Joint Optimization of Lifetime and Transport Delay under Reliability Constraint Wireless Sensor Networks

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Abstract—This paper first presents an analysis strategy to meet requirements of a sensing application through trade-offs between the energy consumption (lifetime) and source-to-sink transport delay under reliability constraint wireless sensor networks. A novel data gathering protocol named Broadcasting Combined with Multi-NACK/ACK (BCMN/A) protocol is proposed based on the analysis strategy. The BCMN/A protocol achieves energy and delay efficiency during the data gathering process both in intra-cluster and inter-cluster. In intra-cluster, after each round of TDMA collection, a cluster head broadcasts NACK to indicate nodes which fail to send data in order to prevent nodes that successfully send data from retransmission. The energy for data gathering in intra-cluster is conserved and transport delay is decreased with multi-NACK mechanism. Meanwhile in inter-clusters, multi-ACK is returned whenever a sensor node sends any data packet. Although the number of ACKs to be sent is increased, the number of data packets to be retransmitted is significantly decreased so that consequently it reduces the node energy consumption. The BCMN/A protocol is evaluated by theoretical analysis as well as extensive simulations and these results demonstrate that our proposed protocol jointly optimizes the network lifetime and transport delay under network reliability constraint.

Index Terms—Wireless sensor networks, network lifetime, transport delay, statistical reliability, cluster-radius

1 Introduction

Wireless sensor networks (WSNs) are commonly used for environmental monitoring, surveillance operations, and home or industrial automation [1], [2], [3], [4]. In cluster based WSNs, the cluster head (CH) performs aggregation of all received data from its cluster members and then forwards it to the sink in a multi hop manner. Due to the unreliability of WSNs, it results in large energy consumption for multiple retransmissions and gains unexpected network performance [4], [5]. For example, since the packet loss for the communication among nodes is up to 30 percent, the success rate becomes only 16.8 percent after five hops to the sink. Thus, the reliability achieves 90 percent only if at least two retransmissions have been done in each hop. In other words, network energy is supposed to be consumed twice more than expected at each hop. Thus, it is necessary to design a new protocol to guarantee QoS in WSNs such as lifetime, end-to-end reliability, and delay. Send and Wait Automatic Repeat-reQuest (ARQ) protocol (SW-ARQ) is commonly used to ensure the reliability by employing multiple retransmissions [5].

Due to the complexity of cluster based networks, there is little research efforts in achieving all of network reliability, transport delay, and lifetime optimization. The main contributions of our work are as follows:

1) We theoretically analyze the node energy consumption and transport delay in cluster based networks under certain reliability δ. The theoretical analysis concludes that there exists the optimal cluster radius to maximize the network lifetime and minimize the transport delay. However, it is not necessarily the same value for the cluster radius which achieves maximum lifetime and minimum delay.
2) A novel data gathering protocol named **B**roadcasting Combined with Multi-**N**ACK/**A**CK(BCMN/A, which NACK; standing for "Negative-Acknowledgment", ACK for "Acknowledgment") protocol is proposed, which jointly optimizes the energy and delay efficiency under statistically reliable constraint.
3) We conduct extensive simulation experiments. Consistently with our theoretical results, simulation results demonstrate that the BCMN/A protocol is efficiency in both energy and delay under network reliability constraint, which on average improves the network lifetime by 8 percent and decreases the transport delay by 25 percent.

The remainder of the paper is organized as follows. Section 2 reviews related works comparing with our approach. Section 3 describes a network model and

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defines problem statements in the paper. In Section 4, we give delay and lifetime analysis under Send and Wait Automatic Repeat-reQuest (SW-HBH ARQ) protocol for cluster based WSNs. In Section 5, we propose a novel data gathering protocol named Broadcasting Combined with Multi-NACK/ACK (BCMN/A) protocol. Section 6 evaluates the performance of BCMN/A protocol and presents the results with some discussion. Finally, we present concluding remarks and outline the directions for future work in Section 7.

2 Related Work

In WSNs, lifetime, delay, and reliability are three important properties to be ensured and many efforts have been made in this research field [6], [7], [8].

Time division multiple access (TDMA) is an efficient MAC protocol, which plays an important role in the delay optimization. The authors of [8] take into account the number of packets being sent at every node, and provide the shortest schedule by eliminating the nodes without packets. However, algorithms proposed in [8], [9] are not scalable solutions because these require global topology information. To overcome this challenge, distributed slot assignment schemes have been proposed, such as DRAND [10], PACT [11], TRAMA [12].

For flat networks, a contention-free TDMA-based integrated MAC and routing protocol named DGRAM have been proposed in [13]. As for the specific data aggregation phenomenon in WSNs, Huang et al. [14] have proposed a centralized scheduling algorithm with the delay bound of $23\ R + \Delta + 18$ time slots, where R is the network radius and Δ is the maximum node degree. Yu et al. [15] have proposed a distributed scheduling method generating collision-free schedules with delay at most $24\ D + 6\Delta + 16$ time slots, where D is the network diameter. Xu et al. [16] have theoretically proved that the delay of the aggregation schedule generated by their algorithm is at most $16\ R + \Delta + -14$ time slots.

However, most of them have not taken the reliability into consideration. In WSNs, packets are forwarded via multiple wireless hops. On each wireless link, it is common that the packet error rates (PER) are around 10-30 percent [5], which significantly decreases the end-to-end reliability. Therefore, retransmission protocols are quite effective to maintain the reliability of WSNs, but most of the proposed delay optimization strategies are not applicable for networks using retransmission protocols. This is beause in protocols based on TDMA, the node time slot is determined according to the number of data packets to be sent. Meanwhile in retransmission protocols [5], [7], the number of data packets to be sent is unknown such that a data packet may be successfully sent only at a time, or may be successfully sent at most m times (m is the maximum retransmission number). Thus, the time slot is unknown for sending one data packet. If the time slot is arranged according to the maximum retransmission number, the transport delay becomes very large. If the time slot is not arranged, many conflicts may occur in retransmission. Thus, it is critical to first consider the network reliability and then design the delay optimization strategy.

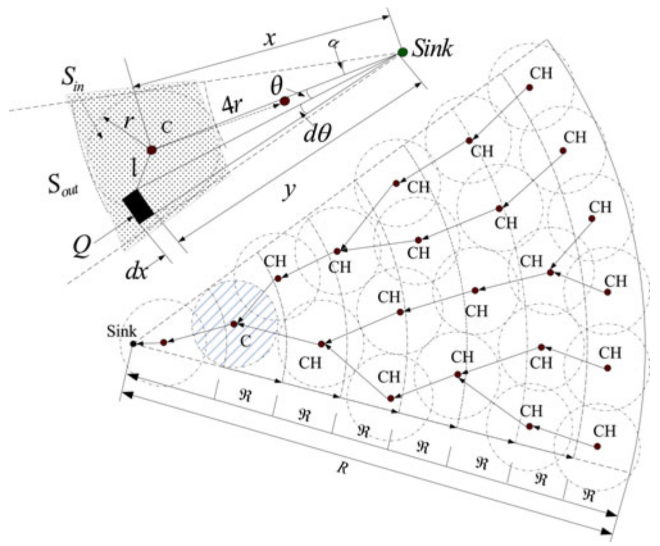

Fig. 1. The data transmission in cluster based networks.

