Cooperative Transmissions in Wireless Sensor Networks with Imperfect Synchronization

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***Abstract*–STBC-encoded cooperative transmission is studied in a typical wireless sensor network communication protocol LEACH (Low-Energy Adaptive Clustering Hierarchy). The effect of imperfect synchronization among cooperative sensors is studied and a new STBC encoding scheme is proposed when asynchronism becomes significant. Cooperation overhead and energy efficiency are analyzed. The analysis and simulation results demonstrate that cooperative transmission is promising in wireless sensor networks in spite of the increased cost of synchronization and circuitry energy consumption.**

I. INTRODUCTION

In wireless sensor networks, energy efficiency is a dominating design criterion. It is especially important to improve the energy efficiency of wireless transceivers because they usually consume a major portion of battery energy.

Due to the fading phenomena of wireless communications, space-time coding and processing are helpful for enhancing transmission energy efficiency if antenna arrays are available. In particular, space-time block codes (STBC) have attracted great attention because of their affordable linear complexity [1]. For mobile users where antenna arrays are not available, STBC may be used with cooperative transmission schemes [2]-[5].

However, the extreme energy efficiency requirement of wireless sensor networks makes the application of cooperative transmission a challenging task. First, although cooperative diversity can enhance *transmission* energy efficiency, the involvement of more than one transmitting sensors increases energy consumption in *electronic circuitry* [5]. Second, there is certain overhead of cooperation or handshaking among the sensors necessary for them to schedule joint transmissions. Such overhead surely brings extra energy consumption. Finally, it is not an easy task to synchronize distributed transmitters, i.e., to make them identical in carrier frequency, carrier phase, symbol timing and timing phase. Without perfect synchronization, direct application of STBC may become a problem [4].

It is well known that diversity brings in transmission energy efficiency. However, although there have been extensive researches addressing the diversity benefits of cooperative transmissions [2], [3], the synchronization and the associated overhead are still open problems. As a matter of fact, idealized synchronization among the cooperative transmitters is usually assumed.

In order to resolve these problems, we consider incorporating cooperative transmissions into a typical communication protocol named *low-energy adaptive clustering hierarchy* (LEACH) [6] and analyze the associated cooperation overhead, synchronization, and energy efficiency. Moreover, we propose a new distributed STBC-encoded transmission scheme for imperfect synchronization among the transmitters.

This paper is organized as follows. The cooperative transmission protocol used in LEACH is introduced in Section II. Then the synchronization problem is addressed in Section III and a new STBC encoding scheme is proposed in Section IV. In Section V, energy efficiency is analyzed. Simulations are in Section VI. Conclusions are in Section VII.

II. LEACH WITH COOPERATIVE TRANSMISSION

We consider a wireless sensor network where sensors need to transmit their data to a remote data collector. LEACH is an interesting networking/communication protocol for sensors to form hierarchical clusters and to schedule TDMA channel access. The operation of LEACH is broken up into rounds, and each round consists of four phases: advertisement, cluster setup, transmission scheduling, and data transmission. In the following, while briefly explaining the four phases, we describe ways to incorporate cooperative transmission and emphasize the associated overhead. For simplification, we consider one hierarchical layer only as in [6].

Advertisement. In this phase, each sensor determines by itself whether it becomes a cluster head during this round. Each self-selected cluster head then broadcasts an advertisement message. We do not need to make any special changes in this phase for cooperative transmission, though we rename the cluster head as *primary head*.

Cluster setup. In this phase, each sensor transmits a cluster-joining packet to its desirable primary head. For *J*-sensor cooperative transmission, besides the primary head, we need to choose *J*-1 secondary heads in each cluster. In our scheme, they will be selected by the primary head in the next phase. Meanwhile, when a sensor transmits cluster-joining packet, it should piggyback information about its capability of being a secondary head, e.g., its current energy status. The overhead of this procedure can be as small as just transmitting one extra byte along with the relatively long cluster-joining packet.

