nodes, and the reciprocal channel is symmetry. $h_{i,j}$ denotes the complex channel gain for communication link from node i to node j. This research supposes that each sensor has the independent additive white Gaussian noise (AWGN) with the identical power spectral density (PSD) N_0. The instantaneous signal-to-noise ratio (SNR) of i to j can be expressed as [12]

$$\gamma_{i,j} = \frac{P_i |h_{i,j}|^2}{N_0 W},\tag{1}$$

where P_i denotes the transmit power of node i and W is the transmit bandwidth. All sensor nodes are assumed to have the constant modulation and coding, so they have the same packet data transmit rate I_p. Without assistance from the relay
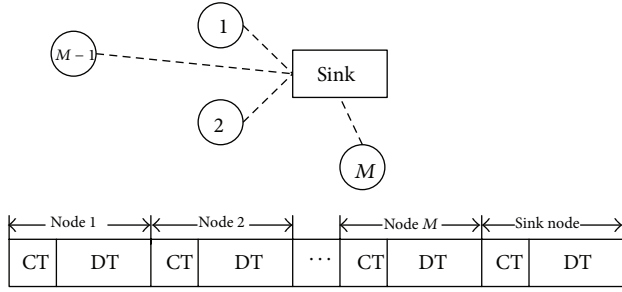
FIGURE 1: Typical data acquisition system and time slot assignment.

Busy state: service its own data traffic
Setup state: cooperative negotiation stage
Cooperation state: cooperative transmission stage
Sleep state: enter the sleep mode
Closedown state: release the cooperative transmission

FIGURE 2: State transition diagram of each sensor node.

node, the transmit power P_i^d of node i satisfies (2) to achieve the packet data transmit rate [11]:

$$P_i^d \geq \frac{1}{\lambda_{i,j}} \left(2^{I_p/W} - 1 \right). \qquad (2)$$

For presentation brevity, $\lambda_{i,j}$ is defined as $\lambda_{i,j} = |h_{i,j}|^2 / (N_0 W)$.

2.2. MS-CTDMA MAC Protocol. To maximize the sensor network lifetime, which is defined as the network working time until one sensor node uses up its energy, we proposed MS-CTDMA protocol. Introducing sleep mechanism into sensor node's idle state can reach low network energy consumption, but it also prolongs average packet delay. And the cooperative transmission could average power consumption over sensor nodes to lengthen the network lifetime. For example, as shown in Figure 1, $d_{M-1,D}$ is greater than $d_{1,D}$ and $d_{i,j}$ denotes the distance between node i and j. So node $M - 1$ drains up its energy faster than node 1 under the same traffic load. Through combining cooperative relay strategy with sleep mode, the source node gets benefit of lowering its transmit power with the help of the relay node. The key idea of our proposed protocol is to efficiently utilize each node's transmit power in its idle state by choosing to sleep or to cooperate, so as to maximize network lifetime.

Each node is in one of the following states: init state, busy state, setup state, closedown state, sleep state or cooperation state. The state transition diagram is depicted in Figure 2. A node is said to be in sleep state when it turns off the radio transreceiver to save its battery energy. In a sensor node's cooperation state, the idle node acts as the relay node to save the source node's energy consumption by cooperative transmission based on source node selection, not relay node selection.

Initially each node starts out with the initial state. In this state the sensor node completes initialization and waits for the packet arrival. If the sensor has data to transmit, it transfers to the busy state. During the busy state, this node acts as the source terminal S. S is listening to the cooperative relay request (CREQ) from other idle sensor nodes by signaling packet. Then S sends the negotiation (CNEG) message back to the request relay node. Once a request sensor node selects S as its cooperative target and replies to S by cooperative acknowledgement (CACK), S and this relay node establish the cooperative relay link to help S to transmit. After all
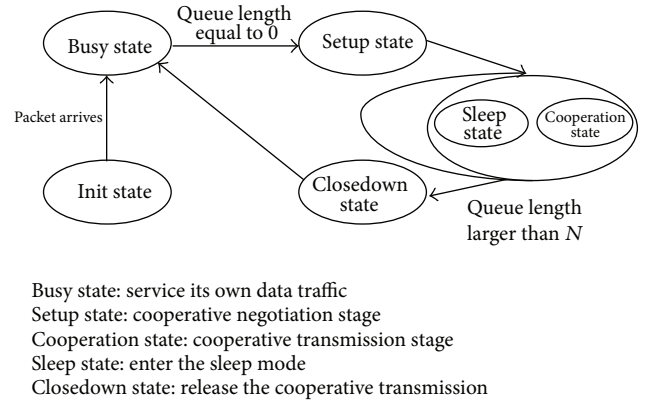
packets in data buffer have been sent out, the node changes back to the idle state, where it can be a relay node R or go into sleep mode according to the following steps. If it were a relay node, first, R enters the setup state to select the optimal S by broadcasting CREQ. If R successfully finds the source node from other nodes, it transfers to the cooperative state. Otherwise, R fails to find an appropriate S and turns off the radio to go into the sleep state. After sleep or cooperation, R reexamines the queue length. If there is not enough traffic coming and the data buffer size is less than N which denotes the predefined threshold, R maintains the cooperative or sleep status. On the contrary, if R's data buffer size grows larger than N, it goes to the closedown state and releases the cooperative relay link or sleep mode. The node turns to be a source node to transmit its own data traffic until the next idle state is satisfied.

The criterion to choose optimal source node for R is vital for the mixed transmission strategy. The mixed strategy tries to give a tradeoff between the network lifetime and packet delay determined by considering the multiple important elements: the residual battery energy, the channel state information at the physical layer, the incoming traffic load at the MAC layer, and the packet delay for a different traffic type. During the same constant time interval, if the predefined threshold N is increasing, the number of entering setup state is decreasing. In other words, the overhead for sleep or cooperation is reducing. For the same reason, the long-sleep time T_s or cooperative time T_c leads to low overhead. But these energy saving behaviors also incur lengthy packet delay.