Network data gathering should not only consider the network delay, but also the network lifetime (energy consumption) as important metrics. In the literature, many research efforts in network delay and energy consumption have been made, such as in [17], [18].

Although there is much reliability research with ARQ retransmission protocols [4], [5], [7], in most studies, they aimed at linear networks, such as Rosberg and Wang et al. [5], [7]. While other studies abstracted the routing path into linear network, such as Ref. [6], these studies are not suitable for multi-to-one networks. To the best of our knowledge, there is no analysis research of the data load and energy consumption with retransmission protocol in plane sensor networks, let alone analysis research with retransmission protocol in cluster based networks. Therefore, our first work is to analyze the lifetime and delay with ARQ protocol under certain reliability in cluster based networks. Liqi Shi and Abraham [18] did a comprehensive study of network reliability, energy and delay.

3 System Model

3.1 Network Model

We employ a network model used in [16], which is described as follows. Fig. 1 shows data transmission of the network.

1) n homogenous sensor nodes are deployed in a circular region with a sink situated at the centre. The node distribution follows a homogenous Poisson point process with a density of ρ nodes per unit area. The nodes in the network are divided into multiple clusters, each comprising a CH and cluster members that communicate via one hop to the CH. Data of CH is sent to the sink via multi-hop among CHs.
2) The transmitting radius of a node is denoted with $\Re$, and the cluster radius is denoted with r. The transmission power of the node is adjustable, i.e. the node can adjust its transmission power according to the distance to a receiver, e.g., Berkeley Mote has 100 transmission power levels [19].
3) For every node i, the probability that data transmission from node i to node $i+1$ is denoded by 1-p_i

(denoted with $\overline{p_i}$) [5]. The probability that node i successfully receives acknowledgment or negative acknowledgment (ACK/NACK) from node $i+1$ is denoted by 1 -q_i(denoted with $\overline{q_i}$) [5]. Assume that reception failures are spatial dependent but time independent.

4) Deploying SW-HBH ARQ protocol [5], nodes within a cluster send data to their CH with TDMA mechanism, and the data reliability within the cluster is δ_1. Data is transmitted with pre-assigned different frequencies inter-clusters so that the data gathering inter-clusters can work simultaneously [1]. The CHs send data to the sink hop by hop with carrier sensing multiple access (CSMA) mechanism and the reliability is δ_2.
5) Time is slotted and the slot time is fixed as Δs seconds corresponding to a single packet transmission. The transmitter serves new arrival packets on an first come first serve (FCFS) basis.

3.2 Energy Consumption Model and Related Definitions

In this paper, we adopt the topical energy consumption model in [7], where the transmission energy consumption E_t follows eq. (1) and energy consumption E_r for receiving follows eq. (2):

$$\begin{cases} E_t = lE_{elec} + l\varepsilon_{fs}d^2 & if\ d \le d_0 \\ E_t = lE_{elec} + l\varepsilon_{amp}d^4 & if\ \ d > d_0 \end{cases} \tag{1}$$

$$E_r = lE_{elec}. \tag{2}$$

E_{elec} represents transmitting circuit loss. Both the free space (d^2 power loss) and the multi-path fading (d^4 power loss) channel models are used in the model, depending on the distance between the transmitter and receiver. ε_{fs} and ε_{amp} are respectively the energy required by power amplification in the two models. l represents the bits of data sent or received by nodes. The above parameter settings are adopted from Ref. [20].

3.3 Problem Statement

Definition 1. (Transport delay). *The transport delay is defined as the time from a packet's first transmission until its successful arrival at the sink [6].*

Definition 2 (Network lifetime). *The network lifetime is defined as the time when first node dies [4], [20].*

In this paper, the main problems are: (1) In cluster based sensor networks, give the node energy consumption (network lifetime) and transport delay under reliability constraint from theoretical analysis; (2) How to further decrease the network delay and improve the network lifetime under the data reliability.

4 Delay and Lifetime Analysis under SW HBH ARQ Protocol

In this section, we present an analysis strategy to meet requirements of the application through trade-offs between the energy consumption and source-to-sink transport delay under SW HBH ARQ protocol for cluster based WSNs. Then, give an optimized Broadcasting combined with multi-NACK/ACK (BCMN/A) protocol in Section 5.

4.1 Analysis of Node Data Load under SW HBH ARQ Protocol

SW HBH ARQ is a data reliability protection protocol, its data gathering process is as the following: (1) Data gathering within the cluster, nodes within the cluster send data to the CH directly. If a transmitter receives an ACK from CH node before the preset timeout occurs, it transmits a new packet; otherwise, it retransmits the preceding packet. CH transmits an ACK for every packet it receives successfully including for duplicates; (2) Data inter-cluster heads is sent to the sink via multi-hop of CHs. The data reliability is assured in every hop. If a transmitter receives an ACK from its subsequent CH node before the preset timeout occurs, it transmits a new packet; otherwise, it retransmits the preceding packet. A receiver (CH or Sink) also transmits an ACK for every packet it receives successfully including for duplicates. In this section we analyze the node data load under SW HBH ARQ protocol.

Theorem 1. *Considering the system required data statistical reliability in intra-cluster is δ_1, then as for the node v_i within the cluster, the sent data amount is $X_i^{1,t}(\delta_1)$ and the number of ACK received is $Y_i^{1,r}(\delta_1)$, the received data amount of the cluster head within the cluster is $X_{ch}^{1,r}(\delta_1)$, and the ACK sent by the cluster head is $Y_{ch}^{1,t}(\delta_1)$, as the following*

$$\begin{cases} X_i^{1,t}(\delta_1) = \frac{1-(1-\overline{p_i q_i})^{\zeta(\delta_1)}}{\overline{p_i q_i}}, Y_i^{1,r}(\delta_1) = \frac{1-(1-\overline{p_i q_i})^{\zeta(\delta_1)}}{\overline{p_i q_i}} \overline{p_i q_i} \\ X_{ch}^{1,r}(\delta_1) = n \frac{1-(1-\overline{p_i q_i})^{\zeta(\delta_1)}}{\overline{p_i q_i}} \overline{p_i}, Y_{ch}^{1,t}(\delta_1) = n \frac{1-(1-\overline{p_i q_i})^{\zeta(\delta_1)}}{\overline{p_i q_i}} \overline{p_i}, . \\ \hfill \zeta(\delta_1) = \left\lceil \frac{\log(1-\delta_1)}{\log(p_i)} \right\rceil \end{cases} \tag{3}$$

Proof. Please refer to Section 1 of the online supplementary file, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2015.2388482, for the proof of Theorem 1. □

CH undertakes not only the data amount of intra-cluster, but also the data forwarding among the CHs. Its data and ACK load is as the following Theorem 2.