Schedule creation. This phase is for each primary head to create TDMA channel access schedule, and to inform each sensor the assigned slot. For cooperative transmission, each primary head first selects the secondary heads based on both the reported energy status E_j and the estimated distance d_j of the sensors in the cluster. Since the distances between the primary head and the secondary heads should be both small for transmission efficiency and large enough for sufficient diversity, we ask the primary head to recursively select $J-1$ secondary heads by

$$\min_{\forall \text{rest node } j} \frac{d_j}{E_j}, \ \ s.t., d_{\min} \le d_j \le d_{\max} , \qquad (1)$$

where the threshold $d_{\min}$ is determined by the carrier wavelength, and $d_{\max}$ is determined by the synchronization requirement as will be discussed in Section III or by the size of the current cluster when the new STBC scheme discussed in Section IV is used. In order to control the minimum distance among the secondary heads, the primary head may avoid choosing sensors with similar d_j.

Then the primary head informs the selected secondary heads about their roles in cooperative transmission, which can be implemented by piggybacking one extra byte in the original scheduling packet. The overhead includes the calculation of (1) in the primary head, and one byte more transmission to each of the J-1 secondary heads. Such overhead is still negligibly small.

Data transmission. In this phase, each cluster head receives data packets from the other sensors in the cluster, fuses these packets, and transmit the fusion result to the data collector. In cooperative transmission mode, it is still the primary head that receives and fuses data packets. However, after that, the primary head first broadcasts the fused data to the secondary heads, and all J heads then transmit the data to the data collector cooperatively in the following slots according to the new STBC scheme proposed in Section IV. This procedure is illustrated in Fig. 1. The overhead in this phase, which is the major one for the proposed scheme, includes the broadcasting procedure and the added electronic energy consumption. The impact of such overhead on energy efficiency will be analyzed in Section V.

III. Synchronization among Cooperative Sensors

In LEACH with cooperative transmission, the distances from the transmitting sensors to the data collector are different and unknown. Among the signals transmitted by the cooperating sensors, the relative delays when they arrive at the data collector are within [-2$d_{\max}$/c, 2$d_{\max}$/c], where c is the speed of light. Note that other delays are also possible but are not considered, such as those of processing circuitry.

Let the passband signal transmitted from a head sensor j be $\mathrm{Re}[\sqrt{\rho}\sum_{n=-\infty}^{\infty} b_j(n)p(t-nT)e^{j2\pi f_c t}]$, where Re[.] stands for real part, ρ is a transmission power adjustor, $b_j(n)$ is the complex symbol at symbol interval [nT, $(n+1)T$), $p(t)$ is the

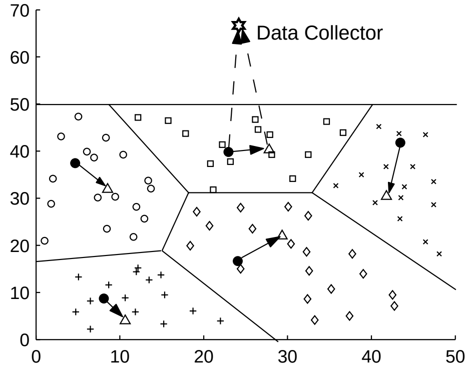

Fig. 1. Illustration of LEACH with cooperative transmission for wireless sensor networks. •: primary heads. Δ: secondary heads.

baseband pulse shaping filter, and f_c is the carrier frequency. The received passband signal at the data collector is

$$x_p(t) = \mathrm{Re}[\sqrt{\rho}\sum_{j=1}^{J}\sum_{\ell=0}^{L_r}\alpha_{j\ell}\sum_{n=-\infty}^{\infty} b_j(n)p(t-nT-\tau_j)e^{j(2\pi f_c t-\theta_j)} + v_p(t)] , \qquad (2)$$

where $\alpha_{j\ell}$ are gains of the multipath channel and $v_p(t)$ is passband noise.

