Analytical Evaluation of Retransmission Schemes in Wireless Sensor Networks

Huimin She[1,3], Zhonghai Lu[1], Axel Jantsch[2], Dian Zhou[3], and Li-Rong Zheng[1]
[1]iPack Vinn Excellence Center, [2]School of Information and Communication Technology, KTH, Sweden
[3]ASIC & System State Key Lab., Dept. of Microelectronics, Fudan University, Shanghai, China
Emails: {huimin,zhonghai,axel,lirong}@kth.se, zhoud@fudan.edu.cn

***Abstract*—Retransmission has been adopted as one of the most popular schemes for improving transmission reliability in wireless sensor networks. Many previous works have been done on reliable transmission issues in experimental ways, however, there still lack of analytical techniques to evaluate these solutions. Based on the traffic model, service model and energy model, we propose an analytical method to analyze the delay and energy metrics of two categories of retransmission schemes: hop-by-hop retransmission (HBH) and end-to-end retransmission (ETE). With the experiment results, the maximum packet transfer delay and energy efficiency of these two scheme are compared in several scenarios. Moreover, the analytical results of transfer delay are validated through simulations. Our experiments demonstrate that HBH has less energy consumption at the cost of lager transfer delay compared with ETE. With the same target success probability, ETE is superior on the delay metric for low bit-error-rate (BER) cases, while HBH is superior for high BER cases.**

I. Introduction

With the advances of wireless communications and micro-electronics, wireless sensor network (WSN) has become a promising technology with a variety of applications, such as remote patient assistant, structural monitoring, and military surveillance [1]. For many applications, a fundamental problem is providing efficient and reliable end-to-end packet transmission [2].

Data transmission in wireless sensor networks is unreliable due to several factors such as the unreliability of wireless links, interference from hostile environments, attenuation and fading. One of the most common approaches for enhancing transmission reliability is retransmission [2], [3], [4]. Park *et al.* [2] propose a scalable framework for reliable downstream data delivery using a *Wait-for-First-Packet (WFP)* pulse. In [3], Wan *et al.* propose a reliable transport protocol called PSFQ (Pump Slowly and Fetch Quickly). These two protocols are typical examples that make use of hop-by-hop retransmissions. In [4], Pai *et al.* present an adaptive retransmission mechanism which allows a fusion center to select the sensors to retransmit their local information according to the reliability of the received information. This protocol belongs to end-to-end retransmission.

Recently, network calculus has been developed as a network dimensioning tool in packet switching networks [5]. Jens *et al.* [6] has extended this theory to analyze the delay and backlog bound in sensor networks, which is called sensor network calculus. In [7], Anis *et al.* proposed a methodology for the modeling and worst-case dimensioning of cluster-tree sensor networks. In [8], the theoretic results of sensor network calculus are validated by simulations of realistic WSN deployment scenarios. In this paper, we also use network calculus theory for analyzing the maximum transfer delay of retransmission schemes.

Many previous works have been done on reliable transport issues in experimental ways, however, there still lack of analytical techniques to evaluate different reliable transport solutions. In [9], Liu *et al.* analyze the roles of packet retransmission and erasure coding in the reliable transport of WSNs by establishing the probability models. In this paper, we propose analytical techniques to evaluate retransmission schemes in WSNs. We first introduce the traffic model, service model and energy model. Based on these models and network calculus, we analytically evaluate the maximum packet transfer delay and energy efficiency of two basic types of retransmission schemes, which are hop-by-hop retransmission and end-to-end retransmission. From the experiment results, the maximum delay and energy consumption of these two schemes are compared in several scenarios. Moreover, the analytical maximum delay is compared with the simulation results. With our method, appropriate retransmission scheme can be chosen based on different requirements and constraints. To the best of our knowledge, this is the first work that analytically studies the transmission delay of reliable data transport schemes in sensor networks.

The rest of this paper is organized as follows. Section 2 presents the system models, including the traffic model, service model and energy model. In section 3, we analytically evaluate the performance of two categories of retransmission schemes. Section 4 contains the experiment results. Conclusions are given in section 5.