Theorem 2. *Considering the distance from cluster head C_l to the sink is l, $l = hr + x$, the required statistical reliability of data to the sink is δ_2, then the data load and ACK load D_l and ACK loadM_l of C_l is:*

$$\begin{cases} D_l^{1,t} = n(l,0)X_{h+0}^h(\delta_2) + n(l,1)X_{h+1}^h(\delta_2) \ + \cdots + n(l,z)X_{h+1}^h(\delta_2) \\ D_l^{1,r} = 0 + n(l,1)X_{h+1}^{h+1}(\delta_2)\overline{p_{h+1}} + \cdots + n(l,z)X_{h+z}^{h+1}(\delta_2)\overline{p_{h+z}} \\ M_l^{1,r} = (D_l^t \overline{p_h q_{h-1}})/N_{clusternode} \\ M_l^{1,t} = \ D_l^{1,r}/N_{clusternode}, \ n(l,i) = \phi\rho\alpha(4lr + 8ir^2) \\ X_{h+j}^h(\delta_2) = \frac{1-(1-\overline{p_h q_h})^{S_{h+j}(\delta_2)}}{\overline{p_h q_h}}, S_h(\delta_2) = \left\lceil \frac{\log(1-\sqrt[h+1]{\delta_2})}{\log(p_h)} \right\rceil, \\ N_{clusternode} = \rho\pi r^2. \end{cases} \tag{4}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 2. □

4.2 Analysis of Node Average Energy Consumption under SW HBH ARQ Protocol

Since the cluster head and common node work in alternate way in cluster based networks, the energy consumption calculation is relatively complicated. The following Theorem 3 gives the average energy consumption calculation.

Theorem 3. *If the distance from cluster head to the sink is l, then the total energy consumption for data of all nodes in intra-cluster sent to the cluster head is:*

$$\begin{aligned} E_{l,total}^{1,in} &= 2X_i^{1,t}(\delta_1)\rho\alpha\{2(E_{elec}+\varepsilon_{fs}l^2)lr + 2lr\varepsilon_{fs}(l^2+r^2)\} \\ &\quad - 4X_i^{1,t}(\delta_1)\rho\varepsilon_{fs}l\sin\alpha\left(2l^2r+\frac{2}{3}r^3\right) \\ &\quad + 4Y_i^{1,r}(\delta_1)\rho\alpha\cdot E_{elec}lr. \end{aligned} \tag{5}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the proof of Theorem 3. □

Then, after one round data gathering, the node average energy consumption is as Theorem 4.

Theorem 4. *In multi-hop cluster based networks, considering the cluster radius is r, after one round data gathering of the entire network, the average energy consumption of node whose distance from the sink is $l = hr + x$, $E_l^{1,avg}$ is as the following:*

$$\begin{cases} E_l^{1,avg} = \Big\{E_{ch}^{1,in} + \big(D_l^{1,t}+M_l^{1,t}\big)(E_{elec}+\varepsilon l^a) \\ \qquad + \big(D_l^{1,r}+M_l^{1,r}\big)E_{elec} + (n-1)\frac{E_{l,total}^{1,in}}{n}\Big\}/n \; if \; l \le 2r \\ E_l^{1,avg} = \Big\{E_{ch}^{1,in} + \big(D_l^{1,t}+M_l^{1,t}\big)(E_{elec}+\varepsilon (2r)^a) \\ \qquad + \big(D_l^{1,r}+M_l^{1,r}\big)E_{elec} + (n-1)\frac{E_{l,total}^{1,in}}{n}\Big\}/n \; if \; l > 2r \\ E_{ch}^{1,in} = X_{ch}^{1,r}(\delta_1)E_{elec} + E_l^{1,ack}, M_{l,ch}^{1,t} = \frac{1-(1-\overline{p_iq_i})^{\zeta(\delta_1)}}{\overline{p_iq_i}}\overline{p_i} \\ E_l^{1,ack} = 2M_{l,ch}^{1,t}(\delta_1)\rho\alpha\{2(E_{elec}+\varepsilon_{fs}l^2)lr \\ \qquad + 2lr\varepsilon_{fs}(l^2+r^2)\} - 4M_l^{1,t}(\delta_1)\rho\varepsilon_{fs}l\sin\alpha\big(2l^2r+\frac{2}{3}r^3\big) \end{cases} \tag{6}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 4. □

Corollary 1. *The network lifetime can be calculated as:*

$$life_1 = Einit/\max\big(E_l^{1,avg}\big) \mid l \in \{l_{\min}, R).$$

Proof. Obviously, the network lifetime is determined by the lifetime of the node which has the maximum energy consumption, that is $\max(E_l^{1,avg}) \mid l \in \{l_{\min}, R)$, so the network lifetime is $life_1 = Einit/\max(E_l^{1,avg}) \mid l \in \{l_{\min}, R)$. □

4.3 Transport Delay of Multi-Hop Cluster Based Network under SW HBH ARQ Protocol

Considering the round-trip time for common nodes send data to CH is t_{rtt} (RTT), the retransmission time out is t_{rto}(RTO), obviously, $t_{rto} > t_{rtt}$. The time for data gathering within the cluster is as the Theorem 5.

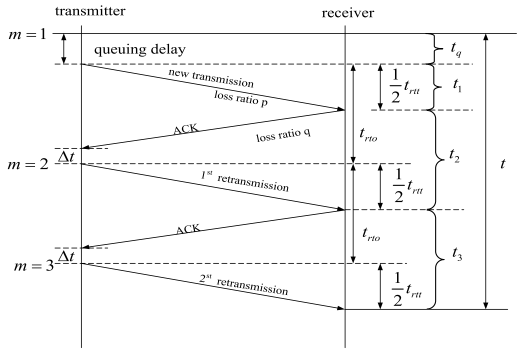

Fig. 2. Traditional transmission among CHs.

Theorem 5. *Considering $m_1 = \zeta(\delta_1)$, the then time for data gathering in intra-cluster is*

$$t_i^{1,in} = (n-1)((m_1-1)t_{rto} + t_{rtt}/2). \tag{7}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 5. □

SW-Hop By Hop ARQ protocol is used in data transmission among CHs, as shown in Fig. 2. The delay at the transmitter includes the queuing delay t_q and transport delay t. t_q is the queuing time for transmission after receiving, t is the time from sending to receiving. The total delay among CHs is shown in Theorem 6.

Theorem 6. *The delay $t_{l,CH}^1$, queuing delay t_q^1 and transport delay $E(t_t^1)$ of CH C_l at $l = hr + x$ from the sink is as following:*

$$\begin{aligned} t_{l,CH}^1 &= t_q^1 + E\big(t_t^1\big) \\ &= \frac{\rho^2}{(1-\rho)\lambda_l} + \sum_{k=1}^{\zeta(\delta_2)}\left\{\left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right)(1-p)p^{k-1}\right\}, \end{aligned} \tag{8}$$

note:

$$t_q^1 = \frac{\rho^2}{(1-\rho)\lambda_l}, \rho = \frac{\lambda_l}{\mu_1}, \mu_1 = \frac{T}{t_{rto}\overline{pq}\sum_{k=1}^{\zeta(\delta_2)}\{k(1-\overline{pq})^{k-1}\}}.$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 6. □

Theorem 6 gives the delay at the CH, and the total delay to the sink includes the data gathering delay in intra-cluster and the total delay at each CH in the routing path. Considering node v_j belongs to the CH C_l whose distance from the sink is $l = hr + x$. C_{l-2ir} denotes the i hop of C_l to the sink, then the routing path of C_l to the sink is $R_j = \{l, l-2r, l-4r, \ldots l-2ir, \ldots, r+x, x\}$, redefine the routing path with distance, that is $R_j = \{l, l-2r, l-4r, \ldots l-2ir, \ldots, r+x, x\}$, then we can get Corollary 2.

