Performance Analysis of an Experimental Wireless Relay Sensor Network

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Abstract

Communication through relay channels in wireless sensor networks can create diversity and consequently improve robustness of data transmission for ubiquitous computing and networking applications. In this paper, we investigate the performances of relay channels in terms of diversity gain and throughput via both experimental research and theoretical analysis. Two relaying algorithms, dynamic relaying and fixed relaying, are utilized and tested to find out what the relay channels can contribute to system performances. The tests are based on a wireless relay sensor network comprising a source node, a destination node and dedicated relay nodes, and carried out in an indoor environment with rare movement of objects nearby. The tests confirm, in line with the analytical results, that more relay nodes lead to higher diversity gain in the network. The test results also show that the data throughput between the source node and the destination node is enhanced by the presence of the relay nodes. Energy consumption in association with the relaying strategy is also analysed.

1. Introduction

Ubiquitous computing and networking makes extensive use of wireless sensor networks to collect, process and distribute context information in numerous applications, such as environmental monitoring and control, telecare, and battle field [1, 2]. These applications feature small, low-cost, and networked processing devices used in a rather volatile communication environment. One of the key technical challenges of this system is how to ensure reliable transmission of critical data between the remote sensor nodes and the sink node or base station, in order to maintain the required accuracy as well as promptness of data delivery. One way to make the transmission reliability more acceptable in a wireless network is to introduce relay nodes for helping the source to deliver information to the destination. We herein investigate the performance of the wireless sensor network with relay nodes, in terms of the diversity gain induced through relaying and subsequently the throughput enhancement due to improved reliability.

Communication through relay channels has received considerable attention from researchers [3-7]. Sendonaris *et. al* have demonstrated in [4] that with the help of a relay node the transmission performance in terms of channel capacity between the source and destination nodes can be enhanced. Several relaying protocols (for defining how relay nodes process the packets received from the source) have been proposed in [5-7], such as amplify-forward and decode-forward. The amplify-forward protocol simply scales the received analogue signal before relaying. This protocol is simple but the received noise at relay nodes is also amplified and forwarded to the destination. The decode-forward protocol involves full or symbol-by-symbol decoding of source information at relay nodes. Following the above pioneering work, the research interest in this area is continuously growing [8-10]. An overview of this promising technology can be found in [11].

The benefits as a result of communication through relays have been revealed in many cases by either theoretical analysis or simulation results. Therefore, to confirm the actually achievable benefits when applying this technique in a real world environment is essential. It is also vital to identify the gaps in performance between theoretical and experimental results. So far, two reports have been found on the subject of the realization of relay networks [12, 13]. Challenges in implementing relay networks using commodity hardware are addressed in [12], such as acquisition of network state information, implementations of network coordination and distributed phased-array or space-time coding, and constraints on total reception energy. A channel access scheme is introduced to acquire network state information and provide the required coordination for analysis. Based on such a scheme, a proper selection of relay nodes by the source node can potentially reduce the total energy consumed by the network. The network implemented in [12] can achieve as much diversity or

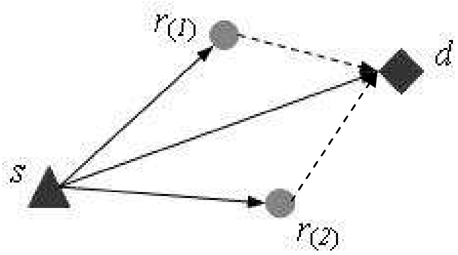

Figure 1. Cooperative relaying from the source node (*s*) to the destination (*d*), with the help from two relay nodes ($r_{(1)}$, $r_{(2)}$).

multiplexing gain as is expected, shown by the diversity-multiplexing trade-off [14]. This network can be regarded as a *centralized* network that requires considerable implementation complexity. In [13], an amplify-forward based relay network is realized using a distributed version of the Alamouti block code and an OFDM-based physical layer. The disadvantages of this realization are the dependency of the adopted relay algorithm on the synchronization between the source and relay nodes, and the omission of the direct link between source and destination. Despite these disadvantages, performance improvement is observed by means of the bit error ratio (BER) at the destination.

In this paper, we model the concerned relay network using fixed and dynamic relaying algorithms, and present its implementation based on wireless sensor transceivers, which features *decentralization* and requires no synchronization. The implementation in the physical layer (PHY) of the sensor transceiver conforms to decode-forward protocol. The relay network is illustrated in Fig. 1, where the relay nodes make their own decisions on whether or not to perform relaying for the source. To avoid transmission interference or collision between the transmit nodes (source and relay nodes), a time division multiple access (TDMA) scheme is applied, so that the transmit nodes send out data only in their assigned time slots. This scheme can avoid complex handshake processes between transmit nodes and significantly reduce the time involved in system developments.

As shown in Fig. 1, the network implemented comprises a source node, a destination node, and one or two relay nodes. The source node encodes the data collected and assembles the coded data for transmission. At relay nodes, the received packets are simply forwarded to the destination node in fixed relaying, while in dynamic relaying the packets are either forwarded or discarded depending on the conditions at the time, which will be explained later. The destination node decodes the received packets and gathers the statistics of the packets for computer analysis.

