A Node-Grouping Superframe-Division MAC Protocol for Smart Home Based on IEEE802.15.4 Protocol

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Abstract. As an application of Wireless Sensor Network (WSN), Smart Home obtained fast development in recent years, and the researches for the Media Access Control (MAC) protocol are mainly focused on energy efficiency and consumption, which pay little attention on the access control of urgent information about the security and guard. To introduce urgent information priorities and reduce the cost of independent security information overhead, this paper proposes a node-grouping superframe-division MAC protocol based on IEEE802.15.4 MAC protocol. This protocol is designed for Smart Home applications, and focused on priority facility in an emergency. This modified protocol has good network performance, especially to the node with transmission priority. The simulation result indicates that the new protocol is better than the traditional IEEE802.15.4 MAC protocol in terms of packet delivery ratio, transmission delay, network throughput, and energy efficiency.

Keywords: Smart Home, IEEE802.15.4 MAC protocol, Superframe-division, Priority.

1 Introduction

With the development of micro-electronic technology, wireless communication technology, and embedded technology, the WSN got rapid development, with the characteristics of low consumption, high efficiency, low complexity and short-distance communication. The IEEE802.15 series standard main applies to short-distance wireless communication network, in which IEEE802.15.4 is a set of early network service standard formulated for the Low-Rate Wireless Personal Area Network (LR-WPAN). Because of the energy efficiency, robustness and flexibility characteristic, IEEE802.15.4 standard is suitable for most WSN applications [1][2]. As an important application of WSN, Smart Home also adopts IEEE802.15.4 standard as one of its main communication protocols [3][4].

The MAC protocol is mainly used to manage and coordinate channel resources for multiple users. The MAC layer is in the bottom of the WSN protocol stack, which is the direct controller for the date message and control frame carrying on transmission and

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receiving on the wireless channel. The quality of the MAC protocol is one of the most essential factors direct related with other protocol track's service quality.

2 IEEE802.15.4 MAC Layer

IEEE802.15.4 standard defined the main functions of MAC layer including six aspects: constructs and maintains PAN (coordinator), supports the connection and separation between the equipment of network (coordinator), channel resource access, applies guaranteed time slot (GTS) for specific application, supports equipment's security, and provides reliable data link between the MAC entity.

The channel access is a major function of MAC, IEEE802.15.4 network accesses the channel in two ways: based on competitive or not. In competition-based channel access pattern, node take Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm to compete channel in the distributed method [5][6], while non-competition channel access is managed completely by the Pan Area Network (PAN) coordinator in the manner of GTS. GTS is similar with CDMA, but it can distribute specific time slot dynamically for the nodes which have sending and receiving requests.

IEEE802.15.4 support two kinds of network operating patterns: the beacon-enabled pattern and the nonbeacon-enabled pattern.

In the beacon-enabled pattern, the coordinator broadcasts beacon-frame which contains network synchronization information and a variety of control information to the entire network periodically. Terminal get synchronize with the coordinator through receiving the beacon frame periodically. The terminal compete the channel through slotted CAMA/CA algorithm.

2.1 Superframe Structure

In the beacon-enabled pattern, the coordinator defines the superframe structure, and MAC takes the superframe as the cycle to organize the communication between the network equipments. Each superframe begins with beacon which contains the superframe's duration, the assignment information and so on. Once equipment receives the beacon, it can act according to the content of the beacon to arrange its duty, such as competing to the channel and entering the inactive period.

The superframe structure main includes Active Period and the optional Inactive Period [7], as shown in Fig 1. In the Inactive Period, the device enters the sleep state to save energy. The Active Period which is divided into 16 equal-long time slots contains three phases that is Beacon, Contention Access Period (CAP), and Contention Free Period (CFP). The length of each slot time, the number of the time slot CAP and CFP contains, and other parameters are all set by the coordinator which broadcasting them to the network.