3. Vacation Queue Model for MS-CTDMA

The $M^X/G/1$ vacation queue model with N-policy multiple exhaustive vacations is explored to analyze the performance of MS-CTDMA protocol in this section. The access mechanism of MS-CTDMA is coincident with the N-policy vacation queue model inherently. The idle state in MS-CTDMA can be modeled by the vacation state in $M^X/G/1$ vacation queue model.

Here, we assume that the traffic data buffer size is unlimited, which is reasonable when analyzing the average

performance of the MS-CTDMA systems. The incoming traffic of each terminal is assumed to be compound Poisson process. The batch arrival rate is λ, and the number of packet in each batch is denoted by stochastic variable X. Batch Markovian arrival process (BMAP) is suited to the bursty nature of packet traffic for wireless data acquisition scenario [21]. The data acquisition moment is triggered by outside environment changing which coincides with the model of Poisson arrival. At this moment, a new batch of sensor data with random packets is generated into the transmit buffer. In this paper, all sensor nodes are equal and have the same traffic load.

We give some general assumptions first. The packet length keeps constant, that is, L_d for data packet and L_s for signaling packet. The number of arrival packets obeys discrete random distribution which is determined by a different sensor type. The discrete probability density function is depicted by $p\{X = x_i\} = g_i$, where $i = 1, 2, \ldots, E$ denotes random acquisition type. Over each transmission link, the physical layer adopts capacity-achieving code and adjusts the transmit power to assure the required bit error rate (BER) [11], so the retransmission mechanism is not considered in this paper. Thus the service time is only determined by the packet transmission time. I_i denotes the packet transmission rate of the terminal i, $(i = 1, 2, \ldots, M)$. Coding and modulation of the transmission keep constant without adaptation, so I_i does not vary with channel state information. Without loss of generality, each sensor node has the same processing ability, that is, $I_i = I_p$ for each i. The corresponding data packets are served as customers on first-come-first-serve (FCFS) basis until the system becomes empty. S_i, $(i = 1, 2, \ldots, M)$ denotes the service time of each terminal, also known as the transmission time in physical layer. Based on the above assumption, S_i follows the deterministic distribution, and the mean of S_i can be expressed as

$$E[S_i] = \frac{L_d}{I_i}. \tag{3}$$

3.1. State Transition for MS-CTDMA Protocol.

First, we illustrate the state transition for MS-CTDMA protocol. In proposed MS-CTDMA protocol with $M^X/G/1$ N-policy vacation queue model, the setup time and closedown time are constant values, denoted by T_u and T_d, respectively, which is determined by the S's negotiation mechanism. Cooperative time T_c is independent identical distributed (i.i.d) random variable with a general distribution function, denoted by $F_c(t)$. Sleep time T_s is also i.i.d random variable depicted by $F_s(t)$. Figure 3 shows the state transitions for each node's operation cycle in the established model [22]. When the incoming traffic length of one node is larger than N, this node transfers from the init state to the busy state. And it services its own data traffic until the queue length is empty. When data length in the queue is less than N, according to MS-CTDMA protocol, it goes into the setup state to determine whether to sleep or to cooperate during its idle state or vacation state. After the vacation time, if the node's queue length is growing larger than N, the state transfers into closedown state and ends from vacation state.

The vacation time in $M^X/G/1$ N-policy vacation queue model can be regarded as the cooperative time or sleep time, which is determined by optimal source selection strategy in MS-CTDMA. And in this research, the vacation time follows the deterministic cumulative distribution function $F_v(t)$, which is

$$F_v(t) = \begin{cases} 0, & t < T_{VE} \\ 1, & t \geq T_{VE}. \end{cases} \tag{4}$$

$F_v(t)$ denotes its probability density function. The mean value of the vacation time is $E[T_v] = T_{VE}$, which is the integral time of the packet transmission time. The long T_{VE} leads to low overhead and vice versa. In this paper, T_c and T_s have identical probability distribution with T_v.

3.2. The Average Queue Length.

We establish the embedded Markov chain to calculate the average queue length in this subsection. The queue length at the packet departure instants can be mapped into the state space of the embedded Markov chain. Let D_n, $n = 1, 2, \ldots$ denote the state space or the embedded Markov chain, where $n = 1, 2, \ldots$ is the packet departure instants. They satisfy

$$D_{n+1} = \begin{cases} D_n - 1 + A, & \text{for } D_n \geq N \\ D_n + A, & \text{for } D_n < N, \end{cases} \tag{5}$$

where A denotes the arriving packets during the vacation time and is determined by batch traffic arrival rate λ. From [16] we know that the rmbedded Markov chain is positive recurrent when the utilization load $\rho < 1$. The queue length D_q in this $M^X/G/1$ vacation model can be decomposed into the sum of the two independent random variables:

$$D_q = D + D_v, \tag{6}$$

where D is the mean queue length of an ordinary $M^X/G/1$ queue without vacations and D_v is the additional mean queue length due to the vacation effect.

