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Space-Time-Block-Code Based Cooperative Routing for Wireless Sensor Networks

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***Abstract*— This paper exploits the idea of cross-layer design for wireless sensor networks to improve the network performance. We present a new energy efficient cooperative routing scheme with space diversity using differential space-time block codes (STBCs). In our solution, the selected multiple nodes act as multiple transmitting and receiving antennas. Full diversity from the orthogonal STBC is utilized to overcome multipath fading and to enhance power efficiency. The differential scheme embeds original message in the consecutive symbols, therefore, nocoherent detection can be done at the receiver without channel tracking or estimation. The network performance measures, such as, network throughput and delay are analyzed via an M/G/1 queueing model. The energy consumption and protocol efficiency are also investigated. The results illustrate that our proposed method outperforms the traditional single relay routing method and the single receiving diversity routing method.**

***Index Terms*— Wireless sensor network, cross-layer design, space-time block code, cooperative relay, energy efficient, network performance.**

1. INTRODUCTION

IN wireless sensor networks (WSN), radio interference and multipath fading make wireless transmission unreliable [1]. The cooperative delivery diversity method is an effective approach to combating multipath fading. In a cooperative diversity scheme, several nodes form a kind of coalition to assist each other in packet transmitting and receiving [2] [3] [4] [5]. The nodes jointly act like a multi-antenna transmitting array, and the destinations act like a multi-antenna receiving array through the interchange of messages [6].

Using space-time block code (STBC) is an effective solution to enhance transmission power efficiency and reduce the effect of multipath fading. The challenge for implementing it as a single node is that multiple transmitting and/or receiving antennas are required. The low-cost, and small sensor nodes cannot fulfill such requirements, but suitably chosen cooperative nodes can provide transmission diversity. The *user cooperative diversity*, utilizing distributed antennas belonging to multiple users, creates "virtual array" by sharing their resources. The *amplify-and-forward* [7] and *decode-and forward* [8] algorithms for information relay are developed. In this paper, we propose a new scheme for multi-hop sensor networks, where each data packet is transmitted by chosen multiple nodes simultaneously, and at the sink, the received data is combined with the data stored and forwarded from the chosen neighbor node. Thus Tx/Rx space diversity is built up. In contrast, only one sensor is selected to perform transmission or relay per hop per routing path in a traditional scheme. The new scheme utilizes two transmitting by two receiving nodes with Alamouti's STBC [9] to achieve the full-rate full-diversity measure.

By using STBC approaches [1] [10], the achievable performance and/or throughput on wireless fading channels can be systematically improved with multiple transmitting and/or receiving antennas and coherent transceivers. However, a coherent detection method needs to estimate and track a time-varying channel, resulting in an increase in system complexity as the number of parallel relays grows [11]. Huges [12], Hochwald and Sweldens [13] independently propose differential unitary space-time modulation (DUSTM) to avoid the channel tracking complexity using noncoherent detection over the block fading channels. In this work, we develop and study the performance of differential STBC scheme for multi-hop data relay.

In this work, we analyze the system performance from the network aspect. By considering the packet passing through the network via the virtual bit pipe from the source to sink, we model the relay system using an M/G/1 queueing model [14]. The system performance is then studied using the Pollaczek-Khintchine (P-K) formula [14] and the steady state distribution of an embedded Markov chain model.

Reduction of energy consumption for nodes in sensor networks is an emerging research and engineering field. Many known energy saving techniques concentrate only on a single protocol layer. In this work, the energy saving is achieved by combining the design of several layers (network, data link and physical layer) in the protocol stack. In particular, the harmonized operation of transmitting power control and medium access control reduces the energy consumption.

The paper is organized as follows, Section 2 introduces the energy efficient routing algorithm is WSN. Section 3 presents the cooperative relay scheme based on differential STBC. Section 4 discusses the system performance in terms of throughput and end-to-end delay. Section 5 analysis the energy consumption and protocol efficiency. Section 6 shows the simulation results and Section 7 conclude the work.