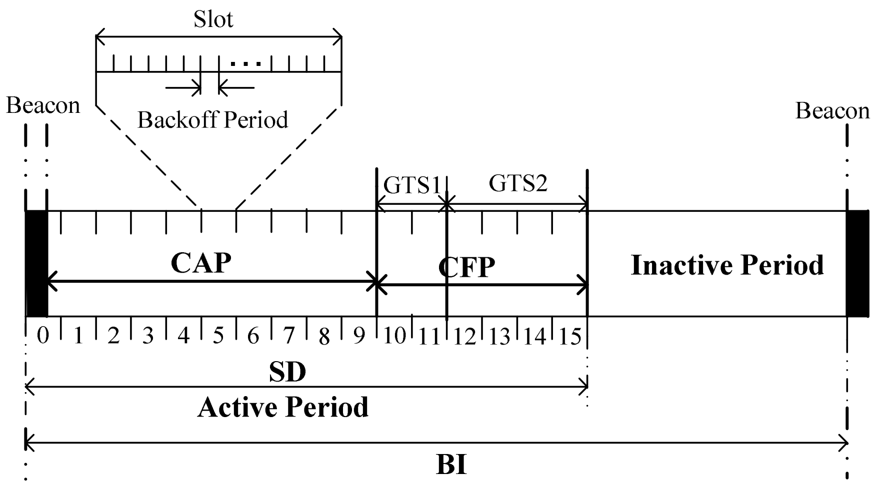

Fig. 1. The superframe structure of IEEE802.15.4

The superframe structure is described by the values of macBeaconOrder (BO) and macSuperframeOrder (SO). The value of Beacon Interval (BI) is given by: when $0 \le BO \le 14$, BI=aBaseSuperframeDuration*2^{BO} symbols, if BO=15, there is no Beacon, the value of macSuperframeOrder is ignored. The value of Superframe Duration (SD) is given by: when $0 \le SO \le BO \le 14$, SD=aBaseSuperframeDuration*2^{SO} symbols, if SO=15, there is no Inactive Period.

In the Contention Access Period, MAC uses slotted CSMA/CA algorithm to compete channel resources. In the Contention Free Period, the coordinator divides this period into a number of GTS according to the application situation of devices in the last superframe. Each GTS is composed of certain time slots, which number is assigned by the coordinator when the device applying GTS. If the application of a device be approved, this device gets the number of time slots it wants. During this time, this device can monopolize channel resources in its GTS without competition.

Fig 2 has given a superframe example. In this example, CAP takes up 9 slots; CFP takes up 6 slots allocated to two devices, one takes up 2 slots, another takes up 4 slots.

2.2 CSMA/CA Algorithm

In the CAP, in order to sent data frames or command frame, devices need to use CSMA/CA mechanism, except that send data frames after the acknowledgement frame immediately. CSMA/CA cannot be used for sending frames in the CFP.

In the slotted CSMA/CA algorithm, the backoff time boundary of each PAN device is consistent with superframe slot boundary. Whenever a device needs to send data frame or command frame, it first locates the boundary of the next slot, and waits for a random number of time slots. After the waiting, the device begins to detect the channel state, if the channel is idle, the device begin to sent data packet at the beginning of the next slot; if channel is busy, the device needs to wait for random number of slots again, and then check the channel state, repeat this process until a idle channel appears. The sending of acknowledgment frame does not need to use CSMA/CA.

To realize the slotted CSMA/CA algorithm, each device needs to maintain three variables: CW, NB, and BE. CW (Contention Window) is the contention window size, which is the number of the continuous detecting channel idle before sending data packet. When the CSMA/CA algorithm starts or the channel is detected to be busy, CW is initialized to 2. CW is only used for the slotted CSMA/CA algorithm. NB (Number of Backoff) is the number of backoff for achieving the algorithm, which is initialized to 0. BE (Back off Exponent) is connected with the backoff period which the device needs to wait for before it sending information. Algorithm use backoff period as the implementation time unit. When macBattLifeExt is set to FALSE, BE is initialized to macMinBE; when macBattLifeExt is set to TRUE, BE is initialized to the lesser between 2 and macMinBE.