Corollary 2. *Considering node v_j belongs to the CH C_l whose distance from the sink is $l = hr + x$, the routing path of C_l to the sink is $R_j = \{l, l-2r, l-4r, \ldots l-2ir, \ldots, r+x, x\}$. Then the transport delay of node v_j is:*

$$t^1_{j,total} = \sum_{s \in R_j} t^1_{s,CH} + n((\zeta(\delta_1) - 1)t_{rto} + t_{rtt}/2). \quad (9)$$

Note:

$$t^1_{s,ch} = \frac{\rho_s^2}{(1-\rho_s)\lambda_s} + \sum_{k=1}^{\zeta_j(\delta_2)} \left\{ \left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right)(1-p)p^{k-1} \right\},$$

$$\rho_s = \frac{\lambda_s}{\mu}, \mu = \frac{T_l}{t_{rto}\overline{pq}\sum_{k=1}^{\zeta_j(\delta_2)} \{k(1-\overline{pq})^{k-1}\}}.$$

Proof. The data gathering time of node v_j is $n((\zeta(\delta_1)-1)$ $t_{rto} + t_{rtt}/2)$, where n is the node number in the cluster. According to Theorem 6, the delay at CH with distance s from the sink is $t^1_{s,CH}$, while the routing path of v_j to the sink is R_j, then the average delay of v_j in the entire path is the total forwarding delay of each CH

$$t^{ch}_{total} = \sum_{s \in R_j} t^1_{s,CH}.$$

Therefore, the total transport delay is derived as follows

$$t^1_{j,total} = \sum_{s \in R_j} t^1_{s,CH} + n((\zeta(\delta_1) - 1)t_{rto} + t_{rtt}/2).$$

□

Corollary 3. *Network delay $delay_1 = \max(t^1_{j,total})||j \in \{1, n)$.*

Proof. Obviously, the network delay is the delay of node with the maximum delay, so $delay_1 = \max(t^1_{j,total})$, note j is the number of $v_j|$j $\in \{1, n\}$. □

5 Broadcasting Combined with Multi-ACK for Optimization Lifetime and Delay

5.1 The Idea of Broadcasting Combined with Multi-NACK/ACK (BCMN/A)

To further improve the performance of cluster based networks, this paper presents Broadcasting combined with multi-NACK/ACK (BCMN/A) protocol. The improvement of BCMN/A protocol is mainly reflected in the following two aspects

1) As for data gathering within the cluster, ACK is send by broadcasting and the data gathering mechanism is as the following. (A) The CH allocates time slot for each node in intra-cluster and the time slot is $\frac{1}{2}t_{rtt}$, each node sends data to the CH during its time slot. (B) After each node has send data to the CH, CH broadcast a message which employ NACK indicate those nodes whose data is not send to CH successful and the time slot scheduling sequence for next round.

   (C) Nodes receive broadcast a message and determine whether CH has received its data according, if received, node sleeps and this data gathering round is completed, if not, node retransmits data according to the arranged time slot. Node will keep silent if it does not receive the broadcasting and wait for the next broadcasting. (D) After the second data gathering round, similar with the first cycle, the ID of nodes which CH did not receive data from and the time sequence is broadcasted, and nodes in intra-cluster adopt the same mechanism and continue until the reliability meets the requirement δ_1.
2) As for data transmission of inter-clusters, the improved protocol is that the CH returns n ACK for each data packet it receives (this is called muti-ACK, see Fig. 3).

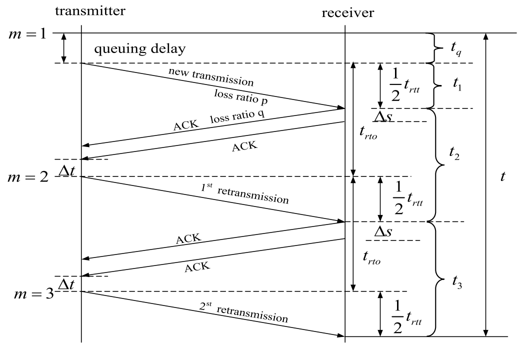

Fig. 3. Transmission among CHs under BCMN/A.

5.2 Analysis of the Lifetime for BCMN/A Protocol

Under the BCMA protocol, after each data gathering in intra-cluster and the broadcasting by CH (one broadcasting or mutil-broadcastings), such process is called one round. The following theorem gives the data load of node in one round.

Theorem 7. *If only one broadcasting is processed for each data gathering for intra-cluster, to meet the reliability δ_1, the number of retransmissions in onde roud should be*

$$m_2 = \left\lceil \frac{\log(1-\delta_1)}{\log(1-(1-q)(1-p))} \right\rceil.$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 7. □

Corollary 4. *As for the data gathering in intra-cluster, if there are z broadcastings for each data gathering process, then the number of rounds needed is:*

$$m_3 = \left\lceil \frac{\log(1-\delta_1)}{\log(1-(1-q^z)(1-p))} \right\rceil.$$

Proof. Obviously, if z broadcastings are processed for each data gathering process, the reliability after k rounds is $1-(1-(1-q^z)(1-p))^k$, set the reliability

$$1-(1-(1-q^z)(1-p))^{m_3} > \delta_1$$
$$\Rightarrow m_3 = \left\lceil \frac{\log(1-\delta_1)}{\log(1-(1-q^z)(1-p))} \right\rceil.$$

□

The following gives the data load under BCMA protocol.

Theorem 8. *Under BCMA protocol, if ACK is only broadcasted only once each time, the node data load intra-cluster is as the following. Note, $D^{2,t}_i$ is the total number of data packets, $M^{2,r}_i$*

is the node received ACK bits amount, $M_{ch}^{2,t}$ is the CH sent ACK bits amount, the number of received data packets is $D_{ch}^{2,r}$. m_2 is the number of gathering rounds, n *is the number of nodes intra-cluster,* c *is the needed bits amount of each node ID*

$$\begin{cases} D_i^{2,t} = (1-q)\sum_{k=1}^{m_2}(1-\overline{pq})^{k-1}, \\ M_i^{2,r} = \sum_{k=1}^{m_2}(1-q)(1-\overline{pq})^{2(k-1)}(n-1)^2 c \\ D_{ch}^{2,r} = (n-1)D_i^{2,t}\overline{p}, M_{ch}^{2,t} = (n-1)c\sum_{k=1}^{m_2}(1-\overline{pq})^{k-1} \end{cases}. \tag{10}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 8. □

Under BCMA protocol, if the ACK broadcasting is repeated z times after each data gathering, namely the multi-ACK, the data load and ACK load of intra-cluster is as Theorem 9.

