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Research Article

Efficient Cross-Layer Optimization Algorithm for Data Transmission in Wireless Sensor Networks

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In this paper, we address the problems of joint design for channel selection, medium access control (MAC), signal input control, and power control with cooperative communication, which can achieve tradeoff between optimal signal control and power control in wireless sensor networks (WSNs). The problems are solved in two steps. Firstly, congestion control and link allocation are separately provided at transport layer and network layer, by supply and demand based on compressed sensing (CS). Secondly, we propose the cross-layer scheme to minimize the power cost of the whole network by a linear optimization problem. Channel selection and power control scheme, using the minimum power cost, are presented at MAC layer and physical layer, respectively. These functions interact through and are regulated by congestion rate so as to achieve a global optimality. Simulation results demonstrate the validity and high performance of the proposed algorithm.

1. Introduction

Wireless sensor networks find many applications in military areas detection, habitat monitoring, and so on. Performance degenerate analysis has gained much interest due to unbalanced power allocation in physical layer, excessive contention wireless channel in MAC layer, unfair link capacity allocation in network layer, and the inappropriate transport protocol in transport layer. WSNs suffer from several restrictions of the sink nodes and sensor nodes on account of the battery powered, computation complexity, communication, and storage capabilities [1–3].

MAC (medium access control), which is critical technology concerning net performance [4], is in charge of allocation wireless communication resources for contention nodes in protocol stack.

Scheduling effectively achieves resource allocation for wireless communication. To reach a satisfying scheduling scheme, scheduling cost, and scheduling objective regularly compromised, the scheduling problem is transferred to multiobjective optimization. Recently, scholars integrated scheduling and power control for better performance and obtained certain achievements [5, 6].

Reference [7] provided an in-depth analysis on the CS-based medium access control schemes and revealed the impact of communication signal-to-noise ratio on the reconstruction performance. Authors showed the process of the sensor data converted to the modulated symbols for transmission and how the modulated symbols are recovered via compressed sensing. Reference [8] studied the optimal flow control by a multiobjective linear programming problem, which achieved the optimization between utility and lifetime in WSNs. Reference [9] jointly designed rate control, scheduling, and power control with stochastic optimization problems to achieve cross-layer optimization protocol designing. Reference [10] investigated optimal power control, rate adaptation, and scheduling for an ultrawideband-based Intravehicular Wireless Sensor Network for one-electronic-control-unit (ECU) and multiple-ECU cases. These methods are widely applied into many-to-one data transmission control protocols and solved the problems in every aspect [11–14]. However, the above algorithms did not give a comprehensive analytic process for considering energy consumption, channel selection, link capacity, and congestion control to ensure better performance.

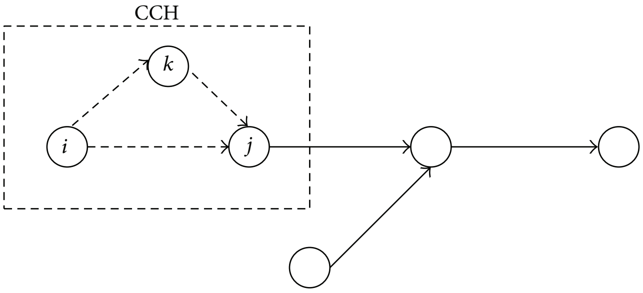

Figure 1: Multihop routing cooperative communication model.

In this paper, cross-layer optimal design is presented, which considers the influence for congestion rate at physical layer, MAC layer, network layer, and transport layer to achieve minimum power cost in WSNs. The algorithm coordinates communication protocols by congestion rate in the several layers to solve lossy wireless channel, excessive contention and unfair access, disabled bandwidth allocation, and the fundamentally inappropriate mechanisms of TCP. First, we design a packet error rate control strategy based on congestion rate, which makes the packet error rate in the domain of validity. The power is exactly allocated on the basis of "to each according to his needs." Second, the optimal schemes of control input and link capacity with compressed sensing are discussed. Third, we construct minimum energy problem with power control function, congestion control function, link allocation function, and so on. The optimum solutions are the optimal power control and channel selection.