2. ENERGY-EFFICIENT ROUTING

Energy efficiency is always an important consideration for wireless sensor networks. Energy efficient routes can be found

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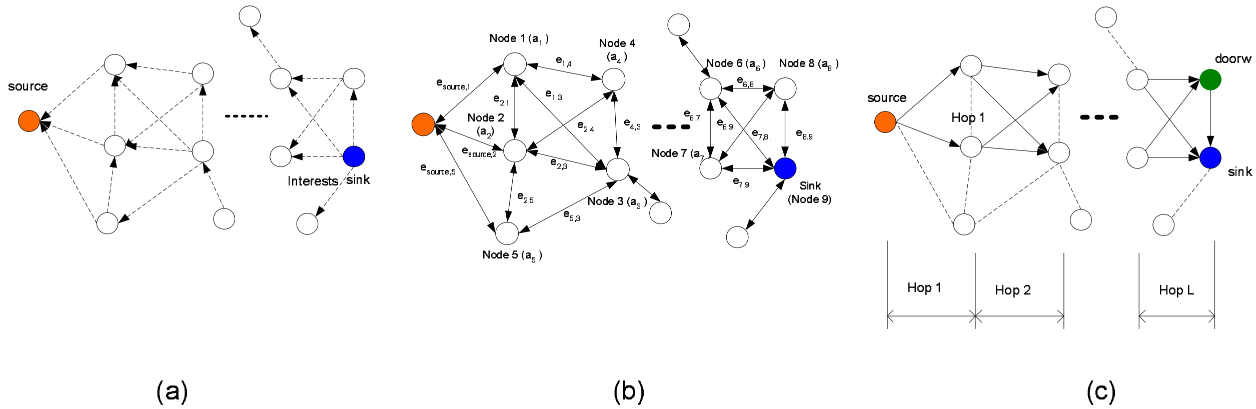

Fig. 1. New transmission and diversity combining scheme for wireless sensor networks (a) Interest propagation (b) LMR (c) Data delivery along cooperative path

based on the available energy (a) in the nodes or the energy required (e) for transmission in the links along the routes, as shown in Figure 1. In this multi-hop wireless sensor network, a sink node sends queries and collects information from sensors [15]. Usually, a sensing event is initiated by a sink or injected to a sink by a human operator. Such an event is also called *interest*. *Interest* is directed to the sink's neighbors via broadcasting and eventually reaches an appropriate node whose function is to perform this query. During the broadcast stage, each node also knows a and e of one hop toward the node initiating the interest. Upon receiving the query, the source replies to the *interest* by sending the sensing data backward to the sink. The source node senses the phenomenon and has several possible relay routes for communication with the sink. In this example of Figure 1 (b), we have

Route 1: Source-1-4$\cdots$6-Sink
Route 2: Source-2-4$\cdots$6-Sink,
Route 3: Source-5-4$\cdots$6-Sink,
Route 4: Source-1-4$\cdots$7-Sink,
Route 5: Source-2-4$\cdots$7-Sink,
Route 6: Source-2-5-4$\cdots$8-Sink,
Route 7: Source-5-2-4$\cdots$8-Sink.
$\cdots$

the energy available a at each node and e at each link are shown in Table I.

Our proposed energy-efficient routing approach is Least-link-energy-consumption and Maximum-node-energy-available Routing (LMR): The relay link that consumes minimum energy e to transmit the data packets from source to sink should be chosen; if the energy is the same, the transmitting node with the maximum available energy a is preferred.

To utilize multipath diversity for the data transmission between source and sink, the source selects two LMR relays. For the next hop, the two nodes respectively select a distinct link with LMR. For the two nodes that are only one hop away from the sink ($L-1$ hop), they select an additional node (doorway node) which is also a one-hop neighbor of the sink. The purpose of a doorway node is to obtain additional copies of transmitted packets. It will cache the packets and send them to the sink during the final transmission period. Therefore, the sink has multiple copies of the original sensing data. Due to the multipath diversity, the average transmission power at each node, then, is expected to be reduced signif cantly while achieving the same bit error rate. This power efficiency feature is critical to sensor networks.

3. COOPERATIVE DIVERSITY WITH DIFFERENTIAL STBC

In this work, we consider a wireless sensor network where the channel coefficients between the source node and relay nodes are statistically independent, but remain unchanged within T symbol periods (block fading channel model). The source node sends a set of data $\mathbf{d}$, a $T\times 1$ vector to the remote sink node through a multi-hop network, as shown in Figure 1. With a traditional single relay method, in the intermediate hop j, only one node is chosen to retransmit the data to $j+1$ hop. While in the cooperative relay scheme, two nodes perform relay with differential STBC encoding to the next hop. The transmitted signal matrices can be written as

$$\begin{cases} \mathbf{S}_0^{(j)} = \mathbf{I} \\ \mathbf{S}_t^{(j)} = \mathbf{D}_t^{(j)}\mathbf{S}_{t-1}^{(j)} \end{cases} \tag{1}$$

