Low-Energy Selective Cooperative Diversity with ARQ for Wireless Image Sensor Networks

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Abstract—Wireless Image Sensor Networks (WISNs) are a type of sensor networks, which have the ability of capturing, processing and transmitting images from a monitored environment. The need to improve the performance of such systems can be attained by using the Selective Cooperative diversity with ARQ (SCA) technique, which is basically a cross-layer design that combines Truncated ARQ at the link layer and cooperative diversity at the physical layer. In addition, the LEACH protocol has the advantage of utilizing randomized rotation of local cluster-heads to evenly distribute the energy load among the sensors in the network. This paper proposes an integrated system, SCA with LEACH, and evaluates its performance with LEACH with Truncated ARQ system. A comparison is obtained based on network lifetime, under varying propagation scenarios, and on the quality of transmitted images in a WISN, using both techniques. Simulation results show better performances for the proposed system.

I. INTRODUCTION

The recent advances in Microscale Electro-Mechanical Systems (MEMS), Nanoscale Electro-Mechanical Systems (NEMS), wireless communications, and digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes. A wireless sensor network (WSN) \cite{1} consists of sensor nodes deployed over a geographical area for monitoring physical phenomena. Typically, a sensor node is a tiny device that has three basic components: a sensing subsystem for data acquisition from the physical surrounding environment, a processing subsystem for local data processing and storage, and a wireless communication subsystem for data transmission. In addition, a power source supplies the energy needed by the device to perform the programmed task. This power source often consists of a battery with a limited energy budget.

If the nodes in a WSN are fitted with image acquiring devices, such as digital cameras, the network is a wireless image sensor network (WISN) \cite{2}. WISNs can provide better quality in the monitored image capturing and processing than the applications in which isolated sensing devices are employed \cite{3}. A distributed system of multiple cameras and sensors enables perception of the environment from multiple disparate viewpoints, and overcomes occlusion effects. Furthermore, heterogeneous media streams with different granularity can be acquired from the same point of view to provide a multi-resolution description of the scene and multiple levels of abstraction. Such feature could be used to recognize people based on their facial characteristics. Other benefit is the redundancy introduced by multiple, possibly heterogeneous, overlapped sensors that can provide enhanced understanding and monitoring of the environment. Overlapped cameras can provide different views of the same area or target, while the joint operation of cameras and audio or infrared sensors can help disambiguate cluttered situations.

However, as in other types of WSNs, the improvement of the network lifetime is a critical issue in the design of WISNs, specially because of the considerable consumption of energy related to the nature of the sensed and transmitted information. In general, sensor networks should have a lifetime long enough to fulfill the application requirements \cite{4}.

Several methods have been proposed which intend to increase the lifetime of WSNs. Cluster based protocols are one of the successful methods for energy saving. Heinzelman \textit{et al} developed LEACH (Low-Energy Adaptive Clustering Hierarchy) \cite{5}, a clustering-based protocol that minimizes energy dissipation in sensor networks.

In WISN channels, the fading caused by multihop, can significantly degrade the performance of the communication system. In this context, the Automatic Repeat Request (ARQ) protocol, at the link layer, is an effective means to mitigate the channel fading, in which Cyclic Redundancy Check (CRC) is used for error checking and retransmissions are requested if the packet is received erroneously. In practice, the maximum number of retransmissions is limited so as to minimize the delay and buffer size, and such variant ARQ is called Truncated ARQ protocol \cite{6}.

Diversity techniques can also improve the performance of those systems, since replicas of the transmitted signals are provided to the sink node \cite{7,8,9}. Time diversity, frequency diversity, spatial diversity and modulation diversity are examples of typical diversity techniques.

However, the application of diversity techniques by the use of multiple antennas, could be impractical in a wireless image sensor network, because of the size of the sensor nodes and the energy constraints present in the network. In order to overcome this limitation, a new form of time-spatial diversity, whereby diversity gains are achieved via the cooperation of the nodes, has been proposed. Lin Dai \textit{et al} \cite{10} proposed the SCA (Selective Cooperative diversity with ARQ) scheme, in which adaptive cooperative diversity gain can be achieved and error
propagation is therefore avoided. SCA uses Space-Time Block Coding (STBC), a paradigm for communication over Rayleigh fading channels using multiple transmit antennas [11], [12].