Backoff delay time= Random()*aUnitBackoffPeriod,
Where, Random()=[0, 2^{BE}-1], aUnitBackoffPeriod=20 symbols.
We'll describe the slotted CSMA/CA algorithm refers to Fig 3 as follows.

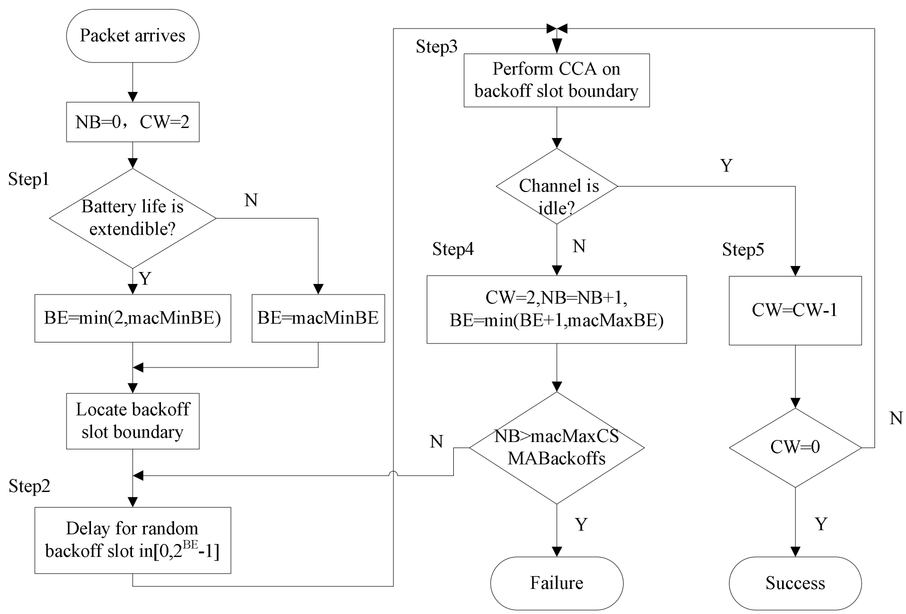

Fig. 2. Slotted CSMA/CA algorithm

Step1: When the device buffer has data frame waiting to be sent, MAC first initializes the algorithm parameters, including NB, CW and BE. After this, MAC positions the next slot boundary.

Step2: MAC selects a random backoff value in [0, 2^{BE}-1], and waits for corresponding backoff slots to avoid collision.

Step3: After the waiting time, MAC sends a channel idle listening request to the physical layer. MAC determines the current channel state through the Clear Channel Assessment (CCA) of the physical layer.

Step4: If CCA demonstration channel condition for busy, MAC increases NB and BE value for 1, and CW value is reset to 2. If NB≤macMaxCSMAbackoffs, the algorithm will jump to Step2, else algorithm declares “Failure”.

Step5: If CCA demonstration channel condition for idle, MAC reduces CW value for 1. If CW>0, the algorithm will jump to Step3, else algorithm declares “Success”.

2.3 The Application of IEEE802.15.4 MAC Protocol in Smart Home

Collision is the main factor affecting network performance, transmission data collision will cause many adverse effect, including energy loss, transmission delay, and data loss.

Generally speaking, IEEE802.15.4 LR-PAN has two kinds of collision, one of which is contention collision. Node A and B both contention channel successfully, and choice the same Unit Backoff Period (UBP), which will lead collision on the coordinator side as a result of simultaneous transmission. This kind of collision occurs in the beginning of the packet transmission. Another collision is caused by hidden node problem (HNP). Such collision may occur in any time spot during the packages transmission.

