LETTER

Interference-aware Energy-efficient Geographical Routing for IEEE 802.15.4a Networks

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SUMMARY The IEEE 802.15.4a standard enables geographical routing in ZigBee networks but previous geographical routing algorithms can suffer high packet loss due to the interference effects. This letter proposes an interference-aware energy-efficient geographical routing algorithm for the IEEE 802.15.4a networks. The proposed algorithm estimates the energy cost by considering the interference effects and forwards a packet to the neighbor with the lowest energy cost to advance. Experimental results show that the proposed algorithm outperforms the previous algorithms in terms of the delivery ratio and the energy consumption.

key words: *Interference, Geographical routing, 802.15.4a*

1. Introduction

IEEE 802.15.4/ZigBee is a standard for the low-rate wireless personal area networks [1]. The ZigBee defines the network layer on the top of the medium access control layer (MAC) and the physical layer (PHY) of the IEEE 802.15.4. In ZigBee networks, the power conservation is very important because nodes are usually operated on limited batteries. A well designed routing protocol can reduce the energy consumption and increase the communication bandwidth. The ZigBee standard defines two routing protocols: the ad-hoc on-demand distance vector routing protocol (AODV) and the hierarchical routing protocol (HRP). The AODV floods the route request (RREQ) message over the network to find the destination, and thus it causes a large message overhead. In the HRP, a packet is forwarded to the coordinator (the root node in a tree topology) and the coordinator forwards the packet to the destination. HRP incurs much less message overhead than AODV, but it establishes long routes.

The IEEE 802.15.4a is an amendment to the IEEE 802.15.4 and it defines two additional PHYs based on the ultra wide band (UWB) and the chirp spread spectrum (CSS) to support high accuracy localization [2]. If the location information is available, the geographical routing protocol is more efficient than AODV or HRP. Most geographical routing protocols use the greedy forwarding and the face recovery [5] [10]. The greedy forwarding transmits a packet to the neighbor geographically closest to the destination. When there is no neighbor closer to the destination, the face recovery routes the packet around the perimeter of faces of the communication graph. ZigBee applications are usually deployed in buildings. The greedy forwarding can perform poorly because it tries to forward packets through obstacles. Many algorithms have been proposed to improve the greedy forwarding [4] [6] [7]. In [4], a node estimates the minimum transmit power based on the log-distance path loss model and forwards a packet to the neighbor with the lowest $energy/distance$ value. However, estimating the minimum transmit power based on the distance can incur high packet loss, because the signal strength is heavily affected by obstacles. In [6] [7], a node estimates the packet reception ratio (PRR) for each neighbor and forwards a packet to the neighbor with the highest $PRR \times distance$ value. The PRR based algorithms cannot adapt to the environmental changes dynamically because it has to send or overhear several packets to estimate the PRR. The link quality fluctuates wildly due to the interference of other wireless products and therefore the previous algorithms can suffer significant performance degradation.

In this letter, we propose an interference aware energy efficient geographical routing algorithm (IEG) for IEEE 802.15.4a networks. In the proposed algorithm, each node estimates the energy cost by considering the interference effects and forwards a packet to the neighbor which requires the lowest energy cost to advance to the destination. Since the energy cost depends on the interference power level, the proposed algorithm routes a packet around the interference region. We evaluate the performance of the proposed algorithm by using the simulator and the testbed. Experimental results show that the proposed algorithm outperforms the greedy algorithm and the PRR×distance algorithm in terms of the energy consumption and the delivery ratio.

2. Overview of IEEE 802.15.4a

The IEEE 802.15.4a standard presents the symmetric double sided two way ranging (SDS-TWR) algorithm. In the TWR, two nodes exchange a packet and an acknowledgment (ACK) as shown in Fig. 1. If the sender transmits the packet at the time t_{start} and receives the ACK at the time t_{stop}, the distance d is estimated as follows:

$$d = \lambda \times \left(t_{stop} - t_{start} - t_{ta}\right)/2 \qquad (1)$$

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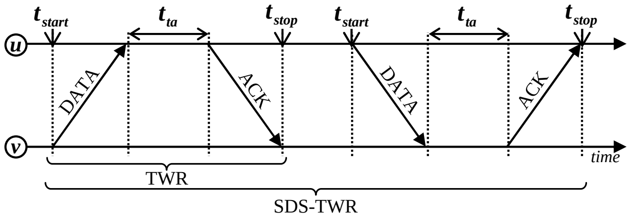


Fig. 1 Symmetric double sided two way ranging (SDS-TWR).

where λ and t_{ta} denote the speed of the light and the Rx-Tx turnaround time. The SDS-TWR repeats the packet exchanging twice, inverting the role of the two nodes in the second exchange in order to reduce the ranging error.