3.3. The Mean Waiting Time.

The mean packet queue waiting time W_q of $M^X/G/1$ multiple vacation models combined with N-policy is used to measure the quality of service (QoS) incurred by packet delay. According to tht Poisson arrivals (see time average (PASTA)) [16], the average queue waiting time of the embedded Markov chain is equal to steady state waiting time. From [23], we can get

$$W_q = \left(D_q + E[X_R] \right) E[S] + P(B) E[S_R] + P(I) \frac{E[N_{I_R}]}{\lambda E[X]}, \tag{7}$$

where $P(B)$ and $P(I)$ indicate the probability of busy time and idle time of each sensor node. They can be expressed as $P(B) = \rho$ and $P(I) = 1 - \rho$. From Little's theorem [16], $D_q = \lambda E[X] W_q$. So (7) can be formulated as follows:

$$W_q = \frac{E[S]}{1 - \rho} E[X_R] + \frac{\rho}{1 - \rho} E[S_R] + \frac{E[N_{I_R}]}{\lambda E[X]}, \tag{8}$$
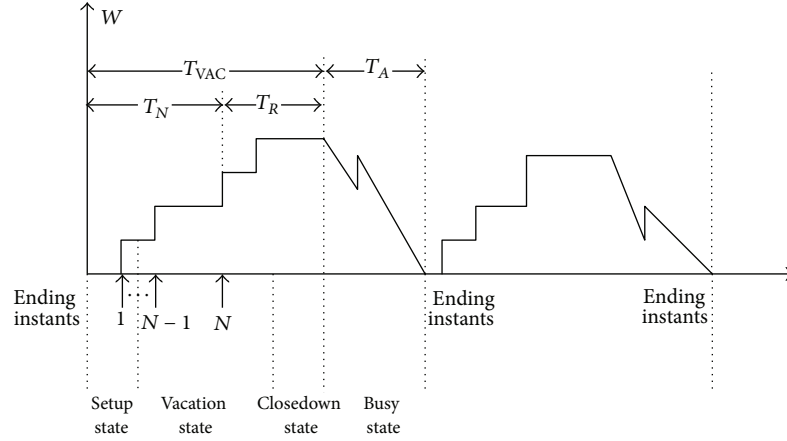
FIGURE 3: The time distribution with the state transition.

where $E[X_R]$ denotes the former waiting packet in the same batch and $E[S_R]$ is residual service time. From [23] we have

$$E[S_R] = \frac{1}{2} \frac{E[S_i^2]}{E[S_i]}, \tag{9}$$

$$E[X_R] = \frac{1}{2} \left[\frac{E[X^2]}{E[X]} - 1 \right]. \tag{10}$$

For N-policy $M^X/G/1$ system with multiple vacations, the last component of (8) can be expressed as

$$\frac{E[N_{I_R}]}{\lambda E[X]} = E[V_R] + \frac{1}{\lambda E[X]} \frac{\sum_{n=0}^{N-1} n\beta_n}{\sum_{n=0}^{N-1} \beta_n}, \tag{11}$$

where $E[N_{I_R}]$ means the additional packets generated by sensor devices during the idle sate. $E[V_R]$ is the expected duration of the residual vacation and can be expressed as

$$E[V_R] = \frac{E[V^2]}{2E[V]}. \tag{12}$$

Through (9)–(12), we could obtain the mean waiting time W_q from (8).

3.4. The Average Cooperative Probability. Each node selects its working scheme within its vacation time or idle state. So the probability of the event P_c that each node takes action to sleep or cooperate for the sink node equals the ratio of the vacation time to one cycle total serving time, which is defined as the interval between two consecutive busy period ending instants, denoted by T_{NN}. And the N_{th} traffic frame accumulation period is defined by T_N. The forward recurrence time of the vacation time is delegated by T_R. The time that the relay node R processes the traffic queue is denoted by T_A. The relationship among T_{NN}, T_N, T_R, and T_A is shown in Figure 3. Equation (13) can be derived from the embedded Markov analysis in Section 3.2 [16] as follows:

$$E[T_{NN}] = \frac{1}{1-\rho} \left(\frac{N}{\lambda_i} + E(T_R) \right). \tag{13}$$

Hence, the cooperative time T_{VAC} is

$$E[T_{\text{VAC}}] = \frac{N}{\lambda_i} + E(T_R). \tag{14}$$

From (13) and (14), we can get the cooperative relay probability $P_c = E[T_{\text{VAC}}]/E[T_{NN}] = 1 - \rho$.

4. Performance Metric and Optimal Source Selection Strategy

In this section, we first present the total energy consumption during one operation cycle. Then the delay sensitive problem is formulated. The analysis queue model of MS-CTDMA protocol can be extended to the whole network based on energy consumption target. The optimal source node selection strategy is depicted extensively when MS-CTDMA protocol is running on the one-hop network.

4.1. Total Energy Consumption. The energy consumption within one operation cycle T_{NN} can be expressed as

$$E_{T_{NN}} = E_{T_{\text{VAC}}} + E_{T_A}, \tag{15}$$

where $E_{T_{\text{VAC}}}$ and E_{T_A} denote the energy consumption during vacation state and busy state, respectively. T_{VAC} and T_A are random variables, so it is necessary to calculate the expected value of total energy consumption $E[E_{T_{NN}}]$. During busy state, node i serves its traffic data with transmit power P_{iS} and the expected energy consumption $E[E_{T_A}] = P_{iS}E[T_A]$.

During the vacation time, node i goes into sleep or cooperation state. The transmit power is denoted by P_{iR}, and the power value for receiving data from source node is equal to P_{iR}, when $P_{iR} = 0$ node i selects the sleep mode. The setup state at the beginning of vacation and the closedown state at the end of the vacation also use energy. From (14), when traffic load λ is constant, $E[T_{\text{VAC}}]$ is attributed to predefined threshold N and the probability distribution of vacation time. Each operation cycle needs one setup stage and closedown

stage. The expected vacation energy consumption can be depicted as

$$E\left[E_{T_{\text{VAC}}}\right] = \frac{E\left[T_v\right]}{E\left[T_u + T_v + T_d\right]} P_{iR} E\left[T_{\text{VAC}}\right] + E\left[T_u + T_d\right] P_{iR}. \tag{16}$$

The last component is the energy overhead.