Because the network scale of WSN in Smart Home is small, and the general transmission range of IEEE802.15.4 is 0.1cm~10m, some may reach 100m, so the impact of collision caused by HNP is relative small.

The competition collision in the IEEE802.15.4 network is caused by node implementing CSMA/CA algorithm and accessing channel. When detected the channel is idle, all devices which have information to sent, produces a backoff delay time to reduce the probability of contention collision. BE decides a devices’ waiting time before accessing channel. Obviously, the bigger the BE value, the bigger the probability of waiting time, which will increase the energy consumptions. Therefore, BE is general assigned range from 3 to 5 in the IEEE802.15.4 protocol. Although the BE value's small scope change may guarantee the device has shorter waiting time, the following transmission easy to cause collision.

In the Smart Home WSN, IEEE802.15.4 MAC protocol cannot reduce contention collision effectively.

3 A MAC Protocol Based on Priority and Superframe-Division

Due to collision or the failure of competition, node need to contend for the channel again, once NB reach the biggest number, it will discard the packets. In order to ensure the nodes which collected urgent information could have priority to sending their information to coordinator successfully, and reduce the impact of collisions in certain emergencies--the invasion, gas leakage, creepage, and etc. This paper presents a MAC protocol based on priority and superframe-division: assign different priorities to different event monitoring sensor.

In this paper, node is classified into three groups according to priorities: the first group nodes (denoted as Priority-node1, P-node1) are designed for security & control system, such as gate control and gas leakage system; The second group nodes (P-node2) are embedded in high-power appliances such as electric heater, electric kettle or air conditioning; The third group nodes (P-node3) are embedded in low-power appliances such as illumination device, fan, and thermometer. For simulations, we take 400W as the boundary of the size power.

To ensure different nodes with different priorities are still take the superframe as the cycle to communicate with each other, and staggered communication from the time, the superframe structure must be adjusted appropriately.

The superframe structure which would be adjusted should maintain as far as possible consistent with the structure which IEEE802.15.4 protocol defines, that is they similar use BO and SO these two values to describe the active period and the inactive period. The active period contains 16 equilong time slots, which was still divided into three stages: beacon transmission period, the contention access period (CAP) and the contention-free period (CFP). The adjusted superframe structure may also support GTS mechanism, when a network selects GTS mechanism, it must guarantee that the CFP has the reservation time slot to assign to the nodes which have request in advance. Otherwise, the entire active period will be assigned completely as CAP to the nodes.

CAP still takes slot as time unit. The aim of slot distribution is then to form different node groups. One or more time slots are assigned to each group and we name these time as Priority-slot (P-slot). The allocation method for P-slots is similar with GTS, but the objects of assigned slots are different, the former is a collection of nodes need competition, while the latter is a collection of nodes don't need competition. Fig 3 describes proposed superframe structure which distributes three equal-long P-slots to different subfield wiht priority.

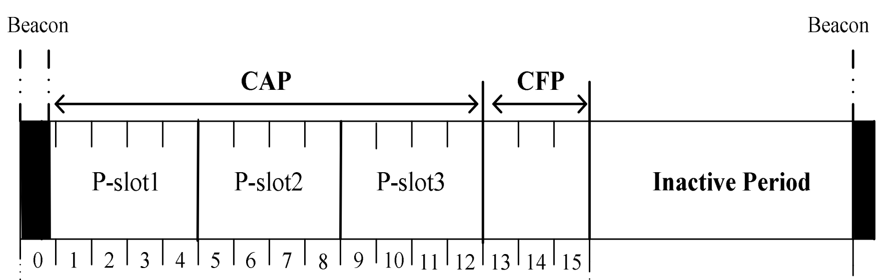

Fig. 3. Superframe division of IEEE802.15.4 based on priority

Based on the above description, this paper proposes two kinds of priority schemes.