The rest of the paper is organized as follows. In the next section, we give the theoretical analysis on outage probability and diversity gain of the relay network. It is followed by the implementation of the wireless relay sensor network for performance investigations. We then present the test settings, results and discussions in Section 4. Finally, we draw our conclusions in Section 5.

2. Preliminaries

In this section, we apply the related theory to the wireless relay sensor network under the investigation.

2.1. Direct transmission network

In this senario, packets from the source node are transmitted directly to the destination node, without involvement of relay nodes. The time slot arrangements for this scheme are shown in Fig. 2(a), where T is the time period for transmitting one packet. This arrangements reflect the secenarios in real applications where sensing data are collected at a certain sampling rate. The mutual information in bits/s/Hz for the transmission can be expressed as

$$I_d = \log\left(1 + \xi\left|\alpha_{s,d}\right|^2\right), \tag{1}$$

where α is the fading coefficient of the channels indexed by its subscript; ξ is the signal-to-noise ratio (SNR) of an additive white Gaussian noise (AWGN) channel $\sim N(0,\ N_0)$. We assume that the wireless channels are uncorrelated and Rayleigh faded, i.e., α ~Rayleigh(0, σ^2). The SNR, ξ, is defined as

$$\xi = \frac{P}{N_0},$$

where P is the available transmit power of each transmit node without fading.

2.2. Relaying network

According to the functionality of relay nodes, wireless relay networks can be categorized into three types: multihop relaying, cooperative relaying and cooperative diversity. The main purpose of employing relay nodes in a network is to exploit either processing or diversity gain that relay nodes can bring to the network, in order to reduce error or loss probability of the wireless channels concerned.

In multihop relaying [15], the source packets are sent out to a specific relay node rather than directly to the destination node in the network. The relay node will

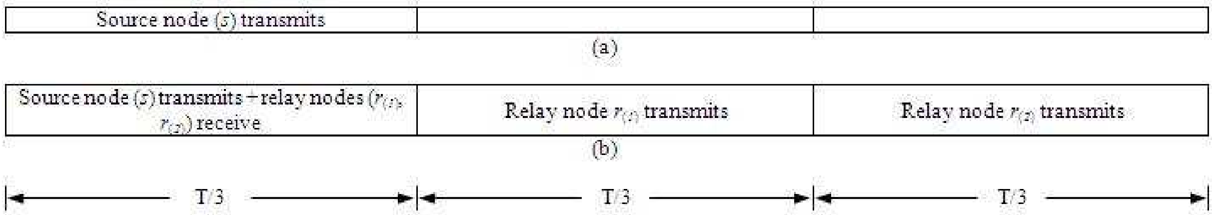

Figure 2. Time division multiple access setting in the tests. (a) direct transmission; (b) cooperative relaying.

process the received souce packets and forward the processed packets to either the next relay node or the desitnation. The packet forwarding continues until the source packets reach the detination.

Different from multihop relaying, in both cooperative relaying and cooperative diversity the source packets can reach the destination node via the relay nodes, in addition to the drect transmission channel. There is however one major difference between cooperative relaying and cooperative diversity. In the former only the source node sends out original information, but the relay nodes are dedicated to performing relaying if required. The time-slot distribution of cooperative relaying is shown in Fig. 2(b). In the cooperative diversity scheme, however, all the transmit nodes can act as the source as well as relay nodes, to receive help from and provide help to other transmit nodes. In this work, our investigation is focused on cooperative relaying and its performance, in comparison with that of direct trans-mission.

The relaying protocol used in the network implemented is decode-forward [4]. In the first time slot (T/3) of transmission, the source node broadcast its packets to the network (shown by the solid arrowed lines in Fig.1) and all the relay and destination nodes are able to receive the packets. Then the relay nodes will use the subsequent time slots in succession to decide whether or not to forward the source packets (shown by the dashed arrowed lines in Fig.1) by applying either of the two algorithms: fixed relaying or dynamic re-laying.

The mutual information of the network regarding the two relaying algorithms can be presented as follows, respectively,

$$I_{fix} = \min\left\{\log\left(1+\xi\left|\alpha_{s,r(1)}\right|^2\right),\ldots,\log\left(1+\xi\left|\alpha_{s,r(n)}\right|^2\right),\right.$$
$$\left.\log\left(1+\xi\left(\sum_n\left|\alpha_{r(n),d}\right|^2+\left|\alpha_{s,d}\right|^2\right)\right)\right\} \tag{2}$$

and $$I_{dyn} = \log\left(1+\xi\left(\left|\alpha_{s,d}\right|^2+\sum_m\left|\alpha_{r(m),d}\right|^2\right)\right), \tag{3}$$

where n is the total number of relay nodes in the network; m is the number of the relay nodes that forward source packets to the destination node in dynamic relaying. For the nodes to perform relaying in dynamic relaying, the following requirement has to be met,

$$\left|\alpha_{r(i),d}\right|^2 \geq \omega(\xi),$$

where $\omega(\xi)=(2^R-1)/\xi$ and i = 1, 2. Unless explained, the logarithm in this paper is taken to base 2.

2.3. Outage probability

Outage occurs when the mutual information between the source and destination is below the target data rate. Outage probability characterizes the outage occurrences of the link(s) between the source and destination. Thus, the outage probability of the networks characterised by mutual information in (1) to (3) can be found as follows.

