Competition-free Period Interleaved Time-Slot Allocation Strategy for Data Transmission of IoT System

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ABSTRACT

The rapid development of wireless communication has accelerated the arrival of the Internet of Things (IoT) era. This article conducts in-depth research on heterogeneous data transmission in large-scale ZigBee presented IoT networks. We start from three aspects of data type classification of the IoT system, then design a time slot request framework and a time slot allocation algorithm involving the terminal and coordinator. We intend to improve the peak-shift transmission during the non-competition period to adapt to more practical IoT application scenarios. The proposed solution can ensure the reliable data transmission of the entire network, then the data transmission delay can be reduced to satisfy the heterogeneous transmission requirements. In the end, the proposed solution will be validated via simulation, and the numerical data demonstrates that our proposed solution outperforms.

CCS CONCEPTS

• **Networks**; • **Network protocols**; • **Transport protocols**;

KEYWORDS

IoT, Reliability, Heterogeneous data transmission, Time slot allocation, Congestion

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1 INTRODUCTION

The Internet of Things (IoT) system [1] is an emerging technology. Over the past ten years, IoT system has become more and more practical to use, and user's demand for wireless data transmission is increasing, especially the large-scale formation and the use of industrial-grade and agricultural-grade ZigBee networks [2].

In the traditional ZigBee network under the beacon mode defined under the 802.15.4 protocol, the default data transmission process is that the node first sends a Guaranteed Time Slot (GTS) request frames to the coordinator in its network to apply for a fixed time slot. The first-come-first-served algorithm can be used to reduce the complexity of request processing by the coordinator, because it does not require additional calculations. However, for IoT system in actual application scenarios, their nodes often perform different functions. Further, for the same procedure in different environments and different transmission cycles, the data that needs to be transmitted is often different. In addition, for different data, because the number of GTS that needs to be transmitted is different, the first-come, first-served algorithm may cause GTS not be fully allocated, which will cause low GTS utilization rate and low data transmission value during the non-competitive period. Finally, this will cause a decline in the performance of the entire network.

To this problem, this article studies the data transmission process of the ZigBee protocol and the competition-free period interleaved time slot allocation strategy of the MAC layer protocol. We propose a solution to ensure the reliable data transmission of the entire Zigbee network, and the data transmission delay can be reduced to satisfy the heterogeneous transmission requirements. Overall, the main contributions of this work are:

- It is an innovative work to simultaneously optimize the data transmission process of the ZigBee network protocol and the specification of the MAC layer protocol. In specific, this article starts from the three aspects of data type classification. Then it designs a time slot request framework and a time slot

allocation algorithm involving the terminal and coordinator. The proposed solution therefore can improve the peak-shift transmission during the non-competition period to adapt to more practical application scenarios.
- It's a pioneer work to ensure the reliability of the entire data transmission of Zigbee network, and the proposed scheme is to satisfy the delay requirements of different data. In addition, the energy consumption of the node during data transmission is saved to prolong the service life.

2 RELATED WORK AND SYSTEM MODEL

2.1 Related Work

There have been many related researches on the time slot request frames during the competition period [3]. Also, some researchers have done a lot of work on the transmission problems on the non-competitive period of Zigbee network. In [4], an optimal work that satisfies the delay constraints of time-sensitive transactions is designed, and the maximum utilization of GTS is achieved while optimizing the network. In [5], a flow-based GTS distribution algorithm is proposed according to the size of the transmitted data, combined with the coloring principle of graph theory, to ensure the maximum communication volume. In [6], an Adaptive GTS Allocation scheme (AGA) is proposed, with low latency and fairness as the optimization goals. And, the peak-shift transmission in the non-competition period under the congestion state is completed. In [7], the performance problem of data packet transmission under congested networks was studied. By adding identifiers to the sensor-level IP data packet header, the QoS software was modified on the router side to prioritize the identifiers, thereby reducing transmission delay. In [8], a priority-based algorithm for adaptive super-frame adjustment and GTS allocation algorithm is proposed, which challenges Beacon Order (BO) and Super-frame Order (SO) through GTS length and network load, and reduces transmission delay. In [9], a new scheme was designed, and the feedback control mechanism and data packet transmission mechanism of Contention Access Period (CAP) and Contention-Free Period (CFP) were considered at the same time to improve the performance of the network. In [10], an optimal GTS allocation algorithm with adaptive duty cycle was proposed to satisfy more node requirements by improving link utilization rate. In [11], by specifying the size of the transmission data packet, setting up a GTS allocation queue and a release queue, the energy consumption of the entire transmission phase is saved.