Because signals from head sensors may have different τ_j and θ_j, it is impossible to achieve synchronization in carrier phase and timing phase. Therefore, without loss of generality, we demodulate (2) with local carrier $e^{-j2\pi f_c t}$ and then perform sampling at time instants $t_n=nT+\tau$ (for arbitrary τ). The baseband samples are

$$x(n) = \sqrt{\rho}\sum_{j=1}^{J}\sum_{\ell=0}^{L_r}\alpha_{j\ell}e^{-j\theta_j}[b_j(n)p(\tau-\tau_j) + \sum_{m\ne n} b_j(m)p((n-m)T+\tau-\tau_j)] + v(n) , \quad (3)$$

where $v(n)$ is baseband noise. Obviously, residual inter-symbol interference (ISI) may present. However, ISI could be negligible if we make $d_{\max}$ small enough and if the propagation is flat fading. In the following section, we consider the more general ISI channels due to both frequency selective fading and asynchronism.

IV. Distributed STBC

Though ISI may be reduced in flat fading by limiting the distances among the transmitting heads, in order to take the advantage of macro-diversity, we may need to extend such distances. In this case, synchronization among the transmitting sensors in terms of carrier phase and timing phase are difficult to be achieved. Considering together frequency selective fading, signals transmitted from the transmitting sensors are no longer synchronized and then channels become dispersive, which makes traditional STBC not directly applicable. Therefore, in this section, we develop a new distributed STBC cooperative transmission scheme that tolerates both the delay asynchronism and dispersive channels.

Node j: for all j	node 1: node 2:	…….	node i: node j:	…….	node J-1: node J:
Frame 0	Frame 1	…….	Frame $p_{i,j}$	…….	Frame P

Fig.2. Space-time encoded transmission scheme, where a packet is divided into J blocks and is cooperatively transmitted by J nodes during P+1 time frames.

Consider the case that J sensors need to transmit a data packet $\{b(n)\}$. Instead of transmitting it directly, each sensor subdivides it into J blocks which we denote as $\{b_j(n): n=0,\cdots,N\}$, where $j=1,\cdots, J$. In other words, the data packet $\{b(n)\}$ has length $J(N+1)$ and is subdivided into J equal length blocks. Note that all sensors do the identical subdivision.

Let the baseband channel from the transmitting sensor j to the data collector be $[h_j(0),\ldots,h_j(L)]$, where for notational simplicity, all channel lengths are L. Because of the requirement of packet-wise encoding as discussed in the sequel, we assume that channels are time-invariant during the transmission of a packet, but may change randomly between packets.

Let the noiseless received signal from the sensor j by the data collector is $\sqrt{\rho}\sum_{\ell=0}^{L} h_j(\ell) b_j(n-\ell-\Delta_j)$, where the parameter Δ_j denotes the relative asynchronous delay. If we assume that the coarse slot synchronization is still available, the delays are bounded, i.e., $0\le\Delta_j\le D$, where D is the upper bound of the delays. Note that Δ_j is an integer since fractional delays are contributed to channel dispersion.

The J sensors then perform cooperative transmission as shown in Fig. 2. The entire packet (J blocks) is to be transmitted in P+1 time frames where

$$P+1=\frac{J(J-1)}{2}+1. \qquad (4)$$

During the first time frame (Frame 0), all the sensors participate in transmission, where the sensor j transmits the symbol sequence $\{b_j(0),\cdots,b_j(N)\}$, $1\le j\le J$. Then, in each of the subsequent time frames, there are only two sensors participating in transmission. In Frame 1, the sensor 1 transmits the sequence $\{-b_2^*(N),\cdots,-b_2^*(0)\}$, where $(\cdot)^*$ denotes complex conjugation, whereas the sensor 2 transmits the sequence $\{b_1^*(N),\cdots,b_1^*(0)\}$. In general, we apply the following rule to determine the transmitting sensors and orders: in Frame $p_{i,j}$ where

$$p_{i,j}=\frac{(i-1)(2J-i)}{2}+j-i, 1\le i\le J-1, i+1\le j\le J\,, \qquad (5)$$

the sensors i and j transmit the sequences $\{-b_j^*(N),\cdots,-b_j^*(0)\}$ and $\{b_i^*(N),\cdots,b_i^*(0)\}$, respectively.

