A Reliable Transmission Strategy in Unreliable Wireless Sensor Networks*

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Abstract. Recent empirical and theoretical studies have shown that wireless links in low-power sensor networks are unreliable. Obviously, it is not a good choice for sensor networks that transmitting data unreliably, which will bring many problems to the networks, such as uncertainty, performance-decline, and so on. In this paper, a novel transmission strategy for reliable transmitting over unreliable links is proposed. Based on the observation that the broadcast nature of the wireless communications has the potential that allows all neighbors receive and process the packets simultaneously, we suggest that using a nodes-set, instead of one node, to receive and relay packets. The key idea is that receiving packets simultaneously and relaying packets competitively. Theoretical and experimental analysis demonstrates that the new strategy can provide reliable transmitting over unreliable links meanwhile improves the performance of networks significantly.

Keywords: Sensor Networks, Reliable Transmission, Nodes cooperation.

1 Introduction

Recent empirical and theoretical studies [1] ~ [4] have shown that wireless links in real sensor networks are unreliable. Particularly, in dense deployments, a large number of links in the sensor network (even higher than 50%) can be unreliable. The unreliability is derived from many factors such as multipath fading, unreliable sensor nodes and stochastic interference. It seems that the unreliability is one of the inherent properties of low-power wireless links.

Obviously, reliable transmission is hoped for communications of networks. In order to overcome the unreliable links in network layer, some efforts ([5] [6] [7]) have been put in defining metrics to characterize the energy efficiency of communication. Based on these metrics, the communication over unreliable links could be optimized. These methods all focus on the single link. However, the performance improvement through the optimization of single link is limited. For example, there are two links (link1 and link2) from node A to node B. In time1, link1 is better than link2. It means link1 has higher PRR (packet reception rate) than link2. But, in time2, link2 is better than link1. It can't be predicted which link would be better in one time. So when you want to send packet from node A to node B, you can't exactly choose the optimal link to send. It can

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be said that it is difficult to get satisfactory transmission performance over unreliable links just only using single link optimization.

In this paper, a reliable transmitting strategy, called *Set Transfer*, is proposed. It can realize reliable transmission over unreliable links meanwhile improves the energy efficiency of networks significantly. The key idea is that using multi nodes receive packets simultaneously and relay packets competitively. The energy efficiency of *Set Transfer* is analyzed theoretically and experimentally.

The rest of the paper is organized as follows. Section 2 is related works. Section 3 proposes the reliable transmitting strategy *Set Transfer*. In Section 4, the energy efficiency of *Set Transfer* is analyzed. Simulation and conclusion are in Section 5, 6.

2 Related Works

Although the ability of single node is limited, the ability of multi-nodes cooperation may be huge. There have been some researches on sensor nodes cooperation in physical layer [8] ~ [11]. Multipath fading is a fundamental phenomenon which makes reliable wireless transmission difficult in wireless communication. In order to reducing the effective error rate in a multipath fading channel, some diversity techniques such as multiple-antenna [8], relay channel model [11], are proposed. The main idea of diversity techniques is that sending one signal through different channels and combining signals from different channels at the terminal. Diversity can achieve signal gains. A. Sendonaris et al. [9] [10] proposed a new form of spatial diversity technique which achieve diversity gains through the cooperation of in-cell users (mobile - base station communication). Unfortunately, this approach sends many duplicate packets, decreasing the energy efficiency of networks. Diversity-techniques studies are now concentrated on physical layer.

Some unreliable-link models [2] [3] [4] have been proposed. It can help us further understand the realistic link layer of sensor networks. According to these models, there are three distinct reception regions in wireless sensor links: connected, transitional, and disconnected. The transitional region is often large in size, and generally has high-various reception rates. M. Zuniga et al. [4] derived expressions for reception rate as a function of distance for different settings.

