

# Energy Balance Quorum System for Wireless Sensor Networks

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## Abstract

In recent years, wireless sensor networks (WSNs) technology has been widely used in various fields because of its advantage of low construction cost. Based on the characteristics of sensor-limited power, there are presently many studies that explore how to extend the life cycle of WSNs under limited power conditions. Some research designed sensor wake-up scheduling mechanisms according to the quorum system that can not only achieve the effect of energy-saving, but also ensure the rendezvousing opportunities between the sensors. However, there is a problem of rendezvous idle when the sensor performs a sensing task. In order to improve the power-saving efficiency of the sensors, this paper designs an energy balance quorum system (EBQS). In addition to ensuring the opportunity to rendezvous between the sensors, this system can also balance the remaining capacity of the sensors and improve the power-saving efficiency of the traditional Quorum System depending on the remaining capacity of the sensors and the way they rendezvous. The experimental results show that the EBQS proposed in this paper can effectively reduce the number of slots compared to the traditional quorum system scheduling mechanism.

**Keywords:** Wireless Sensor Networks; Energy Balance; Quorum System; Rendezvous Mechanism; Power-saving

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## 1. Overview

WSN is a low-cost and short-range wireless communications technology. It has been widely used in various fields, such as ecological environment monitoring, road traffic control, home health care and industrial and commercial enterprises, etc. Because the sensor is powered by a limited battery, the sensor power is consumed quickly and the sensor dies if it can't manage the power consumption reasonably. This results in a fast end-of-life of the wireless sensor networks. As the result, extending the life cycle of wireless sensor networks has become a problem that should be solved urgently.

The best way to save the power of the sensor is to use the sleep mechanism [5]. The basic practice is to allow the sensor to work for a part of the time and sleep for another part of the time. However, in order to maintain the effectiveness of communication, the sensor must be active for most of the time. It causes the sensor to often be in an idle listening state and consume a lot of unnecessary power [7,9]. This can save electricity, but it is not ideal. In response to this shortcoming, it was suggested that the duty cycle be divided into two Beacon Intervals: Low-power Beacon Interval and Full-awake of Beacon Interval. The two Beacon Intervals interact with each other in a periodic rotation so that the adjacent sensors can rendezvous and transmit while saving electricity. Full-awake of Beacon Interval applies to the period in which the sensor is initially in the network, the sensors that have just entered the network can discover the presence of adjacent sensors, or the sensors that need to receive data in Full-awake of Beacon Interval. On the contrary, the Low-power Beacon Interval applies to the sensor in the absence of any transmission requirements, then immediately enters the Low-power Beacon Interval to

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save power. In the study of [2,6], a Quorum-based [3,4] rendezvous mechanism was proposed, which considers  $n^2$  consecutive Beacon Intervals as a time cycle. The Beacon Intervals in the time cycle are in the order of small to large and from left to right corresponding to the  $n \times n$  dimension of the Quorum square matrix system. In this way, the sensor in the network arbitrarily selects a row and a column in the Quorum square system as its working slots and the rest as its sleeping slots, so as to achieve the purpose of saving power without communication. As shown in Fig. 1, the four sensors  $s_i, s_j, s_k$  and  $s_l$  adopt a Quorum system with a duty cycle of  $3 \times 3 = 9$ . The shadows in Fig. 2 show the working schedule of each sensor. The examples in this paper will use the working slots of Fig. 1. This Quorum system can ensure that a sensor has at least two intersections with its adjacent sensors in a cycle consisting of  $n^2$  Beacon Intervals. And one intersection lasts one Beacon Interval. Based on this overlap feature, no matter how much the cycle time offset of the Quorum System between the two sensors is, it must ensure that there are at least two rendezvous opportunities between the two sensors. It not only prevents the sensor from sending frames frequently or wasting a lot of idle listening to maintain the neighbor's information, but also reduces the rendezvous delay to a Quorum cycle length effectively. More importantly, it makes the sensor immediately go into the power-saving state when there is no transmission. Therefore, it can extend the life cycle of network.

$s_i$	$s_j$	$s_k$	$s_l$
1 2 3	1 2 3	1 2 3	1 2 3
4 5 6	4 5 6	4 5 6	4 5 6
7 8 9	7 8 9	7 8 9	7 8 9

Figure 1. Duty slots of  $s_i, s_j, s_k, s_l$ 

Duty cycle $d = n \times n = 3 \times 3 = 9$												
Slot	7	8	9	1	2	3	4	5	6	7	8	9
$s_i$	$a_i^1$	$a_i^2$	$a_i^3$	$a_i^4$	$a_i^5$	$a_i^6$	$a_i^7$	$a_i^8$	$a_i^9$	$a_i^1$	$a_i^2$	$a_i^3$
$s_j$		$a_j^1$	$a_j^2$	$a_j^3$	$a_j^4$	$a_j^5$	$a_j^6$	$a_j^7$	$a_j^8$	$a_j^9$	$a_j^1$	$a_j^2$
$s_k$			$a_k^1$	$a_k^2$	$a_k^3$	$a_k^4$	$a_k^5$	$a_k^6$	$a_k^7$	$a_k^8$	$a_k^9$	$a_k^1$
$s_l$				$a_l^1$	$a_l^2$	$a_l^3$	$a_l^4$	$a_l^5$	$a_l^6$	$a_l^7$	$a_l^8$	$a_l^9$

Figure 2. Working schedule for  $s_i, s_j, s_k$  and  $s_l$ .