For the direct transmission network,

$$\begin{aligned} &P_{out}^{d}(\xi) \\ &:= \Pr[I_d < R] = \Pr\left[\left|\alpha_{s,d}\right|^2 < \omega(\xi)\right] \\ &= 1-e^{-\lambda_{s.d}\,\omega(\xi)} \\ &\sim \lambda_{s.d}\,\omega(\xi), \end{aligned} \tag{4}$$

where "~" stands for asymptotic as $\xi \to \infty$; λ is the parameter of the exponential distribution, which equals $(4-\pi)/4\sigma^2$.

For the fixed decode-forward relaying network with one relay node (FixOne),

$$\begin{aligned} &P_{out}^{fix,1}(\xi) \\ &:= \Pr[I_{fix} < R] \\ &= \Pr\left[|\alpha_{s,r}|^2 < \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,r}|^2 \ge \omega(\xi)\right]\Pr\left[|\alpha_{r,d}|^2 + |\alpha_{s,d}|^2 < \omega(\xi)\right] \\ &\sim \lambda_{s,r}\,\omega(\xi). \end{aligned} \tag{5}$$

When there are two relay nodes in the network (FixTwo),

$$\begin{aligned} &P_{out}^{fix,2}(\xi) \\ &:= \Pr[I_{fix} < R] \\ &= \Pr\left[|\alpha_{s,r(1)}|^2 < \omega(\xi)\right]\Pr\left[|\alpha_{s,r(2)}|^2 < \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,r(1)}|^2 + |\alpha_{s,r(2)}|^2 \ge \omega(\xi)\right] \\ &\quad \times \Pr\left[|\alpha_{r(1),d}|^2 + |\alpha_{r(2),d}|^2 + |\alpha_{s,d}|^2 < \omega(\xi)\right] \\ &\sim \frac{\lambda_{s,r(1)}\lambda_{s,r(2)}\omega^2(\xi)}{2}. \end{aligned} \tag{6}$$

For the dynamic decode-forward relaying network,

$$\begin{aligned} &P_{out}^{dyn}(\xi) \\ &:= \Pr[I_{dyn} < R] = \sum_m \Pr[m]\Pr[I_{dyn} < R \mid m]. \end{aligned} \tag{7}$$

When there is one relay node in the network (DynOne),

$$\begin{aligned} &P_{out}^{dyn,1}(\xi) \\ &= \Pr\left[|\alpha_{s,r}|^2 < \omega(\xi)\right]\Pr\left[|\alpha_{s,d}|^2 < \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,r}|^2 \ge \omega(\xi)\right]\Pr\left[|\alpha_{s,d}|^2 + |\alpha_{r,d}|^2 < \omega(\xi)\right] \\ &\sim \lambda_{s,d}\left(\lambda_{s,r} + \frac{\lambda_{r,d}}{2}\right)\omega^2(\xi). \end{aligned} \tag{8}$$

When there are two relay nodes in the network (DynTwo),

Table 1. Asymptotic diversity gain

Networks	Diversity gain, d_∞
Direct transmission	1
FixOne	1
FixTwo	2
DynOne	2
DynTwo	3

$$\begin{aligned} &P_{out}^{dyn,2}(\xi) \\ &= \Pr\left[|\alpha_{s,d}|^2 < \omega(\xi)\right]\Pr\left[|\alpha_{s,r(1)}|^2 < \omega(\xi)\right] \\ &\quad \times \Pr\left[|\alpha_{s,r(2)}|^2 < \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,d}|^2 + |\alpha_{r(1),d}|^2 + |\alpha_{r(2),d}|^2 < \omega(\xi)\right] \\ &\quad \times \Pr\left[|\alpha_{s,r(1)}|^2 \ge \omega(\xi)\right]\Pr\left[|\alpha_{s,r(2)}|^2 \ge \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,d}|^2 + |\alpha_{r(1),d}|^2 < \omega(\xi)\right] \\ &\quad \times \Pr\left[|\alpha_{s,r(1)}|^2 \ge \omega(\xi)\right]\Pr\left[|\alpha_{s,r(2)}|^2 < \omega(\xi)\right] \\ &\quad + \Pr\left[|\alpha_{s,d}|^2 + |\alpha_{r(2),d}|^2 < \omega(\xi)\right] \\ &\quad \times \Pr\left[|\alpha_{s,r(1)}|^2 < \omega(\xi)\right]\Pr\left[|\alpha_{s,r(2)}|^2 \ge \omega(\xi)\right] \\ &\sim \left[\lambda_{s,d}\lambda_{s,r(2)}\left(\lambda_{s,r(1)} + \frac{1}{2}\lambda_{r(1),d}\right)\right. \\ &\quad \left. + \lambda_{s,d}\lambda_{r(2),d}\left(\frac{1}{6}\lambda_{r(1),d} + \frac{1}{2}\lambda_{s,r(1)}\right)\right]\omega^3(\xi). \end{aligned} \tag{9}$$

The derivation of the asymptotic outage probability in (4) to (9) uses the results given in Appendix and Eqs. (39) and (42) in Ref. (4).