The IEEE 802.15.4a standard presents the UWB based PHY and the CSS based PHY. The UWB PHY uses three frequency bands: a sub-GHz band, a 3-5GHz band, and a 6-10GHz band. At present, IEEE 802.16, ECMA 368, and IEEE 802.22 standard waveforms overlap these bands [2]. UWB PHY supports a mandatory data rate of 851kbps with optional data rates of 110kbps, 6.81Mbps, and 27.24Mbps. The CSS PHY supports a data rate of 1Mbps and 250kbps. CSS PHY is not intended to support the ranging but there are already available CSS based ranging solutions [3]. CSS PHY uses license free 2.4GHz ISM band and this band is being crowded with WiFi and Bluetooth devices.

3. Proposed Algorithm

3.1 Interference-Aware Minimum Energy Consumption Estimation

The proposed algorithm estimates the minimum transmit power by considering the interference power level to forward a packet to where the interference effects are not strong. If the receive power threshold value for a successful reception P_{RX}^{TH} is known, the minimum transmit power, P_{TX}^{min}, can be determined as follows:

$$P_{TX}^{min}(dBm) = PL(dB) + P_{RX}^{TH}(dBm) + \sigma \tag{2}$$

where PL is the path loss between the sender and the receiver due to the distance and the obstacles; σ is the deviation of the path loss in a fading channel. The receive power threshold value can be derived from the signal-to-interference-plus-noise ratio (SINR) model as follows [8]:

$$P_{RX}^{TH} = 10\log\left(10^{P_N/10} + 10^{P_I/10}10^{\zeta^{TH}/10}\right) \tag{3}$$

where P_N and P_I denote the noise power and the interference power in dBm; ζ^{TH} is the SINR threshold for a successful reception in dB. The noise power depends on the hardware and can be set manually. The SINR threshold can be obtained from the bit error rate (BER) model. For example, the BER for IEEE 802.15.4a CSS, when using 250kbps data rate, is defined as follows [2]:

$$\begin{aligned} P_B = & \left(62 \times\ Q\left(\sqrt{10^{\zeta^{TH}/10} \times 560.01}\right)\right)/2 \\ & + Q\left(\sqrt{10^{\zeta^{TH}/10} \times 1120.02}\right)/2 \end{aligned} \tag{4}$$

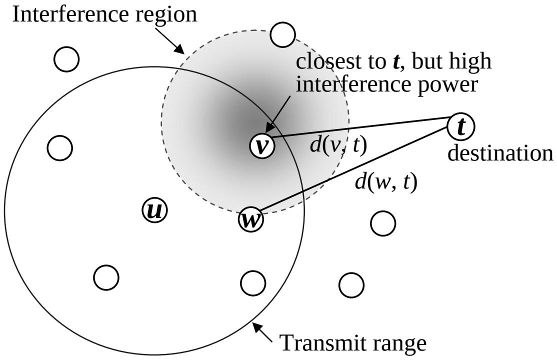


Fig. 2 Proposed algorithm example.

From (4), we set the SINR threshold as -13dB to satisfy the IEEE 802.15.4 receive sensitivity requirement (99% PRR with 20bytes packet size). We assume that a transceiver can measure the interference power level as an IEEE 802.15.4 transceiver measures the interference power level [8].

The energy consumption of sender E is determined as follows:

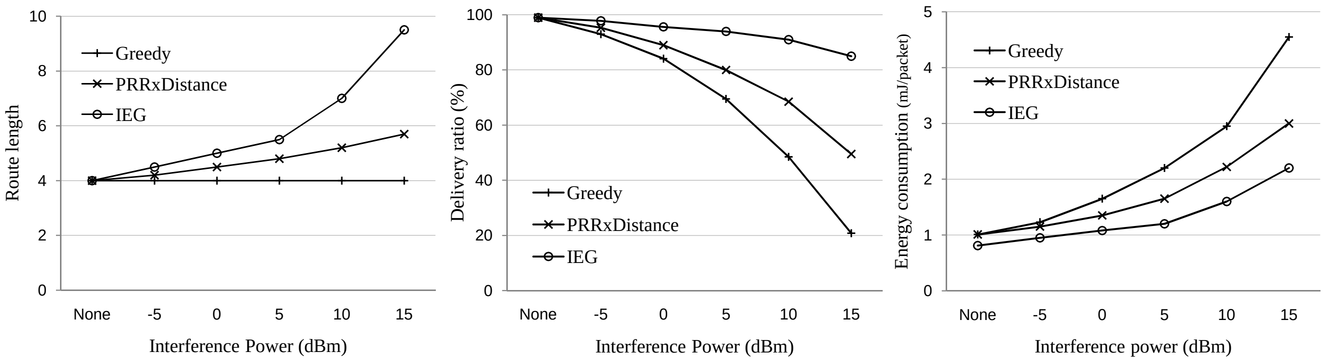
$$\begin{aligned} E = & E_{TX} \times T_{DATA} + \\ & E_{RX} \times (T_{LIFS} + T_{BO} + T_{ACK} + T_{SIFS}) \end{aligned} \tag{5}$$

