An Improved Energy-efficient Algorithm for MAC Layer of ZigBee Network

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Abstract

On the basis of the original algorithm, a kind of optimization algorithm is proposed in consideration of node properties and for the sake of energy utilization being balanced. Combining AODVjr Algorithm with Cluster-Tree Algorithm, traditional ZBR Algorithm has the shortcoming that some nodes would degenerate to RN-nodes and then become death nodes because they transmit too much data during which energy is consumed too fast. In view of this situation, improved Algorithm is put forward which establishes energy identifier energy_flag and energy judgment value E_{judge}, refines RN+ nodes and clearly maps node properties in transmission path to numerical values. It also defines Q value so as to select optimal path according to energy-balanced and short-time transmission principles. RREQ transmitted from different paths would be grouped and qualitatively analyzed. It reduces the rate of RN+ nodes degenerating to RN-nodes, decreases the probability of RN- nodes participating in routing transmission, lengthens lifetime of nodes and increases life cycle of network.

Key words: ZIGBEE NETWORK; MAC PROTOCOL; ENERGY-EFFICIENT

1. Introduction

ZigBee utilizes IEEE802.15.4 Standard with design intentions of low data rate, low power consumption and low cost [1], meeting energy-efficient requirement. Significantly, this research is based on energy conservation of ZigBee network, especially for MAC Layer. Through reviewing literature, we see that there exists a large number of MAC protocols doing researches on duty ratio. They can be divided into asynchronous protocol and synchronous protocol [2]. Asynchronous MAC protocol does not have synchronization requirement on nodes. It adopts distributed control mechanism, needing extra preamble and low-powered listening. All nodes in synchronous MAC protocol have to keep synchronous. S-MAC [3] is a type of MAC protocol based on RTS-CTS. Being a less restrictive synchronous protocol, it keeps low power consumption and supports duty ratio. On the basis of S-MAC, adaptive listening is introduced to reduce latency [4]. When nodes receive CTS or RTS from their neighbors, they would still keep working for a short time although transmission is finished. If nodes lie in the path of next hop when transmission ends, their work could reduce latency and guarantee immediate transmission of packets without waiting for the next working period. However, neighbor nodes of destination node in S-MAC protocol waste unnecessary energy because of keeping listening situation for a period of time. T-MAC [5] protocol is the improved one of S-MAC protocol which shortens nodes' working time with channel being free. Comparing T-MAC against S-MAC, we know that their energy consumption ratio is 1:5. T-MAC consumes less energy. While its network latency increases because of utilization of adaptive listening mechanism. B-MAC [6] protocol is a sort of MAC protocol based on CMSA/CA. It is asynchronous protocol doing low power consumption communication through utilizing low-powered listening mechanism and increasing additional preamble. B-MAC protocol has to provide an interface for the purpose of adjusting sleeping time to adapt to the change of channel flow. B-MAC does better than other MAC protocols in aspects of throughput, latency and energy consumption. However, it would also encounter cross-talk problem and energy consumption problem which is brought by extra preamble. WiseMAC [7] protocol is a MAC protocol using preamble sampling technique to do low power consumption communication. It is also asynchronous protocol. Although WiseMAC solves the problem of low power consumption communication, it does not possess the mechanism of nodes changing with change of channel flow. This paper proposes an improved algorithm through being centered on network energy-efficient properties, taking network layer algorithm as the main research content and comparing with ZBR Algorithm which combines AODVjr [8]used in traditional ZigBee routing Protocol with Cluster-Tree [9]Algorithm. It does improvement on path selection and parameter values which reduces unnecessary energy consumption, lengthens lifetime of nodes and increases life cycle of network.

2. The Improved Algorithm

2.1. Establishing Energy Identifier

During transmission process of ZigBee network, terminal node of mesh network would receive RREQ packets which are transmitted by the same source node through several paths. In order to compare node features in different links which RREQ from different paths going through and definitely label the node type of each link thus better choosing energy-efficient paths, this improved algorithm proposes energy identifier concept. Suppose that destination node does not directly reply RREQ packet with RREP packet after it receives the first RREQ packet. It continues to wait for subsequent RREQ packets. Within the stipulated time T, it would receive n RREQ packets. Do judgment analysis on these packets and utilize selection mechanism established in this algorithm to select a good path to reply RREP packet, thus establishing a transmission path of high quality.

