Application of STBC-Encoded Cooperative Transmissions in Wireless Sensor Networks

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***Abstract*—The efficiency of space-time block code-encoded (STBC) cooperative transmission is studied within low-energy adaptive clustering hierarchy (LEACH), which is a typical networking/communication protocol for wireless sensor networks. Cooperation protocol with low overhead is proposed, and synchronization requirements among cooperating sensors are discussed. Energy efficiency is analyzed as a tradeoff between the reduced transmission energy consumption and the increased electronic and overhead energy consumption. Simulations show that with proper design, cooperative transmission can enhance energy efficiency and prolong sensor network lifetime.**

***Index Terms*—Cooperative diversity, sensor networks, STBC, synchronization.**

I. Introduction

In wireless sensor networks, energy efficiency is a dominating design criterion. Transmission energy efficiency is especially important because wireless transceivers usually consume a major portion of battery energy. Transmission energy efficiency can be enhanced by diversity techniques with antenna arrays, among which space-time block codes (STBCs) are attractive because of their linear complexity [1]. For mobile users without antenna arrays, STBCs with cooperative transmission schemes have been proposed [2]–[4]. Cooperative STBCs not only improve transmission energy efficiency but also distribute energy consumption evenly over multiple sensors, for a more balanced sensor lifetime.

However, the requirement of extreme energy efficiency in wireless sensor networks makes the application of cooperative transmission questionable. First, when sensors schedule joint transmissions, the overhead of cooperation incurs extra energy consumption. Second, it is not an easy task to synchronize cooperating transmitters in terms of carrier frequency, carrier phase, symbol timing (symbol rate), and timing phase (sampling time instant). Without perfect synchronization, STBC-encoded transmission becomes more complex, sometimes even not applicable [4], [5]. Finally, although cooperative diversity enhances *transmission* energy efficiency, the involvement of more than one transmitting sensor increases *electronic* energy consumption [6].

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So far, cooperative transmission has been studied mostly under the assumption of perfect synchronization. The overhead, synchronization, complexity, and energy efficiency are to be justified. To address this task, without loss of generality, we consider a typical networking/communication protocol for wireless sensor networks, i.e., low-energy adaptive clustering hierarchy (LEACH) [7]. We propose ways to incorporate cooperative transmission in LEACH and study the associated overhead, synchronization, and energy efficiency. Although many other protocols, such as directed diffusion and its variations, may be similarly applied, LEACH supports cooperative transmission especially well because of the formation of clusters and cluster heads.

This letter is organized as follows. The cooperative transmission protocol is introduced in Section II with an overhead analysis. The synchronization problem is addressed in Section III. Energy efficiency is then studied in Section IV. Simulations are given in Section V. Finally, conclusions are presented in Section VI.

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 time division multiple access (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 [7].

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 changes in this phase for cooperative transmission, though we rename the cluster head the *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 this scheme, they will be selected by the primary head in the next phase. Meanwhile, when a sensor transmits a 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.

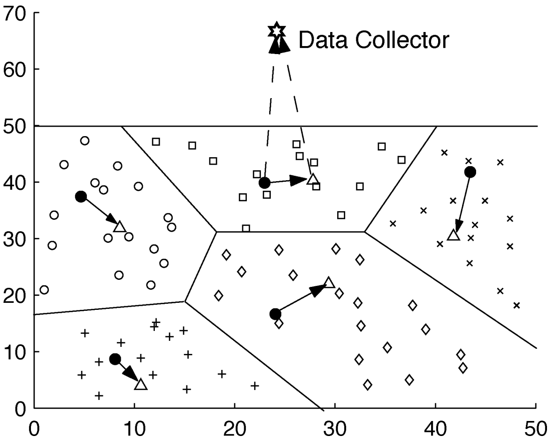

Fig. 1. Illustration of LEACH with cooperative transmission for wireless sensor networks. •: primary heads. △: secondary heads.

Schedule creation: This phase is for each primary head to create a TDMA channel access schedule and to inform each sensor of the assigned slot. For cooperative transmission, each primary head first selects the secondary heads based on both the reported energy status E_i and the received signal power $P_{r,i}$, where i is the node index. The power $P_{r,i}$ can be used as an estimation of the sensor distance d_i according to $d_i = C(P_t/P_{r,i})^{-n}$, where constants C and n depend on the environment. Since the distance between the primary head and the secondary heads should be both small enough for transmission efficiency and large enough for sufficient diversity, we ask the primary head to recursively select $J-1$ secondary heads by

$$\min_{\forall \text{rest node } i} \frac{d_i}{E_i}, \quad \text{s.t.,} \quad d_{\min} \le d_i \le d_{\max} \tag{1}$$

where the threshold $d_{\min}$ is determined by the carrier wavelength, and $d_{\max}$ is determined mainly by the synchronization requirement, as will be discussed in Section III. In order to control the minimum distance among secondary heads, the primary head may avoid choosing sensors with similar d_i.

