Trade-off between Reliability and Energy Consumption in Transport Protocols for Wireless Sensor Networks

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Summary
Efficient design and implementation of wireless sensor networks has become a hot area of research in recent years. In comparison with other existing networks, wireless sensor networks (WSN) have some limitations. Typically, nodes in WSN have limited power, computational capacity, and memory. These problems require the need of having particular protocols designed for WSN. Currently, many research focused on developing transport protocols. This paper proposes a probability model that can be applied in transport protocols using hop-by-hop and end-to-end mechanism. From this model, we evaluate the number of hops that a packet has to pass when it is being sent from source to destination. We also solve the optimal number of transmissions in transport layer. The result from this model shows that there is a trade-off between reliability and energy consumption.

Key words:
Wireless sensor networks, Transport protocols, Energy-Efficiency, Reliability, Retransmission.

Introduction

Every researcher who is interested in WNSs should always consider energy-efficiency problems. In Multiple Access Control (MAC) layer, researchers had proposed power-saving mechanisms which allow sensor nodes to change their states, i.e., if a sensor node does not have any data to send, it changes its state to idle mode to save energy [1,2]. Similarly, in network layer, studies are being conducted to investigate efficient routing protocols to conserve energy.

Energy issue is also considered in transport protocols. Transport protocol studies usually focus on four tasks, as the following [3]:

- *Reliable data transport*: This task requires the ability to detect and repair losses or error of packet in networks.
- *Flow control*: The receiver of a data stream might temporarily be unable to process incoming packets because of lack of resources. We need to control data flow so that it is suitable to resource condition.
- *Congestion control*: Congestion occurs when more packets are created than the network can carry and the network starts to drop packets. The more packets are dropped, the more energy is consumed and the lesser is the reliability
- *Network abstraction*: Transport protocols provide an interface for application.

In this paper, we focus on the first task. Wireless sensor networks are designed to have limited resources, this, unfortunately, results to higher probability of error compared with other type of networks. To guarantee reliability, some methods are proposed:

- Use acknowledgements and retransmit failed data packets.
- Use channel coding to add some redundancy information.
- Redundancy path: Send the same packet through multipaths.
- Redundancy packet: Send redundant copies of the same packet.

In the first method, two mechanisms are proposed: hop-by-hop and end-to-end. These and some other concepts are presented in section 3.

In this paper, we propose a probability model that is applied in two cases, hop-by-hop and end-to-end. From this model, we calculate the number of hops that a packet has to pass when it is being sent from source to destination. The result shows that the higher reliability requires more energy. Clearly, there is a trade-off between reliability and energy consumption. In this paper, we also briefly compare hop-by-hop and end-to-end mechanism in terms of energy-efficiency.

The remainder of the paper is organized as follows. In section 2, we present a review of related works in transport protocol for WSNs and some mechanisms in other layers to save energy. We define a probability model for two mechanisms in section 3. Based on the model, we evaluate probability of error and estimated number of hops. In

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section 4, relationships between reliability and energy savings are shown. That relationship is contra-variant and we need to trade-off between them. Section 5 draws the conclusion and summarizes the result of the paper.

2. Related works

References [4-13] research on transport layer protocols. In these papers, they introduce the position and role of transport layer in WSNs. Two most important roles are reliability and congestion control. A good protocol is not only a protocol that guarantees two such goals but also an energy-efficient protocol.

References [4] and [5] are survey papers. These papers give an introduction to the reliable data transport problem and surveys protocols and approaches, often developed for particular applications to reflect the application specific dependability requirements. Moreover, they list some existing transport protocols for WSN. These protocols are classified, compared, and commented with some advantages and disadvantages.

Reference [6] presents analysis and experiments resulting in specific recommendations for implementing reliable data transport in sensor networks. To explore reliability at the transport layer, they presented RMST (Reliable Multi-Segment Transport). The protocol is designed to run above Directed Diffusion in order to support applications that require transfer of big sized data (JPEG, MPEG file). At source, this big data is divided into fragments which fit into the network MTU and these fragments are reassembled at the sink. RMST guarantees delivery fragments from source to sink correctly. There two modes in RMST: cache and non-cache mode. In cache mode, every node recovers missing fragment. In none-cache mode, only sink do. RMST just focuses on reliability, not on energy-efficiency. The protocol does not propose a retransmission number.