As a result, there have been numbers of work done to improve the data transmission of Zigbee network. However, those work didn't consider the case when multiple nodes request frame transmission phase at the same time. In this case. the nodes often need to wait for a long time to back off, which will not only prolong the transmission time of the time slot request frame, but also consume a lot of energy to complete the node's channel connection. Exiting works fail to figure out the early invalid backoff problems and cause unfairness of short-term channel access. To this end, this article proposes an innovative work to initialize a fixed backoff index value to reduce the collision probability and ensure the same channel access possibility, and then adjust the backoff period according to the result of each Clear Channel Assessment (CCA) detection, to complete the transmission of the time slot request frame during the contention period.

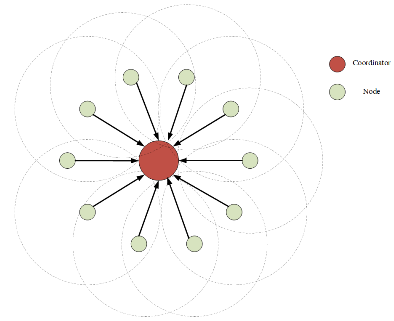

Figure 1: System Model of the Zigbee Network.

2.2 System Model

As shown in Figure 1, This article uses a single-hop star network as the system model. The network contains multiple sensor nodes and a coordinator node. The nodes have different sending periods and data packet sizes. In the system model, the physical distance between each node and the coordinator is 10m. The coordinator receives the time slot request frame and allocates the time slot according to the time slot allocation algorithm, and the node completes the uplink data transmission according to the allocated guaranteed time slot. An event-driven form is used to ensure that multiple nodes send time slot request frames at the same time. In addition, in order to distinguish the sequence of data packets sent by the same node, a time frame header is designed to encapsulate the current time of the system in each time.

2.2.1 Classification of Terminal Node Data Types. In this system model as shown in Figure 1, we mainly concern different degree of data delay, and the data is classified according to the actual situation in the ZigBee network. In practical IoT system, end nodes with a longer acquisition period will have a longer sampling interval, so the end node will not sensitive to data delay. Nevertheless, the data delay should be as small as possible because the sampling interval is set to be short to ensure that accurate and low-latency transmission of this type of data. For the sampling period, the data sent by the node is classified into two categories, namely long-period data and short-period data, and T_{avr} represents the average duration on the data sending period . Assuming there are N nodes and the sending duration of each node is T_i , the average sending duration can be expressed as :

$$T_{avr} = \frac{\sum_{i=1}^{n} T_i}{N} \tag{1}$$

In addition, the research on emergency data shows that when the environment is unchanged, the collected data is normal by default. And when the environment changes drastically due to external factors or its own factors, the collected data fluctuates greatly. At this time, it becomes the default urgent data.

In summary, the types of data can be mainly classified into long-period normal data, long-period emergency data, short-period normal data, and short-period emergency data.

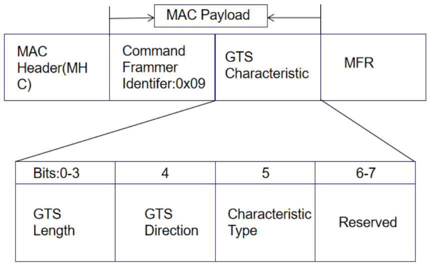

Figure 2: Default Time Slot Request Frame Format.