Analysis on multiple RREQ packets depends on numerical values of energy identifier and Q values. During the process of searching for path in the improved algorithm, add an energy identifier energy_flag to RREQ packet. This energy identifier is composed of energy_low_flag and energy_low_sufficient_flag. The value of energy_low_flag means whether RN- nodes exist in the links which RREQ going through during its transmitted process from source node to current node. energy_low_sufficient_flag stands for the number of Energy-Low-sufficient nodes in the links which RREQ going through during its transmitted process from source node to current node. Actually the improved algorithm utilizes RN+ nodes with higher energy to do transmission as far as possible so as to slow down the speed of RN+ nodes degenerating to RN- nodes thus lengthening lifetime of nodes. According to network condition, the improved algorithm sets the judgment value E_{judge} which is higher than the energy critical value EMR between those of RN+ nodes and RN- nodes and lower than initial energy value E0. If energy value of RN+ nodes is higher than judgment value E_{judge}, it is defined to be Energy-High-sufficient. If it is lower than E_{judge}, it would be defined to be Energy_Low_sufficient.

2.2. Do Numeralization on Transmission Path Quality Analysis Based on Energy Identifier

Establish a transmission path analysis concept. Differing from LQI [10], the set value Q (quality) stands for analysis on the quality of the whole transmission path. Quality judgment standard is based on node properties. Higher value of Q means that path quality is more suitable for energy-efficient transmission. Assume that the first arriving RREQ spends t. Time difference between the first arriving RREQ and the k arriving RREQ is Δt_k. It is obvious that $\Delta t_1 = 0$. Suppose that energy identifier of the k arriving RREQ is E_{kl} during transmission process. Within the specified time T, n RREQ packets would be transmitted. Then comes $k \in [0, n]$.

It is seen that $0 \le \Delta t_k \le \Delta t$. In network with maximum depth being L_m, the smallest hop number is 1 when depth of source node is d. Assume that the maximum hop number of RREQ transmitted to destination node is $L_m + d + 1$. Then the biggest time difference between the first RREQ and the last RREQ is the set T. Its value is calculated below.

$$T = t + (L_m + d)t_{\sin glehop} \text{ (} t_{\sin glehop} \text{ hop is usually 15ms.)} \quad (1)$$

n RREQ packets from the same source node are transmitted to destination node within T. Then there exist n Energy_Low_sufficient identifier values analyzed through n different paths. Choose the maximum value among them and define it to be E_{ml}. Its value is shown below.

$$E_{ml} = E_{Max}(E_{1l}, E_{2l}, E_{3l} \dots E_{nl}) \quad (2)$$

Through analysis, this paper finds that Q value mainly has relationship with node arriving time difference Δt_k and Energy-Low-sufficient identifier value E_{kl}. Therefore it is defined according to this. Actually path quality has relationship with time and energy parameter under most conditions. Literature [11] also thinks so. Under the circumstance of t and Em being definable, Δt_k and E_{kl} could be certainly defined as measuring parameters of Q_k of the k arriving RREQ. Q value is determined as follows.

$$Q_k = \alpha^{\frac{\Delta t_k}{t}} \beta^{\frac{\Delta E_{kl}}{E_{ml}}} \qquad \alpha, \ \beta \in [0,1] \quad (3)$$

In this formula, α is time difference parameter base named time factor coefficient. β is Energy-Low-sufficient parameter base named energy factor coefficient.

Compare these values from Q_1 to Q_n . Select the maximum Q value in them. It is the best path. Then do RREP reply to relevant path.

2.3. Working Steps of the Improved Algorithm

On the basis of judgment of intermediate node and destination node doing on RREQ packet information, the improved algorithm determines that input information corresponding to intermediate node is energy identifier and output information is the corrected energy identifier. Meanwhile input information corresponding to destination node is energy identifier and output information is Q value. It is clear and accurate to utilize working flows of intermediate node and destination node to describe the improved algorithm.