2.4. Diversity gain

Multiple-antenna systems can provide spatial diversity to improve the reliability or reduce error probability of wireless channels. If full spatial diversity is used in a system, it means the same signal is transmitted through the different channels created by the multiple antennas system. Cooperative relaying exploits resources owned by a group of nodes including the use of their antennas, so that can be regarded as an application of virtual multiple antennas, which will lead to a diversity gain as a result. The asymptotic estimation of the diversity gain, d_∞, as $\xi \to \infty$ is defined as [14]

Table 2. Technical specification of MPR400CB

Parameter	Value
Program Flash Memory	128K bytes
Measurement (Serial) Flash	512K bytes
Serial Communications	UART[a]
Analog to Digital Converter	10 bit ADC
Center Frequency	433 MHz
Number of Channels	4/50 (programmable, country specific)
Data Rate	38.4 Kbaud (Manchester encoded)
RF Power	-20 to +10 dBm (programmable, typical)
Receive Sensitivity	-98 dBm (typical, analog RSSI[b] at AD Ch. 0)
Outdoor Range	500 ft (1/4 Wave dipole, line of sight)
Current Draw	27 mA (transmit with maximum power); 10 mA (receive); < 1 µA (sleep)

a. Universal Asynchronous Receiver/Transmitter
b. Received Signal Strength Indication

$$d_{\infty} = -\lim_{\xi \to \infty} \frac{\log P_e(\xi)}{\log \xi}, \tag{10}$$

where $P_e(\xi)$ is the error probability. In the case of the coding block length equal to and longer than the total number of antennas in the system minus one, $P_e(\xi) = P_{out}(\xi, R)$ [14]. Then, the asymptotic diversity gain of the implemented networks described by (1) to (3) can be found, as listed in Table 1 (data rate R is fixed).

3. System implementation

In this section, we first introduce the wireless sensor transceivers that are used to build the wireless relay sensor network. Then, we describe how the relaying algorithms are realized and discuss the implementation of the nodes involved in the network. We assume that all the nodes in the network are aware of what coding scheme is being used at the time of transmission.

3.1. Wireless sensor nodes

As the performance of radio signal propagation is the primary concern in our tests, we utilize just the radio transceiver part of sensor nodes that are supplied

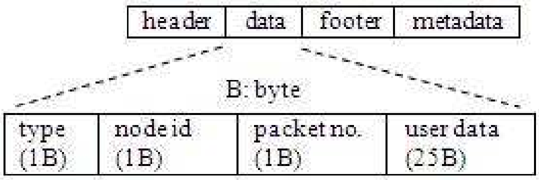

Figure 3. Data fields of source packets.

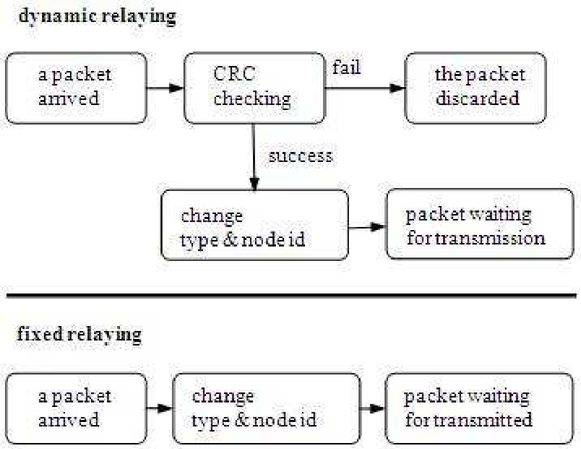

Figure 4. Relaying algorithms implementation.

by Crossbow®. Unlike other wireless devices, such as PCMCIA cards for wireless LANs and modern mobile phones, the sensor transceivers feature smaller physical dimensions with the compromised processor capability and limited embedded memory. The key specifications of the radio transceiver (manufacturer's model name is MPR400CB) are listed in Table 2, which can also be found in [16].

3.2. Relaying algorithms

The two relay algorithms, dynamic relaying and fixed relaying, differ only at the relay nodes but are operated in the same way at the source and destination nodes.

In dynamic relaying, the relay nodes need to decide whether or not it should forward the received source packets, depending on the CRC (cyclic redundancy check) result of the received packets. The packets that pass CRC will be forwarded to the destination with the data fields, "type" and "node id", being modified. The structure of a packet sent by the source is shown in Fig. 3. For those packets that fail to pass CRC, they will be discarded at the relay nodes. The main purpose of this algorithm is to ensure that the quality of the packets transmitted by relay nodes should be as good as that of the packets sent by the source node if the relay nodes

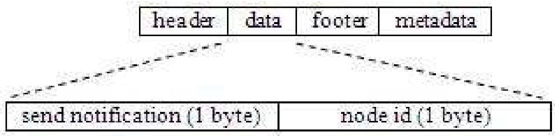

Figure 5. "You-can-relay" packet format.

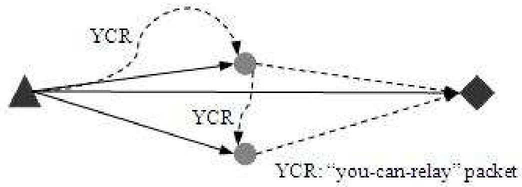

Figure 6. The TDMA scheme. (Dashed arrowed curves show the transmission of YCR packets.