2. Network and Node Model

For energy efficiency purpose, the transmission power at every node is assumed to be adjustable resulting in congestion price: when the congestion rate is bigger, the power should be increased for data transmitted successfully; when the congestion rate is smaller, the power is only satisfied for data transmitted regularly. We assume that the sensor network consists of N nodes, of which the sink node is defined as node #N.

Communication from node i to node j contains directed communication hop (DCH) $i \rightarrow j$ [15] and cooperative communication hop (CCH) $i \rightarrow k \rightarrow j$, as shown in Figure 1. CCH consists of a sender, a relay, and a receiver (i, k, j in Figure 1, resp.), such that both direct and relayed copies of the information transmitted by the sender are received at the receiver.

3. Cross-Layer Optimization Design of Cooperative Communication

In the wireline networks, the protocols hold rigorous constraint at each layer, which is only responsible for oneself, not being infiltrated. Physical layer is mostly in charge of power allocation; channel selection is achieved in MAC layer; flow control is implemented in transport layer; network layer is usually responsible for scheduling design. However, the requirement like this does not occur in WSNs. Cooperative communication is applied for protocols at each layer to make net performance better.

3.1. Power Control. Define packet error rate with white Gaussian noise [15] as follows:

$$\Omega_{ik,\mathrm{DC}} = 1 - \left(1 - \frac{1}{2} e^{-\gamma_{ik}/2}\right)^{L}, \tag{1}$$

where $\gamma_{ik} = (P_{\mathrm{tx,tot},i} g_{ik}/P_n) \times (B_n/R)$ is energy per bit to noise power spectral density ratio, $P_{\mathrm{tx,tot},i}$ is the aggregated power for transmitting a packet at i, B_n is the noise bandwidth, g_{ik} is the path loss of link (i, k) in linear units, P_n is the average noise power, R is the maximum link data rate in bits per second, bits/s, and L is the length of the packet. The power consumption of a packet transmitted successfully is $P_{\mathrm{tx,tot},i} = (1 + p_i) P_{\mathrm{tx},i}$ if congestion occurs in the WSNs, $P_{\mathrm{tx},i}$ denotes transmitted power to a packet at ideal condition (congestion does not occur), and p_i is the congestion rate at node i; the average noise power $P_n = (1 + p_i)\overline{P}_n$, where $\overline{P}_n$ is the average noise power at ideal condition; the maximum link data rate $R = (1 + p_i)\overline{R}$, where $\overline{R}$ is the maximum link data rate at ideal condition. Thus,

$$\gamma_{ik} = \frac{(1 + p_i) P_{\mathrm{tx},i} g_{ik}}{(1 + p_i) \overline{P}_n} \frac{B_n}{(1 + p_i) \overline{R}} = \frac{P_{\mathrm{tx},i} g_{ik}}{(1 + p_i) \overline{P}_n} \frac{B_n}{\overline{R}}. \tag{2}$$

We can conclude that γ_{ik} is adjusted to be smaller, and $\Omega_{ik,\mathrm{DC}}$ is bigger when congestion rate is increased from formula (2). The power, appropriately adjusted by congestion rate, makes the packet error rate constraint the domain of validity. The power is exactly allocated on the basis of "to each according to his needs," which can extensively highlight power efficiency.

3.2. Congestion Control. Recently, lots of researchers have addressed the signal function with cross-layer optimal design to achieve better performance due to the characteristic of higher communication consumption and lower data process consumption in WSNs [16–18]. However, almost all congestion control algorithms did not consider the data preprocessing before being transmitted [19]. In this section, we try to reduce the number of transmissions with a Toeplitz matrix in compressed sensing that enables the number of transmissions to be extensively decreased in WSNs. The transmission of compressed signal is not only relieving the congestion in data process overabundance but also economizing energy in the transmission. Compressed sensing model is expressed as follows:

$$y(t) = \Phi x_i(t) + \varepsilon, \tag{3}$$

where $x_i(t) \in \mathfrak{R}^{n \times 1}$ is input signal, $y(t) \in \mathfrak{R}^{m \times 1}$ is measurement vector, $\Phi \in \mathfrak{R}^{m \times n}$ is sensing matrix, $m \ll n$, and $\varepsilon \in \mathfrak{R}^{m \times 1}$ is unknown vector for measurement noise. Suppose that the input signal is sparse, and sensing matrix satisfies restricted isometry property (RIP) [20]. To speed up congestion control, we select Toeplitz matrix as sensing matrix, meeting $\|\Phi\|_2 \leq 1$.