2.3.1. Working Flow of Intermediate Node

After source node sends RREQ packet, one intermediate node would receive the RREQ packet with energy identifier transmitted by the last hop node through several hops of transmission in the links. Working flow of the current node is shown in Fig.1 on the basis of judgment on energy identification and its value and analysis on its own property.

Working steps as follows:

(1) Determine whether energy identifier is effective. If not, enter step (2). If it is effective, enter step (3).

(2) Judge its property. If it is RN- node, determine whether destination node is its descendant node through address allocation mechanism. If it is its descendant node, hand it to child node. If not, hand it to father node. If it is RN+ node, do flooding on RREQ packet.

(3) Enter the next judgment if energy identifier is effective. Check whether energy_low_flag value in energy identifier from the last hop is 1. If it is 1, store the value of energy_low_flag and enter step. If it is 0, judge its own property. If it is RN- node, enter step (4). If it is RN+ node, enter step (5).

(4) If it confirms itself to be RN- node by judging its own property, correct energy_low_flag value to be 1 and empty energy_low_sufficient_flag value in the original identifier. Determine whether destination node is its descendant node through address allocation mechanism. If it is its descendant node, hand it to child node. If not, hand it to other neighbor nodes.

(5) If it confirms itself to be RN+ node by judging its own property, it needs to judge whether it is energy_low_sufficient in the next step. If it is energy_low_sufficient node, enter step (6). If it is energy_high_sufficient node, enter step (7).

(6) Update low-sufficient indicated value in energy identifier. Add 1 to the original value of energy_low_sufficient_flag and then enter step (7).

(7) Flooding RREQ packets.

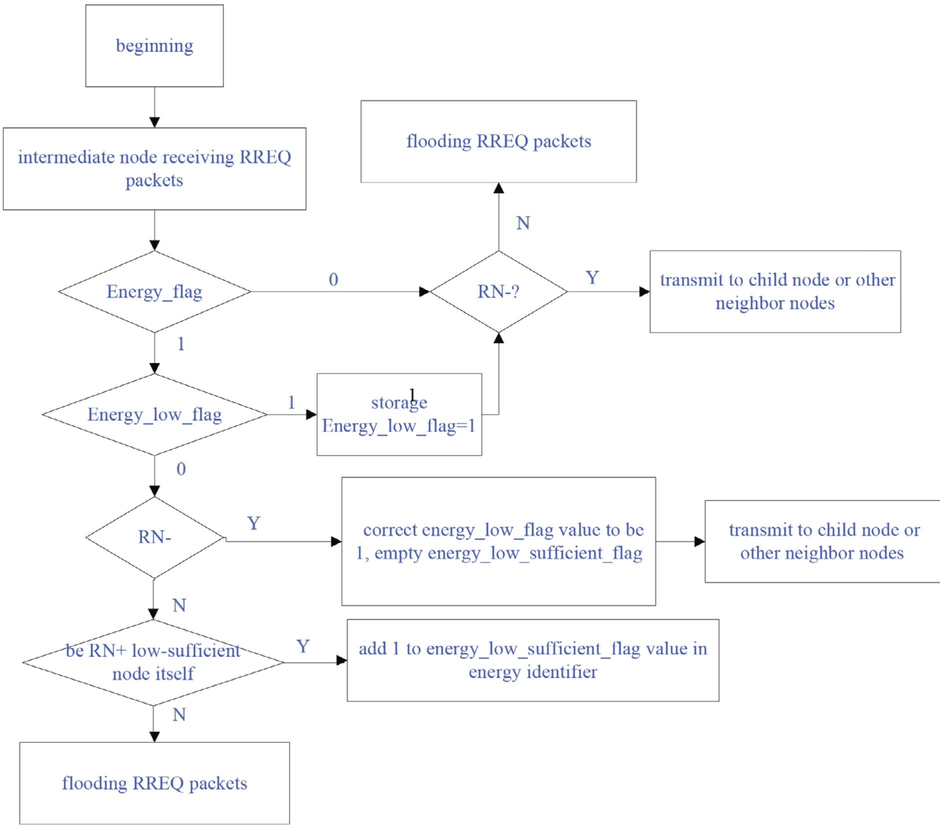

Figure 1. Flow of Intermediate Node Processing RREQ Packets Utilizing Energy Identifier

2.3.2. Working Flow of Destination Node

After source node sends RREQ packet, several RREQ packets arrive at destination node through being transmitted in different paths and by different intermediate nodes in the links. Working flow of destination node is seen in Fig.2 based on judgment of energy identification and its value and analysis on Q value after it receives RREQ packet.