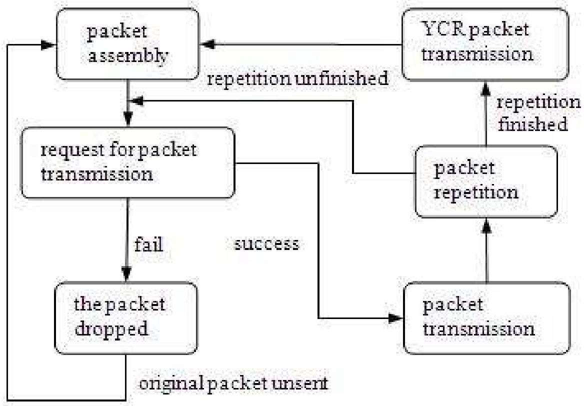

Figure 7. Source node implementation.

decide to forward the packets received. The received packets, $y(t)$, at the destination can be represented by

$$y(t) = g_{s,d}\,x(t)\delta(t - t_0) + g_{r(1),d}\,\chi(t)\delta(t - t_1) + \cdots + g_{r(n),d}\,\chi(t)\delta(t - t_n), \quad (11)$$

where $\chi(t) = \begin{cases} x(t) & \text{if crc is successful} \\ 0 & \text{otherwise} \end{cases}$.

In (11), g is the channel gain between the nodes, indexed by the subscript; $x(t)$ the packets sent by the source; and δ the time shift function.

In the fixed relaying algorithm, relay nodes simply modify the data fields, "type" and "node id", of the received source packets without CRC checking. These packets are then retransmitted when the relay nodes are signalled to do so. How to make this process work will be explained in the next subsection. The received packets, $y(t)$, at the destination can be expressed by the same equation as (11), except for the modification of $\chi(t)$, which is given by

$$\chi(t) = G g_{s,r(i)}\,x(t),$$

where G is the power gain at each relay node, defined as a ratio of the transmit power to the receive power. The identity of relay nodes is indicated by i. The implementation of the two algorithms is illustrated in Fig. 4.

3.3. The TDMA scheme

To avoid the transmission interference or collision between the wireless channels, we apply a simple TDMA scheme which can eliminate the complex handshakes among the transmit nodes for achieving synchronization. The TDMA scheme is realized by introducing a so-called "you-can-relay" (YCR) packet, the format of which is shown in Fig. 5. It can be seen that each YCR packet contains the information specifying the identity of the node. The identities of the nodes (except for the destination node) in the network are given as sequential numbers. Therefore, relay nodes can check if the YCR packet received is for them by adding one to the value of the "node id" and verifying if it equals the value of their own identity. There are two action options for the relay nodes if they are signalled by the YCR packet to transmit. If there is a correct source packet stored, the relay node will retransmit this source packet immediately followed by sending out a YCR packet for its successive relay node; otherwise, the relay node will just send out the YCR packet for its successive relay node. If the relay node is the last one, no YCR packet will be sent out from this node. The TDMA scheme is illustrated in Fig. 6. In order for the scheme to work properly, each relay node should reside in the coverage of both its preceding and the source nodes.

3.4. Node implementation

3.4.1. Source node. The functions of the source node include assembling, encoding and transmitting data packets, and sending relay signalling, i.e., YCR packets. As one of the transmission options, we apply the $(n, 1)$ repetition coding scheme in the network, where n is the code length and its value will be chosen in Section 4. The source node transmits n–1 replica for each original data packet sent out, followed by a YCR packet. The structure of the data packets sent over the radio is shown in Fig. 3. The implementation of the source node is illustrated in Fig. 7. The data packets are generated by the source node at a pace controlled by an internal clock. One clock cycle spans the duration for all relay

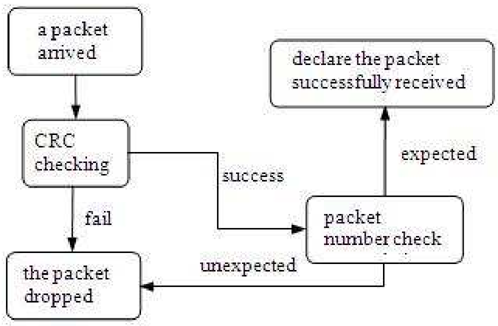

Figure 8. Destination node implementation.

nodes to transmit and the propagation delays between the nodes.

If a packet generated is accepted by the radio transceiver for transmission, then it will be either placed in a queue or transmitted immediately if the queue is empty. Packets will be discarded if the queue is already full. The clock cycle can be adjusted to avoid the loss of data as much as possible and, at the same time, to maintain a data rate as high as possible.

3.4.2. Relay node. The implementation of relay nodes has been explained in Subsections 3.2 and 3.3.

3.4.3. Destination node. Fig. 8 shows how the destination node is implemented. Once a packet has arrived, the destination node will first examine the CRC of the packet. If it fails, the packet is discarded immediately; otherwise, the destination node will then check the packet sequence number, in order to see if the packet is expected. The situation of a received packet being regarded as unexpected occurs when: a) duplicated packets have been received at the destination node; b) a number of consecutive packets are missing due to bust errors or buffer overflow; or c) the packet sequence number is corrupted. In the second case, the destination node enters a deadlock loop and is unable to decode any further packets until the packet number is restarted at the source. One solution to this problem is to increase the buffer size, although it rarely happens.