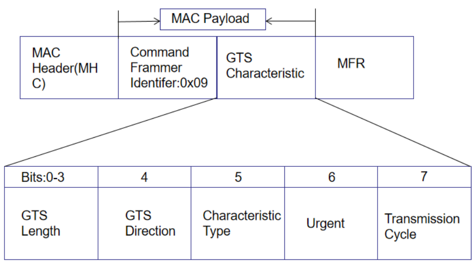

Figure 3: New Time Slot Request Frame Format.

2.2.2 Time Slot Request Frame Structure Design. In the 802.15.4-based ZigBee protocol, the default time slot request frame is shown in Figure 2. The main parts of the GTS characteristics are mainly determined by the MLME-GTS. reuqest primitive sent by the upper layer of the MAC.

The time slot request frame shown in the above figure cannot meet the delay sensitivity of the coordinator for different types of data when the time slot allocation is performed. Therefore, according to the default time slot request frame, the unused bits in the time slot request frame are combined with the data type in the previous section. So, a new time slot request frame format is designed as shown in Figure 3

The 6th bit in Figure 3, i.e. the "Urgent", indicates whether the data to be transmitted is urgent data (1), or not (0). The 7th bit "Transmission Cycle" indicates the relative transmission cycle size of the data to be transmitted, and the short-cycle data is 1. Therefore, the delay sensitivity can be expressed as: short-period emergency data (11)> long-period emergency data (10)> short-period normal data (01)> long-period normal data (00) in the figure.

3 PROPOSED ALGORITHM

According to the system model and related MAC layer design, we can find that, in a limited time slot, it is difficult to decide how to choose the maximize transmission value of a non-contention period. Because the number of time slots available for allocation is determined, so the transmission value of a single time slot is the highest. In order to reflect the transmission value of different types of data, the value of whether the data in the time slot request frame is urgent data and the relative period length of the data is weighted. In order to distinguish unused time slots (weight value is 0), the 6th bit and the 7th bit in the frame format of Figure 2 will be combined with the value represented by the binary plus one.

When these N nodes send request frames at the same time, the number of time slots required for each node's transmission is T_i . The value of the data generated is V_i. If the maximum value of data is transmitted in a limited time slot, V_{total} can be expressed as:

$$V_{total} = \sum_{i=1}^{n} V_i \times X_i \tag{2}$$

where X_i Indicates whether the time slot requested by the i-th node should be allocated (1) or not(0).

Assuming that the total number of time slots is M, because the total number of time slots is determined, the constraint condition generated by M is equation 3), and the target maximum value can be expressed by formula (4) as:

$$\sum_{i=1}^{n} X_i \times T_i \le M \tag{3}$$

$$V_{max} = \max \sum_{i=1}^{n} X_i \times V_i \tag{4}$$

Based on above consideration, a quick sort algorithm based on knapsack algorithm is used to sort the nodes that have been allocated time slots with respect to the classification of data types. This algorithm is to ensure that the nodes that allocated time slots to ensure the data to be sent in the order of weight from being high to low. Therefore, this algorithm not only ensures that the time slot being fully utilized, but also fulfills the delay requirements of different types of data.

Algorithm 1: Improved knapsack algorithm

```
Data: M (Num of GTS), N(Num of Nodes),T (Num of Required
      GTS),V(Data weight)
Result: Assigned node number and maximum weight
// Initialize dynamic array dp = new int[N + 1][M + 1];
// dp[i][0] and dp[0][j] Set all to 0, 1 to start calculation
for i=1:N+1 do
    for j=1:M+1 do
        if T[i − 1] > j then
            dp[i][j] = dp[i − 1][j]
        else
            //The number of time slots required for the i-th node is
             T[i-1], Data weight iV[i-1]
            dp[i][j] = Math.max(dp[i−1][j], dp[i−1][j−T[i−1]]+V[i−1])
// The maximum value of data transmitted during the CFP is
 max = dp[N][M]
// Reverse inference to find out the numbers of all allocated time slot
 nodes
for i=N:0 do
    //if dp[i][j] > dp[i − 1][j], This shows that the i-th item is put in the
     backpack
    if dp[i][j] ¿ dp[i − 1][j] then
        numStr = i + numStr
        j = j − T[i − 1]
// Sort the nodes loaded into the backpack according to the weight of
 the data
// Return the number of the node allocated time slot and the
 maximum weight of transmission in order
```

