Journal of Computers Vol. 27, No. 4, 2016, pp. 15-27
doi:10.3966/199115592016122704002

Relay Forwarding for Wireless Sensor Networks with Disconnected Base Stations

Chia-Ho Ou

Department of Computer Science and Information Engineering, National Pingtung University, Pingtung 90004, Taiwan
cho@mail.nptu.edu.tw

Received 5 May 2015; Revised 11 August 2015; Accepted 28 August 2015

Abstract. In sensor network applications, such as battlefield reconnaissance, disaster relief, and etc., the base stations may be disconnected from the sensor network. Several approaches assume that there exist particular nodes, mobile relays, in the network that are utilized to deliver messages to the base stations for dealing with the disconnection problem. The mobile relays collect messages from the source nodes and physically carry them to the base stations. However, these schemes are designed for delay-tolerant applications. This paper proposes that the mobile relays are exploited to move to designated positions, and to use transceivers with adjustable ranges to form forwarding paths between the sensor nodes and the base stations. The effectiveness of the proposed approach is evaluated in a series of numerical investigations using the ns-2 simulator. The simulation results indicate that the proposed scheme not only outperforms existing mobile relay methods in terms of the end-to-end delay and the energy consumption but also has similar message delivery ratio with existing methods.

Keywords: mobile relays, routing, mobility, wireless sensor networks

1 Introduction

Rapid technological advances in mobile wireless networks and communication paradigms have led to the emergence of wireless sensor networks (WSNs) as a major research topic in recent years [1]. A WSN can be deployed in unattended and harsh geographic areas, where a large number of sensor nodes collaboratively collect, and report sensing data to the base stations. However, in practical deployments of WSNs, such as battlefield reconnaissance, disaster relief, and etc., the sensor nodes form a connected network but may not communicate with the base stations. For example, the sensor nodes are deployed in a hostile region for the battlefield reconnaissance application. A shooter or a commander equipped with a base station may require to keeping away from the region for safety that results in the disconnection between the sensor nodes and the base station.

In general, a routing protocol is used to deliver data from sources to destinations via multi-hop wireless transmissions. Several routing protocols have been proposed for WSNs [2]. Traditional routing protocols are designed on the assumption that the WSN is always fully connected. In the event that a connection may not exist, such protocols either simply wait for the connection to be re-established or directly drop data messages. This kind of passive approach results in unpredictable transmission delays and data loss, thereby degrading system performance considerably. Various mechanisms have been proposed to solve the problem in delay-tolerant applications [3]. Existing node mobility in the network can be utilized [4-8] or particular nodes (i.e., mobile relays) with enhanced capacities can be added to the network [9-16]. The mobile relays move around the network either randomly [5-7, 12-13] or in accordance with pre-planned trajectories [4, 8-11, 14, 16] to help other nodes to deliver messages as they pass within radio range. These approaches reduce multi-hop communication and the relaying overhead of nodes near the base stations.

However, when base stations are disconnected from the sensor network, the proposed delay-tolerant mechanisms cause considerable transmission delays and the proposed mobile relay schemes increase energy consumption since energy is required for relay movement. To reduce transmission delay and moving energy consumption in previous approaches, this paper proposes that the mobile relays moving to the specific fixed locations act as the data forwarders instead of carrying data and travelling around the network in a random or controlled manner. If a sensor node fails to deliver messages to the next hop, it requests the assistance of mobile relays. Based on the exchange of control messages, the sensor node coordinates the movements of the mobile relays to form a straight-line forwarding path. The relays adjust their locations based on location information of both the sensor node and the base station. The proposed scheme thus can be used in the previous example of battlefield reconnaissance. Once an enemy image is captured by a sensor node, mobile relays collaborate to establish a forwarding path for aiding image transmission from the sensor node to the shooter or the commander. The performance of the scheme is evaluated by conducting a series of numerical investigations using the ns-2 network simulator [17-18]. The results will demonstrate that the proposed scheme achieves competitive message delivery ratio and reduced transmission delay and energy consumption when compared to existing mobile relay schemes.

The contributions of this paper are threefold: (1) the movement coordination of mobile relays is proposed to assist message delivery in wireless sensor networks with disconnected based stations; (2) the effectiveness of the proposed scheme is estimated based on mathematical analysis in terms of message delivery ratio and energy consumption; (3) the performance of our mobile relay scheme is evaluated in a series of simulations performed using ns-2 network simulator and is compared to that of the well-known MULE [12] and FERRY [9] mobile relay mechanisms.

The remainder of this paper is organized as follows. Section 2 presents a review of mobile relay methods. Section 3 introduces the proposed protocol for mobile relays, which is analyzed in details in Section 4. Simulation experiments, results and further discussions are presented in Section 5. Finally, the research work is concluded in Section 6.

2 Related Work

Several mobile relay approaches have been proposed to deal with the disconnection problem. Based on the relay movement trajectory, the proposed mobile relay schemes can be categorized into two types: random [5-7, 12-13] and controlled [4, 8-11, 14, 16] movement.

Vahdat and Becker introduced a well-known epidemic routing in disconnected networks based on node random mobility [5]. With their own mobility, the nodes exchanges messages while they meet. Thus, the messages are propagated from sources to destinations based on pair-wise message exchanges. In Beaufour et al.'s article [6], there are mobile smart-tags moving around (i.e., randomly) the network. The disconnected static nodes exchange data with the mobile smart-tags when the mobile smart-tags are within their communication ranges. In ZebraNet project [7] presented by Juang et al., the sensor nodes are carried by the animals across a large sensing field. By exploiting animal mobility, the logged data of the sensor node is transmitted to a mobile base station (i.e., researcher) by hop-by-hop communications. Mobile entities known as data mules are introduced to collect sensor data in sparse sensor networks [12-13]. Data mules can gather data from sensor nodes when mules are close to sensor nodes and store data in their buffers for delivering data to base stations.