The scheduling algorithm and signal control scheme are the same in each link or at each node. In this paper, only consider the scheduling in (i, k) and signal control at i. The linear function $A(f_{ik})$ of the link capacity f_{ik} in (i, k) denotes the service capacity, and the service requirement at node i by a linear function $H(x_i(t), x_i)$ of the control input signal $x_i(t)$ and original signal x_i indicates the service requirement. Consider

$$Z\left(f_{ik}, x_i(t), x_i\right) = \left(1 - p_i\right) A\left(f_{ik}\right) - H\left(x_i(t), x_i\right). \tag{4}$$

Formula (4) represents supply and demand function of the service. The valid service capacity achieves optimality if and only if it is exactly satisfied with service requirement. Otherwise, it will bring unnecessary energy consumption:

$$x_i(t) = \arg\min_{x} Z\left(f_{ik}, x_i(t), x_i\right) + p_i \begin{pmatrix} \varepsilon \\ 0 \end{pmatrix}. \tag{5}$$

The most desired input feedback signal is $\arg\min_x Z(f_{ik}, x_i(t), x_i)$. Considering congestion in the WSNs, however, input signal should reach to expression in (5).

3.3. Scheduling Algorithm. The adjustment of the transmitted power in Section 3.1, being changed in the transmission range and the connectivity of the node, causes the changes in the requirement of the link capacity. In Section 3.2, the input signal satisfying supply and demand function minimum is generated. On this basis, we will discuss the link capacity allocation in the link (i, k) in this section. From analysis, the network optimal condition is that supply and demand function attains minimum. When function (4) is the actual minimum, the link capacity f_{ik} is the optimal link capacity. In this scheduling, on the one hand, unnecessary energy consumption with link capacity too big is effectively avoided; on the other hand, the new congestion with link capacity too small is suppressed. Thus, f_{ik} can be denoted as follows:

$$f_{ik} \in \arg\min Z\left(f_{ik}, x_i(t), x_i\right). \tag{6}$$

3.4. Channel Selection. Power control is applied to dynamically adjust transmission power, which can not only effectively reduce energy consumption in communication, but also prolong network lifetime in WSNs. In addition, power control could remarkably influence the topology control, connectivity, throughput, and real-time of message transmission. Moreover, MAC layer or cross-layer design with power control evidently optimizes network performance and highlights QoS. In this section, we will discuss how to select channel by cutting down unnecessary energy consumption [21]. Energy is mainly expended at communications, and computation brings the energy to be neglected. For a CCH with relay node k, power consumption chiefly includes three parts: the first part is transmission power of a packet sent at node i;

$$C_{S,k,ij} = P_{\mathrm{tx},i,\mathrm{tot}}; \tag{7}$$

the second part indicates that, for relay node k, the power aggregate to receive a packet from node i and successfully transmit a packet to node j is

$$C_{R,k,ij} = P_{\mathrm{rx},k,\mathrm{cir}} + \left(1 - \Omega_{ik,\mathrm{DC}}\right) P_{\mathrm{tx},i,\mathrm{tot}}. \tag{8}$$

The third part indicates that, for node j, the power aggregate to receive a packet from node i and node k is

$$C_{D,k,ij} = P_{\mathrm{rx},j,\mathrm{cir}} + \left(1 - \Omega_{ik,\mathrm{cir}}\right) P_{\mathrm{rx},j,\mathrm{cir}}. \tag{9}$$

Suppose that $P_{\mathrm{rx},k}$ is the required power for receiving a packet for node k at ideal condition. Congestion should be considered for data valid transmission. To achieve energy optimization, let