The event-to-sink reliable transport (ESRT) protocol, a novel transport solution developed to achieve reliable event detection in WSN with minimum energy expenditure, is presented in [7]. While RMST guarantee reliability of each fragment, ESRT guarantee reliability of whole of data stream. ERST only suit applications that sink can receive collective information from many different sources. ERST does not use acknowledgment and retransmission mechanism.

In studying transport protocols, we have realized that most protocols use positive, negative or selective acknowledgment to indicate loss or error. Some protocols use end-to-end mechanism while others use hop-by-hop mechanism. When receiving loss or error notification, a sensor node needs to retransmit loss or error fragment. If the fragment is missed again, the node should continue to retransmit. The problem is now how to determine the number of transmissions needed depending on reliability requirement, probability of link error, and network size. Our mathematical model will show how to calculate number of transmissions and evaluate number of hops that a packet passes to reach destination.

3. Mathematical Model

3.1 Some concepts

Fundamentally, guaranteed reliability is obtained by three following capacities [14]:

- *Error detection:* Receiver detects error based on checksum field or gaps between received packets.
- *Receiver feedback:* After receiving packet, receiver sends acknowledgment message back to sender to confirm if the packet arrives successfully or not
- *Retransmission*: A packet that is received in error at the receiver will be retransmitted by the sender

These capacities are shown in Fig. 1.

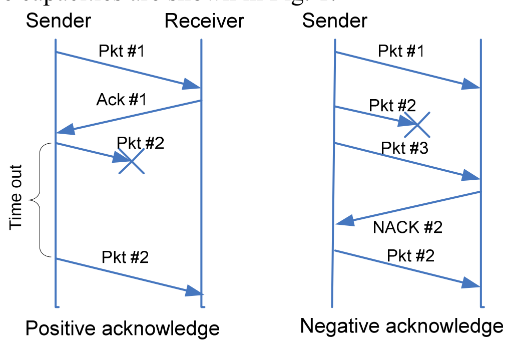

Fig. 1 Error detection - Receiver feedback - Retransmission

Next, we consider hop-by-hop and end-to-end mechanisms (Fig. 2). For example, a packet needs to be transferred from node 1 (source) to node 8 (destination). To reach its destination, the packet passes through the path (1→4→5→8) as indicated in the diagram using heavy line. If every node in the path implemented the three above mechanisms (error detection, receiver feedback, retransmission), we call that the network uses hop-by-hop mechanism. Otherwise, if only source and destination guarantee reliability, other intermediate nodes just forward packets, we call that the network uses end-to-end mechanism. A key difference between hop-by-hop and end-to-end mechanism is when an error occurs, in hop-by-hop case, intermediate node retransmit the packet, but in end-to-end case, the packet needs to be sent from the source.

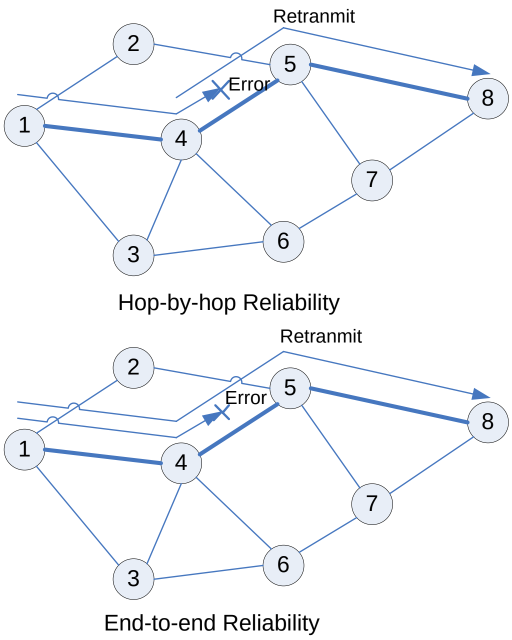

Fig. 2 Hop-by-hop and end-to-end mechanism

Now, we propose a probability model which can be used to estimate the number of hops of a packet from source to destination and the reliability of the network. The parameters are defined as follow:

- n: Number of hops between source and destination. In the previous example, if the path is 1→4→5→8, number of hops is 3
- P_h: Probability of error for a single attempt across one hop.
- R: *maximum number of transmission,* which is maximum number of times that node transmit a packet. It means when the node sends a packet, it will store a copy of the packet in its buffer, and establishes a count variable with initial value 1. If the packet can not reach destination successfully, the node will resend the packet. The variable will increase by 1 each time that the packet is resend. The packet and the variable will not be released until the variable reaches R or the node receives acknowledgement packet.
- S: *number of hops of a packet,* which is the number of links that a packet has to pass to reach its destination. If there is no error, the number of hops equals n (The hops between source and destination). In fact, when an error occurs, a node needs to retransmit the packet. The number of hops of the packet is the total number of hops that the packet needs to pass to reach its destination (that includes the first transmission and retransmissions). That number of hops is often greater than n. Sensor networks are characterized by the situation where "each bit sent brings that node closer to death". Energy consumption is rated by the number of hops of a packet. So we can consider the number of hops of a packet as "cost" of sending packet from source to its destination.
- P_e: *Probability of error*, which is probability of event that a packet can not reach its destination after using retransmission. P_e can be represented as reliability of the network, if P_e is small, the network is reliable and vice versa.
- ε: *maximum probability of error*, which is required threshold of P_e. The value of the threshold should be one of {0.01, 0.05, 0.1, 0.2, 0.5}. In network, the condition of reliability requirement is $P_e<\varepsilon$.

In the next parts of this section we will estimate Pe and S. In every network, the expectation is that Pe and S are as small as possible. Our model will estimate reliability and number of hops in two cases: hop-by-hop and end-to-end.

3.2 Hop-by-hop mechanism

First, consider the need to send a packet using one hop link. The probability of the event that a packet will reach the destination after i transmissions is

$$P_i = P_h^{\,i-1}(1-P_h) \quad (1)$$

Probability of the event that a packet can not reach destination after R transmissions is given by

$$P_R = P_h^{\,R} \quad (2)$$

The estimated number of hops of a packet is

$$S_h = \sum_{i=1}^{R} iP_i = \sum_{i=1}^{R} iP_h^{\,i-1}(1-P_h) + RP_h^R \quad (3)$$

We know that

$$\sum_{i=0}^{R} P_h^i = \frac{1-P_h^{R+1}}{1-P_h} \quad (4)$$

By getting derivative of two sides of Eq. (4), we have

$$\sum_{i=1}^{R} iP_h^{i-1} = \frac{RP_h^{R+1}-(R+1)P_h^R+1}{(1-P_h)^2} \quad (5)$$

Using Eq. (5), we can reduce Eq. (3) such that

$$S_h = \frac{RP_h^{R+1} - (R+1)P_h^R + 1}{(1-P_h)^2}(1-P_h) + RP_h^R$$

$$S_h = \frac{1-P_h^R}{1-P_h} \quad (6)$$

To reach the destination, the packet needs to take n links. So the number of hops is

$$S = nxS_h = n\frac{1-P_h^R}{1-P_h} \quad (7)$$

The probability of forwarding a packet successfully after R transmissions through 1 hop is

$$P_{sh} = 1 - P_R = 1 - P_h^R \quad (8)$$

The probability of sending a packet successfully after R transmissions from source to destination is given by

$$P_s = P_{sh}^n = (1-P_h^R)^n \quad (9)$$

The probability of sending a packet unsuccessfully after R transmissions from source to destination is

$$P_e = 1 - P_s = 1 - (1-P_h^R)^n \quad (10)$$

So, in the case of hop-by-hop, we can see that the estimated number of hops of a packet is determined by Eq. (7) and the reliability is determined in Eq. (10).

To guarantee reliability of operation, it is required that Pe<ε (ε=0.01, 0.1,…). Therefore,

$$P_e = 1 - (1-P_h^R)^n < \varepsilon \quad (11)$$

From Eq. (11), the maximum number of transmission R is satisfied:

$$R > \frac{\log\left|1-(1-\varepsilon)^{1/n}\right|}{\log P_h} \quad (12)$$

Thus, the value of R needs to be a positive integer which agrees with Eq. (12) and minimizes Eq. (7). The solution for this problem is transmission optimization that we need to find.