A representative of the controlled mobility mechanism is proposed by Li and Rus for disconnected ad hoc networks [4]. To prevent disconnected transmissions, the intermediate nodes between the source and the destination dynamically modify their movements. Ssu et al. proposed to use existing mobile nodes to helping nodes, and transport messages across the network partitions. An appropriate helping node chosen by the source moves toward the destination using location service [8]. Zhao et al. presented a message ferry approach for data delivery in sparse mobile ad hoc networks [9-10]. A set of special mobile nodes called message ferries following with pre-defined routes provide data delivery service for the ordinary nodes. Two types of communication method are used in the message ferry scheme. In the node initiated scheme, the ordinary node knowing the ferry routes proactively moves close to a ferry for communication. In the ferry initiated scheme, the ordinary node sends a notification to a ferry if the ordinary node wants to communicate with other nodes. Upon reception of the notification, the ferry moves proactively to meet the node. Multiple messengers are exploited to relay messages among partitioned networks in [11]. The authors also presented an algorithm for scheduling the movement of messengers among partitioned networks. For enhancing random mobility of data mule, Jea et al. proposed a multiple data mule approach by designing mule movement trajectories to collect data from sensor nodes [14]. Recently, Heimfarth and De Araujo proposed to use Unmanned Aerial Vehicle (UAV) for message ferrying in disconnected wireless sensor networks [16]. For using less mobile relays, an UAV acting as a data mule physically carries packets across partitioned networks. A cluster head is elected in each disjoint network and communicates with the UAV for message ferrying.

The previous proposed schemes do not consider base stations may be isolated from the sensor networks and thus result in more transmission delays and energy consumption on message delivery. Therefore, our proposed mobile relay approach focuses on the sensor network applications with disconnected base stations, e.g., battlefield reconnaissance, disaster relief, and etc.

3 The Proposed Protocol

Due to application features, the base stations are partitioned from the sensor network. With the disconnected network, the sensor nodes cannot communicate with the base stations directly or by multi-hop message delivery. The disconnection problem may give a serious impact on the application performance. For example, the emergency message (e.g., enemy image) may not be timely transmitted to the commander in battlefield reconnaissance. Therefore, a mobile relay assisted message delivery scheme is proposed to deal with communication between the sensor nodes and the base stations in the disconnected network. The proposed mobile relay protocol consists of two steps, mobile relay discovery and mobile relay coordination. First, when a sensor node is not able to forward messages to a base station (i.e., no neighboring sensor nodes is available), the mobile relay discovery procedure is activated to request assistance of nearby mobile relays. Second, the movements of mobile relays participating in constructing a forwarding path to a base station are coordinated by the sensor node.

3.1 System model

The sensor network model considered in this paper consists of sensor nodes, mobile relays, and base stations. All sensor nodes are randomly deployed on a sensing field and remain static once they have been deployed. It is considered that no sensor nodes can directly communicate with the base stations. Greedy forwarding [19] is used for message delivery in the sensor network. The sensor nodes determine their locations using some form of localization scheme [20-21], while the mobile relays determine their locations using the global positioning system (GPS) [22]. The locations of the base stations are known to all the sensor nodes, which is an assumption common to all position-based routing protocols [23-24]. It is further assumed that each sensor node has a fixed radio range r_s and each mobile relay can adjust its transmission range r_r between $[r_{\min}, r \max]$. Each mobile relay has two possible states: wait and work. The initial state of the mobile relay is the wait state. A mobile relay changes to the work state when moving to a fixed position.

3.2 Mobile relay discovery

For description purposes, consider that a sensor network consists of n_s sensor nodes such that, n_r mobile relays such that R = $\{ m_i | i = 1, \dots, n_r \}$, and n_b base stations such that B = $\{ b_i | \mathrm{i} = 1, \dots, n_b \}$. The *k*th hop neighboring relays of s_i are denoted as $N_k\ (s_i) = \{ m_j\ | j = 1, \dots, m \}$.

Each sensor node s_i forwards messages to the base station b_i which is closer to itself based on the greedy forwarding. If s_i is not able to find the next hop (e.g., if greedy forwarding fails), then s_i asks neighboring mobile relays to assist forwarding message. First, s_i broadcasts the relay request (RREQ) message to its one-hop neighboring relays $N_1\ (s_i)$. The sensor node s_i starts a reply timer for waiting relay reply (RREP) messages. Each RREQ message contains the positions of both b_i and s_i. On receiving a RREQ message, if m_j is not in wait state, the message will be dropped; otherwise, m_j waits a randomized interval to reply s_i a RREP message and then transits to work state. The RREP message includes the location of m_j. The randomized transmission is used to prevent RREP collisions at s_i. After the reply timer is expired, if s_i does not receive any RREP message, it re-broadcasts the RREQ message to $N_2(s_i)$. If s_i still cannot obtain any RREP message, it does not extend the hop range of the RREQ message until the receipt of response from m_j.

3.3 Mobile relay coordination

The coordination among the movements of the relays is controlled by s_i. Consider that s_i receives m RREP messages from mobile relays $M' = \{m_j' \mid j = 1, \ldots, m\}$. Based on $D = \{d_j = \| m_j' - b_j \| \mid j = 1, \ldots, m\}$, the Euclidean distance between m_j' and b_j, s_i assigns each mobile relay an order $o(m_j')$, where $1 \le o(m_j') \le m$. The maximal d_j is determined as $o(m_j') = 1$, and so on. After order determination, s_i sequentially transmits the ORDER message to M' and starts an ack timer. The ORDER message includes both m and $o(m_j')$ for m_j'.