Working steps as follows:

(1) Determine whether energy identifier energy_flag is effective. If its value is 0, it is noneffective. Then quickly do RREP reply along reversed path. If it is effective which means that its value is not 0, enter step (2).

(2) Check energy_flag value. If it is 1, there exist RN- nodes in the first path. In order to realize energy-efficient target, bypass this path and wait for T. After it receives several RREQ packets, it should analyze whether there is a path with energy_low_flag being 0 namely energy identification value being 1. If there is no path of this kind, do RREP reply on the first path. If there is this kind of path, enter step (4). If energy_ flag value in the first path is higher than 1, there exist no RN- nodes in this path. Then analyze RN+ nodes and enter step (3).

(3) Check energy_low_sufficient_flag value. If it is 0 namely energy identification value being 2, there exist no low-sufficient RN+ nodes in this path. Then quickly do RREP reply along reversed path. If its value is not 0, there exist E_l energy_low_sufficient RN+ nodes as shown in energy_low_sufficient_flag value. At this moment, wait for T within which it would receive RREQ packets transmitted from n paths. Summarize them and enter step (4).

(4) Do path analysis on all received RREQ packets. Abandon the path of energy_low_flag value being 1. Utilize the established path analysis formula to analyze the paths of all received RREQ packets. Do RREP reply on the path which has the maximum Q value.

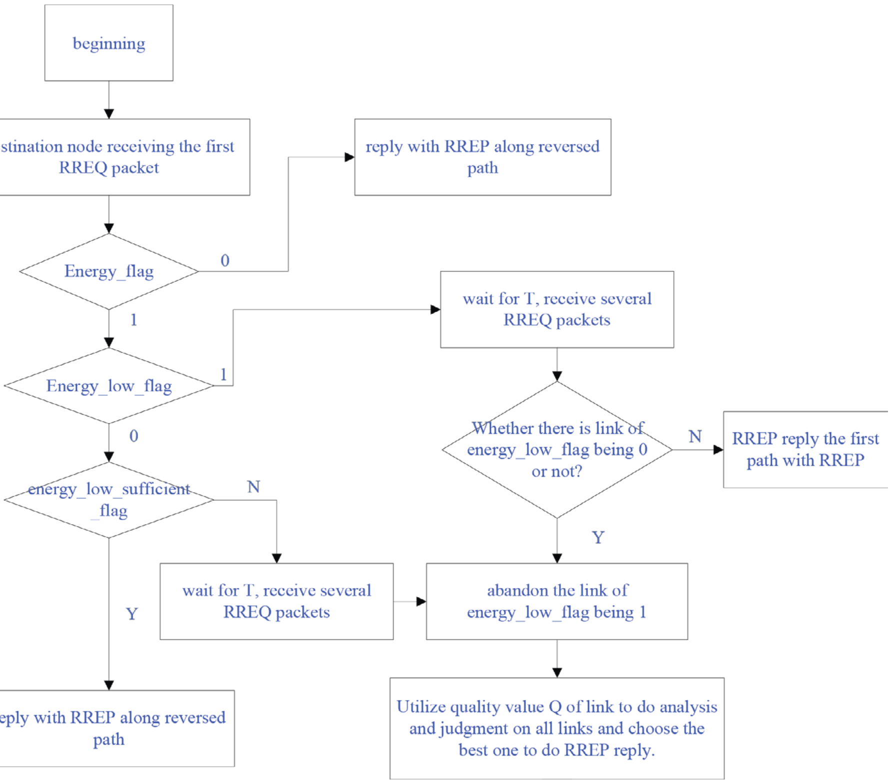

Figure 2. Flow of Destination Node Processing RREQ Packets Utilizing Energy Identifier