However, existing Quorum-based studies fail to consider the remaining capacity of the network sensors. If the residual power of the intermediary sensor is small, it may accelerate the consumption of their own power on account of helping other sensors transmit data and shorten the monitoring life cycle of WSNs quickly. To this end, this paper presents EBQS to reduce the number of idle state, and to balance the remaining capacity of sensors. Thus, it can maximize the lifetime of WSNs.

## 2. Related research

Quorum-based study [1] can ensure that a sensor has at least two Beacon Intervals time intersections with its adjacent sensors in a cycle consisting of  $n^2$  Beacon Intervals. Based on this overlap feature, no matter how long the Quorum System cycle time offset between the two sensors is, it must ensure that there are at least two rendezvous opportunities between the two sensors. This not only prevents the sensor from sending frames frequently or wasting a lot of idle maintaining the neighbor's information, but also reduces the rendezvous delay between the sensors to a Quorum cycle length effectively. More importantly, it makes the sensor go into the power-saving state immediately when there is no transmission. Thereby, it can extend the network life cycle.

However, the existing Quorum-based studies [6,8] limits the data transmission between sender and receiver in that it must be done in the same duty slot. This limitation not only suppresses the improvement of the sensor's sleeping quality, but also makes it difficult to improve the transmission delay at both ends of the data reception and transmission. The study [10] presents an Extended Quorum System (EQS). EQS utilizes the Quorum System to ensure that the sensors can rendezvous directly with each other, and calculates the possible chances of rendezvousing in each slot of all sensors. EQS uses the ratio of rendezvousing opportunity and working energy to find the time slot that uses the least amount of electricity to get the most chance to rendezvous. And through directly or indirectly rendezvousing between sensors, it is easy to find the sensor in sleeping mode with smallest total energy consumption. EQS chooses the first time slot that has maximum ratio of

rendezvousing opportunity and working energy, and the sensor that used it as working slot must maintain working state in the slot in each duty cycle. In this way, we can let this sensor help transmit data. Then the sender can rendezvous with the recipient indirectly and the power consumption of the overall network will be reduced. Fig.3 shows that slots filled with slashes indicate that the sensor must be working during the duty cycle in this time slot, and the sensors can enter the sleeping state in the remaining shadows slots. However, EQS still does not consider the problem of the remaining life cycle of the sensor, as it can't maximize the life cycle. This paper hopes to improve the operation mode of indirect meeting from EQS system in order to improve the efficiency of power management and achieve the purpose of maximizing the life cycle.

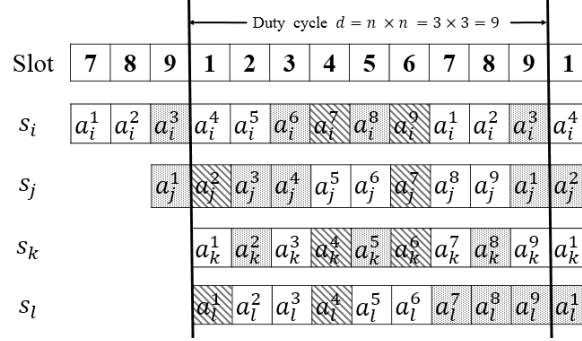


Figure 3. EQS.

### 3. EBQS

#### 3.1. Design Principles

Under the premise of ensuring the sensor's rendezvous opportunity, EBQS hopes to maximize the network lifecycle [2]. Let  $T$  be the life cycle of the WSNs, the remaining life cycle of the sensor  $s_i$  is  $l_i$ , then the target of EBQS can be expressed by the formula (1).

$$\max(T = \min\{l_i\}) \quad (1)$$

Assuming that the remaining capacity of the four sensors  $s_i, s_j, s_k$  and  $s_l$  are 20J, 19J, 45J and 21J, the sensor with the largest remaining capacity is  $s_k$ . As shown in Fig .4,  $s_k$  with the largest power will serve as the data transporter of  $s_j$  with smaller remaining power, so that  $s_j$  will transfer the data to  $s_k$  then enter the power-saving state. And  $s_k$  further communicates the data of  $s_j$  to the corresponding receiver in an indirect way. Compared with Fig .3, it can be found that the number of working slots of sensor  $s_i, s_j$  and  $s_l$  is 1 after using EBQS mechanism. However, in Fig .2, the number of working slots for  $s_i, s_j$ , and  $s_l$  is 2. Therefore, under the conditions that EBQS ensure the sensors rendezvous to each other, it can effectively improve the power consumption of power-weak sensors, and thus, extend the running time of Quorum System.

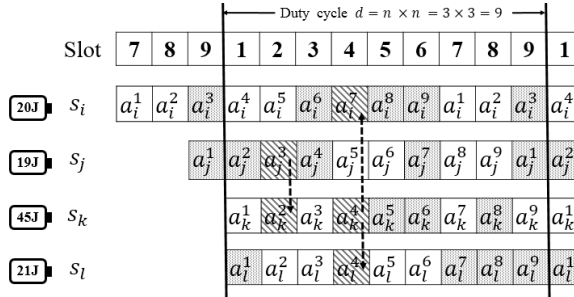


Figure 4. Working mechanism of EBQS.