On receiving the ORDER message, m_j' waits a randomized time to response s_i an ACK message. If not all ACK messages sent by M' are received, s_i will retransmit the ORDER message for m_j' whose ACK message is not received. The relays M' then compute the mathematical equation of the straight-line between s_i and b_i, as shown in Figure 1. The equation of the straight-line $\overline{b_i s_i}$ is formulated as

$$\overline{b_i s_i} : \frac{y - y_c}{x - x_c} = \frac{y_c - y_s}{x_c - x_s} = m \tag{1}$$

Having computed the equation of the straight-line, M' then move to specific positions along the line (designated as Relaying Points (RP_s)) to construct a forwarding path. Accordingly, in specifying the positions of adjacent relays along $\overline{b_i s_i}$, the set of RP can therefore be defined as

$$RP_1 = \{(x_1, y_1) \mid x_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, y_1 = m(x_1 - x_c) + y_c\} \tag{2}$$

in which $a = m^2 + 1, b = -(2m^2 + 2)x_c, c = (m^2 + 1)x_c^2 - r_s^2$, and

$$RP_1 = \{(x_1, y_1) \mid x_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, y_1 = m(x_i - x_{i-1}) + y_{i-1}, i = 2, \ldots, x\} \tag{3}$$

in which $a = m^2 + 1, b = -(2m^2 + 2)x_{i-1}, c = (m^2 + 1)x_{i-1}^2 - r_r^2$. Due to different configurations on transmission ranges, $\|s_i - RP_1\|$ is specified as r_s and $\|RP_{i+1} - RP_i\|$ where $i = 2, \ldots, x-1$ are defined as r_r. The configuration of the adjustable transmission range for m_j' is given by

$$r_r = \frac{D}{n} \tag{4}$$

Where $D = \|RP_1 - b_i\|$.

Fig. 1 depicts that the relay points (e.g., RP_1, RP_2, …, RP_n) calculated based on Equations 2 and 3 and the corresponding transmission range for each mobile relay (r_r) are used to construct a forwarding path between the sensor node s_i and the base station b_i. To connect s_i and b_i, the mobile relay must be physically located at each of RP. The order $o(m_j')$ is used to determine which relaying point is for m_j'. For instance, if $o(m_j') = p$, m_j' should move to RP_P. The order assignment makes the relay is able to move at each of RP without any collision and minimizes the movement distance of relays. As long as each mobile relay arrives its assigned RP, messages can be delivered via one (relay) by one (relay) to the base station. Once the data transmission has been completed, s_i sends an END message containing identities of both s_i and b_i to the relays M'. Upon receiving this message, M' return to wait state.

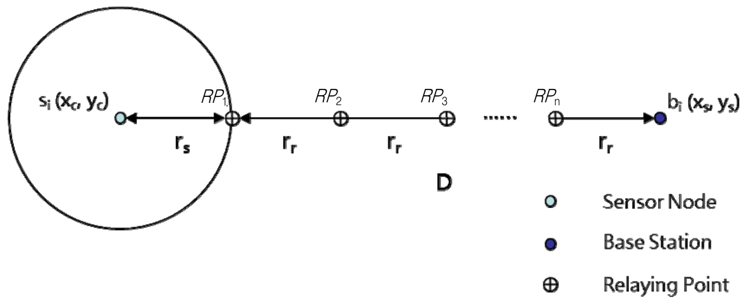

Fig. 1. Relay point determination

4 Analysis

To evaluate the performance of the proposed mobile relay scheme, the message delivery ratio and energy consumption of the proposed scheme are analyzed. First, with the proposed scheme, the message delivery ratio depends on the time required to construct the forwarding path. This is because the sensor node will drop the messages due to a limited buffer before the forwarding path is established. A worst case is investigated to evaluate the path construction time of the proposed scheme. Second, the relay mobility is exploited for message delivery in disconnected sensor networks. The moving energy consumption is essential to our proposed scheme and is thus included in the energy consumption analysis. A worst case considering moving energy consumption in the proposed scheme is presented.

4.1 Message delivery ratio

The effectiveness of the proposed scheme can be gauged largely by measuring the message delivery ratio in the sensor network. For analyzing the message delivery ratio, a time model comprising fixed-length time slots is utilized for illustration purposes [9]. Suppose that all messages have an identical size and that the length of each time slot is denoted by μ. Let $g_i(t)$ be the message generation rate at a source node *i* during time slot *t* . The cumulative number of messages generated over all of the time slots in a time interval [1, *t*] is therefore given by

$$G_i(t) = \sum_{k=1}^{t} g_i(k)\mu \quad \textbf{(5)}$$

In the proposed scheme, the mobile relays do not carry messages transmitted from the sensor node, but simply forward them. Hence the message loss rate for node *i* during time slot *t* is given by $L_i(t) = G_i(t)$.

When the sensor nodes and the base station remain partitioned, all of the messages produced by the sources are dropped. However, as soon as a forwarding path has been constructed, the messages can be transmitted to the base station. The path construction time is thus a critical factor in determining the total number of dropped messages. Consider that there are *M* mobile relays with transmission range r_r are randomly deployed with a relay degree ρ on an $l \times l$ field. The relay degree is defined as the average number of neighboring mobile relays of a sensor node. Therefore, ρ is given by

$$\rho = \frac{\pi M r_s^2}{l^2} \quad \textbf{(6)}$$

where r_s is the radio range of the sensor node.