The received baseband signal in Frame 0 is

$$x_0(n)=\sqrt{\rho}\sum_{j=1}^{J}\sum_{\ell=0}^{L} h_j(\ell) b_j(n-\ell-\Delta_j)+v_0(n), \qquad (6)$$

where the noise $v_0(n)$ is assumed to be AWGN, and $b_j(n)$=0 for n<0 or n>N. Note that because Δ_j and L are bounded, we can select the block length N appropriately to avoid inter-frame interference. Stack samples into L+1 dimensional vectors $\mathbf{x}_0(n)=[x_0(n),\cdots,x_0(n-L)]^T$, where $(\cdot)^T$ denotes transposition. Define symbol vectors $\mathbf{b}_j(n)=[b_j(n),\cdots,b_j(n-2L)]^T$ and noise vectors $\mathbf{v}_0(n)=[v_0(n),\cdots,\ v_0(n-L)]^T$. From (6) we obtain

$$\mathbf{x}_0(n)=\sqrt{\rho}\sum_{j=1}^{J} H_j \mathbf{b}_j(n-\Delta_j)+\mathbf{v}_0(n)\,, \qquad (7)$$

where the channel matrices are

$$H_j=\begin{bmatrix} h_j(0) & \cdots & h_j(L) & & \\ & \ddots & & \ddots & \\ & & h_j(0) & \cdots & h_j(L)\end{bmatrix}. \qquad (8)$$

In each of the subsequent frames $p_{i,j}\in[1,\ P]$ where $1\le i\le J-1$ and $i+1\le j\le J$, the received signal is

$$x_{p_{i,j}}(n)=\sqrt{\rho}\sum_{\ell=0}^{L} h_i(\ell)[-b_j^*(N-n+\Delta_i+\ell)]$$

$$+\sqrt{\rho}\sum_{\ell=0}^{L} h_j(\ell) b_i^*(N-n+\Delta_j+\ell)+v_{p_{i,j}}(n). \qquad (9)$$

Similarly we construct sample vectors $\mathbf{x}_{p_{i,j}}(n)=[x_{p_{i,j}}(N-n+\Delta_i+\Delta_j+L),\cdots,x_{p_{i,j}}(N-n+\Delta_i+\Delta_j+2L)]^H$, where $(\cdot)^H$ denotes conjugate transpose. Then from (9) we have $\mathbf{x}_{p_{i,j}}(n)=\sqrt{\rho}\tilde{H}_j\mathbf{b}_i(n-\Delta_i)-\sqrt{\rho}\tilde{H}_i\mathbf{b}_j(n-\Delta_j)+\mathbf{v}_{p_{i,j}}(n)$, where

$$\tilde{H}_j=\begin{bmatrix} h_j^*(L) & \cdots & h_j^*(0) & & \\ & \ddots & & \ddots & \\ & & h_j^*(L) & \cdots & h_j^*(0)\end{bmatrix}. \qquad (10)$$

We use a linear combiner at the data collector to add the received sample vectors in all frames together

$$y_j(n)=\tilde{\mathbf{h}}_j^T\mathbf{x}_0(n)-\sum_{i=1}^{j-1}\mathbf{h}_i^T\mathbf{x}_{p_{i,j}}(n)+\sum_{k=j+1}^{J}\mathbf{h}_k^T\mathbf{x}_{p_{j,k}}(n),$$

$$j=1,\cdots,J\,, \qquad (11)$$

where $\mathbf{h}_j=[h_j(0),\cdots,h_j(L)]^T$ and $\tilde{\mathbf{h}}_j=[h_j^*(L),\cdots,h_j^*(0)]^T$.