#### 3.2. Initialization

For each sensor, the initial stage is getting into the network. The cycle length is  $d$ . In order to achieve electric balance by an indirect rendezvous, the sensor must exchange information with adjacent sensors in the initial stage, such as the remaining power of the adjacent sensors  $e_i$ , the working slot information based on the traditional Quorum System  $Q_i$ , and the neighbor ID, etc. for the subsequent establishment of the sensor. This information can be used for sensors to establish rendezvous with each other afterwards. At the same time, sensors perform the calculation of the rendezvous arrangement stage internally to make sensors in the network perform an electricity balance mechanism in the next duty cycle. A detailed description of the rendezvous arrangement stage will be detailed in the next section.

In order to effectively reach the goal of energy balance by the way of rendezvousing indirectly and extending the network lifetime further. After each sensor obtains the residual capacity information of adjacent sensors at the initial stage, the cycle time of each sensor can be calculated by the formula (2). Take any sensor  $s_i$  as an example, as it must follow the rules of traditional Quorum System for working schedule, the network of all sensors duty cycle length are  $d$ , and it selected its working schedule  $Q_i$  in the Quorum System randomly, let  $q_i$  be the number of time slots that the sensor  $s_i$  must be kept active, so that sensors perform possible communication operations. Then,  $s_i$  can use the remaining capacity  $e_i$ , the number of active time slots  $q_i$  during the duty cycle and the sensor's energy consumption  $\lambda$  of awaked unit time slot, through the formula (2) to calculate the remaining duty cycle  $l_i$ .

$$l_i = \left\lfloor \frac{e_i}{q_i \times \lambda} \right\rfloor \quad (2)$$

Each sensor  $s_i$  calculates the remaining life cycle of itself and its adjacent sensors', and then the calculation result is sorted by small to large, and represented by the conference path order  $P_i = \{s'_1, s'_2, \dots, s'_p\}$ , as shown in formula(3). Here, if  $l'_{i-1}$  represents the remaining number of duty cycles of the sensor  $s'_{i-1}$ , then  $l'_{i-1} < l'_i$ .

$$P_i = \{s'_1, s'_2, \dots, s'_p\} \quad (3)$$

where  $l'_{i-1} < l'_i$

In the Fig .5, there are four sensors  $s_i, s_j, s_k$  and  $s_l$  in the network. After using the duty cycle of Fig .1, the remaining power is 234J, 182J, 368J and 256J respectively. The sensor  $s_i$  at the beginning of the network, with the remaining power as the basis for calculating the intermediary sensor,  $s_i$  will calculate results with data stored in the database through the internal formula (3), then get  $P_i = \{s_j, s_l, s_k\}$ . The calculation process is that  $s_i$  uses the residual power of itself and all the adjacent sensors  $s_j, s_k$  and  $s_l$  ( $e_i = 234, e_j = 182, e_k = 368$  and  $e_l = 256$ ) to calculate the remaining life cycle by the formula (2) firstly, that is divided by the number of time slots in each duty cycle ( $q_i = 5, q_j = 5, q_k = 5$  and  $q_l = 5$ ), then get  $l_i = 46, l_j = 36, l_k = 73$  and  $l_l = 51$ . Finally, according to the formula (3), the remaining life cycles of all the sensors stored by  $s_i$  are arranged in ascending order from small to large, and the results are recorded in the rendezvous path order  $P_i$  of  $s_i$ .

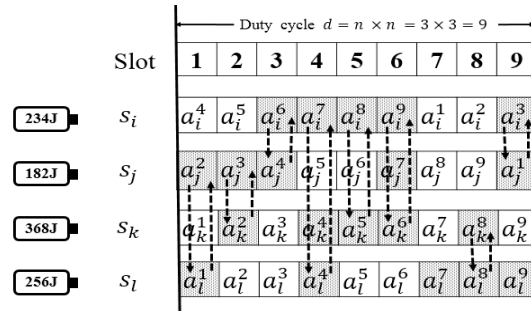


Figure 5. Quorum system and the remaining power of the sensor.

All sensors can plan sensors with longer residual life cycles (sensor  $s_k$ ) to assist the weak sensors (sensor  $s_j$ ) to transmit data by indirect rendezvousing, depending on the path sequence of  $P_i = \{s_j, s_l, s_k\}$ , thus to extend the remaining life cycle of the weak sensors. As shown in Fig .6, the sensors ( $s_i, s_l$  and  $s_k$ ) have a longer residual life cycle, which can help the weak sensor  $s_j$  transmit data through indirect rendezvous, reducing the consumption of electricity of  $s_j$  and delaying the network life termination occurs.