Consider that ρ mobile relays traveling with the same velocity v move to build a forwarding path between node *i* and the base station. The total path length is $D + r_s$. The distance traveled by each mobile relay in moving to its corresponding relaying point can be denoted by d_i, where $i = 1, \ldots, \rho$. Fig. 2 shows a worst case that a mobile relay R_j located at the farthest distance away from the relaying point

$RP_{\rho}[\![(d]\!]_j = D - \frac{D}{\rho} + 2r_s)$ has to move to the relaying point RP_{ρ}. The uppermost limit of the path construction time is therefore determined by the time spent by the remotest relay R_j in traveling to its relaying point. Assume that $D > r_s$, d_j can be inferred as

$$d_j = D - \frac{D}{\rho} + 2r_s \approx (1 - \frac{1}{\rho})D \quad \textbf{(7)}$$

The time required to construct the forwarding path is given by

$$T = \max\{\frac{d_i}{v} \mid i = 1...\rho\} = \frac{d_j}{v} = \frac{(1 - \frac{1}{\rho})D}{v} \quad \textbf{(8)}$$

The total number of dropped messages is therefore derived as

$$L = L_i(T) = L_i(\frac{(1 - \frac{1}{\rho})D}{v}) = \sum_{k=1}^{(1-\frac{1}{\rho})D} g_i(k)\mu \quad \textbf{(9)}$$

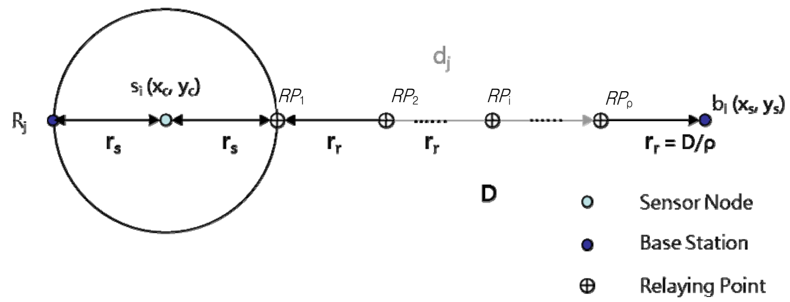

Fig. 2. Message delivery ratio analysis

Equation (9) is inferred that the message delivery ratio can be improved by reducing the path construction time. In practice, this can best be achieved by increasing the moving speed of relays and decreasing the relay degree. Note that the less number of mobile relays causes a shorter movement distance of the remotest mobile relay based on Equations (2) and (3). However, reducing ρ to $\hat{\rho}$ means that r_r has to be extended to $\frac{D}{\hat{\rho}} > \frac{D}{\rho}$, where $\hat{\rho} < \rho$ It can incur more energy consumption on transmitting data packets. There is a tradeoff between the message delivery ratio and the energy consumption. The analysis for energy consumption will be discussed in Section 4.2.

4.2 Energy consumption

The energy consumption for the proposed scheme can be categorized into two types, including communication (transmitting and receiving messages) and movement. The energy model is based on the model presented by Heinzelman et al. [25]. The model assumes that the radio dissipates e_{elec} to activate the transmitter or the receiver circuitry and $\in_{amp}$ to activate the transmitter amplifier.

The model supposes an r^2 energy loss during channel transmission. For transmitting a message of length k over a distance d, the radio thus consumes a total energy of

$$E_{TX}(k,d) = e_{elec} \bullet k + e_{TX} - amp(k,d) \quad \textbf{(10a)}$$

$$= e_{elec} \bullet k + \in_{amp} \bullet k \bullet d^2 \quad \textbf{(10b)}$$

In addition, in receiving this message, the receiver radio requires an energy of

$$E_{RX}(k) = e_{elec} \bullet k \quad \textbf{(11)}$$

The movement of a relay dissipates e_{move} per unit distance. For moving d distance, the mobile relay needs an energy of

$$E_{mv}(d) = e_{move} \bullet d \quad \textbf{(12)}$$

For evaluating energy consumption of the proposed scheme, it is assumed that the node i transmits a message of length m to a base station. As discussed in Section 4.1, ρ mobile relays adjust their transmission ranges (i.e., $r_r = \frac{D}{\rho}$) to connect the path between the node i and the base station. With communication energy consumption, the node i transmits the message and all the mobile relays have to receive and forward the message. Receiving on the base station is not considered due to its energy-efficient capability. The communication energy consumption (E_c) is therefore given by

$$E_c = E_{TX}(m, r_s) + \rho(E_{TX}(m, \frac{D}{\rho}) + E_{RX}(m)) \quad \textbf{(13a)}$$

$$= e_{elec} \bullet m + \in_{amp} \bullet m \bullet r_s^2 + \rho(e_{elec} \bullet m + \in_{amp} \bullet m \bullet (\frac{D}{\rho})^2 + e_{elec} \bullet m) \quad \textbf{(13b)}$$

$$= (2\rho + 1)(e_{elec} \bullet m) + \in_{amp} \bullet m \bullet (\frac{D^2}{\rho^2} + r_s^2) \quad \textbf{(13c)}$$

$$\approx (2\rho + 1)(e_{elec} \bullet m) + \in_{amp} \bullet m \bullet \frac{D^2}{\rho^2} \quad \textbf{(13d)}$$

For estimating moving energy consumption, Fig. 3 displays a worst case where all the relays are located at f and move to their specified relaying points respectively. With the scenario, each relay moves at a maximum distance to construct the forwarding path. The moving energy consumption (E_m) for all the relays is derived as

$$E_m = \sum_{k=0}^{\rho-1} E_{MV}(k \bullet \frac{D}{\rho} + 2r_s) \quad \textbf{(14a)}$$

$$\approx \sum_{k=1}^{\rho-1} E_{MV}(k \bullet \frac{D}{\rho}) \quad \textbf{(14b)}$$

$$= e_{move}(\frac{\rho(\rho-1)}{2} \bullet \frac{D}{\rho}) \quad \textbf{(14c)}$$

$$= e_{move} \bullet (\frac{(\rho-1)D}{2}) \quad \textbf{(14d)}$$

The total energy consumption (E) is therefore given by

$$E = E_c + E_m \quad \textbf{(15a)}$$

$$= (\rho + 1)(e_{elec} \bullet m) + \in_{amp} \bullet m \bullet \frac{D \bullet}{\rho^2} + e_{move} \bullet \frac{(\rho-1)D}{2} \quad \textbf{(15b)}$$

It can be concluded that the communication energy consumption can be improved by increasing the relay degree. Conversely, it results in an increase of the moving energy consumption.