II. The System Models

A. The traffic model and service model

In sensor networks, a sensor node senses its environments and generates an input traffic flow. To characterize this, we model the input flow at a node using its cumulative traffic $F(t)$, defined as the number of bits coming from the flow in time interval $[0, t]$. Furthermore, we use a wide-sense increasing function $\alpha(t)$ to constrain this cumulative traffic flow $F(t)$, which is defined by,

$$F(t) - F(s) \le \alpha(t-s); \quad \forall t \ge 0, t \ge s \tag{1}$$

where $\alpha(t)$ is called the arrival curve of the input flow $F(t)$ [5]. *Affine arrival curve* is one of the most common used arrival curves, which has been adopted in many works [6], [7], [10]. In this paper, we also use affine arrival curve to model traffic generated by source nodes, defined as $\alpha(t) = \rho \cdot t + \sigma$, where σ and ρ represent the burst tolerance (in bits) and the average data rate (in bps), respectively. Fig. 1-a) shows examples of a periodic cumulative flow $F(t)$ and an affine arrival curve $\alpha(t)$.

Service curve has been abstracted to model the resource provided by a node in packet-switched networks [5]. In wireless sensor networks, it mainly depends on link layer characteristics, such as data transmission rate and the way packets are scheduled. In order to minimize energy consumption, sensors are always coordinated in a synchronized time division manner with a periodic sleep and wakeup process for the sensor nodes. Only the nodes involving in transmitting or receiving are kept awake, while others stay in sleeping state. These characteristics of the link layer can be modeled by the *rate-latency* service curve [5], i.e.

$$\beta(t) = C \cdot \frac{S}{T} \cdot [t - (T - S)]^+ \tag{2}$$

where T denotes the frame length, S denotes the length of the slot assigned to the link, C denotes link capacity. In this service curve, CS/T is the average service rate, which describes the average transmission rate; and $(T - S)$ is the maximum service delay which contains queuing delay and sleep time. $[x]^+$ equals x when $x \geq 0$, otherwise it equals to 0. An example of the service curve is shown in Fig. 1-b).

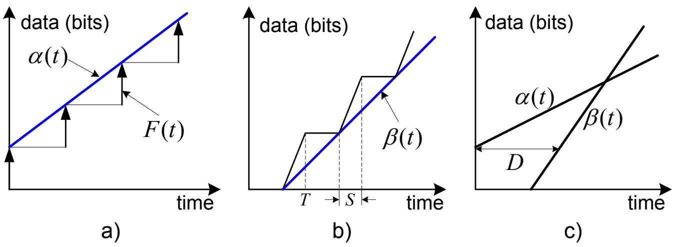

Fig. 1. a) Arrival curve; b) Service curve; c) Delay bound.

With the arrival curve and service curve, the following theorems can be derived based on the network calculus theory. The detailed descriptions and proofs of these theorems can be found in [5].

Theorem 1 Delay bound: Assume a traffic flow $R(t)$, constrained by arrival curve $\alpha(t)$, traverses a system that provides a service curve $\beta(t)$. At any time t, the virtual delay $D(t)$ satisfies,

$$D(t) \leq \sup_{t\geq 0}\{\inf_{\tau \geq 0}\{\alpha(t) \leq \beta(t+\tau)\}\} \tag{3}$$

The delay bound defines the maximum delay that would be experienced by a bit arriving at time t. Graphically, the delay bound is the maximum horizontal deviation between $\alpha(t)$ and $\beta(t)$ (Fig. 1-c).

Theorem 2 Output bound: Assume a traffic flow $R(t)$, constrained by arrival curve $\alpha(t)$, traverses a system that provides a service curve $\beta(t)$. The output flow is constrained by the following arrival curve,

$$\alpha^*(t) = \sup_{s\geq 0}\{\alpha(t+s) - \beta(s)\} \tag{4}$$

Theorem 3 Concatenation: Assume a flow sequentially traverses two systems which offer a service curve of β_1 and β_2, respectively. Then the concatenation of the two systems offers the flow the service curve $\beta(t)$, which is defined by,

$$\beta(t) = (\beta_1 \otimes \beta_2)(t) = \inf_{0\leq s\leq t}\{\beta_1(t-s) + \beta_2(s)\} \tag{5}$$

where $\otimes$ represents *min-plus convolution* (The details can be found in [5]). If β_1 and β_2 are rate-latency service curves, i.e. $\beta_1(t) = R_1[t - T_1]^+$ and $\beta_2(t) = R_2[t - T_2]^+$, then $\beta_1 \otimes \beta_2 = R^*[t - T^*]^+$, where $R^* = min(R_1, R_2)$ and $T^* = T_1 + T_2$.