2.4. Determination of Energy Parameter Values in the Improved Algorithm

2.4.1. Determination of E_{judge} Value

E_{judge} is the critical point of energy_high_sufficient RN+ nodes and energy_low_sufficient RN+ nodes which lies between EMR and initial energy E0. Fixedly influenced by initial energy value E0 and dynamically influenced by dynamic value E_{judge}, E_{judge} would change with the changing of EMR. During operation process of network, it is defined that EMR value has relationship with the proportion of RN- nodes in the whole network so as to coordinate proportions of RN- and RN+ nodes. Similarly, regulates the proportion of energy_low_sufficient RN+ nodes according to that of RN- nodes. Therefore value of E_{judge} is influenced by the proportion p occupied by

RN- nodes in all routing nodes. With operating of network, p becomes higher and higher. Accordingly, proportion of energy_low_sufficient RN- nodes also becomes higher than that of energy_low_sufficient RN+ nodes. Therefore E_{judge} value is more expected to be close to E0 with the increasing of p under the condition of EMR and E0 being determined. For the sake of giving E_{judge} a reasonable position between EMR and E0, Formula (4) defines its value.

$$E_{judge} = \frac{p}{2} E_0 (1 - \frac{P}{2}) E_{MR} \tag{4}$$

In this formula, E0 is initial energy value. EMR is the energy critical point of RN+ and RN- nodes. Meaningful moment of E_{judge} is the utilization moment of the improved algorithm.

2.4.2. Beginning Moment of the Improved Algorithm

In the early stage of establishment, power of all nodes in large-capacity mesh network is sufficient because of which all routing nodes are energy_high_sufficient RN+ nodes. There are no energy_low_sufficient RN+ nodes or RN- nodes. At this moment, utilization of the improved algorithm does not have any effect on lifetime lengthening of network. Therefore it is meaningless for energy-efficient network to utilize the improved algorithm at the beginning moment because it would increase network delay, enlarge storage space, add transmitted data volume and increase meaningless energy consumption thus leading it to become the burden. However, some RN+ energy_high_sufficient nodes would degenerate to RN+ energy_low_sufficient nodes and RN+ energy_low_sufficient nodes would degenerate to RN- nodes after a period of operation. At this moment, utilization of the improved algorithm would slow down their degeneration rates. It also reduces utilization rate of RN- nodes which decreases their speed of becoming death nodes thus lengthening lifetime of nodes and increasing life cycle of network. Established on the basis of judging Q values, the improved algorithm increases energy identifier energy_flag which brings network delay and increases energy consumption because of storage space occupation. Comparing with transmission time and total transmission energy, delay and energy consumption brought by it is not so high. If the cost of redundant energy consumption brought by the improved algorithm is lower than its contribution for lengthening life cycle of network, it is an effective one. The problem involved is when to utilize it to better affect the lengthening of life cycle of the whole network. According to research and simulation feedback, this algorithm establishes a new formula shown as Formula (5).

$$C = C_1 + 2C_2 \tag{5}$$

In this formula, C_1 stands for the proportion of RN+ energy_low_sufficient nodes among all routing nodes. C_2 stands for proportion of RN- nodes among all routing nodes.

Through analysis, it is seen that $C_1, C_2 \in [0,1]$, $C_1 + C_2 \in [0,1]$. When C is higher than the defined judgment value C_{judge}, the improved algorithm would be utilized. It is obvious that the minimum value of C is 0 when C_1 equals 0 and C_2 equals 0. C continually increases with the increasing of C_1 and C2. The maximum value of C is 2 when C_1 equals 0 and C_2 equals 1. Therefore comes C $\in$[0,2]. Value range of determination source C of C_{judge} is from 0 to 2. In practical application, C_{judge} is usually from 0.5 to 0.7. For example, assume C_{judge} to be 0.6 in a network. Then there would be 20% RN- nodes and 20% RN+ energy_low_sufficient nodes after a period of operation in which C equals C_1 plus 2 and C_2 equals 0.6. At this time, the improved algorithm could be utilized. Generally speaking, suitable value of C is 0.6.