where

$$\mathbf{D}_t^{(j)}(\mathbf{d}) = \frac{1}{\sqrt{2}}\begin{bmatrix} d_1^{(j)}(t) & d_2^{(j)}(t) \\ -d_2^{*(j)}(t) & d_1^{*(j)}(t) \end{bmatrix}$$

contains data $\mathbf{d}$. The received data at the hop $j+1$th relay nodes (Node$_{j+1,1}$ and Node$_{j+1,2}$) over two consecutive time slots are

$$\mathbf{X}_t^{(j+1)} = \rho\mathbf{H}^{(j,j+1)}\cdot\mathbf{S}_t^{(j)} + \mathbf{W}_t^{(j+1)} \tag{2}$$

with

$$\mathbf{X}_t^{(j+1)} = \begin{bmatrix} x_{1,1}^{(j+1)}(t) & x_{1,2}^{(j+1)}(t) \\ x_{2,1}^{(j+1)}(t) & x_{2,2}^{(j+1)}(t) \end{bmatrix}$$

and

$$\mathbf{H}^{(j,j+1)} = \begin{bmatrix} h_{1,1}^{(j,j+1)} & h_{1,2}^{(j,j+1)} \\ h_{2,1}^{(j,j+1)} & h_{2,2}^{(j,j+1)} \end{bmatrix}$$

where ρ is the square root of the signal to noise ratio, $\mathbf{H}^{(j,j+1)}$ is the channel coefficient matrix between hop j relay nodes and

TABLE I

ENERGY AVAILABLE AT EACH NODE AND ENERGY REQUIRED FOR TRANSMISSION DATA BETWEEN NODES

Energy (e)	Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Node9
Node 0	$e_{0,1}$	$e_{0,2}$			$e_{0,5}$				
Node 1		$e_{1,2}$	$e_{1,3}$	$e_{1,4}$					
Node 2	$e_{2,1}$		$e_{2,3}$	$e_{2,4}$	$e_{2,5}$				
Node 3	$e_{3,1}$	$e_{3,2}$		$e_{3,4}$	$e_{3,5}$				
Node 4			$e_{4,3}$						
Node 5		$e_{5,2}$	$e_{5,3}$						
Node 6							$e_{6,7}$	$e_{6,8}$	$e_{6,9}$
Node 7						$e_{7,6}$		$e_{7,8}$	$e_{7,9}$
Node 8						$e_{8,6}$	$e_{8,7}$		$e_{8,9}$
Node 9						$e_{9,6}$	$e_{9,7}$	$e_{9,8}$	
Energy Available (a)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9

hop $j+1$ relay nodes, and the noise matrix $\mathbf{W}_t^{(j+1)}$ contains complex i.i.d. Gaussian samples.

Since (1) is the standard differential STBC coded signal, the traditional differential decoding algorithm can be applied without the need for estimating the channel coefficient, which performs the maximum likelihood decoding with a linear complexity [16].

$$\begin{aligned}&\left[\begin{array}{cc}\hat{d}_1^{(j)}(t) & \hat{d}_2^{(j)}(t)\end{array}\right]\\ &= \left[\begin{array}{cc}x_{1,1}^{(j+1)}(t) & x_{1,2}^{*(j+1)}(t)\end{array}\right]\left[\begin{array}{cc}x_{1,1}^{*(j+1)}(t-1) & x_{1,2}^{*(j+1)}(t-1)\\ x_{1,2}^{(j+1)}(t-1) & -x_{1,1}^{(j+1)}(t-1)\end{array}\right]\\ &+ \left[\begin{array}{cc}x_{2,1}^{(j+1)}(t) & x_{2,2}^{*(j+1)}(t)\end{array}\right]\left[\begin{array}{cc}x_{2,1}^{*(j+1)}(t-1) & x_{2,2}^{*(j+1)}(t-1)\\ x_{2,2}^{(j+1)}(t-1) & -x_{2,1}^{(j+1)}(t-1)\end{array}\right]\end{aligned}$$

This process is repeated at each hop until the transmitted signals finally reach the sink.