B. The energy model

Following the energy model presented in [11], we abstract the energy consumption of a packet transmission between two nodes in a similar way,

$$E = 2E_{start} + \frac{L}{R}(P_{tx} + P_{rx} + 2P_{cir} + P_{amp}) \tag{6}$$

where E_{start} represents the energy for startup the radio; P_{tx} and P_{rx} represents the power consumption of the radio in transmission mode and receive mode, respectively; P_{cir} represents the power consumption of the electronic circuitry; L denotes the packet length in bits; and R denotes the transmission data rate. $P_{amp} = cd^n/p_b$ denotes the energy consumption of the power amplifier, which is mainly determined by transmission distance and *BER (bit-error-rate)*. c is a constant depending on channel attenuation and non-linear effect of the power amplifier, p_b denote BER, d is the transmission distance, and n is the poss loss exponent. The energy consumption in the sleeping mode is ignored since it is much smaller than that for packet transmission or reception [11]. However, it is straightforward to extend our model to include the energy consumption in the sleep mode.

III. Analysis of Retransmission Schemes

There have been a lot of papers on designing retransmission schemes in WSNs [2], [12], [4]. These retransmission schemes can be classified into two basic categories, namely hop-by-hop retransmission and end-to-end retransmission (Fig. 2).

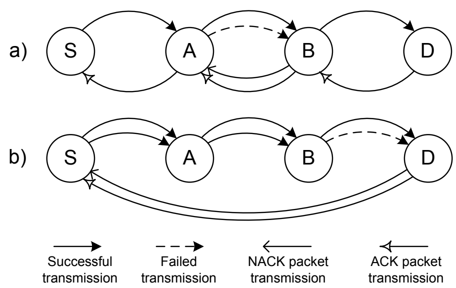

Fig. 2. a) Hop-by-hop retransmission; b) End-to-end retransmission.

We assume there is a multi-hop path with n hops between a source node S and a destination node D. And there is an *automatic repeat request* (ARQ) mechanism running until a packet successfully arrives at the receiver. A packet is not accepted as long as any bit of the packet is received with error (for non-coded systems). Furthermore, we assume an ideal

MAC protocol where there is no interference and collision, so packet delivery failures are only due to channel errors. The packet error rate p_e can be computed by $p_e = 1 - (1 - p_b)^L$, where L denotes the packet length and p_b denotes BER.

A. Hop-by-hop retransmission

In hop-by-hop retransmission scheme, at every hop, the receiver checks the correctness of the packet and requests for a retransmission with an NACK packet until a correct packet arrives. After that, an ACK packet is sent to the transmitter indicating a successful transmission. An example is shown in Fig. 2-a) . The first packet transmission is failed between A and B. Then B sends an NACK packet to A asking for a retransmission. After that, A retransmits the packet. B sends an ACK packet after successfully receiving the packet.

Let m_i denote the number of transmission trials at hop i, and p_i denote the packet error rate at hop i. Then, the transmission delay and energy consumption can be derived as follows.

1) Delay: We assume the length of an ACK and NACK packet is denoted by L_a. At the source node S, the arrival curve is expressed by $\alpha_1(t) = \rho_1 \cdot t + \sigma_1$. According to (2), the service curve at hop i $(1 \le i \le n)$ is expressed as,

$$\beta_i(t) = C \cdot \frac{S_i}{T} \cdot [t - (T - S_i)]^+ \tag{7}$$

where S_i denotes length of the slot assigned to link i. Since the input of current hop equals the output of previous hop, i.e. $\alpha_i(t) = \alpha^*_{i-1}(t)$ $(2 \le i \le n)$, the arrival curve of the traffic at the i^{th} $(1 \le i \le n)$ hop can be recursively derived based on Theorem 2,

$$\alpha^*_i(t) = \sup_{s\ge0}\{\alpha_i(t+s) - \beta_i(s)\} = \alpha_i(t) + \rho_i \cdot (T - S_i) \tag{8}$$