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 of 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 transmits the fusion result to the data collector. In cooperative transmission mode, it is still the primary head who 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 slot. 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 IV.

In summary, LEACH is a protocol that is suitable to adopt cooperative transmission with small overhead. The fact that the distance of inner-cluster transmission is controlled greatly simplifies the synchronization problem, as will be discussed in Section III.

III. Synchronization Among Cooperating Sensors

A. *Synchronization and Channel Models*

Before cooperative transmission, the secondary heads can synchronize their carrier frequency and symbol timing to their received signals when the primary head broadcasts the fused data. The remaining issue is then relative to carrier phase and timing phase synchronization.

We have to omit the transmission delays from the primary head to the secondary heads since they are difficult to estimate and compensate. Therefore, if the maximum distance between the primary head and the secondary heads is $d_{\max}$, then the beginning time of cooperative transmission at the primary head is up to $d_{\max}/c$ earlier than the secondary heads, where c is the speed of light. Among the signals transmitted by the cooperating sensors, the maximum (worst-case) relative delay is $2d_{\max}/c$ when they arrive at the data collector. These delays cause synchronization error in both carrier phase and timing phase. 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 i be $s_i(t) = \text{Re}[\sqrt{\rho}\sum_{\ell=-\infty}^{\infty} b_i(\ell)p(t-\ell T)e^{j2\pi f_c t}]$, where Re$[\cdot]$ stands for the real part, ρ is a transmission power adjustor, $b_i(\ell)$ is the complex symbol at symbol interval $[\ell T, (\ell+1)T)$, $p(t)$ is the baseband pulse-shaping filter, and f_c is the carrier frequency. The received signal at the data collector is then

$$x_p(t) = \text{Re}\left[\sqrt{\rho}\sum_{i=1}^{J}\sum_{\ell=-\infty}^{\infty} a_i b_i(\ell) p(t-\ell T-\tau_i) \times e^{j(2\pi f_c t - \theta_i)} + v_p(t)\right] \tag{2}$$

where a_i and θ_i are the gain and phase of the propagation channel, and τ_i is the delay. We use $v_p(t)$ to denote passband noise. Flat fading propagation is assumed, and with same ρ, the transmission power is evenly distributed among cooperating head sensors.

Because signals from head sensors have different θ_i and τ_i, 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 $x(n) \triangleq x_b(nT+\tau)$ are

$$x(n) = \sqrt{\rho}\sum_{i=1}^{J} a_i e^{-j\theta_i}\left[p(\tau-\tau_i)b_i(n) + \sum_{\ell\neq n} p\left((n-\ell)T+\tau-\tau_i\right) b_i(\ell)\right] + v(n) \tag{3}$$

where $v(n)$ is baseband noise. Obviously, residual intersymbol interference (ISI) is inevitable. In a flat fading environment, we would prefer that single-tap channel model still be used in cooperative transmission, where single-tap channel means that the

TABLE I
PERFORMANCE DEGRADATION DUE TO DISTANCE-INDUCED SYNCHRONIZATION ERROR. $d_{\max} = 0$ REPRESENTS THE CASE WITH PERFECT SYNCHRONIZATION

$d_{\max}$ (meters)	0	10	30	50	70
BER (SNR 20dB)	1.83e-4	1.99e-4	9e-4	.0054	.0565
BER (SNR 15dB)	.0018	.0019	.0032	.0145	.066

baseband channel is modeled as a complex scalar and, thus, no ISI needs to be mitigated by computation-demanding equalizers. This can be achieved by making $d_{\max}$ small enough to effectively reduce the upper bound of τ_i and, thus, the ISI to a negligible level.

For example, for symbol period $T = 10^{-6}$ sec and raised-cosine pulse shaping with roll-off factor 0.35, when $d_{\max} \leq 10$ m, the worst-case τ_i is less than $T/15$, and the ISI can be less than 0.06. However, when $d_{\max}$ is larger, ISI may not be skipped any more, as shown in Table I, where the bit-error-rate (BER) of single-tap equalizer under various received signal-to-noise ratio (SNR) is evaluated by Monte Carlo simulation of quadrature phase shift keying (QPSK) transmissions.