Theorem 9. *If the ACK broadcasting is repeated z times after each data gathering round, the data load is as the following. Note, $D_i^{3,t}$ is the number of total data packets sent by nodes within the cluster, $M_i^{3,r}$ is the ACK bits amount received by nodes, $M_{ch}^{3,t}$ is the ACK bits amount sent by the CH, $D_{ch}^{3,r}$ is the number of data packets received, m_3 is the number of data gathering round,* n *is the number of nodes within the cluster,* c *is the node ID bits amount of each node*

$$\begin{cases} D_i^{3,t} = (1-q^z)\sum_{k=1}^{m_3}(1-\overline{p}(1-q^z))^{k-1}, \\ M_i^{3,r} = \sum_{k=1}^{m_3}(1-q^z)(1-\overline{p}(1-q^z))^{2(k-1)}(n-1)^2 c \\ D_{ch}^{3,r} = (n-1)D_i^{2,t}\overline{p}, M_{ch}^{3,t} = (n-1)c\sum_{k=1}^{m_3}(1-\overline{p}(1-q^z))^{k-1} \end{cases}. \tag{11}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 9. □

Theorem 10. *Under BCMN/A protocol, CH returns z ACK for each data it receives, assuming the distance from CH C_l to the sink is $l = hr + x$, the required statistical reliability is δ_2, then the data load and ACK load of is:*

$$\begin{cases} D_l^{4,t} = n(l,0)X_{h+0}^h(\delta_2) + n(l,1)X_{h+1}^h(\delta_2) \\ \quad + \cdots + n(l,z)X_{h+1}^h(\delta_2) \\ M_l^{4,t} = 0 + n\cdot n(l,1)X_{h+1}^{h+1}(\delta_2)\overline{p} + \cdots + n\cdot n(l,z)X_{h+z}^{h+1}(\delta_2) \\ D_l^{4,r} = M_l^t/n, M_l^{4,r} = nD_l^t\overline{pq}, n(l,i) = \phi\rho\alpha(4lr + 8ir^2) \\ X_{h+j}^h(\delta_2) = \frac{1-(1-\overline{p}(1-(1-\overline{q})^z)^{S_{h+j}(\delta_2)}}{\overline{p}(1-\overline{q})^z)}, S_h(\delta_2) = \left\lceil \frac{\log(1-\sqrt[h+1]{\delta_2})}{\log(p)} \right\rceil \end{cases}. \tag{12}$$

Proof. Under Send and wait hop to hop one data n ACK protocol, the maximum retransmission number is the same with Theorem 4, the transmission times of the source node sends its one data packet is a truncated geometrically distributed r.v. with a success probability of $\overline{p_i}(1-(1-\overline{q_i})^z)$ taking values in the set $\{1,\ldots,S_h(\delta_2)\}$. Its expected value is given by:

$$X_{h+j}^h(\delta_2) = \frac{1-(1-\overline{p}(1-(1-\overline{q})^z)^{S_{h+j}(\delta_2)}}{\overline{p}(1-\overline{q})^z)}$$

Similar with Theorem 4, we can get Theorem 10. □

Theorem 11. *Under multi-hop cluster based protocol, considering the cluster radius is r, as for the data gathering intra-cluster, NACK is broadcasted once for each data gathering round and z ACK is returned for each received data inter-clusters, after an entire data gathering, the average energy consumption $E_l^{2,avg}$ for node whose distance from the sink is $l = hr + x$ is as the following*

$$\begin{cases} E_l^{2,avg} = \Big\{E_{ch}^{2,in} + (D_l^{4,t} + M_l^{4,t})(E_{elec} + \varepsilon l^a) \\ \quad + (D_l^{4,r} + M_l^{4,r})E_{elec} + (n-1)\frac{E_{l,total}^{2,in}}{n}\Big\}/n \ if \ l < 2r \\ E_l^{2,avg} = \Big\{E_{ch}^{2,in} + (D_l^{4,t} + M_l^{4,t})(E_{elec} + \varepsilon (2r)^a) \\ \quad + (D_l^{4,r} + M_l^{4,r})E_{elec} + (n-1)\frac{E_{l,total}^{2,in}}{n}\Big\}/n \ if \ l > 2r \\ E_{ch}^{2,in} = D_{ch}^{2,r}E_{elec} + M_{ch}^{2,t}(E_{elec} + \varepsilon r^a) \\ E_{l,total}^{2,in} = 2D_i^{2,t}(\delta_1)\rho\alpha\{2(E_{elec} + \varepsilon_{fs}l^2)lr + 2lr\varepsilon_{fs}(l^2 + r^2)\} \\ \quad - 4D_i^{2,t}(\delta_1)\rho\varepsilon_{fs}l\sin\alpha(2l^2r + \frac{2}{3}r^3) + 4M_i^{2,r}\rho\alpha\cdot E_{elec}lr. \end{cases} \tag{13}$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 11. □

Corollary 5. *Under multi-hop cluster based protocol, assuming the cluster radius is r, when NACK is broadcasted z times in each data gathering round, z ACK is returned for each data packet received inter-clusters, after an entire data gathering round, the average energy consumption $E_l^{3,avg}$ for node whose ditance from the sink is $l = hr + x$ is as the following*

$$\begin{cases} E_l^{3,avg} = \Big\{E_{ch}^{3,in} + (D_l^{4,t} + M_l^{4,t})(E_{elec} + \varepsilon l^a) \\ \quad + (D_l^{4,r} + M_l^{4,r})E_{elec} + (n-1)\frac{E_{l,total}^{3,in}}{n}\Big\}/n \ if \ l < 2r \\ E_l^{3,avg} = \Big\{E_{ch}^{3,in} + (D_l^{4,t} + M_l^{4,t})(E_{elec} + \varepsilon (2r)^a) \\ \quad + (D_l^{4,r} + M_l^{4,r})E_{elec} + (n-1)\frac{E_{l,total}^{3,in}}{n}\Big\}/n \ if \ l > 2r \\ E_{ch}^{3,in} = D_{ch}^{3,r}E_{elec} + M_{ch}^{3,t}(E_{elec} + \varepsilon r^a) \\ E_{l,total}^{3,in} = 2D_i^{3,t}(\delta_1)\rho\alpha\{2(E_{elec} + \varepsilon_{fs}l^2)lr + 2lr\varepsilon_{fs}(l^2 + r^2)\} \\ \quad - 4D_i^{3,t}(\delta_1)\rho\varepsilon_{fs}l\sin\alpha(2l^2r + \frac{2}{3}r^3) + 4M_i^{3,r}\rho\alpha\cdot E_{elec}lr. \end{cases} \tag{14}$$

Proof. Similar with Theorem 11, it can be proved (omitted). □

5.3 Analysis of the Transport Delay for BCMN/A Protocol

The following analyzes the transport delay under BCMN/A protocol, similarly, the node transport delay includes the delay of data gathering within the cluster and the delay of data sent to the sink. The following gives the analysis results.