If a packet passes CRC and is recognized as the expected one, it will be stated as being successfully received. The advantages of this decoding algorithm are its simplicity and low buffer size requirement. The disadvantage is that the CRC result may be incorrect when undetectable errors are encountered, but the probability of this event is very low.

4. Tests and results

Table 3. Test settings*

Parameters	Settings
Sensor Nodes	one source node, one or two relay node(s), one destination node
Transmit Power	-5dBm
Data Rate	66×*n*×3
Test Duration	approx. 15 minutes for each test

* applied to both dynamic and fixed relaying algorithms

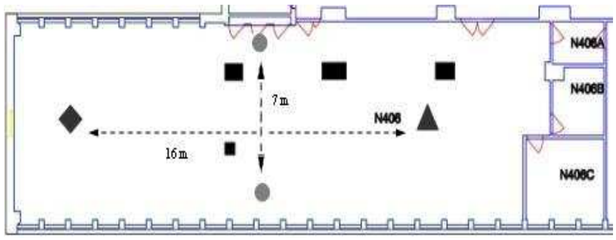

Figure 9. The laboratory layout and the locations of sensor nodes.

In this section, we present the test environment, parameter settings, and the results obtained from the tests.

4.1. Test environment

The tests were carried out in the telecommunication laboratory of the Department of Electronic Engineering at Aston University. The room layout and the location of the sensor nodes are drawn in Fig. 9. The laboratory was packed with a range of equipments including a wireless LAN operating at 2.4 GHz; but object movement was rarely observed during the tests. The source node and the destination node were placed at approximately 1m above the carpeted floor, while 1.2m for the relay nodes, throughout the tests. All the wireless channels are non-line-of-sight (NLOS). The relay nodes were placed with the equal distance to the source node and the destination node. In all tests, the transmit power of the source and relay nodes was set to -5dBm. In the single relay node case, the relay node at the bottom location in Fig. 9 was used. A new data packet was sent out from the source node every 66×*n*×3 ms, where *n* is the number of transmissions of the same packet from each transmit node, the number "66" represents the minimum time duration for one node to complete one non-interfering transmission, and the number "3" is the maximum number of transmit nodes used in our tests. Each test ran for approximately 15 minutes. The test settings are summarised in Table 3.

4.2. Test scenarios and results

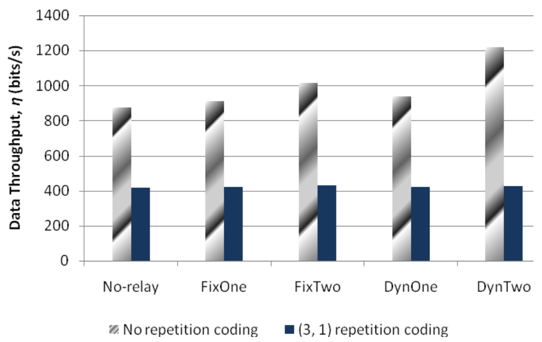

Figure 10. Data throughput, η (bits/s).
Change "no-relay" to "Direct"

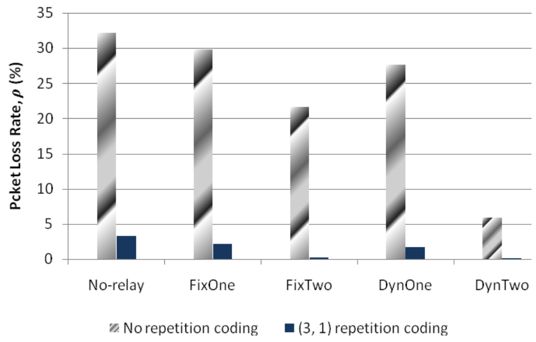

Figure 11. Packet loss rate, ρ (%)

In the tests, the transmit nodes apply the coding schemes with two length options: n=3 and n=1. For n=3, the nodes transmitted each packets three times or performed (3, 1) repetition coding. However, for n=1, no repetition coding was applied and each original packets was transmitted only once if they are not discarded at the source node due to buffer overflow. The (3, 1) repetition coding scheme can tolerate up to two losses out of the three packets transmitted, whilst for n=1 no loss protection is available. These two schemes provide us an opportunity to investigate the trade-off between the two contrast scenarios: high transmission redundancy for improving reliability (with repetition coding) versus no transmission redundancy thus no loss protection (without repetition coding). The performances of the network for our investigation, in terms of data throughput, packet loss rate, diversity gain and energy efficiency, will be examined later.

4.2.1. SNR. In order to work out the SNR, ξ, we only need to measure the noise floor of the test environment using the received signal strength indicator (RSSI). Since the test environment is quasi-static, the measured noise floor for all the tests is around -62 dBm. Thus, ξ = 57 dB (signal power is -5 dBm).