3.3 End-to-end mechanism

Let fj be the link where the packet fails on jth transmission $(1 \le j \le R, 1 \le f_j \le n)$

Let $P_i(f_1, f_2,... f_{i-1})$ be the probability of an event that a packet reaches the destination successfully after i transmissions and in which the packet fails at link f_j (j=1, 2, …, i-1) on j[th] transmission (Fig. 3). The number of hops of the packet on this event is determined as: $f_1 + f_2 + ... + f_{i-1} + n$. We have

$$P_i(f_1, f_2,... f_{i-1}) = (1-P_h)^{f_1-1}P_h][(1-P_h)^{f_2-1}P_h]...$$
$$[(1-P_h)^{f_{i-1}-1}P_h](1-P_h)^n$$

$$P_i(f_1, f_2,... f_{i-1}) = (1-P_h)^{(\sum_{j=1}^{i-1} f_j)+n-i+1} P_h^{i-1} \quad (13)$$

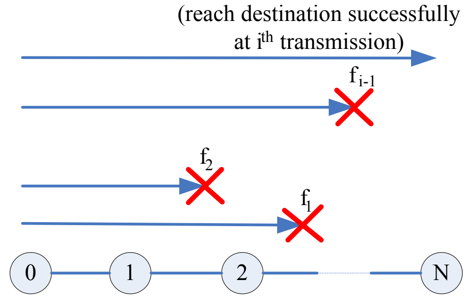

Fig. 3 A packet reaches the destination successfully after i transmissions

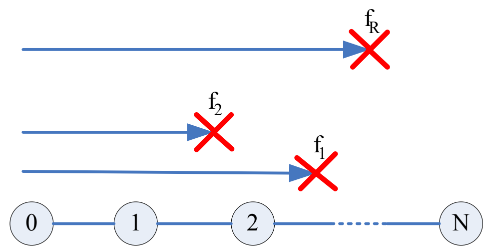

Fig. 4 A packet cannot reach the destination successfully after R transmissions

Let $P_R(f_1, f_2,... f_R)$ be the probability of an event that a packet cannot reach the destination successfully after R transmissions and in which the packet fails at link f_j (j=1, 2, …, R) on j[th] transmission (Fig. 4). The number of hops of the packet in this event is determined as: $f_1 + f_2 + ... + f_R$. We have

$$P_R(f_1, f_2,... f_R) = [(1-P_h)^{f_1-1}P_h][(1-P_h)^{f_2-1}P_h]$$
$$...[(1-P_h)^{f_R-1}P_h]$$

$$P_R(f_1, f_2,... f_R) = (1-P_h)^{(\sum_{j=1}^{R} f_j)-R} P_h^R \quad (14)$$

The estimated number of hops of a packet is:

$$S = \sum_{f_1=1}^{n}\sum_{f_2=1}^{n}...\sum_{f_R=1}^{n}(f_1 + f_2 + ... + f_R)P_R(f_1, f_2,..., f_R) +$$
$$+ \sum_{i=1}^{R}\left(\sum_{f_1=1}^{n}\sum_{f_2=1}^{n}...\sum_{f_{i-1}=1}^{n}(f_1 + f_2 + ... + f_{i-1} + n)P_i(f_1, f_2,..., f_{i-1})\right) \quad (15)$$

The probability of sending a packet successfully from source to destination is:

$$P_s = (1-P_h)^n \quad (16)$$

The probability of sending a packet unsuccessfully after R transmissions from source to destination:

$$P_e = (1-P_s)^R = \left[1-(1-P_h)^n\right]^R \qquad (17)$$

So, in the case of end-to-end, we can see that the estimated number of hops of a packet is determined by Eq. (15) and the reliability is determined by Eq. (17)

To guarantee reliability of operation, it is required that Pe<ε (ε=0.01, 0.1,…). Therefore,

$$P_e = \left[1-(1-P_h)^n\right]^R < \varepsilon \qquad (18)$$

From (18), maximum number of transmission R is satisfied:

$$R > \frac{\log \varepsilon}{\log\left[1-(1-P_h)^n\right]} \qquad (19)$$

Thus, the value of R needs to be a positive integer which agrees with Eq. (19) and minimizes Eq. (15). The solution for this problem is transmission optimization that we need to find.

4. Trade-off between reliability and energy consumption

Now, to show relationship between reliability and energy-efficiency more clearly, we draw diagrams of probability of error and estimated number hops of a packet.