Theorem 12. *Under BCMN/A protocol, if the NACK is broadcasted only once after the first data gathering round, the data delay is*

$$t_i^{2,in} = \frac{1}{2}(n-1)t_{rtt} + (n-1)\sum_{k=2}^{m_2}(1-\overline{pq})^{k-1}\frac{1}{2}t_{rtt} + \frac{1}{2}m_2 t_{rtt}.$$

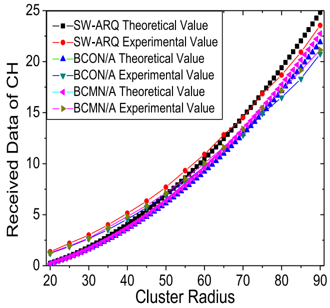

Fig. 4. Data load in the cluster of CH.

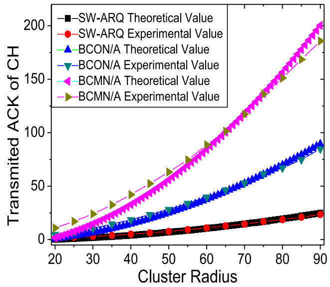

Fig. 5. ACK amount in the cluster of CH.

If the broadcasting is repeated z times in one data gathering round, the delay is

$$t_i^{3,in} = \frac{1}{2}(n-1)t_{rtt} + (n-1)\sum_{k=2}^{m_3}\left(1-\overline{p}(1-q^z)\right)^{k-1}\frac{1}{2}t_{rtt} + \frac{1}{2}m_3 t_{rtt}.$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 12. □

Theorem 13. *Under BCMA/A protocol, the delay is $t_{l,CH}^2$ for CH C_l whose distance from the sink is $l = hr + x$, the queuing delay t_q^2 and transport delay $E(t_t^2)$ are as the following:*

$$t_{l,CH}^2 = t_q^2 + E(t_t^2) = \frac{\rho_l^2}{(1-\rho_l)\lambda_l} + \left(\frac{1}{2}t_{rtt}\right)(1-p) + \sum_{k=2}^{\zeta(\delta_2)}\left\{(k-1)t_{rto}^A(1-p)p^{k-1}\right\}$$

$$Note: t_q^2 = \frac{\rho_l^2}{(1-\rho_l)\lambda_l}, \rho_l = \frac{\lambda_l}{\mu_2},$$

$$\mu_2 = \frac{T_l}{t_{rto}^A\overline{p}(1-q^z)\sum_{k=1}^{\zeta(\delta_2)}\left\{k(1-\overline{p}(1-q^z))^{k-1}\right\}}.$$

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Theorem 13. □

If the data gathering delay of intra-cluster and the transport delay inter-clusters are obtained, the transport delay from node v_j generates data to data received by the sink can be obtained as the Corollary 6.

Corollary 6. *Under BCMA/A protocol, assuming node v_j belongs to the CH C_l whose distance from the sink is $l = hr + x$, then the routing path of C_l to the sink is $R_j = \{l, l-2r, l-4r, \ldots l-2ir, \ldots, r+x, x\}$. Then the transport delay of v_j is:*

$$t_{j,total}^2 = \sum_{s\in R_j} t_{s,CH}^2 + t_i^{2,in} \quad \text{or} \quad t_{j,total}^2 = \sum_{s\in R_j} t_{s,CH}^2 + t_i^{3,in},$$

where $t_{s,ch}^2 = t_{l,ch}^2$ when $s = l$.

Proof. Please refer to Section 1 of the online supplementary file, available online, for the Proof of Corollary 6. □

6 Analysis of Experimental Results

OMNET++ is employed for experimental verification [22]. Without loss of generality, the parameters are $p = q = 0.3$, $\delta_1 = \delta_1 = 0.9$, $R = 500$ m, 1,000 nodes are deployed. The other parameter settings refer to Table 1 of the online supplementary file, available online. The retransmission protocol in Section 4 is called SW-ARQ for short, Broadcasting combined with one-NACK or ACK deployed within the cluster is called BCON/A for short, Broadcasting combined with multi-NACK or ACK deployed both in the cluster and among CHs is called BCMN/A for short.

6.1 Comparison of Theoretical and Experimental Result of Node Data Load

The main purpose of the experiment in this section is to verify whether the analysis in this paper of data load under retransmission protocol in cluster based networks matches the actual situation. Figs. 4 and 5 respectively shows the data load and ACK amount under different cluster radius under SW-ARQ, BCON/A, BCMN/A protocol, from which we can see the analysis model describes the data load of the network well since experimental results and theoretical analysis results are very consistent.

Figs. 6 and 7 shows the data load under ACK load of CH under SW-ARQ, BCMN/A, the same, as can be seen that the theoretical results are consistent with experimental results. Therefore, as can be seen from the above experiments: (1) BCMN/A bears more ACK and less data load of CH than SW-ARQ. (2) CH near the sink bears more data load and ACK load than CH away from the sink.

6.2 Comparison of Theoretical and Experimental Result of Node Energy Consumption

Figs. 8 and 9 respectively shows the node average energy consumption with different distances from the sink under SW-ARQ and BCMN/A. As can be seen from the experimental results, the theoretical model better reflects the network's energy consumption situation, which has good guidance. Figs. 10 and 11 give the three-dimensional map of

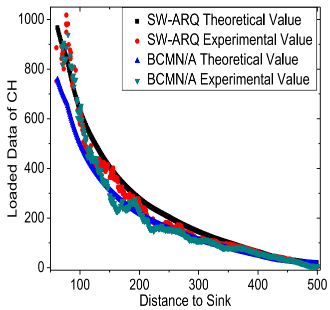

Fig. 6. Total data load of CH.

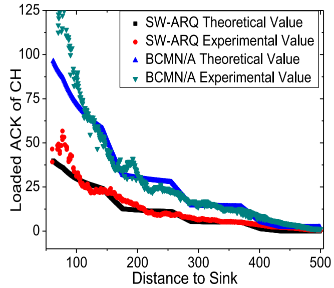

Fig. 7. Total ACK load of CH.

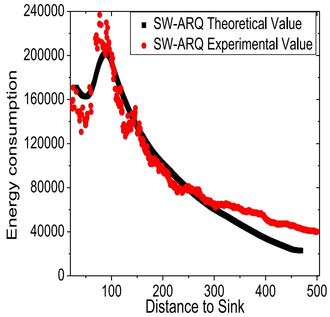

Fig. 8. Energy consumption under SW-ARQ.

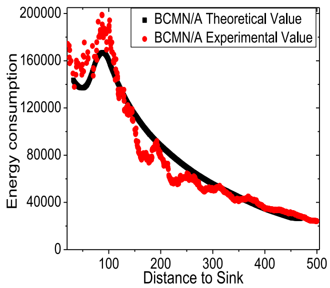

Fig. 9. Energy consumption under BCMN/A.

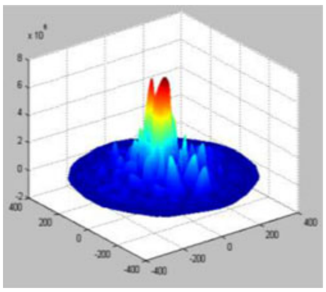

Fig. 10. Three-dimesional map of energy consumption under SW-ARQ.

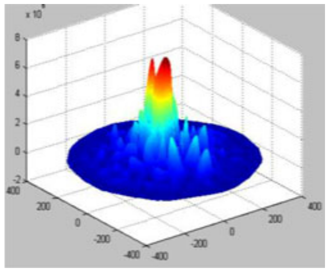

Fig. 11. Three-dimensional map of energy consumption under BCMN/A.