$$\begin{aligned} C_{S,k,ij} &= P_{\mathrm{tx},i,\mathrm{tot}} = \left(1 + p_i\right) P_{\mathrm{tx},i} \\ C_{R,k,ij} &= P_{\mathrm{rx},k,\mathrm{cir}} + \left(1 - \Omega_{ik,\mathrm{DC}}\right) P_{\mathrm{tx},\mathrm{tot},k} \\ &= \left(1 + p_k\right) P_{\mathrm{rx},k} + \left(1 - \Omega_{ik,\mathrm{DC}}\right)\left(1 + p_k\right) P_{\mathrm{tx},k} \\ C_{D,ij,k} &= P_{\mathrm{rx},j,\mathrm{cir}} + \left(1 - \Omega_{ik,\mathrm{DC}}\right) P_{\mathrm{rx},j,\mathrm{cir}} \\ &= \left(1 + p_j\right) P_{\mathrm{rx},j} \\ &\quad + \left(1 - \Omega_{ik,\mathrm{DC}}\right)\left(1 - \Omega_{kj,\mathrm{DC}}\right)\left(1 + p_j\right) P_{\mathrm{rx},j}. \end{aligned} \tag{10}$$

From formula (10), the power aggregate is as follows:

$$\begin{aligned} C_{ij,k} &= C_{S,k,ij} + C_{R,k,ij} + C_{D,k,ij} \\ &= \left(1 + p_i\right) P_{\mathrm{tx},i} + \left(1 + p_k\right) P_{\mathrm{rx},k} \\ &\quad + \left(1 - \Omega_{ik,\mathrm{DC}}\right)\left(1 + p_k\right) P_{\mathrm{tx},k} + \left(1 + p_j\right) E_{\mathrm{rx},j} \\ &\quad + \left(1 - \Omega_{ik,\mathrm{DC}}\right)\left(1 - \Omega_{kj,\mathrm{DC}}\right)\left(1 + p_j\right) E_{\mathrm{rx},j}. \end{aligned} \tag{11}$$

The energy for the packet transmitted or sent is considered equal at each node (not considering congestion); thus (11) becomes

$$\begin{aligned} C_{ij,k} &= C_{S,k,ij} + C_{R,k,ij} + C_{D,k,ij} \\ &= \left(1 + p_i\right) P_T + \left(1 + p_k\right)\left(P_R + \left(1 - \Omega_{ik,\mathrm{DC}}\right) P_T\right) \\ &\quad + \left[\left(1 - \Omega_{ik,\mathrm{DC}}\right)\left(1 - \Omega_{kj,\mathrm{DC}}\right) + 1\right]\left(1 + p_j\right) P_R. \end{aligned} \tag{12}$$

Suppose that the desired packet error ratio at hop is Ω_{obj} and power allocation constraint packet error ratio at hop can be denoted:

$$\begin{aligned} \min \quad & \left\{C_{ij,k},\ \forall k \in [2, N],\ k \neq i, j\right\} \\ \text{s.t.} \quad & \max\left(\Omega_{ik,\mathrm{DC}}, \Omega_{kj,\mathrm{DC}}\right) \leq \Omega_{\mathrm{obj}} \\ & \left(1 - p_u\right) A\left(f_{uv}\right) - H\left(x_u(t), x_u\right) \geq 0 \\ & 0 \leq p_u \leq 1 \\ & x_u(t) = \arg\min_{x} Z\left(f_{uv}, x_u(t), x_u\right) + p_u \begin{pmatrix} \varepsilon \\ 0 \end{pmatrix} \\ & f_{ik} = f_{uv} \in \arg\min_{f} Z\left(f_{uv}, x_u(t), x_u\right) \\ & p_u(t + 1) \\ & \quad = p_u(t) + \gamma_t\left(H\left(x_u(t), x_u\right) - A\left(f_{uv}\right)\right). \end{aligned} \tag{13}$$

Node k making (13) optimal is the optimal occupied node.