where E_{TX} and E_{RX} denote the power consumption in mW in the transmit mode and the receive mode respectively. T_{DATA}, T_{ACK}, T_{LIFS}, T_{SIFS}, and T_{BO} denote the durations of the data packet, the acknowledge packet, the long inter-frame space, the short inter-frame space, and the backoff respectively. The power consumption in the transmit mode is proportional to the minimum transmit power ($E_{TX} \propto c \cdot P_{TX}^{min}$) and the value of c depends on the hardware. Therefore, when a node transmits a packet, the energy consumption value is mostly affected by the interference effects because other values are constant in (5).

3.2 Energy-efficient Geographical Routing Scheme

In the proposed algorithm, each node measures the interference power level periodically and determines the receive power threshold value by using (3). When a node detects the interference effects, it broadcasts the receive power threshold value periodically at the maximum transmit power, P_{TX}^{max}. When a node is received the receive power threshold value, it measures the receive power, P_{RX} and determines the path loss as follows:

$$PL(dB) = P_{TX}^{max}(dBm) - P_{RX}(dBm) \tag{6}$$



(a) (b) (c)

Fig. 3 Simulation results.

The node then determines the minimum transmit power value by using (2) and stores the value in the neighbor table.

When a node u has a packet to transmit, it reads the packet size and estimates the energy consumption, E, for each neighbor by using (5). The node u then forwards the packet to the node v with the lowest E/ADV value. ADV denotes the advance to the destination and is defined as follows:

$$ADV = d(u,d) - d(v,d) \tag{7}$$

where $d(u,d)$ denotes the distance between the node u and the destination d. Since the energy consumption value increases as the interference power level becomes stronger, the proposed algorithm can avoid the interference region. For example shown in Fig. 2, if there are no interference effects, the node u forwards a packet to the node v that is closest to the destination d. When the node v is affected by the interference, it adjusts the receive power threshold value and broadcasts the value. When the node u received the receive power threshold value, it changes the minimum transmit power value for the node v. As a consequence, the node u forwards a packet to the node w because the energy consumption value for the node v has increased much. The proposed algorithm should forward a packet to the neighbor with the positive E/ADV value to prevent the routing loop. When there is no neighbor that has positive E/ADV value, the proposed algorithm uses the AODV temporarily.

4. Experimental Results

We compare the performance of the proposed algorithm (IEG) with that of the greedy algorithm and the PRR×distance algorithm in large scale network by using the ns-2 simulator. In simulations, we use the log-distance path loss model. The path loss at a distance d is defined as follows:

$$PL(d) = PL_0 + 10\eta \log d/d_0 + X_\sigma \tag{8}$$

where PL_0 is the path loss at the close-in reference distance d_0, η is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. We measure above values by using the nanoLOC kit which has the CSS-based NA5TR1 transceiver [3]. Table 1 shows all parameter values used in simulations. The power consumption and duration values are drawn from the data sheet of the NA5TR1. In simulations, we place a hundred 802.15.4a nodes randomly in 300×300m plane and two 802.11g nodes at (150, 150). The farthest two 802.15.4a nodes are selected and one of them transmits 100-byte packets to the other node at the rate of 1 packet per 10 seconds. Meanwhile, each 802.11g node transfers MPEG-4 video file to another by using the Poisson traffic model with 800-byte packet size and 56kbps rate based on [9].

Figure 3 shows the route length, the delivery ratio, and the energy consumption of the algorithms as a function of the interference power. The greedy algorithm establishes the shortest route regardless of the interference power but it shows the lowest delivery ratio because it forwards packets through the interference region. The PRR×distance algorithm shows better performance than the greedy algorithm since it uses the links with over 80% PRR. However, the PRR×distance algorithm has to exchange many packets to estimate the PRR and can change the route after several packet losses. The proposed algorithm establishes the longest route but it shows the highest deliver ratio and the lowest energy consumption. As we mentioned before, the proposed algorithm routes packets around the interference region when the interferences are detected. Table 2 shows that how often the proposed algorithm utilizes AODV, and the delivery performance when AODV and face recovery is used respectively. AODV and face recovery both use the maximum transmit power. The proposed algorithm uses AODV when the interference power is over 10dBm where most nodes are strongly affected by interference; but it does not use AODV under 10dBm interference power. The face recovery shows much lower delivery ratio than AODV because it de-

Table 1 Parameter values.