Inspired by these researches, we study unreliable-links cooperation in network layer. Based on the unreliable-link models [2] [3] [4], a novel cooperation approach is proposed which can be said a new form of diversity technique.

3 The Reliable Transmitting Strategy: *Set Transfer*

3.1 The Preliminaries

In this part, two assumptions and a profile about *Set Transfer* are presented.

A. Assumptions

1. The low-power wireless sensor links are unreliable.
2. The broadcast mechanism such as CSMA-CA is used in link layer protocols.

CSMA-CA mechanism has been widely used in wireless communications, for example, IEEE standard 802.15.4 [12] and IEEE standard 802.11 [13]. It also works well in ad hoc and sensor networks because of its simple and efficiency.

B. The Profile of Set Transfer

The *Set Transfer* uses a node-set, instead of one node, to receive and relay packets. A node-set receives the packets simultaneously (called *Set Receiving*) and relays it competitively (called *Set Relaying*). As Fig.1 shows, the source node sends the packets to set A1, and set A1 uses *Set Receiving* to receive packets and uses *Set Relaying* to relay packets to set A2, and A2 receives and relays the packets to A3, and so on. Finally, through n hops, packets arrived at the set A_n , which includes the destination node. Then any node in the set A_n transmits the packets to the destination node through broadcasting.

Fig. 1. Set Transfer

3.2 Set Receiving

According to the broadcast assumption, the wireless sensor networks have the potential that allows for multi-nodes receive and process packets simultaneously. Thus, instead of using one node to receive packets, we suggest using a nodes-set to receive packets. It is called *Set Receiving*. For example, in Fig.1, the packets sent from source node can be received by node A1' or by nodes-set A1. If nodes-set A1 is used, it means that each node in the set A1 receives packets independently, and if any node receives packets correctly, the receiving-process of set A1 is completed correctly. Here set A1 could be seen an integrity which receives and relays packets as one node. In part 2.3, the integrity of nodes-set will be demonstrated.

According to unreliable links assumption, the wireless sensor links are unreliable. The Pr is used (packet reception rate, $0 < Pr < 1$) to denote the reliability of links. The higher the Pr is, the more reliable the link is. It can be assumed that each link in a

nodes-set is independent with its own Pri ($1 < i < n$). Then, the packet reception rate $Pset$ of *Set Receiving* is:

$$Pset = 1 - (1 - Pr1) \times (1 - Pr2) \times \cdots \times (1 - Prn) \quad (1)$$

$$\geq 1 - (1 - Prmin)^n \quad (2)$$

Where $Prmin = \min Pri$, $1 < i < n$. The n is the power of the nodes-set. From expression (1), the reliability of *Set Receiving* is characterized by a non-decreasing, strictly concave function. If $Prmin$ is 0.7 and $n = 6$, then the packet error rate can be reduced from 10^{-1} to 10^{-4} . It can be said that the *Set Receiving* is reliable.

3.3 Set Relaying

In part 3.2, *Set Receiving* uses a nodes-set to receive packets, and some nodes in the set will correctly receive the same packets in the same time. However, in multi-hop transmission, a nodes-set how to relaying packets is still a question. If all nodes in nodes-set all relay packets to the next hop, the blast of packets replication will occur, just like flooding mechanism, which wastes too many energy and bandwidth of networks. In this part, *Set Relaying* scheme is introduced which guarantees that, in one nodes-set, only one node relays the packets.

Some works on wireless sensor networks [2] [3] [4] proposed some link models based on recent empirical studies [1] [2]. These models revealed that wireless sensor links have three distinct reception regions with different distance between two nodes: connected (normally 0m ~ 11m), transitional (normally 11m ~ 32m), and disconnected (> 32 m). The transitional region is often large in size, and generally has high-various PRR (packet receive rate) which distributed in 10%~90%; the connected region is often small in size, and generally has high PRR. Fig.2 shows the analytical link loss model cited from M. Zuniga *et al* [4]. If consider the unreliable sensor devices and stochastic interference factors, the size of the transitional region will further increase.