3.5. Algorithm Design

Algorithm 1.

```
Step 1. Initialization
    Step 1.1. Initialize original signal $x_0 \in R^{n\times 1}$, and select appropriate $\Phi \in R^{m\times n}$, $m \ll n$, calculate $L$;
    Step 1.2. Given $g_{ik}$, $B_n$, $\overline{p}_n$, $\overline{R}$.
Step 2. Given the original $p_u(0)$ and the expression of $H(x_u(t), x_u)$, $A(f_{uv})$,
    Step 2.1. $\forall t \in [0, N]$, calculate $p_u(t)$, $x_u(t)$ and $f_{uv}$;
    Step 2.2. Given $\Omega_{\text{obj}}$,
    If $(1 - p_u)A(f_{uv}) - H(x_u(t), x_u) \geq 0$
        Then calculate $\Omega_{ik,\text{DC}}$, $\Omega_{kj,\text{DC}}$;
    Else go to Step 1.
Step 3
For $f_{uv} \in \arg\min_f Z(f_{uv}, x_u(t), x_u)$
If $0 \leq p_u(t) \leq 1$, $\max(\Omega_{ik,\text{DC}}, \Omega_{kj,\text{DC}}) \leq \Omega_{\text{obj}}$
    Then calculate $C_{ij,k}$;
Else if $0 \leq p_u(t) \leq 1$, $\max(\Omega_{ik,\text{DC}}, \Omega_{kj,\text{DC}}) > \Omega_{\text{obj}}$
    Then go to Step 2.2;
    Else if $p_u(t) > 1$
        Then go to Step 2.1;
        End
      End
  End
  End For.
```

The performance analysis of the algorithm is presented and proves its validity.

Theorem 2. *If $x_u(t) \in \mathfrak{R}^{n\times 1}$ is sparse signal satisfying formula (5), measurement vector with noise is expressed to $y_u(t) = \Phi x_u(t) + \varepsilon$, where the optimal vector is y_u^* constrained by $\|y_u^* - y_u(t)\| \leq \delta_u$. Let sensing matrix $\Phi \in \mathfrak{R}^{m\times n}$ obey restricted isometry property (RIP); then*

$$\left\|x_u(t) - x_u^*\right\|_2 \leq \frac{p_u \delta_u}{1 - p_u \left\|\Phi\right\|_2}, \tag{14}$$

where x_u^* is the optimal value of $x_u(t)$.

Proof. By formula (5), we have

$$\begin{aligned}
\left\|x_u(t) - x^*\right\|_2 = \Bigg\| & \arg\min_x Z(f_{uv}, x_u(t), x_u) \\
& - \arg\min_x Z(f_{uv}, x_u^*, x_u) \\
& + p_u \begin{pmatrix} y - \Phi x_u(t) - (y^* - \Phi x_u^*) \\ 0 \end{pmatrix} \Bigg\|_2
\end{aligned} \tag{15}$$

$$\begin{aligned}
\leq \Big\| & \arg\min_x Z(f_{uv}, x_u(t), x_u) \\
& - \arg\min_x Z(f_{uv}, x_u^*, x_u) \Big\|_2 \\
& + \left\| p_u \begin{pmatrix} y - \Phi x_u(t) - (y^* - \Phi x_u^*) \\ 0 \end{pmatrix} \right\|_2
\end{aligned} \tag{16}$$

$$\begin{aligned}
\leq \Big\| & \arg\min_x Z(f_{uv}, x_u(t), x_u) \\
& - \arg\min_x Z(f_{uv}, x_u^*, x_u) \Big\|_2 + p_u \left\|y - y^*\right\|_2 \\
& + p_u \left\|\Phi x_u(t) - \Phi x_u^*\right\|_2 .
\end{aligned} \tag{17}$$

The optimal value x_u^* is the minimum value of $x_u(t)$; formula (17) is transformed into

$$\begin{aligned}
\Big\| & \arg\min_x Z(f_{uv}, x_u(t), x_u) \\
& - \arg\min_x Z(f_{uv}, x_u^*, x_u) \Big\|_2 = 0.
\end{aligned} \tag{18}$$

Thus, formula (17) becomes

$$\begin{aligned}
& = p_u \left\|y - y^*\right\|_2 + p_u \left\|\Phi x_u(t) - \Phi x_u^*(t)\right\|_2 \\
& \leq p_u \left\|y - y^*\right\|_2 + p_u \left\|\Phi\right\|_2 \left\|x_u(t) - x_u^*(t)\right\|_2 .
\end{aligned} \tag{19}$$

Therefore formula (15) becomes

$$\begin{aligned}
\left\|x_u(t) - x^*\right\|_2 & \leq \frac{p_u}{1 - p_u \left\|\Phi\right\|_2} \left\|y - y^*\right\|_2 \\
& \leq \frac{p_u \delta_u}{1 - p_u \left\|\Phi\right\|_2}.
\end{aligned} \tag{20}$$

Thus, algorithm (5) converges statistically to within a small neighborhood of the optimal values x^*.