Based on Theorem 1, (7) and (8), the maximum delay at hop i can be derived as,

$$D_i = \sup_{t\ge0}\{\inf_{\tau\ge0}\{\alpha_i(t) \le \beta_i(t+\tau)\}\} = \frac{\sigma_i T}{C S_i} + (T - S_i) \tag{9}$$

At each hop, the expected number of transmissions can be evaluated by $1/(1 - p_i)$. Therefore, the expected maximum delay (D_{hbh}) of sending a packet from S to D can be calculated by summing up the delays at each hop,

$$D_{hbh} = \sum_{i=1}^{n} \frac{1}{1 - p_i} D_i \tag{10}$$

2) Energy consumption: The energy consumption is contributed by two factors: data packets and ACK (NACK) packets. For simplicity, the energy consumption for decoding is ignored although it is straightforward to include it. According to the energy model, the energy consumption at the i^{th} hop can be calculated by,

$$E_i = 2E^i_{start} + \frac{L + L_a}{R}(P^i_{tx} + P^i_{rx} + 2P^i_{cir} + P_{amp}) \tag{11}$$

Therefore, the total expected energy consumption E_{hbh} of transmitting a packet from S to D can be computed by,

$$E_{hbh} = \sum_{i=1}^{n} \frac{1}{1 - p_i} E_i \tag{12}$$

B. End-to-end retransmission

In end-to-end retransmission scheme, the intermediate nodes simply forward received packets to the next hop and do not check the correctness of the packets. When a packet arrives at the destination D, D checks the packet, and asks for a retransmission with an NACK packet directly to S if the packet is incorrect. Otherwise, it sends an ACK packet to S indicating a successful packet transmission. See example in Fig. 2-b).

Let p_i denote the packet error rate at hop i, and m denote the number of transmission trials. Then, the transmission delay and energy consumption can be derived as:

1) Delay: In this scheme, the retransmission is performed in an end-to-end manner, so we can derive an equivalent service curve for the whole link based on Theorem 3 and equation (7),

$$\beta_{e2e} = \beta_1 \otimes \beta_2 \otimes \cdots \otimes \beta_n = R_{e2e} \cdot (t - T_{e2e}) \tag{13}$$

where R_{e2e} and T_{e2e} can be calculated by,

$$R_{e2e} = \min_{1\le i\le n}(C \cdot \frac{S_i}{T}), \quad T_{e2e} = \sum_{i=1}^{n}(T - S_i) \tag{14}$$

According to the traffic model, the arrival curve of the input flow at S is defined as: $\alpha_{in}(t) = \rho_{in} \cdot t + \sigma_{in}$. Based on Theorem 1, the maximum delay D_{st} for one single transmission from S to D can be calculated by,

$$D_{st} = \sup_{t\ge0}\{\inf_{\tau\ge0}\{\alpha_{in}(t) \le \beta_{e2e}(t+\tau)\}\} = \frac{\sigma_{in}}{R_{e2e}} + T_{e2e} \tag{15}$$

In end-to-end retransmission, the total expected number of transmissions can be evaluated by $1/p_{st}$, where $p_{st} = \prod_{i=1}^{n}(1 - p_i)$. Then, the expected maximum delay D_{e2e} can be calculated by,

$$D_{e2e} = \frac{1}{p_{st}} D_{st} \tag{16}$$

2) Energy consumption: In the end-to-end retransmission scheme, only the sink node needs to send ACK and NACK packets, other intermediate nodes simply forward data packets. According to the energy model, the energy consumption at the i^{th} hop can be calculated by,

$$E_i = 2E^i_{start} + \frac{L}{R}(P^i_{tx} + P^i_{rx} + 2P^i_{cir} + P_{amp}) \tag{17}$$

Therefore, the total expected energy consumption E_{hbh} of transmitting a packet from S to D can be computed by,

$$E_{e2e} = \frac{1}{p_{st}} \left[\sum_{i=1}^{n} E_i + \frac{L_a}{R}(P^i_{tx} + P^i_{rx} + 2P^i_{cir} + P_{amp}) \right] \tag{18}$$

In (18), the first item computes the energy consumption for transmitting data packets, while the second item computes the energy for ACK and NACK packets transmissions.