3. Simulations and Analysis on the Improved Algorithm

For the purpose of verifying energy-efficient effect of this algorithm on the whole system, OMNeT++4.0 version is utilized to do simulation on it. Comparison is also done between the original algorithm and this one. Suppose that network coverage area is 250m×250m. Except for coordinator, the number of network nodes is 500. Initial energy of nodes is 5000 joules. Data transmission rate is 200KB. Network property is $C_m = 5$, $R_m = 4$ and $L_m = 6$. Through simulation tests, it is suitable to set parameter C to be 0.6 and power number of depth α to be 0.5 in the improved algorithm. Comparing with delay which is restrained to some extent, energy balance is put more attention in simulation. Therefore β is set to be 0.3. Through simulation of OMNeT4.0, the output curves are seen in Fig.3.

Horizontal axis stands for time t in s in Fig.3. Vertical axis stands for the number of failure node changing with time. Its range is from 0 to 500. The underlying curve 1 represents the number of death node changing with time in the network during operation process of the improved algorithm. Curve 2 explains the number of death node changing with time in the network during operation process of the original ZBR algorithm. In preliminary stage of network operation namely the preceding 40s, the improved algorithm is unenforced. It is to say that the utilized algorithm during preceding 40s is ZBR. Therefore changes of death nodes in ZBR and the improved algorithm are

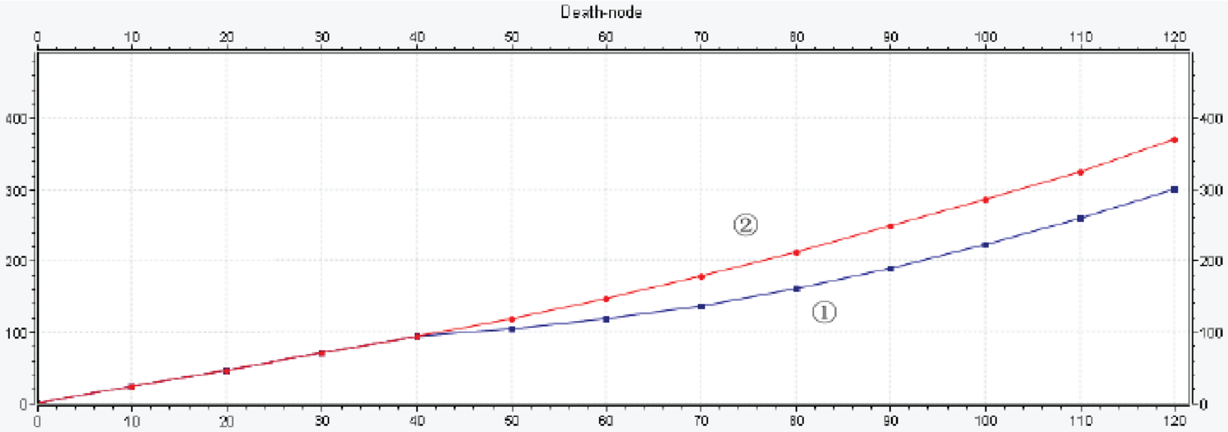

Figure 3. Curves of the Number of Death Node in Network Changing with Time

the same during the 40s in which curve 1 and curve 2 are coincident. After 40s, the number of death node would continually increase in ZBR algorithm thus adding workload to valid nodes and accelerating node death. The increasing of slope of curve 2 means that death rate of survival nodes also increases.

Meanwhile, the improved algorithm takes effect after 40s. Slope of curve 2 reduces before 80s which means that the improved algorithm slows down the death rate of survival nodes. In addition, curve 1 lies under curve 2 at the same time. It means that the number of death node in the improved algorithm is less than that in ZBR algorithm. Comprehensively speaking, curve 1 develops slower than curve 2. Therefore the improved algorithm could slow death rate of nodes, increase their survival time and lengthen network lifetime.

4. Conclusions

Through utilizing energy balance, the improved algorithm reduces utilization frequency of nodes with lower energy thus lengthening their utilization lifetime. Meanwhile, it increases the utilization frequency of nodes with higher energy thus lengthening life cycle of the whole network. This leads network labor maintenance to tend to be one-time concentrated battery replacement on a large scale, which decreases engineering quantity of labor maintenance.

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