4.2.1. Data throughput. Data throughput, η, is defined as the ratio of the number of successfully received packets, N_{suc}, to the time period, T, during which these packets are received,

$$\eta = \frac{N_{suc}}{T}. \quad (12)$$

Fig. 10 shows the data throughput of the network implemented when there is (are) no relay node, one relay node and two relay nodes, respectively. It is observed that the presence of relay nodes makes no major difference in throughput for both relaying algorithms, compared to the direct transmission case, when a (3, 1) repetition code is applied in the network. This is due to the added redundancy of the repetition code used even though the loss rate can be reduced in this case. When no repetition coding is applied, however, the throughput is improved significantly by the presence of relay nodes.

4.2.2. Packet loss rate. The packet loss rate, ρ, is defined as the percentage ratio of the number of un-received packets to the total number of the packets generated at the source node, N_{gen}, i.e.,

$$\rho = \left(1 - \frac{N_{suc}}{N_{gen}}\right) \times 100\%. \quad (13)$$

The packet loss rate for the networks with and without (3, 1) repetition coding can be found in Fig. 11, respectively. As it is expected, the packet loss rate is reduced considerably when repetition coding is used, with improvements up to approximately 26%, which is far lower than that of the network with no repetition coding applied. This result has highlighted once again the trade-off between the two transmission options: one for enhancing reliability (loss rate) and the other for increasing efficiency (throughput).

4.2.3. Diversity gain. To extract the result for the diversity gain from our tests, a modification to the formula in (10) is required, such that

$$d = -\frac{\log \rho}{\log \xi}. \quad (14)$$

Since an infinite SNR is hardly achievable in the real-world environment, the measured diversity gain is non-asymptotic and can be obtained for each of the scenarios in our tests, as shown in Fig. 12. It can be observed that the introduction of relay nodes can enhance the diversity gain between the source node and

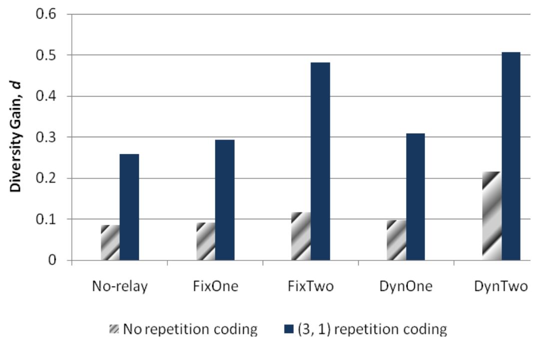

Figure 12. The diversity gain, *d*.

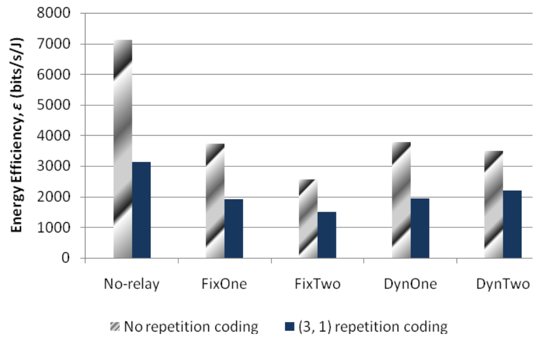

Figure 13. Energy efficiency, ε (bits/s/J)

the destination node, and that more relay nodes lead to higher diversity gain.

Fig. 12 also shows that the diversity gain in the (3, 1) repetition coded network is higher than that in no repetition coded network. This is because repetition coding generates a time diversity gain on top of the spatial diversity gain contributed by the relay nodes employed. Diversity gain, no matter in which format, is regarded as a direct contributor to the enhancement of system reliability, e.g., leading to reduced packet loss rate.

It is worth mentioning that the measured diversity gain is lower than the asymptotic value shown in Table 1. There are two reasons for this. First, the SNR value in our tests is finite. Secondly, the conventional asymptotic diversity gain is calculated in the scale of "bit", rather than of "packet" which is used in our measured diversity gain. A single erroneous bit in a packet can cause a failure in CRC checking of the whole packet, while in calculating the asymptotic diversity gain the uncorrupted bits in that packet are still considered as successfully delivered. This means that in general the packet loss rate is higher than the bit error rate under the same conditions.

4.3. Discussion

According to the diversity-multiplexing trade-off discussed in [14], any change in diversity is accompanied by the variation of multiplexing gain on the opposite direction, and vice versa. In our work, since the same data are transmitted via both direct and relaying channels, in an attempt to create full diversity, there will be no multiplexing gain. In addition, the diversity is created at the cost of energy consumption at relay nodes. To examine this type of trade-off (diversity vs efficiency), we assess the energy efficiency of the relaying algorithms used in the wireless relay sensor network implemented. The energy efficiency can be defined as the ratio of the average throughput to the total amount of energy consumed (here we are only concerned with the transmission energy consumption – the major source of energy consumption in the sensor transceivers), i.e.,

$$\varepsilon = \frac{\eta}{E} = \frac{\eta}{\sum_{i=1}^{l} P_i T_i}, \quad (15)$$

where P_i is the transmit power (fixed) at the ith transmit node in Watt, T_i is the total transmission time (including transmission of both data and YCR packets) at the ith transmit node in second, l is the number of transmit nodes; and $\sum_{i=1}^{l} T_i = T$.

As shown in Fig. 13, direct transmission consumes the least amount of energy, so has the highest energy efficiency in both cases (with and without repetition coding), although it has no advantages in throughput over the schemes using relays. It is also true for the networks applying any relaying algorithms that the efficiency will decrease as the number of relays used increases.