IV. Performance Evaluation

A. Experiment setup

In this section, the maximum transmission delay and energy consumption of hop-by-hop and end-to-end retransmission schemes are compared. The parameters used in experiments are shown in Table I, which follow those used in [11], [13]. The link distance is randomly selected between $5m$ and $10m$, which is typical for most applications. We set the frame length T and slot length S to $0.2s$ and $0.01s$, respectively. The input data rate of end-to-end retransmission scheme $\rho_{in} = 30bps$, which corresponds to one packet in every eight seconds. For hop-by-hop scheme, the number of ACK (NACK) packets are the same as data packets, so the data rate at the first hop $\rho_1 = (1 + L/L_a)\rho_{in}$. The burstiness is set to $60bits$.

TABLE I
Experimental Parameters

Parameter	Notation	Value	Unit
Tx power	P_{tx}	19.1	mW
Rx power	P_{rx}	14.6	mW
Circuit power	P_{cir}	12	mW
Start energy	E_{start}	1.0	uJ
Data pkt length	L	240	bits
ACK(NACK) pkt length	L_a	80	bits
Link capacity	C	19.2	kbps
Path loss exponent	n	3.5	-

B. Comparisons of two schemes

We conduct the following experiments to compare the maximum transmission delay and energy consumption of two retransmission schemes. The BER varies from $1e-4$ to $5e-3$. From Fig. 3, we can see that the maximum delay of end-to-end and hop-by-hop retransmission schemes increases as the BER increases. Also, the maximum delay increases as the number of hops raises. Moreover, the maximum delays of hop-by-hop retransmission scheme is bigger than those of the end-to-end retransmission scheme. When the hop number is 2, the average maximum delay of end-to-end scheme is 28.9% less than that of hop-by-hop scheme. When the hop number are 4 and 6, the improvements on maximum delays of end-to-end scheme are 43.8% and 49.2%, respectively. The reason is that, in hop-by-hop scheme, every intermediate node needs to transmit ACK (NACK) packets and thus leads to more traffic, so the delay is higher than that of end-to-end scheme.

Fig. 4 illustrates the energy consumptions of two schemes with differet BERs. When the BER increases from $1e-4$ to $1e-3$, the energy consumption decreases. But when the BER increases from $2e-3$ to $5e-3$, the energy consumption increases. The reason is that the power amplifier needs consume more energy in order to guarantee a smaller BER at the receiver (equation (6)). Therefore, when the BER is very lower, the energy consumption can be higher. Fig. 4 also shows that the energy consumption of hop-by-hop scheme is less than that of end-to-end scheme. It is because, in end-to-end scheme, the error packets will not be thrown until they reach the destination and thus leads to energy waste. But this kind of energy waste can be avoided in hop-by-hop retransmission scheme.