Fig. 2. Analytical PRR vs Distance

For the efficiency of transmission, data transmitting usually occurs in transitional region. According to broadcast assumption and above analyze, we get two observations as follows.

1. The broadcast nature of the wireless medium allows sensor nodes detecting their neighbor's transmission.
2. There are three distinct reception regions in wireless sensor links: connected, transitional, and disconnected.

Based on the two observations, the *Set Relaying* can be described as follows:

1. *One nodes-set should be lies in one connected region.*
2. *When a nodes-set receive packets, it stochastically select one node from the nodes that receive packets successfully to relay the packets with broadcast mechanism which informs other nodes the packets' relaying. (Competitive scheme)*

Rule1 guarantees that the relayed packets can be detected reliably. Rule2 guarantees that only one node in the set relays the packets to the next-hop nodes-set.

Combining *Set Receiving* and *Set Relaying*, we get an end-to-end transmission approach *Set Transfer*, which can realize reliable transmission over unreliable links.

4 Performance Analysis

Section 3 has demonstrated that *Set Transfer* can provide reliable transmission over unreliable links. This section will demonstrate that *Set Transfer* can improve the energy efficiency of wireless sensor networks, which is an important design issue.

To evaluate the energy efficiency of different transmission strategies, the metric Energy Per Packet (*EPP*) is used, which represents the average energy consumption for each delivered packet from the source node to the destination node. Without loss of generality, each packet length could be assumed equivalent. The *EPP* of a sensor network is comprised as follows:

$$EPP = E_{maintain}(E_{elec}) + E_{RF} + E_{process} \quad (3)$$

- $E_{maintain}(E_{elec})$: the amount of energy required to maintain the sensor nodes working, namely the energy consumption of circuits.
- E_{RF} : the amount of energy required to transmit packets in wireless environment.
- $E_{process}$: the amount of energy required to process packets in the sensor nodes.

In the design of modern processors, the power consumption $E_{process}$ can be made negligible compared to transmit powers [14]. So it can be deduced that

$$E_{RF} \gg E_{process} \quad (4)$$

E_{elec} is the power that supports sensor nodes in working state which can not be ignored compared to transmit powers. On the other hand, *Set Transfer* can work with any MAC layer protocols as long as it accords with the broadcast assumption, such as IEEE 802.11, 802.15.4 and some new medium access control (MAC) protocols designed for WSN [15] [16]. It guarantees that the number of working nodes in two different transfer strategies is equal. According to above discussion, we have

$$E_{elec-set} = E_{elec-single} \quad (5)$$

Where $E_{elec-set}$ denotes the E_{elec} of *Set Transfer*, and $E_{elec-single}$ denotes the E_{elec} of *Single Link Transfer*.

It is important that *Set Transfer*'s one nodes-set only use one node to relay packets (see *Set Relaying* 3.3), which guarantees that

$$E_{RF-set} = E_{RF-single} \quad (6)$$

First consider the links are reliable, according to (3) ~ (6), we get

$$\begin{aligned} EPP_{set_reliable} &= E_{elec-set} + E_{RF-set} + n E_{process} \\ &= E_{elec-single} + E_{RF-single} + n E_{process} \\ &\approx EPP_{single_reliable} \end{aligned} \quad (7)$$

Where n is the average number of nodes-set.

Second consider the links are unreliable, re-transmission is needed. As section 2 mentioned, the PRR of *Single Link Transfer* is Pr , and *Set Transfer* is $Pset$. Then through computing the expectation of transmissions, we get

$$EPP_{set_unreliable} = \frac{1}{pset} EPP_{set_reliable} \quad (8)$$

$$EPP_{single_unreliable} = \frac{1}{pr} EPP_{single_reliable} \quad (9)$$

According to equations (7) (8) (9), we have

$$EPP_{set} \approx \frac{Pr}{pset} EPP_{single} \quad (10)$$

If the pr is 0.7 and $pset \approx 1$, then $EPP_{set} \approx 0.7EPP_{single}$. Obviously, *Set Transfer* improved the energy efficiency of the networks with unreliable links.