Clearly, by comparing the results shown in Fig. 12 and Fig.13, it can be confirmed that diversity and energy efficiency are a trade-off pair. In other words, diversity is achieved by lowering energy efficiency in this case, and vise versa.

5. Conclusions

In this paper, we have presented the theoretical model and the implementation of relaying algorithms in wireless sensor networks with dedicated relay nodes. The relaying algorithms performed at the relay nodes include: fixed relaying and dynamic relaying. In fixed relaying, relay nodes simply retransmit the received source packets; while in dynamic relaying, relay nodes will decide based on certain conditions whether or not to forward the packets received to the destination.

The tests are carried out under two scenarios: with and without (3, 1) repetition coding applied at the source and relay nodes. The results have shown that diversity gain is created by introducing the relay nodes to the network, and that consequently the system reliability in terms of the packet loss rate is improved significantly, as shown in Fig.12 and Fig. 11, respectively. Moreover, applying repetition coding can further reduce the packet loss rate as it added temporal diversity to the spatial diversity created. However, the throughput of the different transmission schemes tested remains relatively the same when repetition coding is applied. In general, dynamic relaying outperforms fixed relaying, especially when more relays are employed or there is no coding applied at the transmit nodes.

The results have also demonstrated the performance trade-offs between diversity and energy efficiency, which can be used as a guidance in the design of proper wireless sensor networks for different applications. For example, for the applications where data transmission reliability is a paramount factor and power supply can be guaranteed, such as telecare in a residential environment, adding relay nodes in the network is essential for recovering losses and insuring the reliability required.

This work can be extended to the cooperative diversity scheme where all the transmit nodes can send off their own data and, at the same time, help deliver other nodes' packets, in order to improve the resource utilization of the nodes involved.

6. Appendix

The joint frequency function $p_x(x = u+v)$ is found as

$$\begin{aligned} &p_x(x) \\ &= \int_{-\infty}^{\infty} p_u(u) p_v(x-u) du \\ &= \begin{cases} \dfrac{\lambda_u \lambda_v}{\lambda_v - \lambda_u}\left(e^{-\lambda_u x} - e^{-\lambda_v x}\right) & \lambda_u \neq \lambda_v \\ \lambda^2 x e^{-\lambda x} & \lambda_u = \lambda \end{cases}. \end{aligned}$$

Thus,

$$\begin{aligned} &\Pr[x < \omega] \\ &= \int_0^{\omega} p_x(x) dx \\ &= \begin{cases} 1 - \left(\dfrac{\lambda_v}{\lambda_v - \lambda_u} e^{-\lambda_u \omega} - \dfrac{\lambda_u}{\lambda_v - \lambda_u} e^{-\lambda_v \omega} \right) & \lambda_u \neq \lambda_v \\ 1 - (1 + \lambda\omega) e^{-\lambda\omega} & \lambda_u = \lambda_v \end{cases}. \end{aligned}$$

If $y = u+v+w$, then

$$\begin{aligned} &p_y(y) \\ &= \int_{-\infty}^{\infty} p_w(w) p_x(y-w) dw \\ &= \begin{cases} \dfrac{\lambda_u \lambda_v \lambda_w}{(\lambda_u - \lambda_w)(\lambda_v - \lambda_w)} e^{-\lambda_w y} \\ + \dfrac{\lambda_u \lambda_v \lambda_w}{(\lambda_v - \lambda_u)(\lambda_w - \lambda_u)} e^{-\lambda_u y} & \lambda_u \neq \lambda_v \\ + \dfrac{\lambda_u \lambda_v \lambda_w}{(\lambda_u - \lambda_v)(\lambda_w - \lambda_v)} e^{-\lambda_v y} \\ \dfrac{\lambda^3}{2} y^2 e^{-\lambda y} & \lambda_u = \lambda \end{cases}, \end{aligned}$$

Thus,

$$\begin{aligned} &\Pr[y < \omega] = \int_0^{\omega} p_y(y) dy \\ &= \begin{cases} 1 - \left(\dfrac{\lambda_u \lambda_v}{(\lambda_u - \lambda_w)(\lambda_v - \lambda_w)} e^{-\lambda_w \omega} \right. \\ - \dfrac{\lambda_v \lambda_w}{(\lambda_v - \lambda_u)(\lambda_u - \lambda_w)} e^{-\lambda_u \omega} & \lambda_u \neq \lambda_v \neq \lambda_w \\ \left. - \dfrac{\lambda_u \lambda_w}{(\lambda_v - \lambda_u)(\lambda_w - \lambda_v)} e^{-\lambda_v \omega} \right) \\ 1 - \left(1 + \lambda\omega + \dfrac{\lambda^2}{2}\omega^2 \right) e^{-\lambda\omega} & \lambda_u = \lambda_v = \lambda_w \end{cases}. \end{aligned}$$

In the above derivation, *u*, *v* and *w* are nonnegative and independent to each other. Also, this fact is true that

$$\lim_{\xi \to \infty} \frac{1}{\omega^3(\xi)} P_{y<\omega}(\omega(\xi)) = \frac{\lambda_u \lambda_v \lambda_w}{6}.$$

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