Since p_u is continuous, Theorem 2 implies that the input signal approaches the optimal x^* when δ_u is small enough. □

4. Simulation Analysis

In this section, we exhibit numerical examples and simulation results for the proposed algorithm (cross-layer optimal design, CLOD). We conduct numerical experiments using NS2 to confirm the efficiency of the proposed algorithm. We also perform simulations using Lee and Lim [3] and DCH to validate our assumptions. In our numerical examples, we set

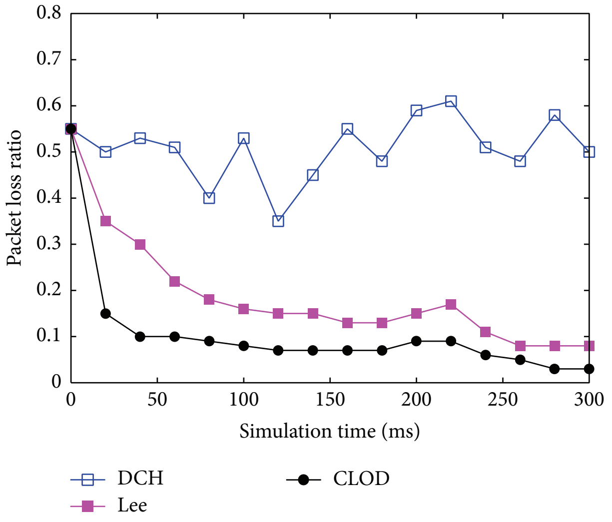

Figure 2: Comparison of dropped packet.

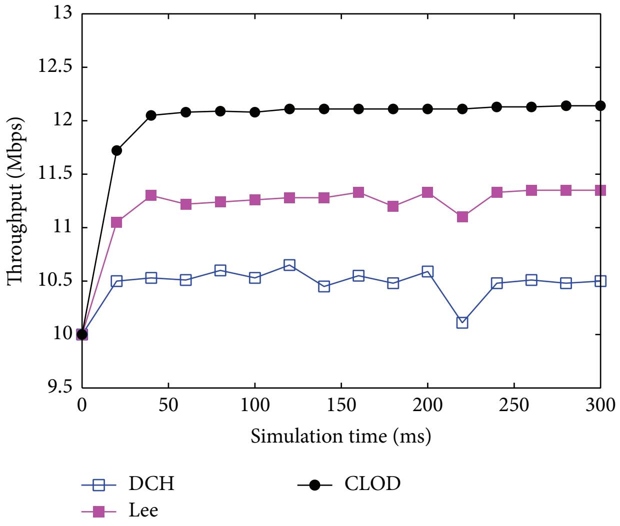

Figure 3: Comparison of throughput.

a net topology with 100 nodes placed randomly in a 10 × 10 field, where the distance of neighboring nodes is set to 20 m. The buffers are 10–100 packets. Packet size is 1024 bits, and simulation time is 300 ms.

Figure 2 indicates that the dropped packets of the Lee algorithm and CLOD algorithm are relatively lower. This illustrates that the algorithms could relieve congestion at a certain extent. However, there are some differences in the algorithms: CLOD dropped packet is the lowest when node-level congestion and link-level congestion are simultaneously existing. This verifies that the algorithm achieves better network control by signal compressed and channel selection; the dropped packet is lower in CLOD algorithm than Lee algorithm, which is owing to only dispose node-level congestion and ignore link-level congestion in Lee algorithm; DCH makes the congestion stay at the top because the coping mechanism for congestion is weak.

Figure 3 shows that CLOD makes transmitted packet remarkably increase per second for signal compressed and channel selection strategy. The other algorithms cannot achieve so high throughput for required transmitted data too large resulting in congestion. In addition, the Lee algorithm and DCH algorithm show incapability of channel contention triggered congestion.

Figure 4 displays comparison with energy in three algorithms. From Figure 4, it can be observed that the best results of CLOD can reach the lowest energy consumption. Such a phenomenon implies that compressed data makes the transmission traffic drastically decrease, which can effectively reduce energy consumption, and distinctly relieve node-level congestion. Channel selection makes certain positive contribution to save energy, and link capacity allocation can be used to take full advantage of limited energy. The others are to be considerably inferior to CLOD in this problem.