Scheme one: The highest priority nodes are located at the P-slot1 to compete channel; the second-priority nodes are located at the P-slot2 to transmit information with competition; the lowest priority nodes are located at the P-slot3, as shown in Fig 3. In this scheme, because the higher priority nodes are in the preceding P-slot, this node can prior transmit their information to the coordinator. However, the same rank of priority nodes are set at a P-slot, which cannot reduce collision effectively. Then, we propose another scheme.

Scheme two: Assigns the different priority nodes mixed in different P-slots, that is, a P-slot contains different priority nodes. In the CSMA/CA algorithm, we set different BE value for different priority nodes, and increase the max backoff number of the higher priority nodes appropriately. The specific improvement measures of the algorithm are as follows:

(1) The BE's initial value is different for different priority node, e.g., 1 for P-node1, 2 for P-node, and 3 for P-node;
(2) In the fourth step of the original algorithm, every time backoff let the BE value (when BE<macMaxBE) add 1. In the new algorithm, BE value add 1 every three time backoff for P-node1, two time for P-node2, and three for P-node3 until BE equal to macMaxBE.
(3) For the purpose of guarantying the reliable transmission of the urgent information, and preventing those nodes from discarding the package, the NB value of P-node1 is increased suitably.

This improved algorithm enables the urgent information to get reliable transmission and priority treatment by the coordinator, and could reduce the transmission collision caused by the small scope change of BE.

4 Simulations and Analysis

The goal of the proposed scheme is to reduce the collision of the communication information, especially the urgent information, and then meets the goals of reducing the delivery delay, increasing the throughput of data transmission, and conserving energy. In order to evaluate the performance of the proposed schemes, this paper uses the OMNET++ discrete event simulator to simulate the wireless sensor network environment. Three slotted CSMA/CA based MAC protocols are evaluated in the simulation: IEEE802.15.4 MAC, scheme 1, and scheme 2 this paper designs.

4.1 Environment and Parameter Configuration

The simulations of this paper are all based on slotted CSMA/CA algorithm. The bandwidth is set to 250kb/s. The topology network we used is as shown in Fig 4, which is beacon-enabled star network with superframe structure. Nodes exchange messages using the wireless communication. We assume that there is no noise and no error model in wireless channel. In this network, seven nodes distributed in a 10m radius circular area, which contains a PAN coordinator (ID=0) and 6 fixed ordinary nodes (ID=1, 2… 6), the max sending distance is 15m. There is no CFP in a superframe, which is all consisting of CAP. All of the nodes need to competing channel using CSMA/CA algorithm.

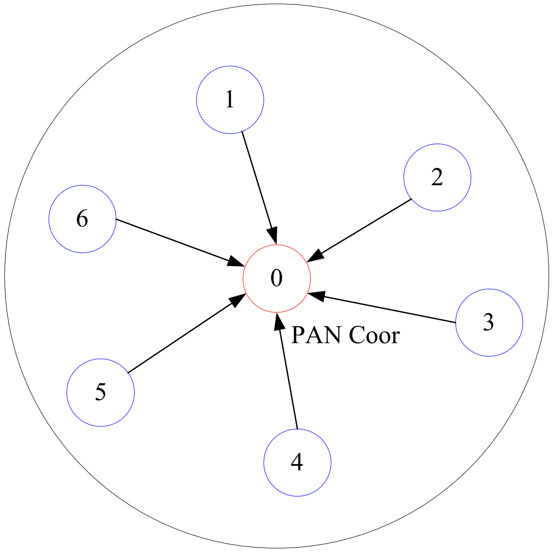

Fig. 4. Topology

There are some constant parameters need to use in the simulations as follows:

aNumSuperframeSlots = 16;
aBaseSlotDuration = 0.96ms;
aBaseSuperframeDuration = 15.36ms.