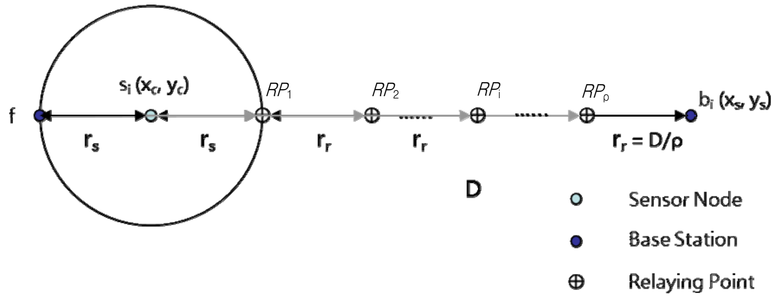

Fig. 3. Energy consumption analysis

5 Performance Evaluation

The effectiveness of the proposed scheme was evaluated by performing numerical investigations using the ns-2 simulator with Monarch Project wireless and mobile extensions [26]. The simulations were performed using IEEE 802.11 and its distributed coordination function (DCF) as the medium access control (MAC) protocol. GPSR [19] was selected as the routing protocol because it is currently one of the most popular location-based routing protocols.

5.1 Evaluation metrics and methodology

The size of simulation field is 500 m x 500 m. Three base stations are located at (0, 500), (250, 500), and (500, 500), respectively, while the sensor nodes (200 in total) and the mobile relays with a relay degree ρ are randomly deployed within an area measuring 250 m x 500 m in the lower field. The node deployment is based on the configurations for targeted applications (e.g., battlefield reconnaissance). The transmission range of the sensor node is r_s = 50 m and the transmission range of the mobile relay is adjustable between $r_r \in [r_{\min}, r_{\max}]$, where $r_{\min} = r_s$ and $r_{\max}$ = 250 m. Each relay can move at a constant speed v. Transmitter/receiver electronics (e_{elec}) consume 50 nJ/bit and transmitter amplifier ($\in_{amp}$) consumes 100 pJ/bit/m^2. Based on the suggestions for the energy model [27], the moving energy (e_{move}) is specified as 961.92 μJ/m (i.e., calculated from Equation (10) based on the 64 bytes packet). In each simulation, ten Constant Bit Rate (CBR) traffic sources are simultaneously originated from ten arbitrarily nominated sensor nodes in the beginning of each simulation. The message generation rate for each source is four messages per second through the simulation period, with each packet having a length of 64 bytes. The timeout for both the reply and the ack timer for the sensor node is one-second. Each simulation has duration of 500 seconds. For each set of simulation conditions, fifty simulation runs were performed with different initial node deployments.

In the simulations, the performance of the proposed scheme was benchmarked against that of two representative mobile relay methods, MULE [12] and FERRY [9]. With MULE scheme, sensor nodes discover and ask neighboring relays transporting data to base stations. The original design of MULE assumes that the relays move randomly. For fair performance comparison, the relays are assumed to know the locations of the base stations and thus directly carry data to the base stations. With FERRY scheme, the relays move based on a predefined route (i.e., (0, 250) → (0, 500) → (500, 500) → (500, 250) → (0, 250)). Sensor nodes are aware of the route and moving speed of the relays, and then can deliver data to relays when relays are within their transmission ranges. In implementing MULE and FERRY schemes, it was assumed that each relays has a buffer of 1920 bytes to store messages and moves at a constant speed v.

The performance of the proposed scheme was evaluated using the following metrics:

(1) Message delivery ratio: the ratio of the number of messages successfully received by the base stations to the total number of messages transmitted by the sources.

(2) End-to-end delay: the time taken for a message to be transmitted from the sources to the base stations.

(3) Energy consumption: the energy consumed in communication (data and control messages) and moving during the simulation period.

5.2 Results

Impact of relay speed. Fig. 4 presents the message delivery ratios for MULE, FERRY, and the proposed scheme under different relay speeds (from 10 to 30 m/s). Obviously, increasing relay speed improved the message delivery ratios for all schemes. Because relays have to physically carry messages to base stations, increasing the moving speed yielded a significant increase in the message delivery ratio for MULE and FERRY schemes. When the relay speed accelerated to 30 m/s, MULE scheme achieved the best performance. The proposed scheme uses mobile relays to build forwarding paths to base stations. As presented in Section IV-A, the message delivery ratio depends on the moving speed of relays. The message delivery ratio advanced from 74% to 84% as the relay speed increased from 10 to 30 m/s. The proposed scheme surpassed MULE and FERRY schemes with the relay speed less than 30 m/s in the message delivery ratio.