4.2. Delay Tolerant Constraint. In data collection scenarios, the traffic load is always low and nonrealtime. In other words, the collecting data needs to be sent to the sink node more reliably, while the time requirement is relatively relax. However, if the delay is longer than the deadline time D_T, QoS of the traffic decreases rapidly, and the sink node is not able to process the usable data. Thus, mean waiting time must satisfy $W_q \geq D_T$. From (16), prolonging T_v and N can minimize the energy overhead, which also incurs longer average packet delay. We can formulate the problem as

$$\min_{N, T_v} \frac{E\left[T_{\text{VAC}}\right]}{E\left[T_B\right]} E\left[T_u + T_d\right] P_{iR} \tag{17}$$

$$\text{s.t. } W_q \leq D_T,$$

where T_B indicates the minimum vacation time. This optimization is a tradeoff between the additional delay for node i and decreasing energy overhead incurred by state transition. And this solution is independent with optimal source selection strategy during the vacation time.

4.3. Extend the Results to the Whole Network. M-node data collection system is an open network, each node has its independent BMAP traffic with the batch arrival rate λ_i, $i = 1, \ldots, M$. Particularly, in a single-hop TDMA system, each node transfers its traffic in its assigned time slot and receives other nodes' traffic during its idle state with the cooperative probability $P_c(i)$, $i = 1, \ldots, M$. During the busy state, each node has the probability $P_s(i)$, $i = 1, \ldots M$ to be the source node with a relay. So, the network scenario satisfies the definition of the open Jackson network from [16].

According to the Jackson network, an M-node network can be divided into several single nodes to analyze the network performance. For simplicity of deduction, we assume that there are always multiple available relays between the source and the destination, and one source node only chooses one cooperative relay node. Based on the independent characteristic of each node, P_c and P_s can be derived as

$$P_c = P(I)\left(1 - P(I)^{(M-1)}\right),$$
$$P_s = P(B)\left(1 - P(B)^{(M-1)}\right). \tag{18}$$

4.4. Optimal Source Selection Strategy. In this paper, the cost function [12] is established to evaluate operation mode of each node. At ending instants of the busy period, each node determines whether to sleep or to be as a cooperative relay for one source node. When the node acts as a source node,

it also has the opportunity to be selected as the cooperative target by a relay node. During T_{VAC}, each node can choose to sleep to save battery energy or to be a relay node and find the optimal cooperative source node to minimize the cost. Therefore, within T_A, each node may have the chance to be assisted by one node. The whole cost function can be formulated as

$$C_i = P_c T_{\text{VAC}} \left(\omega_i P_{iR} + \omega_k P_{kS}\right)$$
$$+ P_s T_A \left(\omega_i P_{iS} + \omega_j P_{jR}\right) + \omega_i \frac{T_B}{T_{\text{VAC}}} E_{TS}. \tag{19}$$

The first component denotes the cost value during T_{VAC}, which is the stochastic random variable. P_{kS} depicts the transmit power of source node k selected by relay node i during its vacation or idle period. The second component is the cost within T_A, which is equal to $T_{NN} - T_{\text{VAC}}$. P_{jR} represents the power allocation of relay node j, which selects the node i as its source node. The last component indicates that setup and release energy consumption cost of each node. And $E_{TS} = E[T_u + T_d] P_{iR}$. The expected value of C_i is expressed as

$$E\left[C_i\right] = E\left[T_{VAC}\right] \left(\omega_i P_{iR} + \omega_k P_{kS}\right)$$
$$+ E\left[T_A\right] \left(\omega_i P_{iS} + \omega_j P_{jR}\right)$$
$$+ \omega_i \frac{E\left[T_B\right]}{E\left[T_{VAC}\right]} E_{TS}. \tag{20}$$

Compared with (19), we incorporate P_c and P_s into the source node selection strategy. The first component and second component are determined by working strategy during vacation time and power allocation within one operation cycle. Minimization of the last component is discussed in Section 4.2. The optimal sleep or cooperation selection and power allocation are to minimize (20).

4.4.1. The Energy Cost Factor. The energy cost factor is critical for the optimal source node selection. In this paper, we take into account the residual battery energy, the initial battery energy, and the traffic load to calculate the cost factor as follows:

$$\omega_i = \omega_0 \left(\frac{E_{i,\text{ini}}}{E_{i,\text{rem}}}\right)^l \left(\frac{\rho_i}{\rho_B}\right)^m, \tag{21}$$

where ω_0 denotes the initial cost factor of each node in the network, which reflects priority level of each node. The proportion of $E_{i,\text{ini}}$ to $E_{i,\text{rem}}$ indicates the cost factor of per unit energy for each node. The node with low proportion is likely to assist other nodes in its vacation or idle state. ρ_B is the basic traffic measurement, and the ratio of ρ_i to ρ_B implies the normalized traffic load for each node. The node with traffic load is reasonable to sleep in its idle state, since it has already consumed a lot of energy. l and m are exponent components of energy and traffic, respectively, to adjust the cost between residual energy and traffic load. For the sake of simplicity, l and m take value 1 or 2.