$$\mathbf{Y}_t = \rho \mathbf{H}^{(L-1,s)} \cdot \mathbf{S}_t^{(L-1)} + \mathbf{W}_t^{(s)} \tag{3}$$

with

$$\mathbf{Y}_t = \left[\begin{array}{cc}y_{1,1}(t) & y_{1,2}(t)\\ x_{2,1}(t) & x_{2,2}(t)\end{array}\right]$$

and

$$\mathbf{H}^{(L-1,s)} = \left[\begin{array}{cc}h_{1,1}^{(L-1,s)} & h_{1,2}^{(L-1,s)}\\ h_{2,1}^{(L-1,s)} & h_{2,2}^{(L-1,s)}\end{array}\right]$$

where $\mathbf{H}^{(L-1,s)}$ is the channel coefficient matrix between hop $L-1$ relay nodes and the sink plus doorway nodes, and the noise matrix $\mathbf{W}_t^{(s)}$ contains complex i.i.d. Gaussian samples.

$$\begin{aligned}&\left[\begin{array}{cc}\hat{d}_1^{(L-1)}(t) & \hat{d}_2^{(L-1)}(t)\end{array}\right]\\ &= \left[\begin{array}{cc}y_{1,1}^{(s)}(t) & y_{1,2}^{*(s)}(t)\end{array}\right]\left[\begin{array}{cc}y_{1,1}^{*(s)}(t-1) & y_{1,2}^{*(s)}(t-1)\\ y_{1,2}^{(s)}(t-1) & -y_{1,1}^{(s)}(t-1)\end{array}\right]\\ &+ \left[\begin{array}{cc}y_{2,1}^{(s)}(t) & y_{2,2}^{*(s)}(t)\end{array}\right]\left[\begin{array}{cc}y_{2,1}^{*(s)}(t-1) & y_{2,2}^{*(s)}(t-1)\\ y_{2,2}^{(s)}(t-1) & -y_{2,1}^{(s)}(t-1)\end{array}\right]\end{aligned}$$

The combination of the transmission, relay, receiving and decoding from the source to the sink appears to higher layers as a virtual bit pipe with a bit error rate (P_e). In section 4, we will show the role of P_e in the expression of throughput and delay.

4. PERFORMANCE ANALYSIS USING AN M/G/1 QUEUEING MODEL

In this section, we use a continuous model to model the system. Consider a queueing system immediately after a customer has departed and service times assumed to be i.i.d. random variables with an arbitrary probability distribution. We denote the service time by b, and the cumulative distribution function by $B(t)$. The arrival process is Poisson with parameter λ. The imbedded stochastic process $X(t_i)$, where X denotes the number in the system and $t_1, t_2, \ldots, i, \ldots$ are the successive times of completion time of the first, second ... and ith customer, can be shown to be Markovian as follows [14].

$$Pr\{X_{n+1} = j | X_n = i\} = \begin{cases}\int_0^\infty \frac{e^{-\lambda t}(\lambda t)^{j-i+1}}{(j-i+1)!} dB(t) & (j \geq i-1, i \geq 1),\\ 0 & (j < i-1, i \geq 1).\end{cases} \tag{4}$$

4.1. Delay Performance Analysis

A given packet transmitted might be retransmitted due to errors as shown in Figure 2. It follows that the time interval between the start of the first transmission and the last transmission of a given packet is $k\tau$ with probability $P_{ST}P_{FT}^{k-1}$, where $P \triangleq P_{FT} = 1 - P_{ST}$, P_{ST} is a packets successful transmitting probability and P_{FT} is the probability that packet transmission fails.

$$P_{ST} = (1 - P_e)^M$$

where P_e is the BER and M is the packet length. The transmitter queue behaves like an M/G/1 queue with service time distribution given by

$$P\{b = k\tau\} = P_{ST}P_{FT}^{k-1} = (1-P)P^{k-1}, \ \ k = 1, 2, \ldots$$

The first two moments of the service time are

$$\overline{b} = \sum_{k=0}^{\infty} k\tau(1-P)P^{k-1} = \frac{\tau}{1-P}$$

$$\overline{b^2} = \sum_{k=0}^{\infty} k^2\tau^2(1-P)P^{k-1} = \tau^2\frac{1+P}{(1-P)^2}$$

The P-K formula [17] gives the average packet time in the queue

$$W = \frac{\lambda\overline{b^2}}{2(1-\lambda\overline{b})} \tag{5}$$

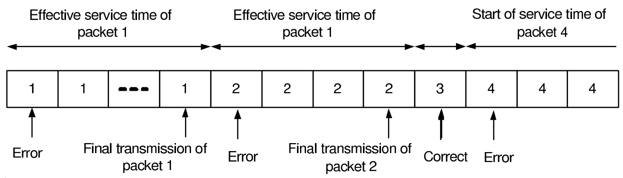

Fig. 2. Illustration of the effective service time of packet in the system. For example, packet 1 has an effective service time of 4 because there were 3 errors in the first three times attempt to transmit it, but no error in the forth attempt