In this case, we suppose that a packet needs to be sent from source to destination. The distance between source and destination is 3 hops. Probability of failure ε when transmitting a packet through a link is one of {0.01, 0.05, 0.1, 0.2, 0.3}.

4.1 Hop-by-hop mechanism

Fig. 5 shows the probability of error (Eq. (10)). The horizontal axis shows the number of transmissions while the vertical axis shows the probability of error. Clearly, when the number of transmissions increases, the probability of error decreases, thus, reliability goes up. We also see that reliability goes down when probability of error per link increases.

Fig. 6 illustrates the relationship between estimated number of hops and the number of transmissions (Eq. (7)). The number of hops between source and destination is 3 but the estimated number of hops that a packet has to go through to reach its destination is slightly greater. It is because when a packet is lost, it is retransmitted. The higher probability of error per link, the higher the estimated number of hops is. We see that the estimated number of hops goes up when the number of transmissions increases; it also means that energy consumption increases. Estimated number of hops converges when number of transmissions is high enough. It converges at the same time the probability of error reaches 0 (absolute reliability). From Figs. 5 and 6, when the number of transmissions increases, it guarantees reliability better but at the same time, estimated number of hops goes up, that means it consumes more energy. In WSNs, we need that probability of error as small as possible and energy consumption also as small as possible. Unfortunately, they are contra-variant. When probability of error goes down (more reliable), estimated number of hops goes up (consume more energy) and vice versa. So we need a trade-off between reliability and energy-efficiency.

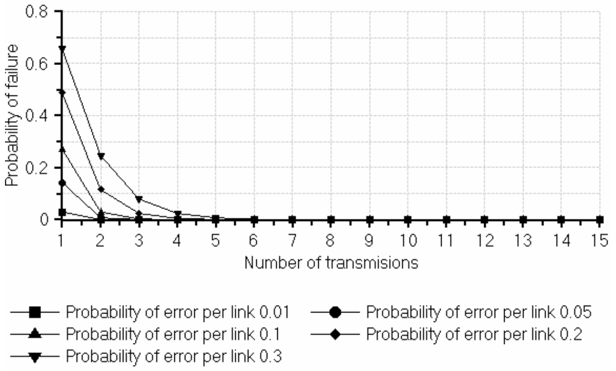

Fig. 5 Probability of sending a packet unsuccessfully– Hop-by-hop mechanism, using R transmissions

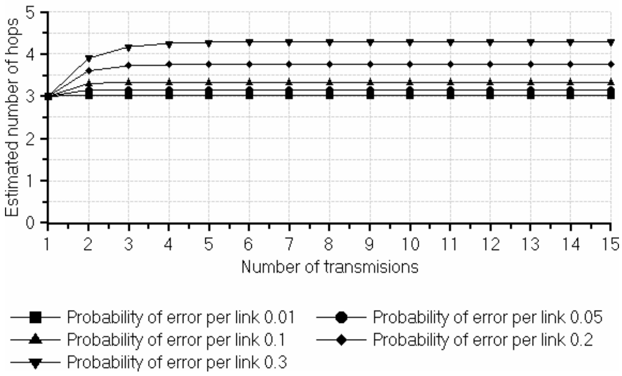

Fig. 6 Estimated numbers of hops of a packet – Hop-by-hop mechanism, using R transmissions

For example, we consider that probability of error per link is 0.3. If reliability is required the probability of error should be smaller than 10%, from Fig. 5 and Eq. (12), we can see that the maximum number of transmissions equals 3. From Fig. 6, when number of transmissions is 3, the estimated number of hops is approximately 4.2. These data are put in 3rd line of table 1. Similarly, we can obtain all data in this table. The table shows the relationship between reliability, maximum number of transmissions and estimated number of hops. Based from the result the reliability requirement and maximum number of retransmissions are contra-variables. When we require more reliability, estimated number of hops goes up which also means more energy is consumed.

Table 1 Maximum number of transmission and estimated number of hops when probability of error per link equals 0.3 – Hop-by-hop mechanism

Reliability requirement	Maximum number of retransmissions	Estimated number of hops
0.3	2	3.9
0.2	3	4.2
0.1	3	4.2
0.05	4	4.3
0.01	5	4.3

If we change probability of error per link in table 1, we can get other similar tables. That data show that optimal number of transmission R is an increasing function of probability of error per link Ph and number of hops between source and destination n (i.e. as Ph or n increases, R increases), and is also a decreasing function of reliability requirement ε.