4.4.2. The Optimal Source Selection Strategy. According to (20), the cost value can be decomposed into three independent targets. Within T_{VAC}, the optimal source node selection can be expressed as a linear programming problem:

$$\min_{P_{iR},P_{kS},k} C_{i1} = \omega_i P_{iR} + \omega_k P_{kS}$$

$$\lambda_{k,D}P_{kS} + \lambda_{i,D}P_{iR} \geq 2^{2I_p/W} - 1 \qquad (22)$$

$$\text{s.t.} \qquad P_{S,\text{low}} \leq P_{kS} \leq P_{\max}$$

$$0 \leq P_{iR} \leq P_{\max}.$$

The first constrained condition is depicted extensively in [24]. $P_{S,\text{low}}$ is determined by instantaneous SNR between nodes k and D denoted by $\gamma_{k,D}$ and between nodes k and i depicted by $\gamma_{k,i}$. $P_{S,\text{low}}$ guarantees that the achieved rate of k to D is I_p and that the transmit rate of k to i is $2I_p$. $P_{iR} = 0$ means that the node selects to sleep during its idle state. $P_{\max}$ is a constant value which is constrained by sensor device. So, it can be expressed as

$$P_{S,\text{low}} = \min\{P_{S,\text{low}A}, P_{S,\text{low}B}\}$$

$$P_{S,\text{low}A} = \frac{1}{\lambda_{k,D}}\left(2^{I_p/W} - 1\right) \qquad (23)$$

$$P_{S,\text{low}B} = \frac{1}{\lambda_{k,i}}\left(2^{2I_p/W} - 1\right).$$

Similarly, the problem that each node becomes the optimal target source assisted by other relay nodes can also be formulated as the following linear programming problem:

$$\min_{P_{iS},P_{jS},j} C_{i1} = \omega_i P_{iS} + \omega_j P_{jR}$$

$$\lambda_{k,D}P_{iS} + \lambda_{j,R}P_{iR} \geq 2^{2I_p/W} - 1 \qquad (24)$$

$$\text{s.t.} \qquad P_{S,\text{low}} \leq P_{iS} \leq P_{\max}$$

$$0 \leq P_{jR} \leq P_{\max}.$$

The energy consumption incurred by state transition is a minimized base on the precondition that the average packet delay must be satisfied. This optimal programming problem is discussed in Section 4.2.

4.4.3. Solutions to Optimal Power Allocation. The linear programming problem (22) can be solved by geometric methods effectively introduced by [12]. From (23), when $P_{S,\text{low}A} \leq P_{S,\text{low}B}$, there is no need for node i to assist node k, since the cost of i and k would both increase under the cooperation relay scheme. But other than that, i and k will always get benefit from the cooperation transmission, when $P_{iR} = 0$, in other words, no power is allocated to i, and i goes to sleep state during its vacation time.

As shown in Figure 4, $Y1$, $Y2$, and $Y3$ represent the constrained condition $\lambda_{k,D}P_{kS} + \lambda_{i,R}P_{iR} = 2^{2I_p/W} - 1$ in the plane when I_p is set to different values. According to constraint values of $P_{S,\text{low}}$ and $P_{m}ax$, the valid power
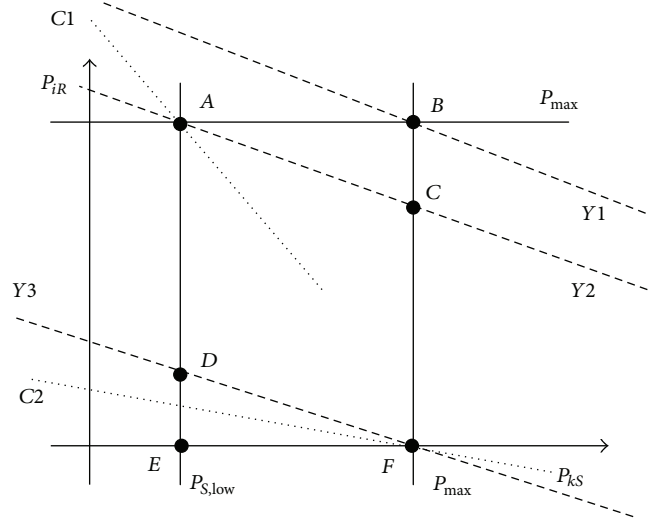

FIGURE 4: Geometric solutions for different regions.

allocation region is the intersection of $ABEF$ and one of the upper half plans of $Y1$, $Y2$, or $Y3$. This optimal power allocation problem is convex optimization, so the optimal solutions are intersection point, such as A or C, which is determined by the slope of objective line and condition line. When $\omega_k/\omega_i \geq \lambda_{k,D}/\lambda_{i,R}$, that is, $C1$, the left point A is the solution point. On the contrary, when $\omega_k/\omega_i < \lambda_{k,D}/\lambda_{i,R}$, that is, $C2$, the right point F is the optimal point. The rectangle $ABEF$ is divided into three regions ABC, $ACDF$, and DEF.

The research in this paper focuses on sleep state, $P_{iR} = 0$. So our study below is in region DEF, where I_p satisfies

$$2^{2I_b/W} - 1 > \lambda_{k,D}P_{S,\text{low}}$$

$$2^{2I_b/W} - 1 \leq \lambda_{k,D}P_{\max}. \qquad (25)$$

When $\omega_k/\omega_i \geq \lambda_{k,D}/\lambda_{i,R}$, the solutions is

$$P_{kS}^* = P_{S,\text{low}}$$

$$P_{iR}^* = \frac{1}{\lambda_{i,R}}\left(2^{2I_p/W} - 1 - \lambda_{k,D}P_{S,\text{low}}\right). \qquad (26)$$

In this case, the cost of per unit energy for source node k is much greater than relay node i. The cooperation scheme is able to average power consumption over i and k, which maximizes the network operation time.