In this paper the authors propose a system, SCA with LEACH, that integrates the SCA cross-layer design with the LEACH protocol, for wireless image sensor networks. STBC is the diversity scheme adopted. The lifetime performance and the quality of transmitted images are evaluated and compared with the LEACH with Truncated ARQ system. The remaining of the paper is organized as follows: Sections II and III describe the LEACH protocol and the SCA scheme, respectively. The proposed system, the channel model used and the STBC characteristics are presented in Section IV. Simulation parameters and results are discussed in Section V and the conclusions are devoted to Section VI.

II. THE LEACH PROTOCOL

LEACH is a self-organizing, adaptive clustering protocol that uses randomization to distribute the energy load among the sensors in the network. In LEACH the nodes organize themselves into local clusters, with one node acting as the cluster-head. In addition, LEACH performs local data fusion to compress the amount of data being sent from the clusters to the sink node, further reducing energy dissipation and enhancing system lifetime [5].

The LEACH protocol provides a conception of round, and contains two states: the cluster set-up state and the steady state. In the cluster set-up state it forms a cluster in self-adaptive mode. In the steady state it transfers data [13].

Initially, when clusters are being created, each node decides whether to become a cluster-head for the current round. This decision is based on the suggested percentage of cluster-heads for the network (determined a priori) and the number of times the node has been a cluster-head so far. This decision is made by node $n$ choosing a random number between 0 and 1. If the number is less than a threshold $T(n)$ the node becomes a cluster-head for the current round. The threshold is set as [5]:

$$T(n) = \begin{cases} P & \text{if } n \in G \\ 1 - P \cdot \left(\text{mod} \frac{1}{T}\right) & \text{otherwise,} \end{cases}$$

in which $P$ is the desired percentage of cluster-heads, $r$ is the current round, and $G$ is the set of nodes that have not been cluster-heads in the last $\frac{1}{T}$ rounds. Using this threshold, each node will be a cluster-head at some point within $\frac{1}{T}$ rounds.

Once the clusters have been created, a TDMA schedule is fixed and data transmission can begin. This is the steady-state operation of LEACH networks. Then, the next round begins with each node determining if it should be a cluster-head for this round and advertising this information.

III. ADAPTIVE COOPERATIVE DIVERSITY

Selective Cooperative diversity with ARQ (SCA) is a cross-layer design which combines Truncated ARQ at the data link layer and cooperative diversity at the physical layer [10]. With this combination, adaptive cooperative diversity gain can be achieved. Besides, the channel quality is significantly improved in the retransmissions by using relays so that substantial throughput gains can be obtained [10].

SCA uses orthogonal relay transmission to achieve diversity gain. Each node has one or several partners. The node and its partners are responsible for transmitting not only their own information, but also the information of their partners. Therefore, a virtual antenna array is obtained with the use of the relays’ antennas without complex signal design or adding more antennas to the nodes [10].

In SCA scheme, error propagation can be avoided, since only the relay candidates, who correctly detect the packet, are selected to be relay nodes. Furthermore, node cooperation is adopted only when the receiver fails to detect the packet correctly. Therefore, the cooperative diversity is employed in a selective and an adaptive manner.

IV. THE PROPOSED SYSTEM: SCA WITH LEACH

This paper assumes a wireless image sensor network with $K$ nodes and each node is equipped with one antenna. Among the $K$ nodes, $Q$ nodes are the cluster-heads of the correspondent round selected by the LEACH algorithm, $Q - 1$ idle cluster-heads are assumed to be available as the possible relays for the source cluster-head during the packet transmission. The source cluster-head transmits a data packet with a $C$-bit CRC attached and the sink node detects the CRC. Then, an acknowledgement that is either positive (ACK) or negative (NACK) is sent back to the source cluster-head, from the sink node. At the same time, all the $Q - 1$ relay candidates check the CRC and the ones who get positive results are selected to be relay cluster-heads. If the packet is correctly detected by the sink node (with ACK feedback), the source cluster-head continues to transmit a new data packet and the above process is repeated. Otherwise, retransmission will start. Both the source and the relay cluster-heads will jointly retransmit the packet by utilizing a suitable orthogonal STBC. The retransmission continues until the packet is successfully delivered, or the number of retransmissions exceeds $N_{r}^{max}$, which is a preset parameter indicating the maximum number of retransmissions allowed per packet [14].

A. The Channel Model

The adopted channel model was introduced in [10] and is presented in Fig. 1. The communication between the source cluster-head and the sink node is a flat Rayleigh fading channel and is facilitated by $v$ relay cluster-heads, which are selected from $Q - 1$ relay candidates. In addition, perfect channel knowledge is assumed to be available at the receiver side, by using training sequences.