In our experiments, we set the transmitting power to 52.2mW, receiving power to 56.4mW, and in sleep mode to 0.06mW (referenced to the TI Chipcon2420 chipset data sheet) [8].By changing packet arrival interval, we can adjust the network load. The "Interval" parameter will use 0.1s as one unit and it increases from 0.1s to 1.0s. It represents that the network load changes from its upper-bond to its lower-bond.

4.2 Results and Analysis

Fig 5 describes the packet delivery ratio for nodes using different MAC protocols. For Scheme1 this paper proposed, the packet delivery ratio for the highest priority nodes (P-node1) is steady relatively, while the packet delivery ratio for other priority nodes is much lower than IEEE802.15.4 MAC', which is not good to improve the network performance. Scheme2 not only guarantee high packet delivery ratio for nodes with higher priorities, but also ensures most nodes deliver packets relatively stable. The result on the other hand proves that the proposed Scheme2 effectively avoids packet access collisions and reduces the packet loss probability.

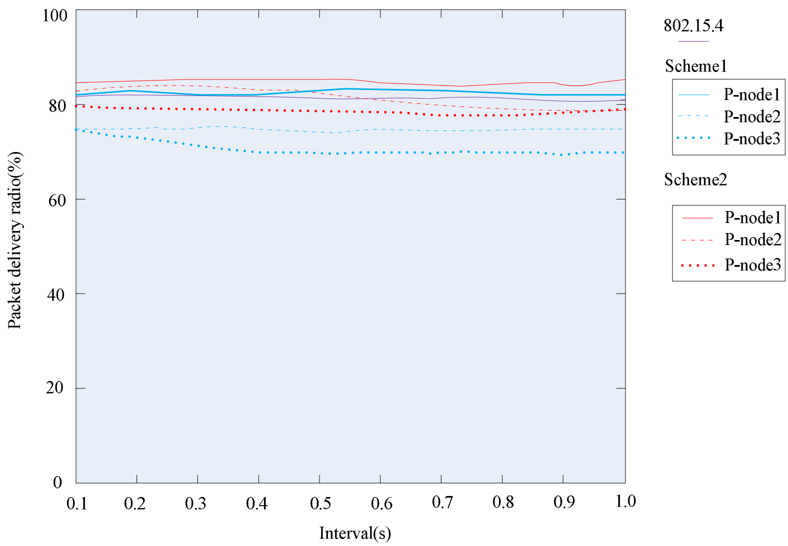

Fig. 5. Packet delivery ratio

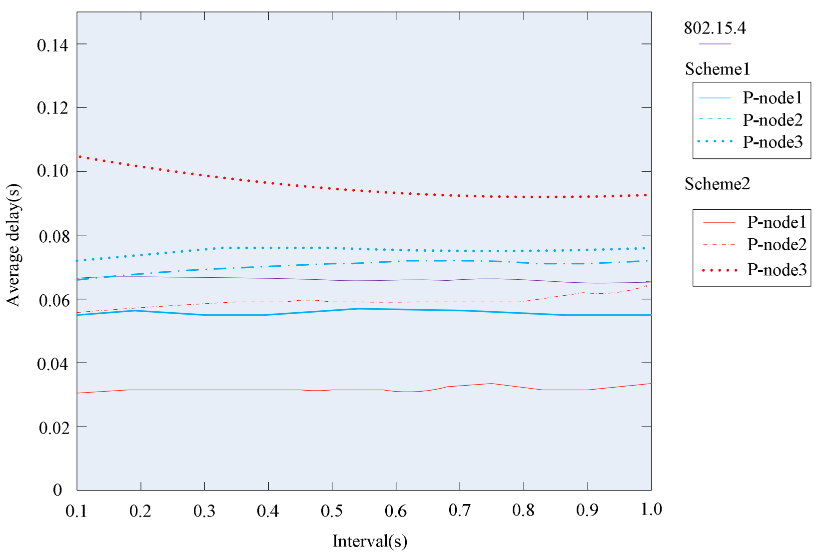

Fig. 6. Average transmission delay

Fig 6 presents average transmission delay using different MAC protocols. We can see from the results that the packet transmission delays of P-node1 using Scheme2 is very small, which has reached the design goal to transmit urgent information with priorities. However, the transmission delay of P-node2 and P-node3 are relative higher. Overall, the average transmission delay of the network is improved when compared to original 802.15.4 MAC.