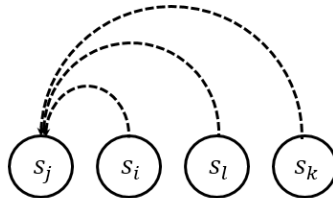


Figure 6. Sort the rendezvous paths of the sensors

### 3.3. Rendezvous arrangement

In order to interpret the sensor's path of rendezvousing more easily, we changed Figure 5 to Figure 7 (a) for demonstration purposes. First, we converted the time slot order from 'left to right' to 'top to bottom' and the order of the sensors in the network ( $s_i, s_j, s_k, s_l$  and  $s_l$ ) from 'top to bottom' to 'left to right'. In Fig. 7 (a), the sensor only retains the working slots, and the idle slots are not displayed.

We use the formula (4) to represent the meaning of the rendezvous path between sensors, which consists of  $m$  sensors' indirect rendezvous, and  $s'_1 = s_i, s'_m = s_j$ .

$$P_{ij}^y = \{s'_1, s'_2, \dots, s'_m\} \quad (4)$$

According to the example in Fig. 5 and the formula (3), we sort the remaining power of sensors, and use formula (4) to calculate the pairing of sensors' rendezvous path. The order is  $P_{jk}^y, P_{jl}^y$  and  $P_{ji}^y$ , where  $y$  represents the serial number of rendezvous paths between the two sensors. Although the sensors at both ends of the rendezvous path have been specified, there are several possibilities for data transmission between the two sensors where  $P_{jk}^y$  has 10 kinds. They are  $P_{jk}^1 = \{s_j, s_l, s_k\}$ ,  $P_{jk}^2 = \{s_j, s_k\}$ ,  $P_{jk}^3 = \{s_j, s_i, s_k\}$ ,  $P_{jk}^4 = \{s_k, s_i, s_j\}$ ,  $P_{jk}^5 = \{s_k, s_l, s_j\}$ ,  $P_{jk}^6 = \{s_k, s_i, s_j\}$ ,  $P_{jk}^7 = \{s_j, s_k\}$ ,  $P_{jk}^8 = \{s_k, s_l, s_j\}$ ,  $P_{jk}^9 = \{s_j, s_i, s_k\}$ ,  $P_{jk}^{10} = \{s_j, s_l, s_k\}$ . Fig. 6(a) gives a kind of rendezvous path (the path represented by the black line)  $P_{jk}^3$  for  $P_{jk}^y$ .

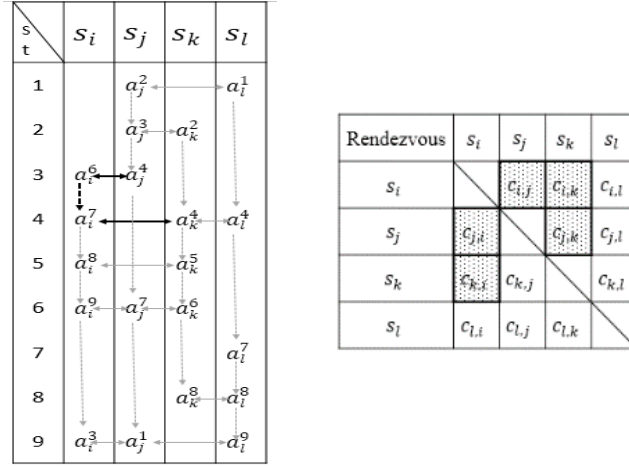


Figure 7. Figure similar to Quorum and the schematic diagram of rendezvous path.

All the rendezvous paths of  $P_{jk}^y$  are the path candidates for the rendezvous paths between the sensors. Later we will choose the best rendezvous path by calculating the weight value. To make the two sensors rendezvous with each other, we use formula (5) to indicate the assumed working time slot selected by the sensor in a duty cycle. It is worth noting that it must be assumed from the original Quorum's working slots and the shadow slots in Fig. 1 instead of non-working slots.

$$Q_i^{tmp} = (Q_i^{tmp} \cup \{a_i^k \times \gamma_i^k\}), 1 \leq k \leq d \quad (5)$$

Where  $Q_i^{tmp}$  stores the selection information ( $Q_i$ ) of working slots during a duty cycle of  $s_i$  temporarily. Let  $a_i^k$  be a Boolean value, which is the state of working slot of the sensor  $s_i$  in the original Quorum System. When  $a_i^k = 1$ ,  $s_i$  is active in the  $k$ -th time slot, otherwise  $a_i^k = 0$ .  $\gamma_i^k$  is a Boolean value that represents the state of Quorum working slot in the temporary rendezvous path selected by the sensor  $s_i$ . When  $\gamma_i^k = 1$ ,  $s_i$  selects the  $k$ -th slot as active slot temporarily, otherwise  $\gamma_i^k = 0$ . Taking  $P_{jk}^3 = \{s_j, s_i, s_k\}$  as an example, we can get it that  $Q_i^{tmp} = (0,0,1,1,0,0,0,0,0)$ ,  $Q_j^{tmp} = (0,0,1,0,0,0,0,0,0)$ ,  $Q_k^{tmp} = (0,0,0,1,0,0,0,0,0)$ ,  $Q_l^{tmp} = (0,0,0,0,0,0,0,0,0)$ .