At time slots $t_{0} + 1, \ldots, t_{0} + \varsigma$, the source cluster-head sends a packet $x_{t_{0}+1}^{s}, \ldots, x_{t_{0}+\varsigma}^{s}$ with transmission power $P_{t}$ per symbol, in which $x_{t_{0}+1}^{s}$ is an $M$-QAM modulated symbol and $\varsigma = L/b$ is the number of symbols per packet with a total packet length of $L$ bits and a modulation level of $b = \log_{2} M$ bits. The signal received by the sink node at time slot
in which the channel gain $h_0$ is assumed to be a complex Gaussian random variable with zero-mean and variance $\sigma_0^2$, and $\sigma_0^2$ accounts for the effect of large-scale path loss and shadowing, $z_0$ represents the additive white Gaussian noise with zero-mean and variance $N_0$. At the $j$-th relay candidate, $j = 1, \ldots, Q - 1$, the received signal is given by

$$y_{t_0+1}^r = h_{sj}x_{t_0+i}^s + z_{sj},$$

in which the noise $z_{sj}$ and the fading coefficient $h_{sj}$ are complex Gaussian random variables with zero-mean and variance $N_0$ and $\sigma_{sj}^2$, respectively, $j = 1, \ldots, Q - 1$. In the following, the packet $x_{t_0+1}^s, \ldots, x_{t_0+\zeta}$ is directly transmitted.

If the sink node fails to detect the packet correctly, retransmission starts at time slot $t_L + 1$. Let $N_r$ be the number of retransmissions, $1 \leq N_r \leq N_r^{\text{max}}$. The received signal at the sink node at time slot $t_L + i$ is given by

$$y_{t_L+i}^d = h_{s0}x_{t_L+i}^s + z_0 + \sum_{j=1}^v h_{rj}x_{t_L+i}^r + z_{rj},$$

for $i = 1, \ldots, N_r$, in which $R$ is the rate of the STBC. The symbols $x_{t_L+i}^s$ and $x_{t_L+i}^r$ are the STBC symbols transmitted by the source cluster-head and the $j$-th relay cluster-head with the transmission power $P_t/(v + 1)$, respectively. The additive noise $z_{rj}$ and the fading coefficient $h_{rj}$ are complex Gaussian random variables with zero-mean and variance $N_0$ and $\sigma_{rj}^2$, respectively, $j = 1, \ldots, v$.

B. Space-Time Block Codes

The Alamouti scheme is the first STBC to provide full transmit diversity for systems with two transmit antennas [15]. This scheme achieves the full diversity with a very simple maximum-likelihood decoding algorithm. The key feature of the scheme is orthogonality between the sequences generated by two transmitters. This scheme was generalized to an arbitrary number of transmitters by applying the theory of orthogonal designs. The generalized schemes are referred to as space-time block codes. Full transmit diversity is specified by the number of the transmitters and the decoding algorithm is based only on linear processing of the received signals [15].

For comparing the bit error rate (BER) between the schemes with and without diversity, the Fig. 2 illustrates a BER performance. The curves are very similar to those found in [16]. The best performance is for the STBC scheme, with three transmitters and one receiver, followed by the Alamouti scheme, with two transmitters and one receiver. They are used for the diversity transmission stage. The worst performance corresponds to the QPSK scheme, which is used for the direct transmission stage (without diversity). In this paper, cooperative diversity uses STBCs with two or three transmitting cluster-heads.

Fig. 1. Channel model.

Fig. 2. Bit Error Rate as a function of the SNR.

V. SIMULATION PARAMETERS AND RESULTS

The performance evaluation of the image transmissions over the WISN consider that digital cameras are embedded in the nodes, which are deployed on the monitored environment. They obtain the desired informations and the images of a specific cluster are concentrated and processed at the corresponding cluster-head. The simulation consider that after the fusion and image processing at the cluster-head, the resulting data is the image Lena, with $256 \times 256$, 8 bits by pixel and 256 possible levels of grayscale. That image is presented in Figure 3.