Observe that the average service time is constant given P, the average waiting time increases as the packets arrival rate λ increases, and when it approaches the service rate, the average waiting becomes the infnity. Hence, the system is stable when $(1-\lambda\bar{b})>0$, that is $\lambda<1/\bar{b}$ (the packet arrival rate is less than the average service rate). The average delay time of each packet is

$$T=\bar{b}+W \tag{6}$$

4.2. Departure-Point Steady-State System-Size Probability

In this subsection, we try to derive the closed form expression for system throughput. Let π_n represent the probability of n packets in the system at a departure point (a point in time just after a customer has completed the service) after a steady state is reached. The imbedded stochastic process at departure points is a Markov chain, and the transition probability matrix is

$$\mathbf{P}=\{p_{ij}\}$$

where

$$\begin{aligned} p_{ij} &= Pr\{\text{system size after a departure point is } j| \\ &\quad \text{system size after previous departure was } i\} \\ &= Pr\{X_{n+1}=j|X_n=i\} \end{aligned} \tag{7}$$

Defne

$$k_n = Pr\{n \text{ arrivals during a service time}\} \tag{8}$$

$$= \int_0^\infty \frac{e^{-\lambda t}(\lambda t)^n}{(n)!}dB(t)$$

Then p_{ij} can be seen to equal k_{j-i+1} and

$$\mathbf{P}=\begin{pmatrix} k_0 & k_0 & 0 & 0 & 0 & \cdots \\ k_1 & k_1 & k_0 & 0 & 0 & \cdots \\ k_2 & k_1 & k_0 & k_0 & 0 & \cdots \\ k_3 & k_3 & k_2 & k_1 & k_0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & & \ddots \end{pmatrix} \tag{9}$$

By assuming that the steady state is achievable, the steady-state probability vector $\boldsymbol{\pi}=\{\pi_n\}$, can be found as the solution to the stationary equation

$$\mathbf{P}\boldsymbol{\pi}^T=\boldsymbol{\pi}^T$$

This yields

$$\pi_i=\pi_0\,k_i+\sum_{j=1}^{i+1}\pi_j\,k_{i-j+1}\quad(i=1,2,\ldots) \tag{10}$$

Now defne the generating functions

$$\Pi(z)=\sum_{i=0}^{\infty}\pi_i z^i \quad \text{and} \quad K(z)=\sum_{i=0}^{\infty}k_i z^i \quad (|z|<1)$$

Then multiplying (10) by z^i, summing over i, and solving for $\Pi(z)$

$$\Pi(z)=\frac{\pi_0(1-z)K(z)}{K(z)-z}$$

By using the fact $\Pi(1)=1$, along with L'Hôpital's rule, and realizing that $K(1)=1$ and $K'(1)=\frac{\lambda}{\mu}$, we find that

$$\pi_0=1-\rho \quad (\rho\equiv\lambda E[\text{service time}])$$

Hence

$$\Pi(z)=\frac{(1-\rho)(1-z)K(z)}{K(z)-z} \tag{11}$$

The throughput is the average number of the successfully transmitted data packets per period, i.e.,

$$R=\sum_{i=1}^{\infty}\pi_i\cdot P_{ST}=P_{ST}\,(1-\pi_0) \tag{12}$$

5. ENERGY CONSUMPTION AND PROTOCOL EFFICIENCY

We assume that nodes communicate over a slow-fading channel with addictive white Gaussian noise. Consider that node l transmits data to its neighbor node m over such a channel. The energy per bit over noise at the receiver is [18]

$$\frac{E_b}{N_0}=\frac{P_{t(l,m)}}{P_{loss}\alpha}\cdot\frac{1}{WN_{th}N_{rx}} \tag{13}$$

where $P_{t(l,m)}$ is the transmission power, P_{loss} is the large scale path loss, α is the average attenuation factor due to fading, W is the signal bandwidth, N_{th} is the thermal noise and N_{rx} is the noise at the receiver known as the noise fgure. In general, $P_{loss}\propto\frac{1}{4\pi d^k}$, $2\le k\le 4$.

The transmitting power $P_{t(l,m)}$ can be written as

$$P_{t(l,m)}=P_{loss}\alpha WN_{th}N_{rx}\frac{E_b}{N_0} \tag{14}$$

The average energy required to transmit a bit is

$$E_{RF}=P_{RF}T=P_{RF}\frac{1}{R}$$

where T is the time interval for transmitting a bit and R is the data rate.