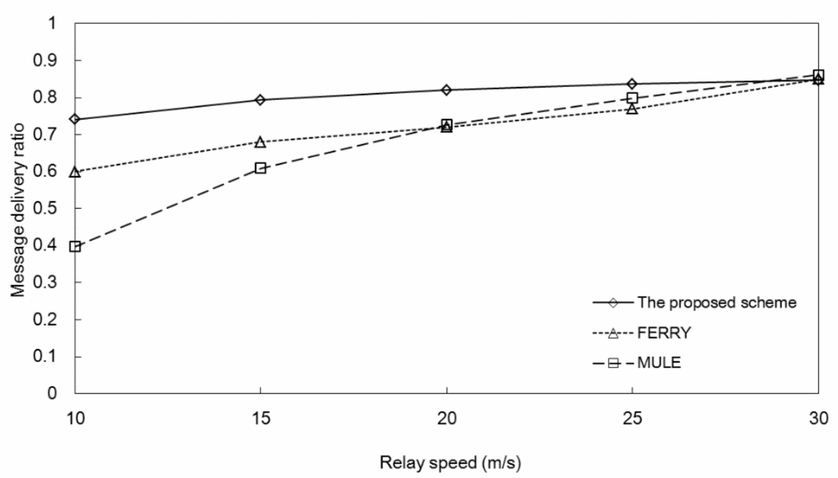

Fig. 4. Message delivery ratio versus relay speed ($\rho = 1$)

Fig. 5 shows the impact of relay speed on the end-to-end delay for three schemes. Apparently, increasing the relay speed decreased the end-to-end delay for all mechanisms. The delay of both MULE and FERRY was much longer than that of the proposed scheme. This is because message delivery of MULE and FERRY schemes primarily depends on physical movements. Conversely, the proposed scheme delivers messages based on hop-by-hop wireless transmissions and thus performed much better than MULE and FERRY schemes under varying relay speeds.

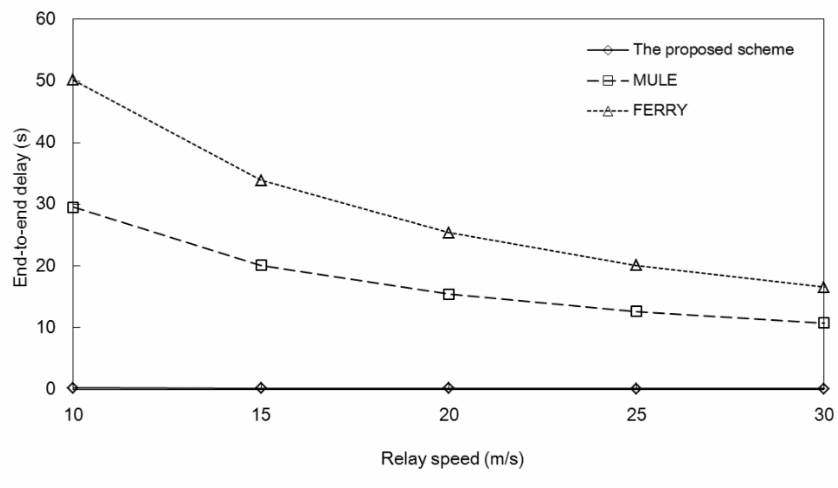

Fig. 5. End-to-end delay versus relay speed ($\rho = 1$)

Table 1 illustrates different parts of energy consumption for three methods. The energy consumption counts transmitting / receiving data / control messages and moving. The proposed scheme may extend transmission range to deliver messages to base stations so that the data energy consumption was more than that of MULE and FERRY schemes. However, both MULE and FERRY schemes had a larger moving energy consumption due to lots of round-trip data transportation. In the proposed scheme, relays only move to the relaying points for forwarding data packets so the moving energy consumption was almost 8.2 and 18.5 times less than that of MULE and FERRY schemes, respectively. In addition, FERRY scheme did not need to discover relays so its energy consumption on control messages was less than MULE and the proposed scheme.

Table 1. Energy consumption for three schemes (ρ = 1, v = 20 m/s)

Type	The proposed scheme (joule)	MULE (joule)	FERRY (joule)
Data	0.275	0.185	0.121
Move	1.25	10.206	23.086
Control	0.006	0.006	0.003
Total	1.532	10.398	23.21

As shown in Fig. 6, the energy consumption for MULE and FERRY significantly increased as the relays moved faster. More messages were transported by relays to the base stations so more moving and data energy consumptions were needed. In the proposed scheme, its energy consumption enlarged a little on data transmission. The faster speeds make mobile relays to build the forwarding path more quickly. For that reason, the data energy consumption extended with the increase of the successfully delivered messages. The proposed scheme had a better energy saving then other methods under varying relay speeds.

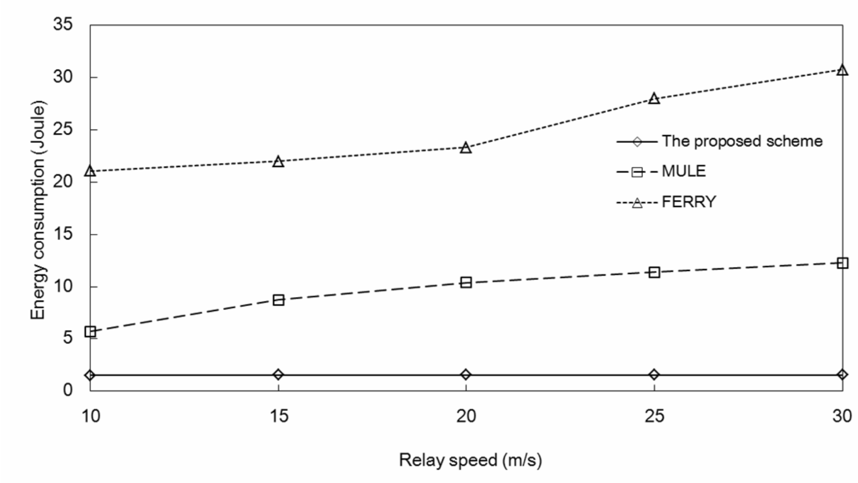

Fig. 6. Energy consumption versus relay speed (ρ = 1)

Impact of relay degree. Fig. 7 illustrates the message delivery ratio for three schemes under different relay degrees (from 0.5 to 4). With the increase of the number of relays, MULE and FERRY schemes gradually advanced the message delivery ratio about 37% (from 49% to 86%) and 33% (from 60% to 93%), respectively. Conversely, the delivery ratio of the proposed scheme slightly fell down about 4%. With the proposed scheme, all the available mobile relays (i.e., within the sensor node's communication range) will join the forwarding path construction process. In other words, as the number of mobile relays increases, the sensor node has to spend more time for waiting that all the relays move to their specific positions. The number of dropped messages thus increases (see equation (9)). However, the proposed scheme performed better than other schemes when the relay degree is less than 2.