The algorithm based is shown as Algorithm.1 above, which includes the processing flow of the coordinator end using the improved knapsack algorithm on the time slot requests that arrive in the same super-frame. The algorithm is mainly classified into three main parts: The first part is to solve the value of the maximum transmission data that can be accommodated by the current number of time slots through the method of dynamic programming,

Table 1: Simulation Parameters

Parameter	Value
Simulation times/ GTS in CFP	10min/7
Num of GTS request frame	0-20
Random data weights	1-4
Num of GTS occupied	1-3
Probability of emergency data	0.1
BO/SO	2/1

The second part is to find out the node numbers of all allocated time slots through inverse calculation. Corresponding to the node information contained in the time slot request frame. The third part, through the sorting algorithm, the nodes that have been allocated time slots are sorted according to the weight of the type of data they need to transmit. And finally the weight is ordered from large to small sequentially. And the output of the algorithm is the numbers of time slots allocated in the current super-frame and the maximum transmission value of the non-contention period.

When the coordinator finishes all time slot requests by the above algorithm, it returns the node numbers into the corresponding request frame time slot, and then reads the node network address from the frame head. The coordinator will allocate the period of a non-competition time slot, and broadcast Beacon with GTS information to all nodes, and node receives the beacon frames. If the application is successful, the data will continue to be sent. If the application is not successful, the data will continue to wait for a GTS Desc Persistence Time (i.e. 4 Super-Frame) and if it remains unallocated, it will be considered a failed operation.

For example, when five nodes send request frames to the coordinator, according to the improved knapsack algorithm, it can be known that in order to make the value of the transmitted data higher, the nodes that will be assigned time slots as: node 4, node 2 and node 3. It can be seen that the total weight of the transmitted data is from the total weight of 4 led by the first-come, first-served scheme to 6 led by the delay demand. In comparison the back-knapsack algorithm allocates 7, then the utilization rate of the time slot is changed from being wasted at the first time slot to the maximum utilization of the later time slot, which improves the average transmission weight of a single time slot and can maximize the value of data collection.

4 PERFORMANCE EVALUATION

The simulation in this section is mainly aimed at the verification of the allocation algorithm of the network coordinator to guarantee the time slot allocation during the non-contention period. Table 1 lists the parameters and their values required for the simulation of different time slot allocation algorithms. And the simulation follows the system model as defined before.

The simulation uses Matlab software to simulate the allocation process of the guaranteed time slot in the non-competition period of 1000 Super-Frame using the default FCFS algorithm, the weight first algorithm and the improved knapsack algorithm proposed in this article.

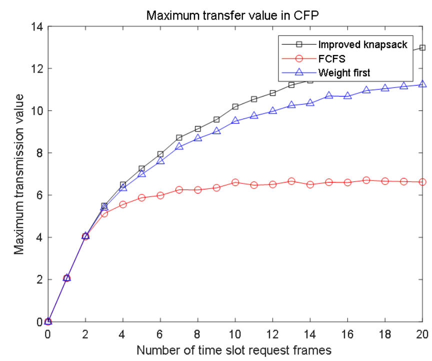

Figure 4: Maximum Transmission Value during CFP.

Figure 4 compares the maximum transmission value during the non-contention period under different time slot allocation algorithms. The abscissa is the number of time slot request frames that arrive at the coordinator during the contention period in the same super-frame, and the ordinate is the maximum value of transmission. Indicating the sensitivity of the node to delay. As the number of time slot request frames increases, the coordinator has more allocation options, and the advantages of the weight first algorithm and the improved knapsack algorithm in the time slot allocation are gradually becoming apparent. When the maximum transmission value stabilizes with the number of time slot request frames, the maximum transmission value of the improved knapsack time slot allocation algorithm is increased by 19% and 62% compared with the weight first allocation algorithm and the first-come, first-served allocation algorithm.