In order to achieve an optimal operating point with respect to the energy consumption of a wireless sensor network, one has to make a trade-off between RF transmission power and MAC retransmission. If there are no bit errors, no collision and no protocol overhead occur in a system. Thus energy E_{ideal} required to transmit data is

$$E_{ideal}=\bar{P}_t\times\bar{T} \tag{15}$$

where $\bar{P}_t$ is the mean transmitted power and $\bar{T}$ is the average transmission time.

The energy needed to transmit data is higher in reality because of protocol overhead and retransmission (bit error and

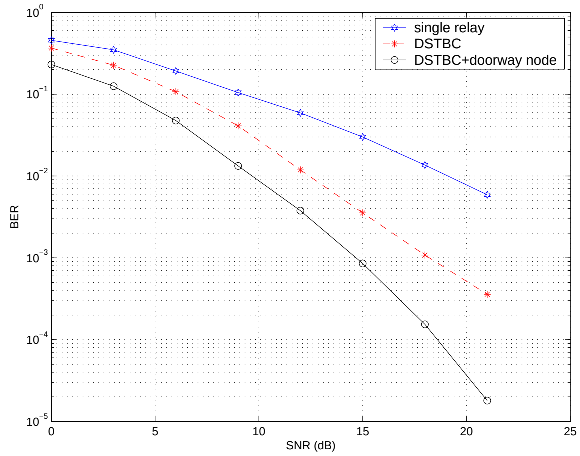

Fig. 3. BER vs. SNR

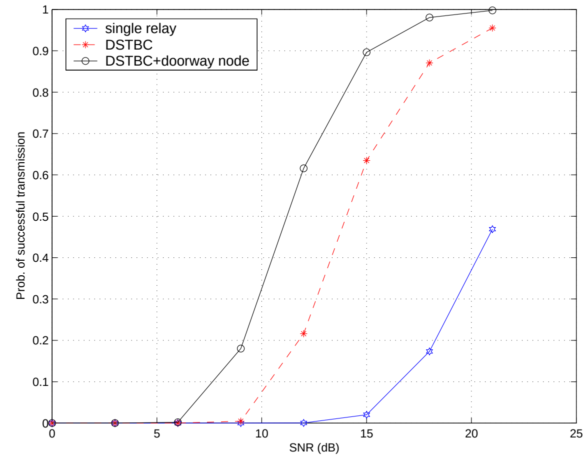

Fig. 4. Probility of Packet successfully transmission vs. SNR

collision). Therefore, we define the protocol efficiency η_{pe} as the number of successful transmitted data bits B_{suss} over the number of overall transmitted bits B_{all}

$$\eta_{pe} = \frac{B_{suss}}{B_{all}}$$

where B_{all} includes MAC layer control packets, successful and retransmitted data bits and MAC + PHY packet header and trailer. η_{pe} indicates the protocol efficiency during the data transmission.

6. SIMULATION RESULTS

6.1. Error Performance Simulation

To observe the performance of the differential STBC for cooperative relays with doorway method, which provides the full diversity at Rx/Tx, we compared it with other two methods: 1) the original single relay method and 2) the cooperative relay without doorway method which just has the transmission diversity. In the simulation system, the channel model is assumed to be a block flat Rayleigh fading. Each packet contains $M = 128$ symbol periods. The data symbol is BPSK. Assume the amplitudes of fading from each transmitting antenna to receiving antennas conform to a mutually uncorrelated Rayleigh distribution and that the average signal power at each receiving antenna is same. Assume there are $L = 3$ hops from the source to the destination, and at each hop, two nodes are selected for packets relay. The source node's buffer with inf nite capacity is feeded by Poisson sources with density λ. Figure 3 shows the BER vs. SNR for different relay schemes. The diversity gain of the new scheme at BER of 10^{-2} is about 4 dB better than the transmitting-diversity-only scheme; and 9 dB better than the traditional method. Figure 4 shows the probability of the successful packet transmission of uncoded coherent BPSK using a conventional method (no diversity) and cooperative diversity scheme in Rayleigh fading. The performance of the new scheme is better than the conventional scheme and the cooperative relay without doorway method.