Fig. 8 depicts the impact of relay degree on the end-to-end delay for three methods. The delay of the proposed scheme slightly increased as the relay degree extended. More mobile relays participate in data forwarding; more time is required to establish the forwarding path. Conversely, the delay of MULE and FERRY remained a constant value with different relay degrees. Placing more mobile relays did not affect the transmission delay of MULE and FERRY schemes.

Fig. 9 displays the impact of the relay degree on energy consumption for three schemes. Deploying more relays in the networks increased more energy consumptions for all schemes. As the relay degree

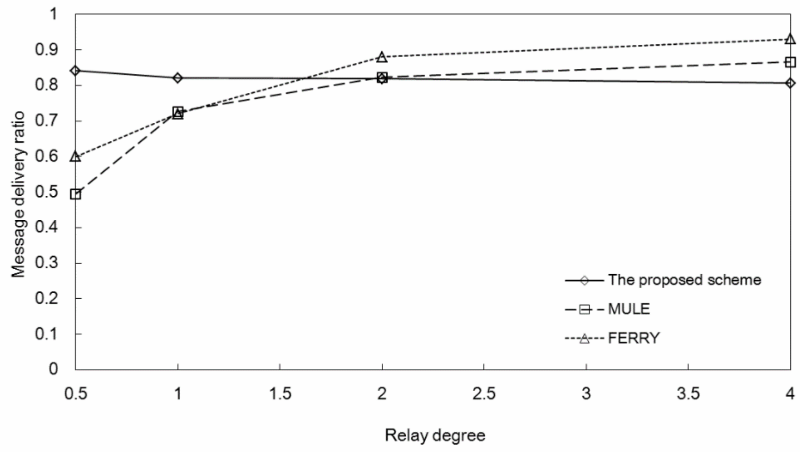

Fig. 7. Message delivery ratio versus relay degree (v = 20 m/s)

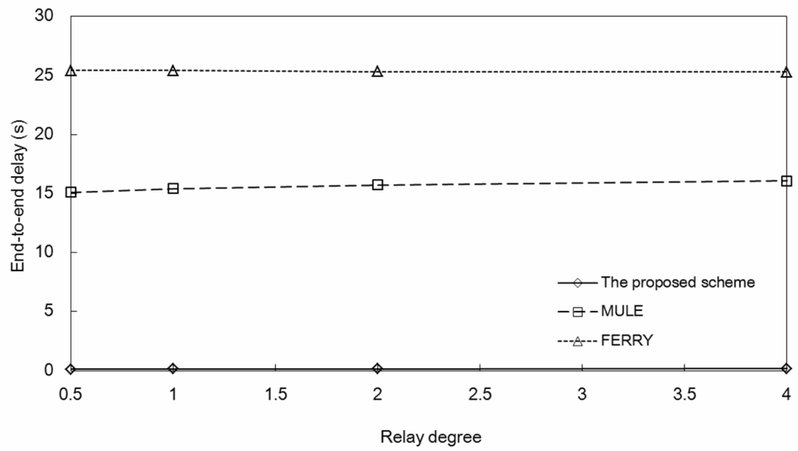

Fig. 8. End-to-end delay versus relay degree (v = 20 m/s)

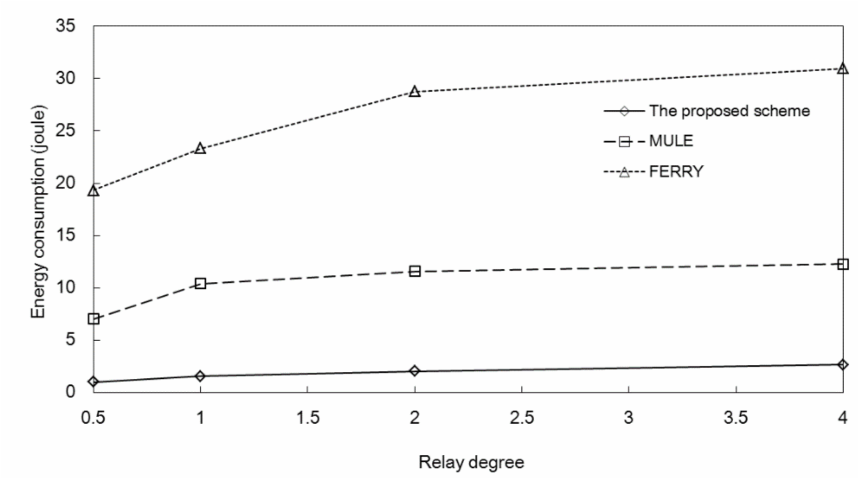

Fig. 9. Energy consumption versus relay degree (v = 20 m/s)

increased from 0.5 to 4, MULE and FERRY schemes consumed about 5.2 and 11.5 joules, respectively, more on data, control messages, and moving. With a higher relay degree, more relays moving to relaying points form forwarding paths in the proposed scheme. As analyzed in Section IV-B, more moving and control energy was required. Though the data energy consumption was reduced, the increase of the moving energy consumption was still more than the decrease of the data energy consumption. When the relay degree increased from 0.5 to 4, the total energy consumption raised from 1 to 2.6 joules. However, the energy consumption of the proposed scheme was significantly lower than that of MULE or FERRY schemes.