4.2 End-to-end mechanism

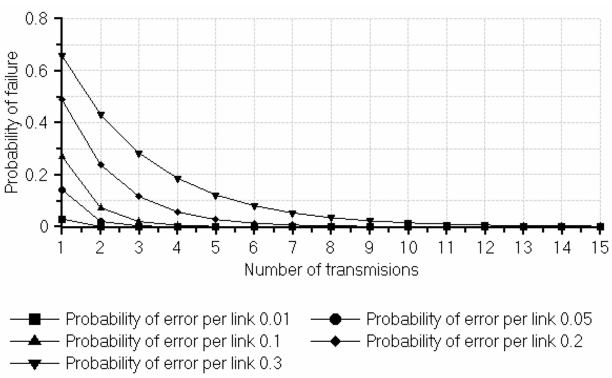

Fig. 7 Probability of sending a packet unsuccessfully – End-to-End mechanism, using R transmissions

We have obtained similar results as shown by Fig. 7 (Eq. (17)) and Fig. 8 (Eq. (15)), that is, a trade-off between reliability and energy-efficiency is also required.

Similar result is shown in table 2. It shows that reliability requirement and maximum number of retransmissions are contra-variables. When we require more reliability, estimated number of hops goes up that means more energy is consumed.

Optimal number of transmission R is an increasing function of probability of error per link Ph and number of hops between source and destination n (i.e. as Ph or n increases, R increases) and is also a decreasing function of reliability requirement ε.

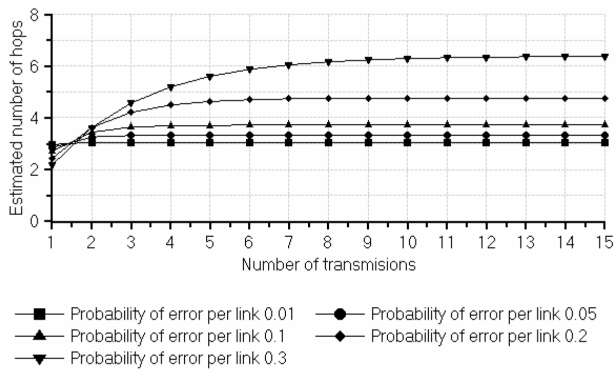

Fig. 8 Estimated number of hops of a packet – End-to-End mechanism, using R transmissions

Table 2 Maximum number of transmission and estimated number of hops when probability of error per link equals 0.3 – End-to-end mechanism

Reliability requirement	Maximum number of retransmissions	Estimated number of hops
0.3	3	4.5
0.2	4	5.2
0.1	6	5.9
0.05	8	6.2
0.01	11	6.4

From the above figures and tables, we see that in the case of high probability of error per link, we should use hop-by-hop mechanism. For example, we consider a context that the probability of error per link is 0.3 and probability of error is smaller than 10%. If we use end-to-end mechanism, maximum number of transmissions is 6 (Fig. 7), and estimated number of hops is approximately 5.9 (Fig. 8). But in the same context, if we use hop-by-hop mechanism, we need a maximum number of transmissions of 3 (Fig. 5) and estimated number of hops is approximately 4.2. So, estimated number of hops of hop-by-hop mechanism is quite smaller than end-to-end mechanism. t means that op-by-hop mechanism consumes less energy than end-to-end mechanism.

Similarly, if the number of hops between source and destination is high, we also should use hop-by-hop mechanism. But using hop-by-hop mechanism requires that each node is more complex.

5 Conclusion

In this paper, we introduce our research on transport layer protocols for WSNs. Probability theory is applied in the mathematical model, in which, we evaluate reliability (using probability of error) and energy consumption (using estimated number of hops). Here are the main results found in this model:

- Reliability and energy-efficiency have contra-variant relationship. An application that requires more reliability consumes more energy.
- In practice, with different network condition (probability of error per link, number of hops between source and destination), we should use a different number of transmissions. A suitable number is one that both guarantees reliability and saves energy.
- In the case of high probability of error per link or high number of hops between source and destination, we should use end-to-end instead of hop-by-hop.

Although the model assumes that the probability of error per link and number of transmissions are homogeneous; this limitation is acceptable in small networks.

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