Figure 5 also compares the successful allocation probability during the non-contention period under different time slot allocation algorithms, and the number of time slot request frames arriving as an independent variable is the ratio of successfully allocated request frames to the total time slot request frames. As the number of request frames increases, the limited number of guaranteed time slots cannot meet more and more allocation requests, and the allocation success rate is gradually reduced. Compared with the other two allocation algorithms, the use of the improved backpack allocation algorithm can significantly increase the allocation success rate. To ensure the maximum transmission value while satisfying more time slot requests and transmitting more sensor data.

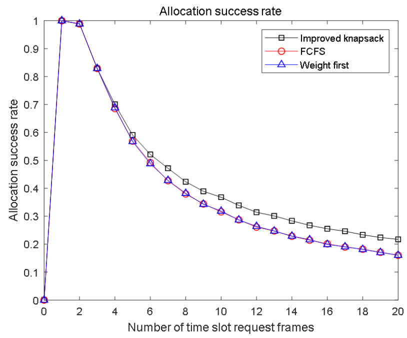

Figure 5: Maximum Transmission Value during CFP.

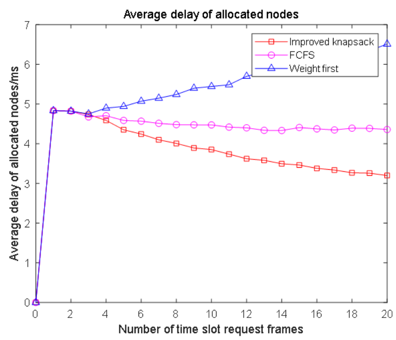

Figure 6: Average Delay of Allocated Nodes.

Figures 6 and 7 compare the data transmission delay of nodes successfully allocated to guaranteed time slots in a single super-frame, and the average delay of all nodes in the data transmission phase with the number of time slot request frames as the independent variable. In Figure 6, when the number of request frames increases with the number of request frames, the limited number of guaranteed time slots cannot satisfy more and more time slot allocation requests. In Figure 7, the data transmission phase delay of all nodes in the data collection congestion state is mainly aimed at. The nodes that are successfully allocated to the time slot enter the data transmission phase, and the nodes that are not successfully allocated wait for the time slot allocation in the next super-frame.

5 CONCLUSION

In target scale Zigbee network, the allocation strategy of heterogeneous data transmission is proposed. The data type is classified based on the transmission period and emergency at the application layer of the terminal, and the corresponding time slot request frame is designed in the MAC layer to meet the heterogeneous data requirements for latency. At the coordinator side, the knapsack algorithm is improved to complete the allocation of guaranteed time slots during the non-competition period, and the performance indicators of the entire strategy are analyzed to meet more time slot requests while ensuring the maximum transmission value, for transmitting more node data and improve the performance of the entire network. Finally, this article analyzes the proposed data

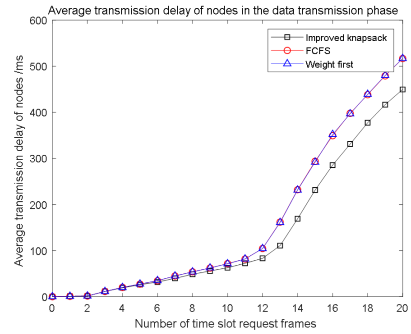

Figure 7: Average Transmission Delay of Nodes in the Data Transmission Phase.

transmission strategy at the algorithm level and network simulation level respectively, and compares it with the algorithm of the protocol standard and the algorithm of existing research. The simulation results show that the proposed scheme in this article has an improved effect in the transmission delay of heterogeneous data, node throughput and energy consumption in the large-scale ZigBee sensor network scenario. This validates the feasibility of the scheme.

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