6 Conclusion

This paper has presented a mobile relay scheme for achieving energy-efficient, fast, and reliable data delivery in the sensor network with disconnected base stations. In the approach, relays move to appropriate relaying points to construct data forwarding paths from the sensor network to the base stations. They simply act as forwarders in transmitting the collected data so the transmission delay and consumed energy are significantly reduced. The analysis of the message delivery ratio and the energy consumption are presented to verify the effectiveness of the proposed scheme. In addition, a series of numerical investigations have been conducted using the ns-2 network simulator. The performance of the proposed approach is compared with MULE and FERRY methods. The results have shown that the message delivery ratio of the proposed scheme is competitive to that of MULE and FERRY schemes. Moreover, the proposed scheme spends much less time and energy on message delivery than MULE and FERRY schemes.

Acknowledgement

The authors would like to thank the anonymous reviewers and the editors for the valuable suggestions that improved this paper. This work was supported by Ministry of Science and Technology of Taiwan under Contract 101-2221-E-251-004.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Computer Networks 38(4)(2002) 393-422.

[2] K. Akkaya, M. Younis, A survey on routing protocols for wireless sensor networks, Ad Hoc Networks 3(3)(2005) 325-349.

[3] L. Pelusi, A. Passarella, M. Conti, Opportunistic networking: data forwarding in disconnected mobile ad hoc networks, IEEE Communications Magazine 44(11)(2006) 134-141.

[4] Q. Li, D. Rus, Sending messages to mobile users in disconnected Ad-Hoc wireless networks, in: Proc. of ACM International Conference on Mobile Computing and Networking (MOBICOM), 2000.

[5] A. Vahdat, D. Becker, Epidemic routing for partially-connected ad hoc networks, Duke University, Tech. Rep. CS-2000-06, 2000.

[6] A. Beaufour, M. Leopold, P. Bonnet, Smart-tag based data dissemination, in: Proc. of ACM International Workshop on Wireless Sensor Networks and Applications (WSNA), 2002.

[7] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. Peh, D. Rubenstein, Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet, ACM SIGOPS Operating Systems Review 36(5)(2002) 96-107.

[8] K.F. Ssu, C.H. Chou, W.T. Wang, S.H. Chung, Improving data transmission with helping nodes for geographical ad hoc routing, Computer Networks 51(18)(2007) 4997-5010.

[9] W. Zhao, M. Ammar, E. Zegura, A message ferrying approach for data delivery in sparse mobile ad hoc networks, in: Proc. of ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC), 2004.

[10] W. Zhao, M. Ammar, E. Zegura, Controlling the mobility of multiple data transport ferries in a delay-tolerant network, in: Proc. of IEEE Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), 2005.

[11] K. Harras, K. Almeroth, Inter-regional messenger scheduling in delay tolerant mobile networks, in: Proc. of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2006.

[12] R. Shah, S. Roy, S. Jain, W. Brunette, Data MULEs: modeling a three-tier architecture for sparse sensor networks, in: Proc. of IEEE International Workshop on Sensor Network Protocols and Applications (SNPA), 2003.

[13] S. Jain, R. C. Shah, W. Brunette, G. Borriello, S. Roy, Exploiting mobility for energy efficient data collection in wireless sensor networks, Mobile Networks and Applications, 11(3)(2006) 327-339.

[14] D. Jea, A. Somasundara, M. Srivastava, Multiple controlled mobile elements (data mules) for data collection in sensor networks, in: Proc. of IEEE/ACM International Conference on Distributed Computing in Sensor Systems (DCOSS), 2005.

[15] M. D. Francesco, S. K. Das, G. Anastasi, Data collection in wireless sensor networks with mobile elements: a survey, ACM Transactions on Sensor Networks 8(1)(2011) 7.

[16] T. Heimfarth, J.P. De Araujo, Using unmanned aerial vehicle to connect disjoint segments of wireless sensor network, in: Proc. of IEEE International Conference on Advanced Information Networking and Applications (AINA), 2014.

[17] The Network Simulator - ns-2. [Online]. 〈http://www.isi.edu/nsnam/ns/〉

[18] The ns Manual. [Online]. 〈http://www.isi.edu/nsnam/ns/doc/index.html〉

[19] B. Karp, H. T. Kung, GPSR: greedy perimeter stateless routing for wireless networks, in: Proc. of ACM International Conference on Mobile Computing and Networking (MOBICOM), 2000.

[20] T. He, C. Huang, B. Blum, J. Stankovic, T. Abdelzaher, Range-free localization schemes for large scale sensor networks, in: Proc. of ACM International Conference on Mobile Computing and Networking (MOBICOM), 2003.

[21] K. F. Ssu, C. H. Ou, H. C. Jiau, Localization with mobile anchor points in wireless sensor networks, IEEE Transactions on Vehicular Technology 54(3)(2005) 1187-1197.

[22] B. Hofmann-Wellenhof, H. Lichtenegger, J. Collins, Global Positioning System: Theory and Practice, Springer-Verlag, 1997.

[23] I. Stojmenovic, Position-based routing in ad hoc networks, IEEE Communications Magazine 40(7)(2002) 128-134.

[24] M. Mauve, A. Widmer, H. Hartenstein, A survey on position-based routing in mobile ad hoc networks, IEEE Network 15(6)(2001) 30-39.

[25] W. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: Proc. of the Hawaii International Conference on System Sciences (HICSS), 2000.

[26] J. Broch, D. Maltz, D. Johnson, Y.-C. Hu, J. Jetcheva, A performance comparison of multi-hop wireless ad hoc network routing protocols, in: Proc. of ACM International Conference on Mobile Computing and Networking (MOBICOM), 1998.