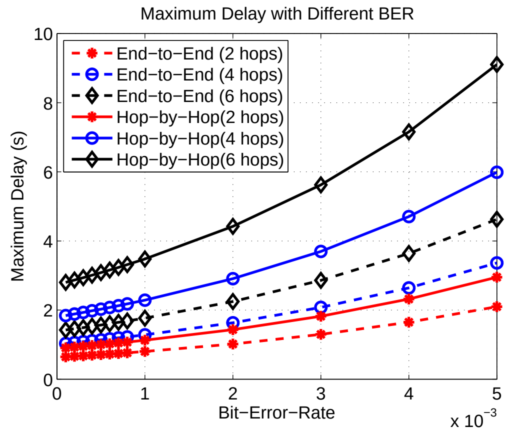

Fig. 3. Compare the maximum packet transfer delay when BER varies

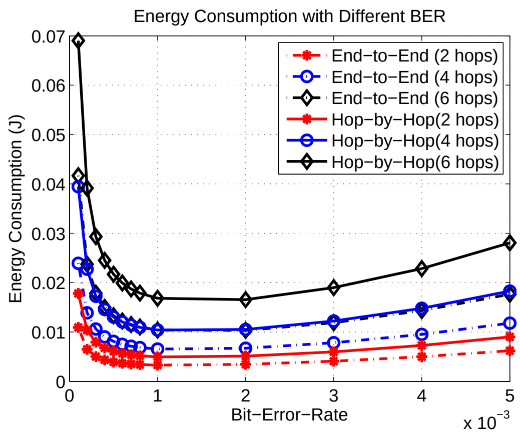

Fig. 4. Compare the energy consumption when BER varies

Fig. 5 and 6 show the comparisons of the delay and energy consumption with target success probability varying, respectively. In Fig. 5, when the BER is low $(1e-4)$, the maximum delay of end-to-end scheme is less than that of hop-by-hop scheme. But when the BER is high $(1e-3)$, the hop-by-hop scheme has less delay. This indicates that when the BER is high, more trials of retransmissions are required by end-to-end scheme to achieve the same target success probability. Fig. 6 plots the energy consumption varies with the required success probability. We observe the end-to-end retransmission scheme consume 35.8% and 65.9% more energy in average than hop-by-hop scheme when the BERs are $1e-4$ and $1e-3$, respectively. Moreover, we observe that for hop-by-hop scheme, the energy consumption with high BER $(1e-3)$ is less than that with low BER $(1e-4)$. The reason is that the power amplifier consumes more energy in order to guarantee a smaller BER at the receiver.

To validate results of delay bound, we compare the analytical results with the simulation results in a chain scenario. The simulations are performed using Omnet++ 3.3. The path length is 4 hops and BER is $5e-4$. Other parameters are shown in table I. From Fig. 7, we observe that all the simulation

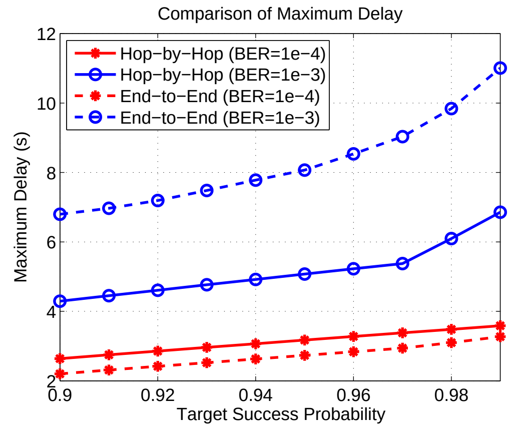

Fig. 5. With the same target success probability, compare the maximum transmission delay

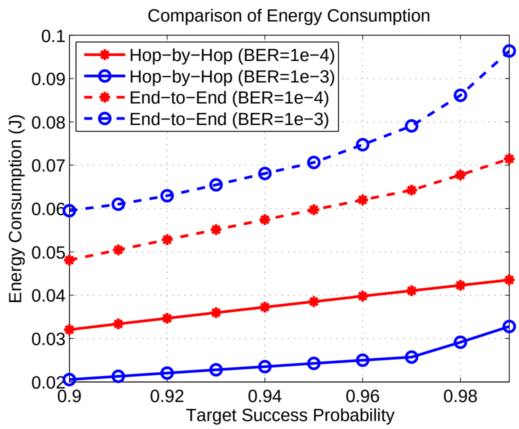

Fig. 6. With the same target success probability, compare the energy consumption

values are within the scopes of the analytical results. This indicates network calculus performs well on bounding the packet transfer delay. For end-to-end and hop-by-hop retransmission scheme, the analytical delays are 4.3% and 5.8% bigger than simulated maximum delays, respectively.