Parameter	Value	Parameter	Value
d_0	1m	T_{LIFS}	24us
PL_0	40dB	T_{SIFS}	8us
η	2.7	T_{ACK}	36us
σ	2dB	E_{TX}	75mW
M	3dB	E_{RX}	82.5mW
Data Rate	250kbps	P_N	95dBm
P_{TX}^{max}	0dBm	P_{TX}^{min}	-33dBm

Table 2 Effect of interference on network performance.

Interference Power (dBm)	10	15	20
radius of WLAN transmit range (m)	**165**	**255**	**340**
frequency of using AODV with proposed algorithm (%)	**0**	**21.6**	**70.0**
delivery ratio of face recovery only (%)	**55.3**	**19.8**	**8.8**
delivery ratio of AODV only (%)	**83.5**	**69.8**	**55.2**

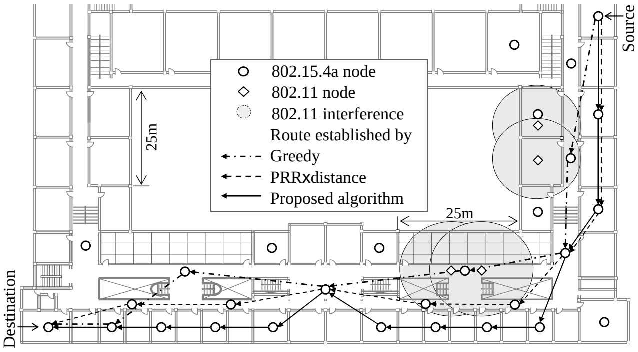


Fig. 4 Testbed experiments in building.

Table 3 Experimental results without 802.11 interference.

	Greedy	PRR×distance	IEG
Route length	7	8	8
Delivery ratio (%)	78.73	93.25	93.43
Energy consumption (mJ/packet)	4.01	3.03	2.72

Table 4 Experimental results under 802.11 interference of FTP traffic.

	Greedy	PRR×distance	IEG
Route length	7	9	13
Delivery ratio(%)	13.47	51.33	88.25
Energy consumption (mJ/packet)	8.75	4.83	3.54

pends only on the location, whereas AODV does not route to nodes that cannot receive RREQ packets due to the interference effects.

To investigate the performance of algorithms, we also conduct testbed experiments with thirteen 802.15.4a nodes and four 802.11 nodes as shown in Fig. 4. The 802.15.4a nodes have the CSS-based NA5TR1 transceiver and the 802.11 nodes have the 802.11a/b/g RT2870 transceiver. In the experiments, the source 802.15.4a node transmits to the destination 802.15.4a node at the rate of 1 packet per 20 seconds. In the meanwhile, a 802.11 node downloads a big file from another 802.11 node by using the file transfer protocol (FTP) program. Since the NA5TR1 transceiver cannot distinguish the interference signal from the 802.15.4a signal, we use the CC2420 transceiver to measure the interference power value and CC2420 transfers the value to NA5TR1 [8].

Table 3 shows the route length, the delivery ratio, and the energy consumption of the algorithms when there is no interference of 802.11 nodes. The greedy algorithm shows the lowest delivery ratio because it decides the next node only based on the location information and hence tries to forward packets across walls. The PRR×distance algorithm and the proposed algorithm show similar delivery ratio but the proposed algorithm consumes less energy than PRR×distance. The reason is that the proposed algorithm reduces the energy consumption by adjusting the transmit power.

Table 4 shows the performance of the algorithms when 802.11 nodes generate the interference effects. Figure 4 shows routes established by different algorithms. The greedy algorithm has the shortest route but its delivery performance is degraded significantly due to the 802.11 interferences. The PRR×distance algorithm has longer route than the greedy algorithm, but two links of its route are affected by 802.11 interferences which inducing around 15% packet loss per link. The proposed algorithm establishes the longest route but it avoids the 802.11 interference region. Since the proposed algorithm forwards packets through good quality links, it does not waste the energy for retransmissions. From testbed experiment results, we can say that the proposed algorithm is robust to the interference effects in real world deployments.

5. Conclusions

The proposed algorithm estimates the energy cost by considering the interference effects and forwards a packet to the neighbor with the lowest energy cost for relay to its destination in order to avoid the interference region. The proposed algorithm is thoroughly examined by using the simulator and the testbed, and the results show that it outperforms the previous algorithms in terms of the delivery ratio and the energy consumption.

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