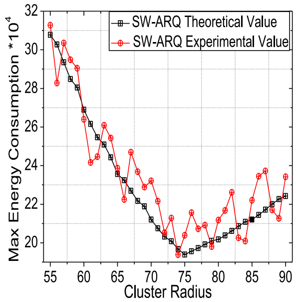

Fig. 12. The maximum energy consumption of node under different cluster radius under SW-ARQ.

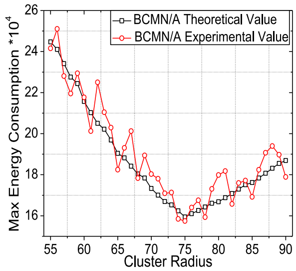

Fig. 13. The maximum energy consumption of node under different cluster radius under BCMN/A.

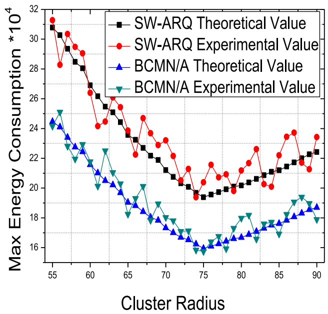

Fig. 14. Max energy consumption comparison under SW-ARQ and BCMN/A.

network node energy consumption under SW-ARQ, BCMN/A protocol.

Figs. 12 and 13 respectively shows the energy consumption of node with maximum energy consumption under different cluster radius under SW-ARQ and BCMN/A protocol, as can be seen, the maximum energy consumption is different under different cluster radius r. Therefore, we can choose optimized r to achieve maximum lifetime. Fig. 14 shows the maximum energy consumption comparison under different cluster radius under SW-ARQ and BCMN/A protocol, as can be seen from the results, the improved BCMN/A can reduce the energy consumption nearly by 20 percent. Fig. 15 shows the network lifetime comparison under SW-ARQ and BCMN/A, we can see that the BCMN/A protocol in this paper can improve the network lifetime effectively.

6.3 Comparison of Theoretical and Experimental Result of Network Delay

Fig. 16 shows the data gathering delay of intra-cluster under SW-ARQ and BCMN/A, as can be seen that BCMN/A

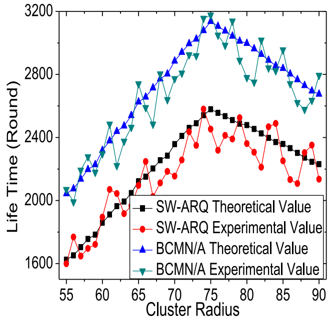

Fig. 15. Lifetime comparison under SW-ARQ and BCMN/A.

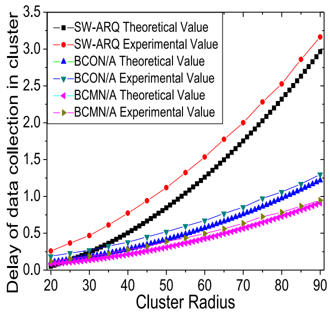

Fig. 16. Data gathering delay under different cluster radius.

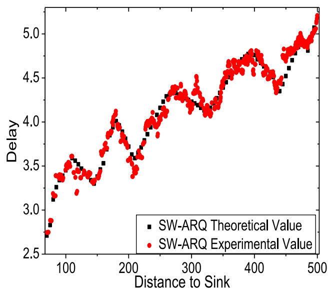

Fig. 17. Delay of different distances from the sink under SW-ARQ.

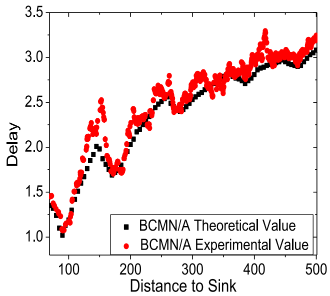

Fig. 18. Delay of different distances from the sink under BCMN/A.

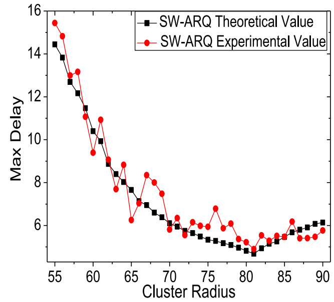

Fig. 19. Max delay under different cluster radius under SW-ARQ.

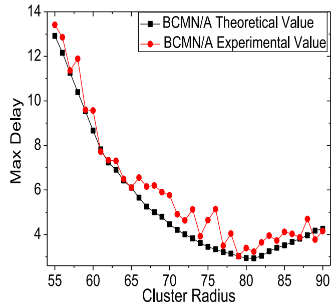

Fig. 20. Max delay with different cluster radius under BCMN/A.

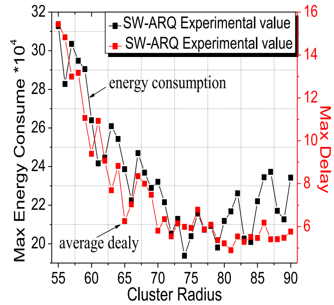

Fig. 21. Max energy consumption and max delay with different cluster radius under SW-ARQ.

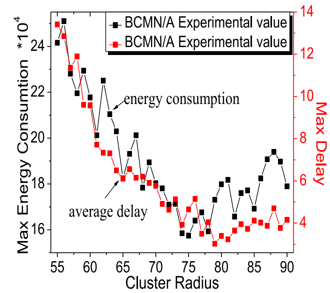

Fig. 22. Max energy consumption and max delay with different cluster radius under BCMN/A.

protocol can better reduce the delay. Figs. 17 and 18 respectively shows the node average delay with different distances from the sink under SW-ARQ and BCMN/A, as can be seen that the farther from the sink, the greater is the node delay. However, the average delay is not a line growth, but the undulating rise. The reason is: the average delay is mainly proportional to the number of hops, and for nodes with the same hops from the sink, the data load decreases as the distance from the sink, so the average delay decreases, and the data load increases in the next hop, so the average delay increases.

Figs. 19 and 20 respectively shows the maximum network delay with different cluster radius under SW-ARQ and BCMN/A protocol, as can be seen that the maximum average delay is not the same when the cluster radius is different, but there must be an optimal cluster radius r to achieve the minimum network delay.

6.4 Overall Optimization of Network Lifetime and Delay

Figs. 21 and 22 respectively shows the maximum energy consumption and network average delay with different

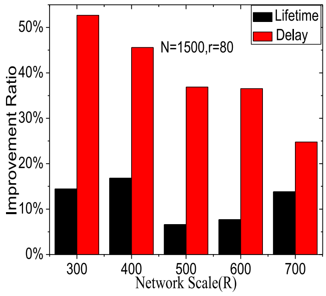

Fig. 23. Improved ratio of network lifetime and delay with different network scale under BCMN/A.

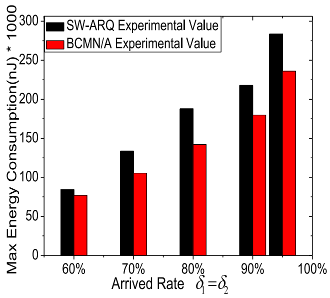

Fig. 24. Max energy consumption under different reliability requirements.