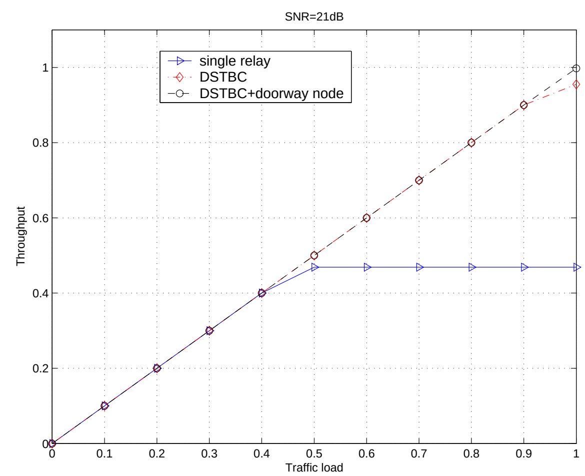

Fig. 5. Throughput performance vs. Traffic load comparison of BPSK in Rayleigh fading (SNR=21dB)

6.2. Analytical Results about Throughput and Delay

Considering the packet arrival is a Poisson process. Figure 5 shows the throughput versus traffic load using different approaches. The cooperative diversity approach with 2 transmitting cooperative nodes and 2 receiving cooperative nodes has the best performance. The delay performance is shown in Figure 6 as a function of the traffic load. The simulation results demonstrate that the new scheme is better than the cooperative relay without doorway approach and the single relay method.

6.3. Simulation Results about Energy Efficient

Assume $P_{loss}\alpha$ is about 70 dB, the signal bandwidth is W = 1Mhz, R = 1Mbit/s, $N_{th} = -174$dBm and $N_{rx} \approx$ 10dB, the length of MAC header and trailer is 30 bytes (the same as that of IEEE 802.11b standard). Figure 7 shows the simulation result for BER vs. transmitting power. It is important to note that the higher the transmission power, the lower the BER for the same method. To achieve the same BER, the new scheme clearly needs the lowest transmission power.

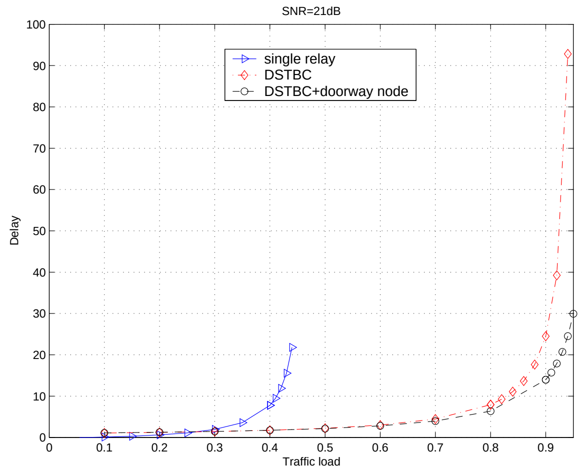

Fig. 6. Delay performance comparison in Rayleigh fading(21 dB)

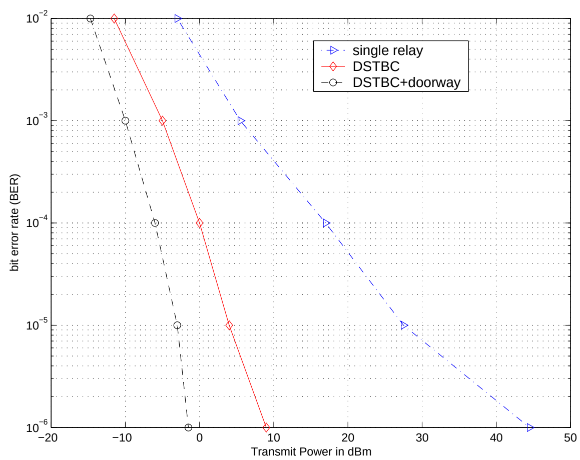

Fig. 7. Bit Error Rate vs. Transmission Power using various of transmission methods

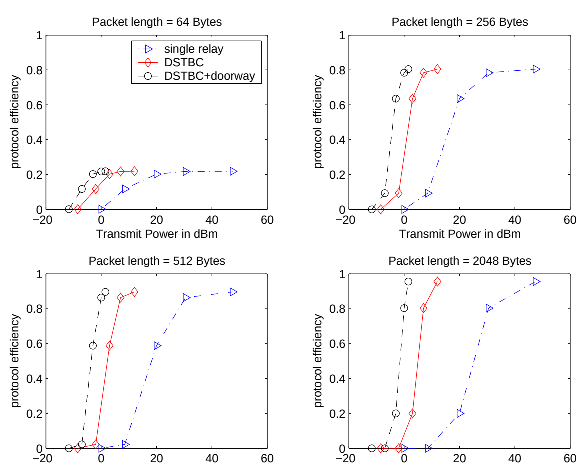

Fig. 8. The protocol efficiency η_{pe} vs. mean transmission power for 64, 256, 512 and 2048 byte packets using various of transmission methods