Proposition. The combiner (11) gives

$$y_j(n)=\mathbf{g}^T\mathbf{b}_j(n-\Delta_j)+w_j(n),\quad j=1,\cdots,J\,, \qquad (12)$$

where $\mathbf{g}^T=\sqrt{\rho}\sum_{j=1}^{J}\tilde{\mathbf{h}}_j^T H_j$, and the noise $w_j(n)=\tilde{\mathbf{h}}_j^T\mathbf{v}_0(n)-\sum_{i=1}^{j-1}\mathbf{h}_i^T\mathbf{v}_{p_{i,j}}(n)+\sum_{k=j+1}^{J}\mathbf{h}_k^T\mathbf{v}_{p_{j,k}}(n)$.

Proof: see [4].

From (12), the output of the combiner preserves diversity $J(L+1)$. Hence full diversity can be achieved if the optimal maximum likelihood detection is applied on (12) to detect symbols. On the other hand, linear MMSE equalizers can be used for reduced complexity.

The bandwidth efficiency of this scheme is determined by *J* (the number of cooperative sensors) and the overhead required to tolerate asynchronism. Since we need to choose frame length to be at least *N*+2*L*+*D*+1 in order to avoid inter-frame interference, the rate (or bandwidth efficiency) of this transmission scheme is

$$R_c = \frac{J(N+1)}{(J(J-1)/2+1)(N+1+2L+D)} \quad . \qquad (13)$$

The rate is within [2/*J*, 2/(*J*-1)] if $N+1 >> 2L+D$, which is the case when the symbol block length is large. Especially, for *J*=2,3,4,5, the rates R_c are 1, 3/4, 4/7, 5/11, respectively. These rates are comparable to those of traditional STBC based on orthogonal designs [1].

The proposed scheme is based on the orthogonal transmission matrix $\mathcal{G}_2$ and can be easily extended to using any $\mathcal{G}_m$ or $\mathcal{H}_m$ [7], where *m* is the number of transmitters. It is trivial to show that any of these extensions has the decoding and equalization procedures similar to the proposed scheme, and achieves full diversity as well. However, in term of the bandwidth efficiency, they are equal or inferior to the proposed scheme because $\mathcal{G}_2$ is the only minimal delay scheme which transmit complex symbol in a full data rate [7]. To illustrate this, let us compare the proposed scheme with its two variations using $\mathcal{H}_3$ and $\mathcal{G}_4$. The bandwidth efficiencies of the latter are

$$R_{H_3} = \frac{J(N+1)}{(J(J-1)(J-2)/2+1)(N+1+2L+D)} \, , \qquad (14)$$

and

$$R_{G_4} = \frac{J(N+1)}{(7J(J-1)(J-2)(J-3)/24+1)(N+1+2L+D)} \, , \qquad (15)$$

respectively. It is obvious that $R_{H_3} \le R_c$ for $J \ge 3$ and $R_{G_4} < R_c$ for $J \ge 4$.

V. Energy Efficiency

A. Improvement on transmission power efficiency

Consider the signal (12) after the linear combiner and assume $h_j(\ell)$ be complex Gaussian distributed with zero-mean and unit variance. The AWGN has zero mean and variance σ_v^2, whereas the variance of $\{b(n)\}$ is σ_b^2. The instantaneous output SNR γ_J of (12) is

$$\gamma_J = \frac{\rho\sigma_b^2}{\sigma_v^2} \sum_{j=1}^{J} \sum_{\ell=0}^{L} \left| h_j(\ell) \right|^2 . \qquad (16)$$

In the proposed cooperative transmission scheme, because each head sensor participates in transmission in *J* frames only, with 1/*J* packet transmitted per frame, the energy consumption ratio of the single transmission to the cooperative transmission can be calculated as $1/(J\rho)$. We call it *energy saving*, and can evaluate it through the analysis of either outage probability or symbol error rate (SER). In [4], we used the SER and Monte-Carlo simulations to find the energy saving. Here we show that the outage probability can be used to obtain the theoretical results that fit well with [4].