Let  $q_i^{tmp}$  denote the number of sets of  $Q_i^{tmp}$ , we use formula (6) to calculate the total number of communications of

the sensor  $s_i$ , in each rendezvous path selected temporarily in a duty cycle. Taking  $P_{jk}^3 = \{s_j, s_i, s_k\}$  as an example, we can get it that  $q_i^{tmp} = 2, q_j^{tmp} = 1, q_k^{tmp} = 1, q_l^{tmp} = 0$  and  $q_l^{tmp} = 0$ .

$$q_i^{tmp} = |Q_i^{tmp}| = \sum_{k=1}^d \gamma_i^k \quad (6)$$

In addition, for each rendezvous path  $P_{ij}^y$ , the opportunity to rendezvous is in pursuit of the greatest interests at the minimum cost. The cost is determined by the energy consumption of the sensor required in the rendezvous path, and the benefit is determined by the connection relationship between the sensors in the rendezvous path. The relationship includes all the direct and indirect rendezvous relationship. It is the interests of the product of rendezvous path  $P_{ij}^y$ . We use the formula (7) to indicate the total number of rendezvous opportunities for the rendezvous path between sensors.

$$c_{P_{ij}^y} = \sum_{s_u, s_v \in s_{i,j}, s_u \neq s_v} (1 - c_{u,v}) \quad (7)$$

Here,  $c_{u,v}$  is a Boolean value, which indicates the relationship between any two sensors in the network, but it doesn't contain the relationship between itself. When  $c_{u,v} = 1$ , it means that the two sensors have a chance to rendezvous, otherwise  $c_{u,v} = 0$ . The formula (7) is explained by Fig. 6 (a), taking  $P_{jk}^3 = \{s_j, s_i, s_k\}$  as an example, we can get  $c_{P_{jk}^3} = 5$ . It indicates that  $P_{jk}^3 = \{s_j, s_i, s_k\}$  facilitates an indirect rendezvous  $c_{j,k}$  and four direct rendezvous, which are  $c_{i,j}, c_{j,i}, c_{i,k}, c_{k,i}$ , and an indirect rendezvous  $c_{j,k} \cdot c_{j,i}$  and  $c_{i,k} \cdot a$ . As shown in Fig. 6 (b), it is represented by the black line, so the total number of rendezvous opportunities for rendezvous path  $P_{jk}^3$  is  $c_{P_{jk}^3} = 5$ .

After sorting the rendezvous path of the sensor, we will get a direct or indirect transmission path. Next, the sensor needs to calculate the weight value of each path for itself and then use the information contained in each transmission path to select a path that all sensors in the network will have the best interests to extend the overall network life cycle. However, whenever the sensor selects a best path solution, it will update the information of working schedule between all sensors in the network. The sensor will continue to select the path until the basic conditions of the Quorum System are met, that is, the connection status of all sensors in the network and their adjacent sensors should be satisfied. The EBQS algorithm is considered to be satisfied with the end of the calculation of the rendezvous arrangement stage. Take  $P_{jk}^y$ , the rendezvous paths combined between the sensors  $s_j$  and  $s_k$ , as an example to calculate each predicted rendezvous path and assess whether it is the best way to benefit all the sensors in the network. The sensor brings the information contained in each predicted transmission path to formula (8) and calculates the weight value, which we used as the basis for selecting out the best path.

$$w_{P_{ij}^y} = \left\lfloor \frac{c_{P_{ij}^y}}{\sum \frac{q_i^{tmp}}{e_i}} \right\rfloor \quad (8)$$

Taking  $P_{jk}^3 = \{s_j, s_i, s_k\}$  in Fig. 6 (a) as an example, its weight value is  $w_{P_{jk}^3} = \left\lfloor \frac{5}{\frac{2}{234} + \frac{1}{182} + \frac{1}{368} + \frac{0}{256}} \right\rfloor$ . It indicates that  $P_{jk}^3$  facilitates the total number of opportunities for the sensors to rendezvous with each other ( $c_{P_{jk}^3} = 5$ ), and consumes the individual energy consumption of the sensor. That is, the total number of communications for each predicted rendezvous path:  $q_i^{tmp}$  is  $q_i^{tmp} = 2, q_j^{tmp} = 1, q_k^{tmp} = 1, q_l^{tmp} = 0$ , and  $q_l^{tmp} = 0$ . And  $e_i$  denotes the remaining amount of electricity consumed by communication for one time. After calculation, we get  $w_{P_{jk}^3} = \lfloor 298.3488 \rfloor = 298$ .

All the rendezvous paths in the network are sorted by formula (3), and then the predicted paths of multiple rendezvous are calculated by formula (4). Finally, the weight value of the relative path is obtained by the formula (8). And the sensor selects a best rendezvous path as the key decision to solve the rendezvous idle of Quorum System according to the interests of the rendezvous and the balance of electricity of all the sensors in the network. We use the formula (9) to select the best choice for all sensors in the network. That is the largest weight value of rendezvous path.