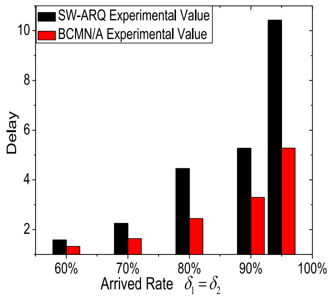

Fig. 25. Delay under different reliability requirements.

cluster radius under SW-ARQ and BCMN/A. As can be seen, when the cluster radius r is small, with the growth of cluster radius, the network energy consumption and average delay decrease, but when the r grows to a certain degree, the energy consumption and average delay also increase, and the optimal r for network delay and energy consumption are not entirely consistent. Obviously, it is easy to obtain the optimal r to optimize the lifetime and delay under application requirements. With optimized r under different network scale R, Fig. 23 shows the improved ratio of network lifetime and delay under BCMN/A compared with SW-ARQ, showing BCMN/A protocol improves the network lifetime by average 8 percent above and optimizes the delay by more than 25 percent.

6.5 Effects of Network Parameters

6.5.1 *Effects of Reliability Constraint*

Figs. 24 and 25 show the effect of reliability constraint on the network energy consumption and delay. As can be seen, the reliability δ_1 and δ_2 (respectively refers to the reliability of intra-cluster and reliability inter-clusters) have a very big impact on the energy consumption and delay. When $\delta_1 = \delta_2 = 90\%$, the energy consumption and delay is four

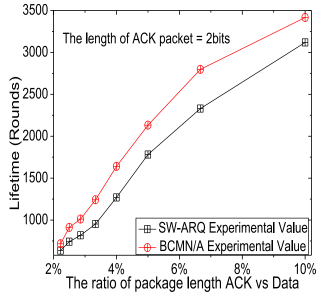

Fig. 26. Lifetime under different ratios of ACK length and data packet length.

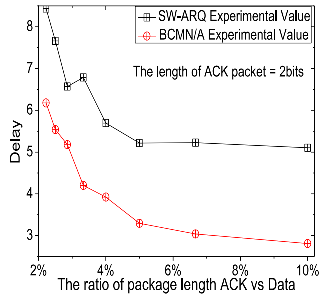

Fig. 27. Delay under different ratios of ACK length and data packet length.

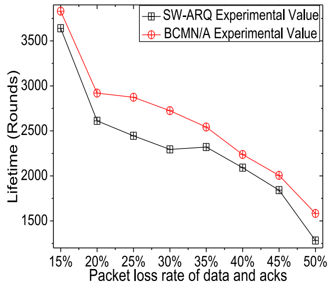

Fig. 28. Lifetime under different packet loss rates.

times of that when $\delta_1 = \delta_2 = 60\%$. Therefore, in the evaluation of sensor network performance, the fact that the reliability in WSNs is relatively low should be taken into consideration, and there is often big difference between the result under the optimal network without packet loss and that of the actual network.

6.5.2 *Effects of Different Length of ACK and Data Packets*

Figs. 26 and 27 show the lifetime and delay under different ratios of ACK length and data packet length. As can be seen, when the ACK length is fixed, the bigger is ratio of ACK length and data packet length, indicts the smaller packet length, so the network lifetime is bigger, and the delay is smaller. Meanwhile, as can be seen from the result, ACK has big effect on the network lifetime and delay, which cannot be ignored.

6.5.3 *Effects of Packet Loss*

Figs. 28 and 29 show the effects of different packet loss rates on the network lifetime and delay. As can be seen, when the application required reliability is fixed, the higher is the

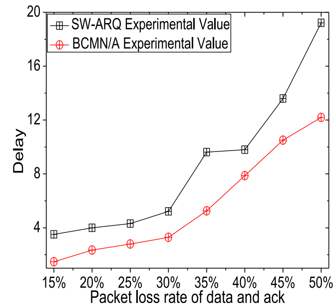

Fig. 29. Delay under different packet loss rates.

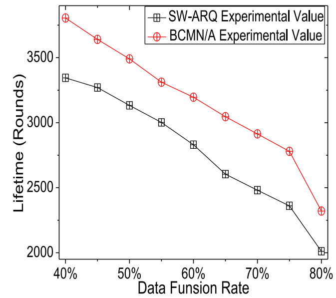

Fig. 30. Lifetime under different data fusion rates.

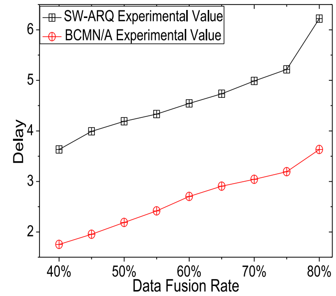

Fig. 31. Delay under different data fusion rates.

network packet loss rate, the more retransmissions are required, and this causes the increase of data load and energy consumption, and thus the network performance of delay and lifetime and are deteriorating.

6.5.4 Effects of Data Fusion Rate

Figs. 30 and 31 show the effects of different data fusion rates on the network lifetime and delay. As can be seen, when the data fusion rate is higher, since the data load is decreased, the network lifetime is improved and the network delay is reduced.

Fig. 32 shows the effect of more ACK transmissions after receiving one data packet on the lifetime under BCMN/A protocol. In previous experiments, two ACK are returned for each data received under BCMN/A, and the result in Fig. 32 shows that three-four ACK can better improve the lifetime. Fig. 33 shows the longer time period of data collection cycle, the less network transport delay. The reason is that when T increases, although the node data load is the same, the packet arrival rate is decreased, thus reducing the queuing delay, thus reducing the delay.

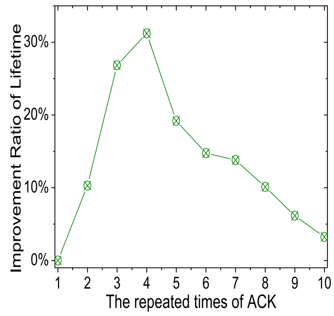

Fig. 32. Improvement ratio of lifetime under different repeated times of ACK.

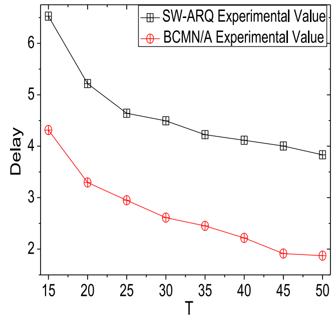

Fig. 33. Delay under different data gathering cycles T.

7 Conclusion

In this paper, we propose the advanced BCMN/A protocol, BCMN/A protocol broadcasts intra-cluster and returns multi-ACK for each data received from clusters for improving the network lifetime and decrease the network delay. We first give a detailed theoretical analysis results of BCMN/A protocol. Then a large number of experiments was conducted to confirm the theoretical analysis, as well as the validity of BCMN/A, which can increase the network lifetime by more than 8 percent and reduce network delay by more than 25 percent.

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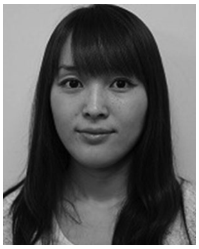

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