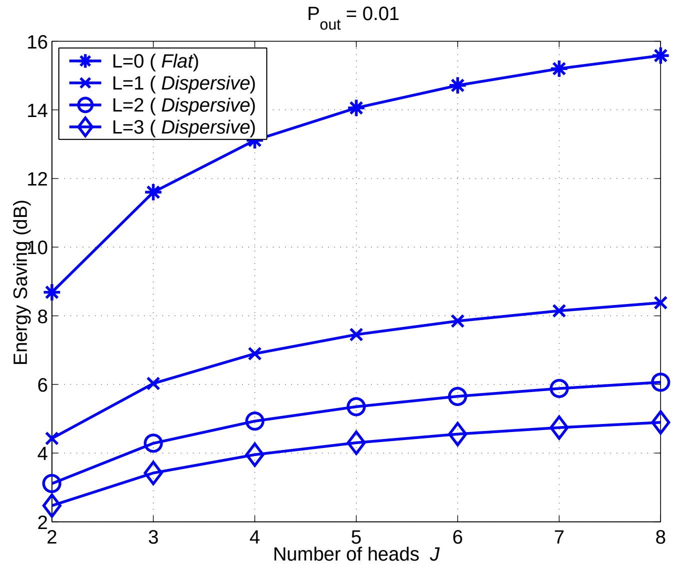

Fig. 3. Energy saving as functions of the number of transmitting sensors *J* and the channel length *L*. For the single transmission *J*=1, the energy saving factor is 0 dB, i.e., ρ=1.

Outage probability is defined as the probability that the instantaneous output SNR, γ, falls below a certain specified threshold, γ_{th}, i.e.,

$$P_{out} = P[\gamma < \gamma_{th}] \, . \qquad (17)$$

The energy saving factor can be calculated by plugging (16) into (17) and evaluate $P[\gamma_J < \gamma_{th}] = P[\gamma_1 < \gamma_{th}] = P_{out}$. This gives

$$\frac{1}{J\rho} = \frac{Q^{-1}_{\chi^2_{2J(L+1)}}(1-P_{out})}{JQ^{-1}_{\chi^2_{2(L+1)}}(1-P_{out})} \, , \qquad (18)$$

where $Q^{-1}_{\chi^2_v}(x)$ is the inverse of the complementary cumulative distribution function of a Chi-square random variable with v degrees of freedom. Fig. 3 shows the energy saving in dB with various channel lengths *L* and transmitting sensor number *J*. An interesting result is that the energy saving depends on the channel length.

B. Overall sensor energy efficiency

In order to study energy efficiency with the consideration of the overhead and the electronic energy, we use the energy consumption model as in [6]. Transmission energy consumption is modeled as $E_a^t(k,d) = kd^2 E_a$, a function of both the number of symbols transmitted (*k*) and the transmission distance (*d*). Electronic energy consumption is modeled as linear functions of *k*, i.e., $E_e^t(k) = kE_e^t$ for transmitters and $E_e^r(k) = kE_e^r$ for receivers.

In this section, we consider only the data transmission phase discussed in Section II. The overheads of other phases will be addressed in the simulations in the Section VI. For the traditional single transmission, the total energy consumption of both the transmitter and the receiver is

$$E_e^t(k) + E_a^t(k,d) + E_e^r(k) = kE_e^t + kE_e^r + kd^2 E_a . \qquad (19)$$

For the cooperative transmission, first the primary head broadcasts fusion results to the secondary heads, during which the total energy consumption is

$$E_a^t(k, d_{\max}) + E_e^t(k) + (J-1)E_e^r(k) = kE_e^r + (J-1)kE_e^r + kd_{\max}^2 E_a . \qquad (20)$$

Then, when all J heads perform cooperative transmission, the energy consumption is

$$JE_e^t(k_J) + E_a^t(k_J, d) + E_e^r(k_J) = Jk_J E_e^t + k_J E_e^r + k_J d^2 E_{aJ} . \qquad (21)$$

In this case, $k_J \in [k, 2k]$ depends on J and the proposed STBC encoding scheme. E_{aJ} is the total transmission energy of the cooperative transmission. The distance from each head to the data collector is approximated as d, whereas finer treatment will be employed in Section VI.