When $\omega_k/\omega_i < \lambda_{k,D}/\lambda_{i,R}$, the solutions is

$$P_{kS}^* = \frac{1}{\lambda_{k,S}}\left(2^{2I_p/W} - 1\right)$$

$$P_{iR}^* = 0. \qquad (27)$$

In this case, node i selects going into sleep state to save power other than cooperative transmission. At the beginning of each vacation time of node i, (27) is solved. Likewise, the solutions for region, $ACDF$ and DEF can be solved. Due to space limitation, we omit the detailed results.
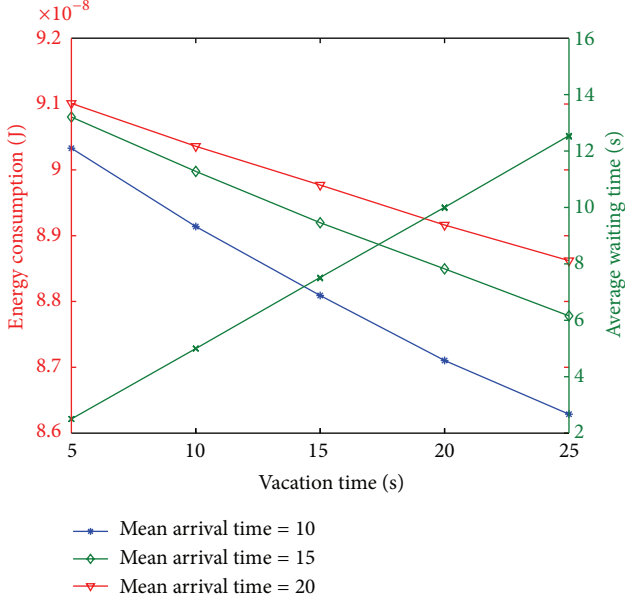
FIGURE 5: The average energy consumption and average waiting time by changing vacation time.

FIGURE 6: The energy consumption and average waiting time by changing predefined N.

4.4.4. The Implementation of Optimal Source Selection. The optimal relay selection is the usual way to perform cooperation. But in this paper, we implement the optimal source selection strategy within setup state during the vacation time. Once node i reaches setup state, it transmits CREQ control packet during CT. In the same frame time, when source node k receives CREQ signaling, it responses to node i a CNEG control packet containing the received signal strength indication (RSSI), traffic load, and residual battery energy. When node i gathers all the valid source candidates information, it makes decision whether to sleep or to cooperate during vacation time due to problem (22) and (24) solutions. Then, i sends the CACK packet data in the next frame time.

5. Numerical Results

In order to evaluate the performance of MS-CTDMA, we consider the scenario depicted in Figure 1. The sink node D is in the center of this region. In the research analytical evaluations, the signaling packet length L_c is 32 bits and data packet length L_d is 1000 bits. The received signal strength is lessening with proportion of square transmission distance. The fading is assumed to be constant in each vacation time. In addition, it is assumed that the average number of each batch is that $E[X] = 8$. Other parameters are set as $N_0 = 10^{-14}$ W/Hz, $W = 1$ MHz, $I_p = 1$ Mbps, and $P_{max} = 0.1$ W, respectively.

First, we explore the relationship between average packet delay and average energy consumption. Three different batch arrival rates are assigned to each node, and the node adopts the identical pure sleeping strategy. In this evaluation, the cooperative mechanism is not considered, because it does not affect vacation overhead.
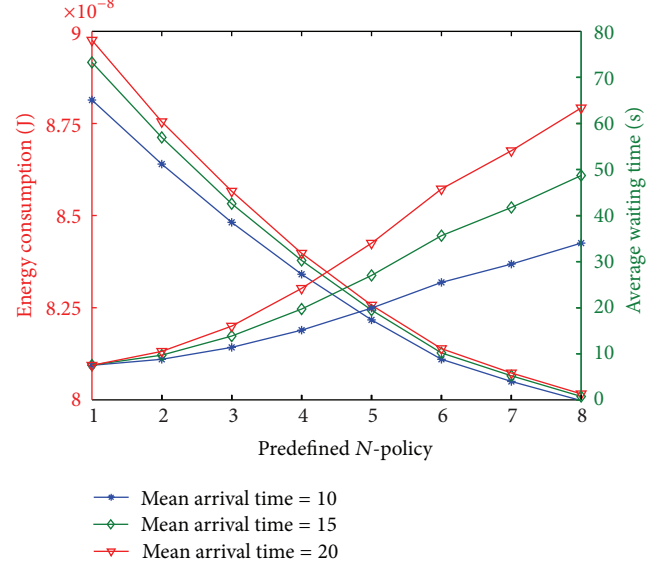
Figure 5 shows a plot of the average packet delay and average energy consumption by varying the vacation time T_v. We can save energy by increasing the vacation time or sleep time, but it also causes the packet delay. The longer T_v leads to low energy overhead for state transition. This benefit is obvious, and the energy overhead of state transition is stable at the end. Thus, ultimate energy conservation is determined by the traffic load, and the appropriate value of T_v is selected according to the system requirements. From Figure 5, the heavy traffic load can lead to less average energy consumption due to the reduced state transition number when serving the same number of packets. In this scenario, average waiting time is dominated by the vacation time.

Figure 6 shows several curves of the average energy consumption versus delays by varying the predefined threshold N. The increasing line demonstrates that the additional delay of each node introduced by N and the decreasing line demonstrates the average energy consumption of the same node. We clearly concluded that the tradeoff between average energy consumption and average delay can be adjusted by N. Compared to Figure 5, we discover that the average waiting time is insensitive to mean arrival time by changing T_v, but low traffic load can lead to heavy delay by varying N. So it is reasonable to adjust T_v to reach the delay and energy requirements.