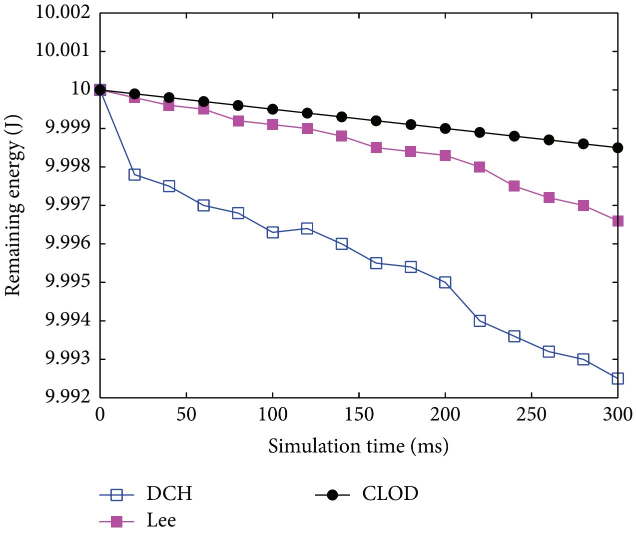

Figure 4: Comparison of remaining energy.

5. Conclusions

In this paper, we propose a cross-layer optimal protocol by integrating using "cross-layer design," "optimal theory," and "compressed sensing" to achieve higher throughput and power efficiency. In the power control protocol, by adjusting congestion rate to the reduction of power, we could attain lower power consumption than the former algorithms. In the proposed input signal control algorithm, the signal size is adjusted to stable state. Link capacity allocation is presented by supply and demand function of the service. Channel is selected by energy minimum optimal. Through the analysis, accuracy of signal transmission is guaranteed, although signal is to be lossy compression. In addition, simulation results show that the proposed algorithm offers better performance in terms of throughput and power consumption compared with the other protocols.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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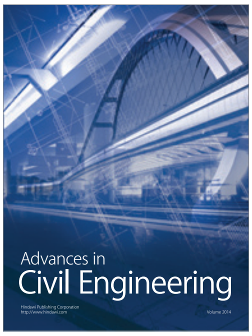
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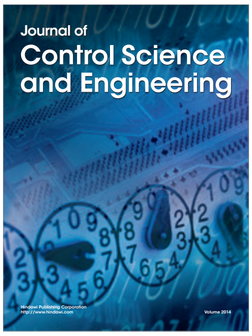
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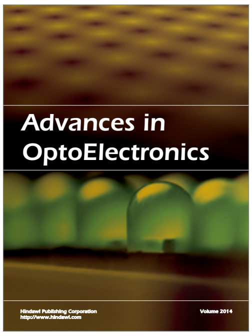
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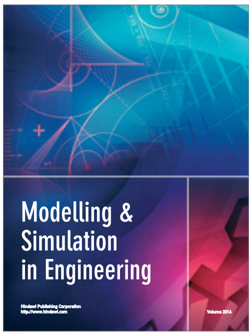
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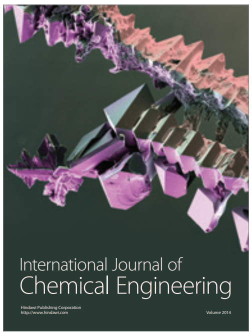
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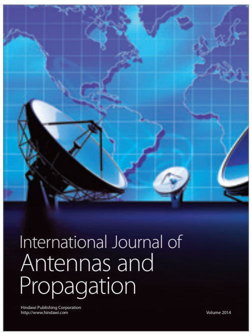
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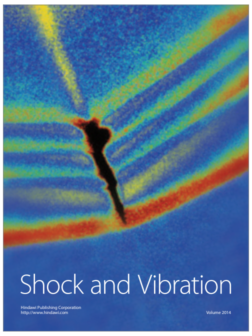
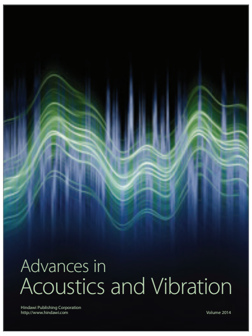

Shock and Vibration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