Cooperative transmission enhances energy efficiency if the sum of (20) and (21) is less than (19). It should be readily seen that this depends on the transmission distance d. Therefore, cooperative transmission is advantageous if

$$d^2\left(\frac{k}{k_J}\frac{E_a}{E_{aJ}} - 1\right) > J\frac{E_e^t}{E_{aJ}} + \left[(J-2)\frac{k}{k_J} + 1\right]\frac{E_e^r}{E_{aJ}} + d_{\max}^2 \frac{k}{k_J}\frac{E_a}{E_{aJ}} . \qquad (22)$$

For example, with typical STBC code rate k/k_J [1], energy model parameters $E_e^t = E_e^r = 50nJ/bit$ and E_a =100 $pJ/bit/m^2$ [6], and $d_{\max}$=10, using the energy ratio E_a / E_{aJ} calculated in Section V-A with L=0, the minimum distances can be calculated as d=44,61,73,92 meters for J=2,3,4,5, respectively. Since those transmission distances are typical in wireless sensor network applications, cooperative transmission is useful for enhancing energy efficiency.

VI. SIMULATIONS

To simulate the proposed LEACH with cooperative transmission, we use the same network settings as [6]. The location of the data collector is (25, 150), whereas 100 sensors are randomly deployed on a 50×50 field, as shown in Fig. 1. Each sensor transmits 2000 bits as a packet. For the transmissions between the primary head and the secondary heads, as far as the synchronization is concerned, we add 100 more bits transmission and processing in order to count in cooperation overhead. Specifically, the primary head broadcasts 2100 bits as a packet to the secondary heads and consumes 2100 bits electronic energy. So do the secondary heads. Channels $h_j(\ell)$ are randomly generated in each transmission slot.

The overall network energy efficiency (in terms of network lifetime) is the evaluated. As shown in Fig. 4, cooperative transmission can extend the network lifetime over traditional LEACH. When J=2, 30% longer lifetime is realized. When the data collector is nearer to the network up to (25,50), LEACH with cooperative transmission is still better than traditional LEACH.

VII. CONCLUSIONS

We studied the cooperation overhead, synchronization and energy efficiency of cooperative transmissions in a typical

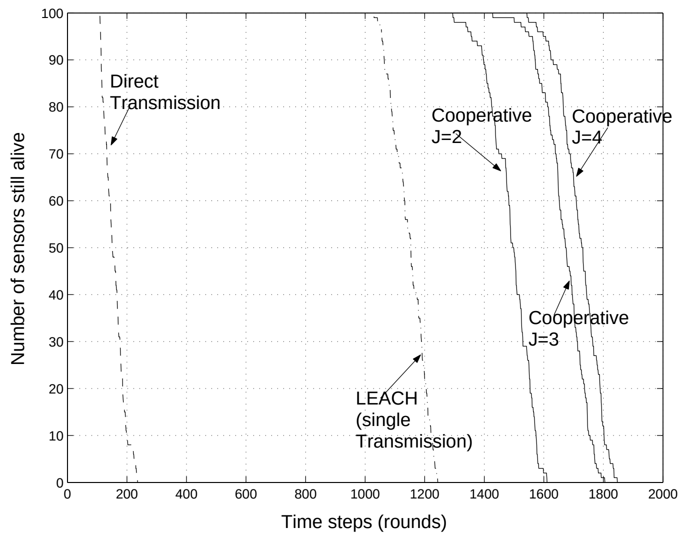

Fig.4. Compare energy efficiency with/without cooperative transmissions in LEACH.

wireless sensor network communication protocol LEACH. To tolerate imperfect synchronization, a new distributed STBC encoded transmission scheme is proposed. Analysis and simulation results demonstrate the applicability and usefulness of cooperative transmission in wireless sensor networks.

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