It is assumed that each node has an initial energy of 3 mJ. The dissipation radio model used for the simulations was proposed in [5]. The radio dissipates $E_{\text{elec}} = 50 \text{ nJ/bit}$ to run the transmitter or receiver circuitry and $\epsilon_{\text{amp}} = 100 \text{ pJ/bit/m}^2$ for the transmitting amplifier to achieve an acceptable $\frac{E_{\text{elec}}}{E_{\text{amp}}}$ (the loss of energy in the transmission is proportional to $r^2$). Thus, to transmit a $k$-bit message a distance $d$ using the radio model, the radio spends [5]

$$E_{\text{T}_x}(k, d) = E_{\text{elec}} \cdot k + \epsilon_{\text{amp}} \cdot k \cdot d^2$$

and to receive this message, the radio spends

$$E_{\text{R}_x}(k) = E_{\text{elec}} \cdot k.$$
The sensor network is composed by 100 nodes, with five clusters, each with one different cluster-head per round. Then, in Eq. (1), \( P = 0.05 \) and for at last 20 rounds each node will be a cluster-head at some point. The nodes are deployed randomly in an area of \( 50 \times 50 \) meters. The sink node is located at the coordinates \( x = 25 \) and \( y = 150 \) meters.

Heinzelman et al did not mention if they used any ARQ scheme for the original LEACH protocol. But in order to evaluate the performance of the proposed system (SCA with LEACH) it is wise to compare it with LEACH with Truncated ARQ, instead of original LEACH. This combination of the LEACH with Truncated ARQ consists of a system based in LEACH operation, but the Truncated ARQ is specified to be used as a link layer protocol. Then, retransmissions are allowed, but in a direct manner, without the use of diversity techniques. This system appends the Truncated ARQ scheme for the original proposed LEACH protocol. The maximum number of retransmissions can change based on the design specifications.

Both systems use a Truncated ARQ scheme. A CRC with \( C = 16 \) bits is assumed with a cyclic generator polynomial of \( G_{CRC16}(D) = D^{16} + D^{12} + D^{5} + 1 \). The packet length \( L \) is 120 bits and QPSK is the modulation scheme adopted. All the algorithms used for the simulations were developed using Matlab 7.

Four different propagation environments were used for the simulations, according to the random SNR distribution range of the propagation paths. When the source cluster-head transmits the signal, it travels through five different paths (four relay candidates and one sink node). Scenario 1 comprehends the following SNR range: \([4 \ 8 \ 12 \ 16 \ 20]\) dB. These values are attributed randomly to each path in each round. The other SNR range scenarios, are shown in Table I. It is expected that the best performance can be reached as long as the last scenarios become the transmission option adopted for the simulation, because it is more probable the choose of higher SNR values and so, they have better propagation conditions than the first.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SNR range (dB)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>[4 8 12 16 20]</td>
</tr>
<tr>
<td>2</td>
<td>[5 10 15 20 25]</td>
</tr>
<tr>
<td>3</td>
<td>[6 12 18 24 30]</td>
</tr>
<tr>
<td>4</td>
<td>[7 14 21 28 35]</td>
</tr>
</tbody>
</table>

Network lifetime is the time span from the deployment to the instant when the network is considered nonfunctional. When a network should be considered nonfunctional is, however, application-specific. It can be, for example, the instant when the first sensor dies, a percentage of sensors die, the network partitions, or the loss of coverage occurs [17]. In this paper, the network lifetime measurement is based on the amount of rounds (time steps) that the first or last sensor node dies.

To evaluate the quality of the transmitted images over the network, the metric peak signal-to-noise ratio (PSNR) is used, as a function of the propagation scenarios presented in Table I. The performance evaluation of the transmission to the sink node is compared between the proposed system and LEACH with Truncated ARQ. Examples of received images for the scenarios 1 and 3 are illustrated in Figs. 4, 5, 6 and 7. It can be perceived that the image transmitted by the proposed system presents better subjective quality in all the considered scenarios. The objective evaluation by means of the PSNR is shown in Table IV. For all the scenarios, SCA with LEACH has enhanced performance, since higher values of PSNR indicate the superiority in the relationship between the signal power and the noise power.

Specific behaviors containing the amount of rounds for the first and last dead node, are shown in Tables II and III. For better channel conditions (scenarios three and four), the lifetime is extended, since less errors occurs and less retransmissions are needed. The maximum number of retransmissions in this simulation is \( N_{r}^{\text{max}} = 4 \).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Rounds for the first dead node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Rounds for the last dead node</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>118</td>
</tr>
<tr>
<td>4</td>
<td>121</td>
</tr>
</tbody>
</table>

Fig. 3. Original Lena.
Truncated ARQ system. achieves better performance when compared to LEACH with transmitted in the network. SCA with LEACH system propagation scenarios, and the PSNR of the images generated on two metrics: the network lifetime, considering four different scheme (LEACH with Truncated ARQ) was compared based system and the LEACH system using the Truncated ARQ Time Block Codes. The performance of SCA with LEACH analysis was carried out considering a flat Rayleigh fading on the results of the Truncated ARQ process. The performance supported this work.

**REFERENCES**