By choosing $d_{\max}$ to be small enough, the baseband received signal (3) can be approximated as

$$x(n) = \sqrt{\rho} \sum_{i=1}^{J} \alpha_i b_i(n) + v(n) \tag{4}$$

where $\alpha_i = a_i e^{-j\theta_i}$. Hence, the flat fading channel assumption, as in [1], can still be applied.

B. Long-Term Effect of Frequency and Timing Offsets

In Section III-A, we assume that synchronization on carrier frequency and symbol timing is perfect. However, such synchronization may not be accurate due to, for example, noise, Doppler shifting, and difference on processing circuitry, in which case, there are frequency and timing mismatches among cooperating nodes.

Carrier frequency mismatch makes channels time varying so that channels have to be adaptively tracked. Timing mismatch is more devastating because it destroys the space-timing signal structure, which makes STBC not directly applicable [5]. If the ratio of the symbol rate of sensor 1 to sensor 2 is r, then when sensor 1 transmits K symbols, sensor 2 can transmit K/r symbols.

One way to mitigate this problem is to limit the packet (or slot) length. Consider first the case: $r \leq 1$. In order to keep correct timing, both sensors need to transmit K symbols in one slot, which gives $K \leq K/r < K+1$ (the difference on transmission delay is omitted for simplicity), and we have $K < r/(1-r)$. Similarly, if $r \geq 1$, we have $K < r/(r-1)$. In summary, we need to choose the packet length K such that $K < r/|1-r|$. Therefore, r needs to be close to 1 for reasonable packet lengths. For practical oscillators with up to 100 ppm drifting, we have $r \in [1-10^{-4}, 1+10^{-4}]$.

IV. ENERGY EFFICIENCY

Consider the baseband signal model (4) with quasistatic Rayleigh flat fading channels, i.e., α_i are complex Gaussian distributed with zero-mean and unit variance and are constant in one STBC block but may vary randomly between blocks. The noise is additive white Gaussian noise (AWGN) with zero mean and variance σ_v^2. After the synchronization problem is resolved, traditional STBC [1] can be directly applied. With standard STBC decoding, the data collector estimates symbols from

$$\hat{b}(n) = \left(\rho \sum_{i=1}^{J} |\alpha_i|^2\right)^{\frac{1}{2}} b(n) + w(n) \tag{5}$$

where $w(n)$ is AWGN with zero mean and variance σ_v^2.

A. Improvement on Transmission Power Efficiency

To compare the transmission power efficiency of cooperative transmission against single transmission, we consider the SNR of (5) for each channel realization, i.e., SNR $= \rho \sum_{i=1}^{J} |\alpha_i|^2 \sigma_b^2/\sigma_v^2$, where σ_b^2 is the variance of the symbols $b(n)$. In order to make the SNR above some threshold value A with a high probability B, from (5), we need to choose carefully the overall cooperative transmission power $J\rho\sigma_b^2$ such that $P[\rho \sum_{i=1}^{J} |\alpha_i|^2 \sigma_b^2/\sigma_v^2 > A] = B$. For single transmission, we assume $J = \rho = 1$ and that the channel is α_1. The ratio of single transmission power to cooperative transmission power is $1/(J\rho)$.

Proposition 1: Cooperative transmission can use less overall transmission power than single transmission for some SNR A and probability B, i.e., there exist A, B, and $\rho < 1/J$ such that $P[\rho \sum_{i=1}^{J} |\alpha_i|^2 \sigma_b^2/\sigma_v^2 > A] = P[|\alpha_1|^2 \sigma_b^2/\sigma_v^2 > A] = B$.

Proof: For single transmission, $|\alpha_1|^2$ is Chi-square with 2 degrees of freedom, whereas for cooperative transmission, $\sum_{i=1}^{J} |\alpha_i|^2/J$ is Chi-square with $2J$ degrees of freedom. Since there exists a region near zero such that the probability of the former is always greater than the latter, there are some values β and B such that $P[\sum_{i=1}^{J} |\alpha_i|^2/J > \beta] > P[|\alpha_1|^2 > \beta] = B$. In other words, there exists $\beta_J > \beta$ such that $P[\sum_{i=1}^{J} |\alpha_i|^2/J > \beta_J] = P[|\alpha_1|^2 > \beta] = B$. Let $A = \beta\sigma_b^2/\sigma_v^2$. Then, we can choose $\rho = \beta/(J\beta_J)$, which gives $\rho < 1/J$. □

Though such a conclusion may not be surprising, the advantage of this approach lies in the convenient evaluation of power saving. Because of the lack of general BER expressions, many other approaches, such as [6], have to either consider a special case or resort to Monte Carlo simulations. In this case, from the proof procedure, we can numerically calculate β_J and β for fixed A and B, which then gives power saving $1/(J\rho) = \beta_J/\beta$.