5 Simulations and Comparisons

In this section, we first study the reliability of *Set Transfer* through numerical experiments, and second study the performance of *Set Transfer* through simulations.

In numerical experiments, each link is assigned a value of Pr (0.1~0.6: 30%; 0.6~0.9: 70%), and then study the packet lost rate with scales in the number of nodes. It can be seen from Fig.3 that the curve about Set Receiving has the shape of log functions, and six or more nodes could have reliable one-hop transmission in this unreliable environment. In Fig.4, the number of working sensors in receiving set is fixed at 3 and the Pr is changed. As Fig.4 shows, 3 nodes Set Receiving improve the transmission's reliability significantly. The curve of Set Receiving changes smoothly, and when the Pr is 0.9~1, the 3 nodes Set Receiving nearly do not lost any packets.

In the simulations, 250 nodes are randomly deployed in a 200m×200m square area. The radio model ([4]) with three distinct reception regions: connected, transitional and disconnected is used. To simplify the simulation, each reception region has a random PRR (packet reception rate), such as connected (0~11m): 0.9~1, transitional

(11m~32m): 0.5~0.7 30%, 0.7~0.9 70%, transitional (32~40m): 0.1~0.6 70%, 0.6~0.9 30%, disconnected (>40m): 0. Four transmission mechanisms are compared: ETX transmission in [7]; Optimized GF transmission in [6]; Lazy loss detection transmission in [5]; *Set Transfer* transmission as proposed in this paper.

Fig. 3. Packet Lost Rate with different number of nodes

Fig. 4. Packet Lost Rate with different PRR

Fig.5 shows the energy efficiency of various transmission strategies. The average consumed energy of transmitting 1000 data packets successfully is observed. The end-to-end distance is described by hop counts. If just use original ETX metric to choose the next hop node, each hop distance will be too short to acquire good energy efficiency. So ETX strategy is slightly adjust like this: using ETX metric to choose the next hop node in a set of nodes. The power consumptions of each node in receiving, transmitting modes are 14.4mW and 36mW respectively [17]. From Fig.5, *Set Transfer* improves the energy efficiency of networks significantly. It is mainly because Set Transfer can provide reliable transmission which saves retransmission energy. In simulation, the results of each test of the ETX, Optimized GF and Lazy detection are changed acutely. For example, the E_ETX (6hops) changed from 806.3W*S to 1498.6W*S, although the average consumed energy is 932.9 W*S. The link's unreliability results in this acutely changing, and single link methods all have this problem. However, the Set Transfer has no this problem. The E_Set (6hops) changed from

Fig. 5. The end-to-end consumed energy

Fig. 6. The end-to-end delay (second)

553.008 W*S to 576.776 W*S, and the average consumed energy is 561.336 W*S. This phenomenon further reflects that the links Set Transfer provided is reliable and the energy Set Transfer consumed is smooth.

Fig.6 shows the average end-to-end delay time of various transmission strategies. From Fig.6, the delay time of *Set Transfer* is obviously shorter than single link strategies. Through providing more reliable transmission than single link strategies, *Set Transfer* can effectively reduce the packet loss which will cause cascading effects, such as ACK delay, retransmitting, and so on.

6 Conclusion

The unreliable wireless links in real sensor networks will decrease the performance of networks seriously. In this paper, through studying the characteristics of the wireless links deeply, we proposed a multi-nodes cooperation strategy *Set Transfer*, which provides reliable transmission over unreliable links meanwhile improve the energy efficiency of networks. Further theoretical and experimental analysis gives us some insights on the improvements in energy efficiency that cooperation can bring to networks when the underlying links are unreliable.

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