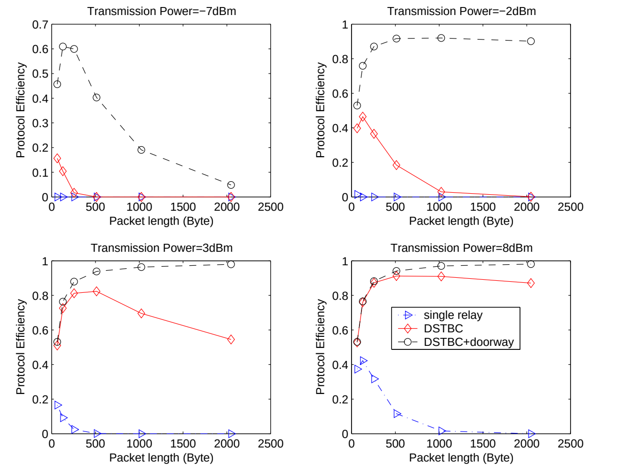

Fig. 9. The protocol efficiency η_{pe} vs. packet size for various transmission power

Figure 8 show the protocol efficiency dependence on the transmission power used. The graph show, that the protocol efficiency is very small for relatively low transmission power for each transmission scheme. The primary reason is corrupted packets, which have to be retransmitted by the MAC protocol. By increasing the transmission power, the protocol efficiency increases relatively quickly up to a certain level, which depends on the transmission method chosen in the network. An increased transmission power is equivalent to a smaller BER, which result in a better protocol efficiency. Furthermore, it is important to note that if the transmission power reaches a certain level (approximately -1 dBm, 5 dBm and 31 dBm for our new scheme, cooperative relay without doorway method and traditional approach for 512 byte packets), only a marginal increase of protocol efficiency is reported. One can observe that the protocol efficiency remains small for 64 byte packets and slightly higher by using 2048 byte packets. Under the same protocol efficiency, our new scheme has the lowest transmission power level.

In Figure 9, the protocol efficiency η_{pe} vs. packet length is shown for different transmission schemes. At the same transmission power level, the new scheme provides the highest protocol efficiency. The figure clearly shows that there is an optimal packet size providing the highest protocol efficiency for different transmission schemes. In Figure 9, the protocol efficiency curve indicates that for the higher BER, which is equivalent to low transmission power, the smaller packets the better performance. For low BER, the larger packets have the better efficiency. For example, when BER is 10^{-5}, the optimal packet size is about 500 bytes. The protocol efficiency is mainly inf uenced by MAC (header, trailer and control packet) for small packet cases. For long packets, MAC plays a minor role, but long packets are corrupted with high probability, resulting in retransmissions.

7. Conclusion

This work introduces a cooperative space-time coding and energy-efficient cooperative routing scheme for cross layer design in multi-hop wireless sensor networks. Multiple nodes are selected as the transmitting and receiving antenna array acording to the energy efficiency. Secondly, the orthogonal space-time blok code is used to provide transmission diversity. Thirdly, the sink node uses a maximum ratio combining together with its neighbors to make decision. Both the analytical and simulation results show that this new sheme is capbale of overcoming the multipath fading and reducing the interference. Moreover, we also prove that the cooperative scheme is energy-efficient and robust. The major contribution of this work are: Selected multiple nodes according to the energy efficiency act as the transmitting and receiving antenna array. The orthogonal space-time block code is used to provide full (transmitting and receiving) diversity, and the sink uses a maximum ratio combining together with doorway to make decisions. The utlizition of differential STBC avoids the complexity of channel tracking and estimation and can reduce the system cost. We find that the new scheme is capable of overcoming the multipath fading and reducing the interference. We also demonstrate that the cooperative scheme is energy-efficient and robust.

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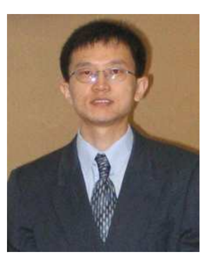

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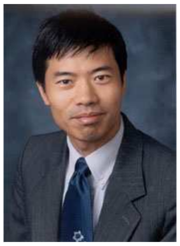

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