For single transmission (with binary PSK), we require $\beta = 0.0158$ in order to achieve probability $B = P[|\alpha_1|^2 > \beta] = 0.9$, which gives SNR $A = 15$ dB if $\sigma_b^2/\sigma_v^2 = 1000$. Similarly, we can calculate β_J. The power-saving $1/(J\rho)$ can be calculated as 5.7, 11.3, 16.8, 20.4 for $J = 2, 3, 4, 5$, respectively. Interestingly, these values are close to the results in [5] obtained from BER Monte Carlo simulations.

B. Overall Sensor Energy Efficiency

In order to study energy efficiency with the consideration of overhead and electronic energy, we use the energy consumption model, as in [7]. Transmission energy consumption is modeled as $E_a^t(k,d) = kd^2E_a$, which is 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 of Section II. The overheads of other phases will be addressed by simulations in Section V. For traditional single transmission, the total energy consumption of both the transmitter and the receiver is

$$E_e^t(k) + E_a^t(k,d) + E_e^r(k) = kE_e^t + kE_e^r + kd^2E_a. \quad (6)$$

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

$$E_a^t(k,d_{\max}) + E_e^t(k) + (J-1)E_e^r(k) = kE_e^t + (J-1)kE_e^r + kd_{\max}^2E_a. \quad (7)$$

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

$$JE_e^t(k_J)+E_a^t(k_J,d)+E_e^r(k_J) = Jk_JE_e^t+k_JE_e^r+k_Jd^2E_{aJ}. \quad (8)$$

In this case, $k_J \in [k,2k]$ depends on J and the STBC encoding scheme [1]. E_{aJ} is the total transmission energy of cooperative transmission. The distance from each head to the data collector is approximated as d, whereas finer treatment will be employed in Section V.

Cooperative transmission enhances energy efficiency if the sum of (7) and (8) is less than (6). It should be readily seen that this depends on the transmission distance d. Therefore, cooperative transmission is advantageous if

$$d^2\left(\frac{k}{k_J}\frac{E_a}{E_{aJ}} - 1\right) > J\frac{E_e^t}{E_{aJ}} + \left[(J-2)\frac{k}{k_J}+1\right]\frac{E_e^r}{E_{aJ}} + d_{\max}^2\frac{k}{k_J}\frac{E_a}{E_{aJ}}. \quad (9)$$

For example, with typical STBC code rate k/k_J [1], energy model parameters $E_e^t = E_e^r = 50$ nJ/bit and $E_a = 100$ pJ/bit/m^2 [7], and $d_{\max} = 10$, using the energy (power) ratio E_a/E_{aJ} calculated in Section IV-A, 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.

V. Simulations

To simulate the proposed LEACH with cooperative transmission, we use the same network settings as [7]. 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 of 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 of electronic energy. So do the secondary heads. Channels α_i are randomly generated in each transmission slot.

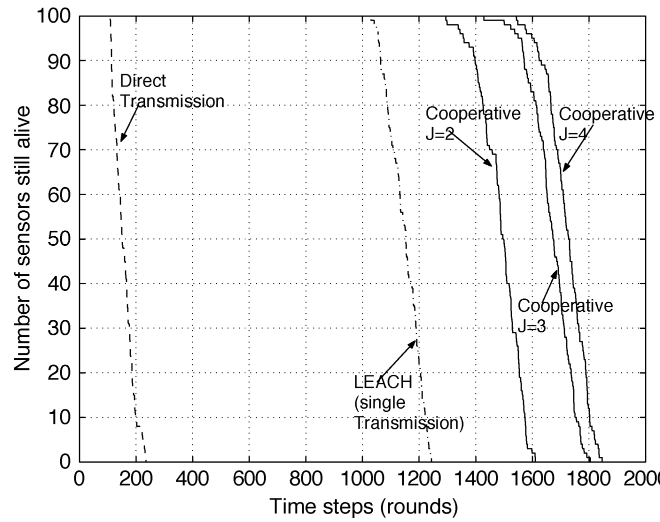

Fig. 2. Compare energy efficiency with/without cooperative transmission in LEACH.

The overall network energy efficiency (in terms of network lifetime) is evaluated. As shown in Fig. 2, 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.

VI. Conclusions

We studied the cooperation overhead, synchronization, and energy efficiency of STBC-encoded cooperative transmission in sensor networks. Analysis and simulation results demonstrate the applicability and usefulness of cooperative transmission.

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