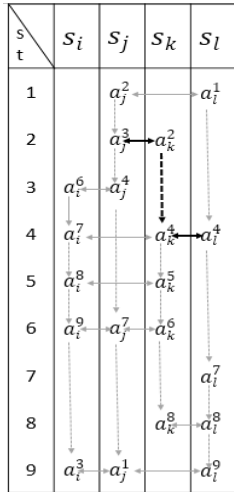
$$Max(w_{P_{ij}^y}) \quad (9)$$

Here, we use Fig. 8 (a) to illustrate the formula (9). Taking  $P_{jl}^2 = \{s_j, s_k, s_l\}$  in the figure as an example, in this path, the total number of the Quorum's working communications selected by the sensor is the individual energy consumption of the sensor which is  $q_i^{tmp} = 0, q_j^{tmp} = 1, q_k^{tmp} = 2, q_l^{tmp} = 1$  respectively. In addition, as the black box shown in Fig. 8 (b), the total number  $c_{P_{jl}^2} = 5$  of rendezvous opportunities between the sensors is used to calculate  $w_{P_{jl}^2}$ , and then we get the value  $w_{P_{jl}^2} = \left\lfloor \frac{5}{\frac{0}{234} + \frac{1}{182} + \frac{2}{368} + \frac{1}{256}} \right\rfloor = \lfloor 337.2086 \rfloor = 337$ , which is the largest rendezvous path weight value in all predicted rendezvous path combinations in the network.

The network records the rendezvous path that has the best balance of energy after sorting the remaining power in the first selection. Its purpose is to avoid the follow-up selection behaviour by network for rendezvous path. It can also accurately make the next selection result balance the sensor power in the overall network. We use formula (10) to get the maximum weight of the rendezvous path, and make it as the basis for picking the next best rendezvous path.

$$Q_i^{final} = (Q_i^{tmp}), 1 \leq k \leq d \quad (10)$$

According to the example in Fig. 7 (a), after the first selection in the network, the first best rendezvous path is  $w_{P_{jl}^2}$ . We can get the information as follows.  $Q_i^{tmp} = (0,0,0,0,0,0,0,0,0) = Q_i^{final}$ ,  $Q_j^{tmp} = (0,1,0,0,0,0,0,0,0) = Q_j^{final}$ ,  $Q_k^{tmp} = (0,1,0,1,0,0,0,0,0) = Q_k^{final}$ ,  $Q_l^{tmp} = (0,0,0,1,0,0,0,0,0) = Q_l^{final}$ . A rendezvous path information not only contains the communication state in Quorum selected by the rendezvous path of the sensor, but also contains the remaining life cycle of the sensor, which is also important for the network. It will affect the judgment for the sorting of the next sensor rendezvous path combination by network.



(a) The best rendezvous path solution based on EBQS.

Rendezvous	$s_i$	$s_j$	$s_k$	$s_l$
$s_i$		$c_{i,j}$	$c_{i,k}$	$c_{i,l}$
$s_j$	$c_{j,i}$		$c_{j,k}$	$c_{j,l}$
$s_k$	$c_{k,i}$	$c_{k,j}$		$c_{k,l}$
$s_l$	$c_{l,i}$	$c_{l,j}$	$c_{l,k}$	

(b) The rendezvousing opportunity state diagram of  $P_{jl}^2$ .

Figure 8. The rendezvous path information based on EBQS.

After the selection of the rendezvous path, the remaining life cycle of the sensor will change the selected communication status of Quorum. We use formula (11) to calculate the remaining life cycle of each sensor in the network after a best path selection.

$$l_i = \left\{ \begin{array}{l} e_i, \text{ if } q_i^{final} = 0 \\ \left\lfloor \frac{e_i}{q_i^{final} * \lambda} \right\rfloor, e_i \geq q_i^{final} * \lambda, \text{ otherwise} \end{array} \right\} \quad (11)$$

Here, let  $q_i^{tmp}$  denote the number of sets of  $Q_i^{tmp}$ ,  $\lambda$  presents the sensor's energy consumption of working unit time slot. After selecting the  $w_{P_{jl}^2}$  path, the sensor calculates the remaining lifecycle respectively according to the selected communication state of Quorum in the rendezvous path. According to the formula (11), in path  $w_{P_{jl}^2}$ , there is a no selected communication state of Quorum  $q_i^{final}$  ( $q_i^{final} = 0$ ), so we get some results:  $l_i = e_i = 234$ ,  $l_j = \left\lfloor \frac{182}{1 * \lambda} \right\rfloor = 182$ ,  $l_k =$

$$\left\lfloor \frac{368}{2 \times \lambda} \right\rfloor = 184, l_i \text{ and } l_l = \left\lfloor \frac{256}{1 \times \lambda} \right\rfloor = 256.$$

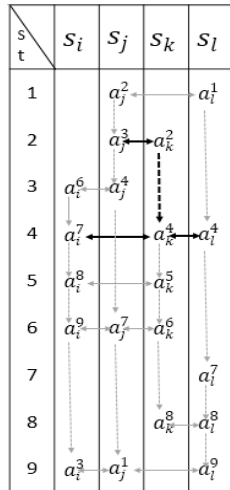
This study is based on the Quorum System of WSNs applications. In the Quorum System protocol it can ensure that the sensors can rendezvous with each other with adjacent sensors in a duty cycle. So, we use the formula (12) to check the relationship state of rendezvous between the sensors so far. If it is satisfied, the sensor will no longer continue to pick the rendezvous path. Otherwise, the sensor needs to continue to do the next selection and calculation until the formula (12) is satisfied.

$$\prod_{(s_i, s_j) \in S, s_i \neq s_j} c_{i,j} = 1 \quad (12)$$

As is shown in Fig. 8 (a), the sensor picks out the best path W in the first selection and obtains the result in Fig.8 (b), but the result doesn't satisfy formula (12). So the sensor needs to be evaluated and continue to be selected.