Figure 7 shows the network lifetime of senor network using sleep scheme and our MS-CTDMA protocol by changing the relay node traffic load, when the predefined N has two values. In this simulation, three nodes have the same channel condition to the destination D, such as distance and fading condition. But the traffic load of relay node is lower than the other nodes. From Figure 7, we see that MS-CTDMA protocol considers the impact of different traffic load, and the nodes which have longer idle state are responsible for assisting other heavy traffic nodes to maximize the network
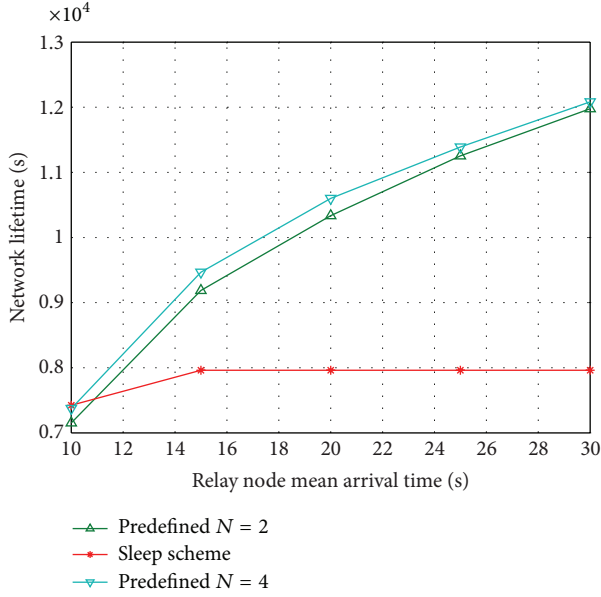
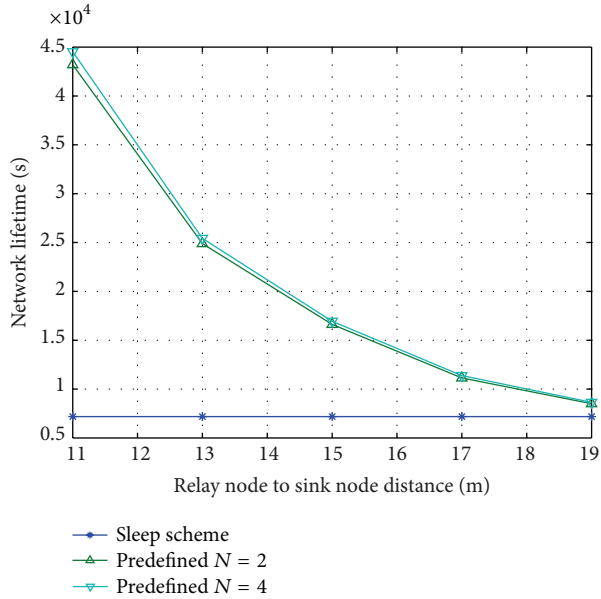FIGURE 7: Network lifetime by changing average arrival time.

FIGURE 8: Network lifetime by changing distance to sink node.

lifetime. When the network operates with pure sleep scheme, the network lifetime is up to the shortest lifetime node. But with MS-CTDMA protocol, the node with more idle time or less traffic load can lend its energy to other nodes.

Figure 8 shows the network lifetime of the senor network by changing distance to sink node. Here, we assume that three nodes have the same traffic load. The relay node is near to the sink node so the channel condition is different. In this condition, the performance of MS-CTDMA is also superior to the pure sleep mode. Comparing Figure 8 with Figure 7, we find that the impact of network lifetime with relay traffic load
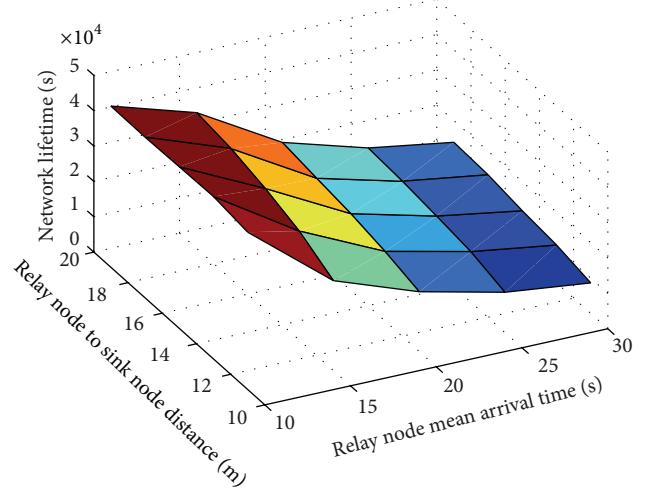

FIGURE 9: Network lifetime by changing average arrival time and distance.

is more distinct than that with relay distance to sink node by the predefined threshold N.

In Figure 9, we compare the network lifetime by changing traffic load and distance to sink node simultaneously. It is obvious that the maximization point is reached when the distance is nearest and the mean arrival time is smallest.

6. Conclusion

In this paper, we propose a novel mixed cooperative TDMA MAC protocol with sleep mode, namely, MS-CTDMA, for wireless data acquisition networks. When traffic queue length of a terminal is less than the predefined threshold N, it actively devotes itself to be a cooperative relay for its single-hop neighbor or go to the sleep state. And the $M^X/G/1$ N-policy vacation queue model is developed to analyze the delay performance of MS-CTDMA to obtain the best tradeoff between the energy consumption in network and the additional delay of the node. In addition, we find that the achievements of the proposed relaying model can be extended to the network under the Jackson network theorem's conditions. Then, an optimum source node selection strategy is given for the maximization of the network lifetime. The analysis and numerical results demonstrate that MS-CTDMA can improve the operation time of data collection significantly.

As a future work, we would like to investigate the multi-hop TDMA systems with multiple relays based on dynamic slot assignment scheme.

Conflict of Interests

The authors do not have any conflict of interests with the content of the paper.