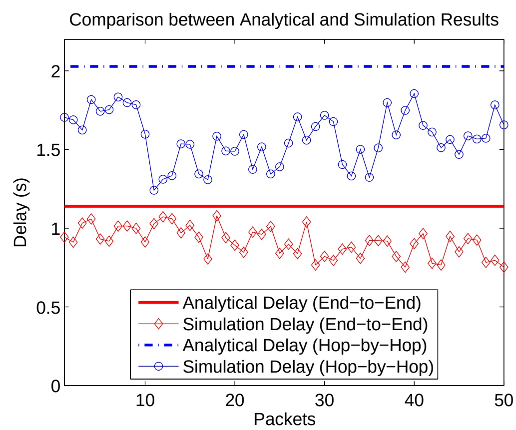

Fig. 7. Compare analytical maximum transmission delay with the simulation results

V. Conclusions

Due to the unreliable wireless links and limited energy budget, providing reliable data transmission has turned out to be a non-trivial problem in wireless sensor network. Retransmission has been adopted as one of the most prevalent schemes for addressing this issue. In this work, we first introduced the traffic model, service model and energy model. Based on these models, we presented analytical techniques to evaluate the maximum transmission delay, energy consumption and success probability of two categories of retransmission schemes: hop-by-hop retransmission and end-to-end retransmission.

With the experiment results, we compared the maximum packet transfer delay and energy efficiency of two types of retransmission schemes. For the same BERs, the hop-by-hop scheme has less energy consumptions at the cost of bigger transmission latency compared with the end-to-end scheme. Also, given target success probability, the transmission delay and energy consumptions of two schemes are studied and compared. Moreover, our analytical method for deriving delay bound was validated through simulations. Our future work will focus on validating the analytical method through realistic experiments.

Acknowledgment

This work was financially supported in part by Vinnova (The Swedish Governmental Agency for Innovation Systems) through the Vinn Excellence centers program.

References

[1] D. Culler, D. Estrin, and M. Srivastava. Overview of sensor networks. *IEEE Computer*, 37(8):41–49, 2004.

[2] S. J. Park, R. Vedantham, R. Sivakumar, and I. F. Akyildiz. A scalable approach for reliable downstream data delivery in wireless sensor networks. *in Proc. of the 5th ACM MobiHoc*, pages 78–89, 2004.

[3] C. Y. Wan, A. T. Campbell, and L. Krishnamurthy. PSFQ: a reliable transport protocol for wireless sensor networks. *in Proc. of the 1st ACM international workshop on Wireless Sensor Networks and Applications (WSNA'02)*, 2002.

[4] H. Pai, J. Sung, and Y. S. Han. Adaptive retransmission for distributed detection in wireless sensor networks. In *IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC'06)*, 2006.

[5] J. Boudec and P. Thiran. Network calculus: A theory of deterministic queuing systems for the internet. *Springer, LNCS 2050*, 2004.

[6] Jens B. Schmitt and U. Roedig. Sensor network calculus - a framework for worst case analysis. *IEEE/ACM Int. conference on Distributed Computing in Sensor Systems (DCOSS'05)*, 2005.

[7] Anis Koubaa, M. Alves, and E. Tovar. Modeling and worst-case dimensioning of cluster-tree wireless sensor networks. *the 27th IEEE International Real-time Systems Symposium (RTSS'06)*, 2006.

[8] Jens B. Schmitt Utz Roedig, Nicos Gollan. Validating the sensor network calculus by simulations. *2nd Performance Control in Wireless Sensor Networks Workshop at the 2007 WICON Conference*, 2007.

[9] B. Liu, F. Ren, C. Lin, and Y. Ouyang. Performance analysis of retransmission and redundancy schemes in sensor networks. In *IEEE International Conference on Communications (ICC'08)*, 2008.

[10] Jens B. Schmitt, F. A. Zdarsky, and L. Thiele. A comprehensive worst-case calculus for wireless sensor networks with in-network processing. In *Proceedings of the 28th IEEE Int. Real-time Systems Symposium (RTSS'07)*, 2007.

[11] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava. Energy-aware wireless microsensor networks. *IEEE Signal Processing Magazine*, 19:40–50, Mar. 2002.

[12] C. Taddia and G. Mazzini. On the retransmission method in wireless sensor networks. *in Proc. of VTC2004-Fall*, 2004.

[13] Crossbow. Mica2 date sheet. *http://www.xbow.com/ products/ Product_pdf_files /Wireless_pdf/MICA2_Datasheet.pdf.*