According to formula (3), we can get that  $P_i = \{s_k, s_j, s_i, s_l\}$ . The rendezvous-path's pairs of the sensor are obtained by the formula (4) followed by  $P_{kl}^y, P_{jl}^y, P_{il}^y, P_{jl}^y$  and  $P_{il}^y$ . According to the above-mentioned rendezvous path combination, we use formula (8) to calculate the benefit weight value of each rendezvous path, and find the most valuable rendezvous path weight solution with the formula (9). As is shown in Fig. 9 (a), the best rendezvous path solution is evaluated for the second round, that is  $w_{P_{il}^3} = \left\lfloor \frac{7}{\frac{1}{234} + \frac{1}{182} + \frac{2}{368} + \frac{1}{256}} \right\rfloor = 36$ . The state it accomplished the rendezvous relationship is shown in Fig. 9 (b),

the number of slashed boxes in the figure indicates the total number of opportunities for the rendezvous between the sensors, which is expressed as  $c_{P_{il}^3} = 7$ . In accordance with the formula (10), record the communication status that is selected of Quorum for sensors. According to the formula (11), we calculated the remaining life cycle of the sensor after updating and the result is  $l_i=234, l_j = 182, l_k = 184, l_l$  and  $l_l = 256$ . Finally, the formula (12) is used to check whether the best rendezvous path is selected to satisfy with the rendezvous condition of the Quorum System. If the relationship state of all the sensors in the network is satisfied after selecting  $P_{il}^3$ , then the EBQS algorithm ends. As a result, for the example in Figure 6 (a), it begins with the mechanism of the power balance between the sensors in the network, and finally succeeds in increasing the power savings of the sensor without destroying the rendezvous model built on the Quorum System.



(a) The best rendezvous path solution of the second round based on EBQS.

Rendezvous	$s_i$	$s_j$	$s_k$	$s_l$
$s_i$		$c_{i,j}$	$c_{i,k}$	$c_{i,l}$
$s_j$	$c_{j,i}$		$c_{j,k}$	$c_{j,l}$
$s_k$	$c_{k,i}$	$c_{k,j}$		$c_{k,l}$
$s_l$	$c_{l,i}$	$c_{l,j}$	$c_{l,k}$	

(b) The rendezvousing opportunity state diagram of  $P_{il}^3$ .

Figure 9. The second round of evaluation based on EBQS.

#### 4. Simulation

In order to evaluate the EBQS algorithm proposed in this paper, this section will analyze and compare the Quorum System-QS algorithm proposed in [6] and the Extended Quorum System-EQS algorithm proposed in [10]. This simulation will be compared for two different Quorum sizes:

**Algorithm:** The procedure of EBQS

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```

Receive(ID,  $e_i$ ,  $Q_i$ ); //get information from  $s_i$ 
Calculate( $Q_i^{final}$ ,  $l_i$ );
if  $a_i^k = 1$  //slot is active
    if neighbor exist
        // detects the new neighboring sensor's ID
        oldneighbourlist = neighbourlist;
        while oldneighbourlist != neighbourlist
            //  $s_i$ 's the neighboring sensors list is changed
            rendezvous();
            //  $s_i$  keep the Quorum system  $Q_i$  to rendezvous neighboring sensors each other
            Addneighbourlist(ID,  $e_i$ ,  $Q_i$ );
            // exchange the information of neighboring sensors list.
            while  $\prod_{(s_i, s_j \in S, s_i \neq s_j)} c_{i,j} = 0$ 
                Calculatelifetime( $l_i$ );
                Sort( $l_i$ );
                getRendezvousPath();
                Calculateweight();
                Max(weight);
                if  $\prod_{(s_i, s_j \in S, s_i \neq s_j)} c_{i,j} = 1$ 
                     $Q_i^{final} = (Q_i^{tmp}) \ 1 \leq k \leq d$ ;
                     $l_i = \left\lfloor \frac{e_i}{q_i^{final} * \lambda} \right\rfloor$ ,  $e_i \geq q_i^{final} * \lambda$ ;
                    break;
                end if
            end while
        end while
    end while
end if

```

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Figure 10. Algorithm for EBQS.

- Comparison of the Neighboring Sensors Density to the Energy Consumption of Network initialization.
- Comparison of the Packet Loss Rate to the Energy Consumption.

First, as is shown in Table. 1, it is the initial environment of the network simulated by this experiment. Then we will discuss the comparison of different parameters from the simulation results between the thesis and other papers. The related parameters of the simulation experiment are shown in Table. 1.

Table 1. Simulation parameters

Parameter	Value
Simulator	Java
The number of sensors	100
Deployment	Random
The size of sensing field	200m×200m
Transmission distance	10m
The density of sensors	5-50
The energy of sensors	300-2000J

This paper assumes that there are 100 sensors, located in the 200m × 200m analog monitoring scene randomly, and the sensor transmission radius is 10 m. Among them, the density distribution between the sensors ranges from 5 to 50 adjacent sensors, and the remaining power of the sensor ranges from 300 to 2000J. So as to simulate the discontinuous network scene between the sensors, the Neighboring Sensors Density and the Packet Loss Rate are dynamically adjusted according to the experimental requirements. Every simulation result is the average of 20 independent simulation results.

In the experiment, we compare three objects that are included in the algorithm of study [6], the algorithm of study [10] and the EBQS algorithm proposed in this paper. Fig. 11 illustrates the Comparative Effect on the Energy Consumption of Network initialization by the Neighboring Sensors Density when the Quorum Size is  $3 \times 3$ . It can be seen that the EBQS algorithm makes the sensor have less energy consumption when the Neighboring Sensors Density is high. It is quite helpful for the extension of the network life cycle.

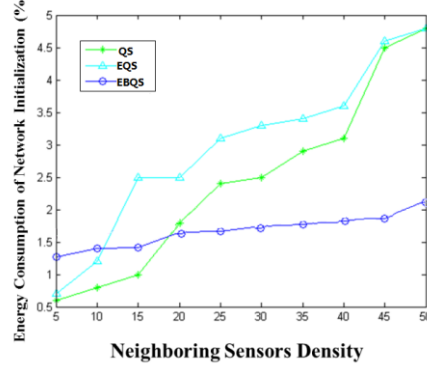


Figure 11. Comparison of the neighboring sensors density to the energy consumption of network initialization.

Fig. 12 illustrates the Comparative Effect on the Energy Consumption of Network initialization by the Neighboring Sensors Density when the Quorum Size is  $5 \times 5$ . It can be seen that the EBQS algorithm makes the sensor have less energy consumption when the Neighboring Sensors Density is high. It is quite helpful for the extension of the network life cycle.

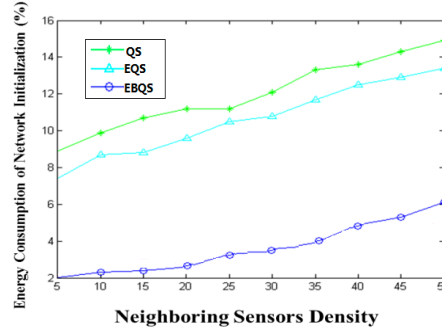


Figure 12. Comparison of the Neighboring Sensors Density to the Energy Consumption of Network initialization

Fig. 13 illustrates the Comparative Effect on the Energy Consumption by the Packet Loss Rate when the Quorum Size is  $3 \times 3$ . According to the simulation results, we know that when the Packet Loss Rate is higher, the higher the energy consumption ratio of the sensor is. It can be seen that the EBQS algorithm makes the sensor have less energy consumption when the Packet Loss Rate is high. It is quite helpful for the extension of the network life cycle.

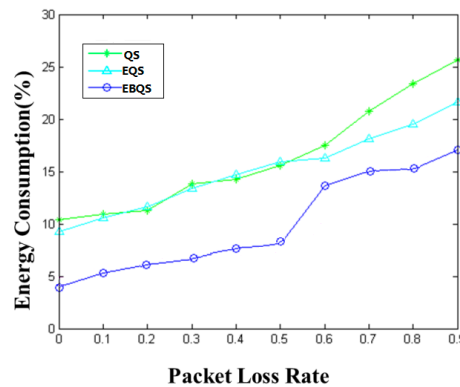


Figure 13. Comparison of the packet loss rate to the energy consumption.

Fig. 14 illustrates the Comparative Effect on the Energy Consumption by the Packet Loss Rate when the Quorum Size is  $5 \times 5$ . It can be seen that the EBQS algorithm makes the sensor drop about twice energy consumption when the Quorum Size is increased. It is quite helpful for the extension of the network life cycle.

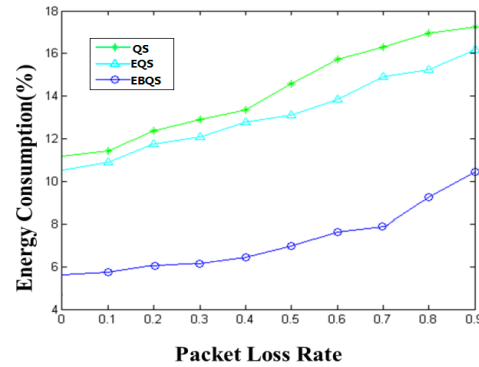


Figure 14. Comparison of the packet loss rate to the energy consumption.

## 5. Conclusion

The EBQS proposed in the paper takes into account the remaining capacity of sensors so that the sensors in the WSNs can rendezvous directly or indirectly through the Quorum System. Among them, the sensor that has a longer life cycle can assist the sensor that has a shorter life cycle to transmit data. This achieves the dual purpose under the premise of the indirect rendezvous of sensors. One is achieving the balance between the sensor power and the other is reducing the number of idle slots. The simulation results show that the EBQS uses the operational concept of Quorum System to design a direct or indirect rendezvous path between the sensors through the remaining power of sensors. Compared to the traditional Quorum System operating mechanism, in addition to ensuring the rendezvous of sensors, EBQS balances the power between sensors more effectively and extends the life cycle of WSNs.

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