Acknowledgments

References

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[2] D. Wang, L. Bai, X. Zhang, W. Guan, and C. Chen, "Collaborative relay beamforming strategies for multiple destinations with guaranteed QoS in wireless machine-to-machine networks," *International Journal of Distributed Sensor Networks*, vol. 2012, Article ID 525640, 10 pages, 2012.

[3] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 660–670, 2002.

[4] Z. Yang, Y.-D. Yao, X. Li, and D. Zheng, "A TDMA-based MAC protocol with cooperative diversity," *IEEE Communications Letters*, vol. 14, no. 6, pp. 542–544, 2010.

[5] J. K. Lee, H. J. Noh, and J. Lim, "Dynamic cooperative retransmission scheme for TDMA systems," *IEEE Communications Letters*, vol. 16, no. 12, pp. 2000–2003, 2012.

[6] I. Cerutti, A. Fumagalli, and P. Gupta, "Delay models of single-source single-relay cooperative ARQ protocols in slotted radio networks with poisson frame arrivals," *IEEE/ACM Transactions on Networking*, vol. 16, no. 2, pp. 371–382, 2008.

[7] W.-J. Huang, Y.-W. Peter Hong, and C.-C. Jay Kuo, "Lifetime maximization for amplify-and-forward cooperative networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1800–1805, 2008.

[8] D. Zhang and Z. Chen, "Energy-efficiency of cooperative communication with guaranteed E2E reliability in WSNs," *International Journal of Distributed Sensor Networks*, vol. 2013, p. 11, 2013.

[9] Q. Gao, K. J. Blow, D. J. Holding, and I. Marshall, "Analysis of energy conservation in sensor networks," *Wireless Networks*, vol. 11, no. 6, pp. 787–794, 2005.

[10] A. Savvides, C.-C. Han, and M. B. Strivastava, "Dynamic fine-grained localization in ad-hoc networks of sensors," in *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MobiCom '01)*, pp. 166–179, Rome, Italy, July 2001.

[11] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, "Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 8, pp. 3066–3079, 2008.

[12] F. Ke, S. Feng, and H. Zhuang, "Relay selection and power allocation for cooperative network based on energy pricing," *IEEE Communications Letters*, vol. 14, no. 5, pp. 396–398, 2010.

[13] J. J. Liaw, C. W. Chou, and C. Y. Dai, "The Lifetime Extension of Wireless Sensor Networks Using Adaptive Energy Allocation by Distance," *International Journal of Distributed Sensor Networks*, vol. 2013, Article ID 982573, p. 8, 2013.

[14] A. Fallahi and E. Hossain, "Distributed and energy-aware MAC for differentiated services wireless packet networks: a general queuing analytical framework," *IEEE Transactions on Mobile Computing*, vol. 6, no. 4, pp. 381–394, 2007.

[15] E. Chu, B. H. Jung, D. K. Sung, and Y. Park, "Modeling and analysis of an energy-efficient sleep-mode operation in IEEE 802.16e system," in *Proceedings of the Communications IEEE International Conference on (ICC '09)*, June 2009.

[16] N. Tian and Z. J. Zhang, *Vacation Queue Models: Theory and Application*, Springer, New York, NY, USA, 2005.

[17] W. Zhuang and M. Ismail, "Cooperation in wireless communication networks," *IEEE Wireless Communications*, vol. 19, no. 2, pp. 10–20, 2012.

[18] M. W. Baidas and A. B. Mackenzie, "Auction-based power allocation for many-to-one cooperative wireless networks," in *Proceedings of the 7th International Wireless Communications and Mobile Computing Conference (IWCMC '11)*, pp. 1677–1682, July 2011.

[19] D. Yang, X. Fang, and G. Xue, "Game theory in cooperative communications," *IEEE Wireless Communications*, vol. 19, no. 2, pp. 44–49, 2012.

[20] J. G. Proakis and M. Salehi, *Digital Communications*, MCGraw-Hill, New York, NY, USA, 2007.

[21] Y. Wu, T. Shu, Z. Niu, and J. Zheng, "A vacation model with setup and close-down times for transmitter buffer of ARQ schemes," in *Proceedings of the 14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '03)*, pp. 2054–2058, September 2003.

[22] H. W. Lee, S. S. Lee, J. O. Park, and K. C. Chae, "Analysis of the $M^X/G/1$ with N-policy and mutiple vacations," *Journal of Applied Probability*, vol. 31, pp. 476–496, 1994.

[23] K. C. Chae and H. W. Lee, "$M^X/G/1$ vacation models with N-policy: heuristic interpretation of the mean waiting time," *Journal of the Operational Research Society*, vol. 46, no. 2, pp. 258–264, 1995.

[24] T. Wang, A. Cano, G. B. Giannakis, and J. N. Laneman, "High-performance cooperative demodulation with decode-and-forward relays," *IEEE Transactions on Communications*, vol. 55, no. 7, pp. 1427–1438, 2007.

Journal of
Engineering

The Scientific
World Journal

International Journal of
Rotating
Machinery

Journal of
Sensors

International Journal of
Distributed
Sensor Networks

Advances in
Civil Engineering

Journal of
Control Science
and Engineering

Journal of
Robotics

Journal of
Electrical and Computer
Engineering

Advances in
OptoElectronics

VLSI Design

International Journal of
Navigation and
Observation

Modelling &
Simulation
in Engineering

International Journal of
Aerospace
Engineering

International Journal of
Chemical Engineering

International Journal of
Antennas and
Propagation

Active and Passive
Electronic Components

Shock and Vibration

Advances in
Acoustics and Vibration

Hindawi

Submit your manuscripts at
http://www.hindawi.com