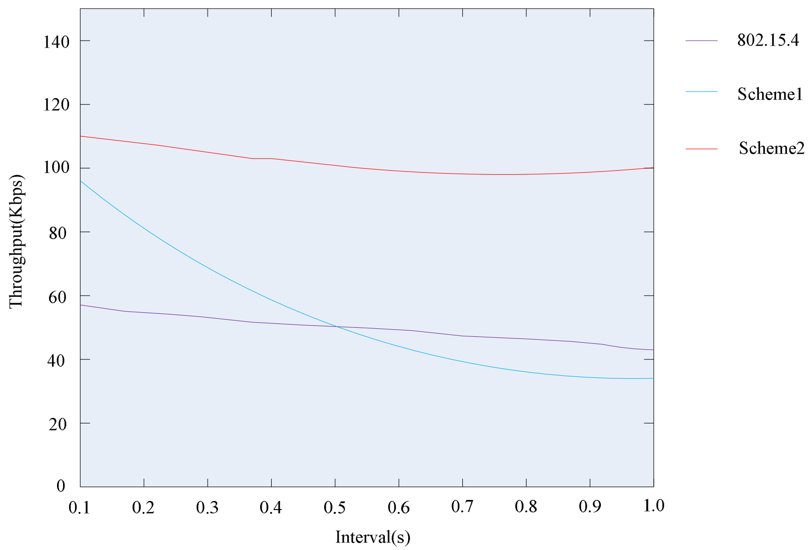

Fig. 7. Average data throughput

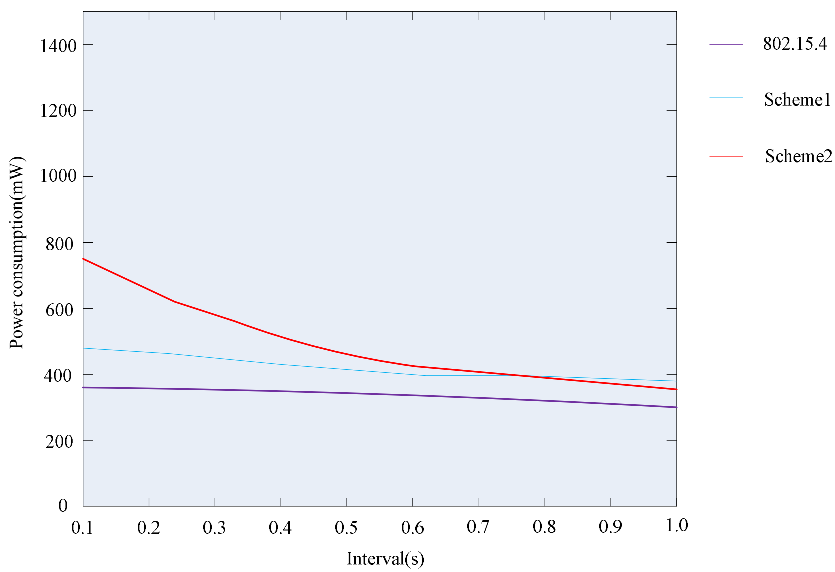

Fig. 8. Average energy consumption

Fig 7 shows the results of throughput with different network load. The x-axis denotes the network load and the y-axis denotes the average throughput. The higher the network load, the higher the throughput. It can be seen, Scheme1's throughput changes large, and Scheme2' throughput is ideal. With the increase of network load, competition collisions are happening with increasing frequency, and packet loss also increased, then network throughput has a slight fluctuation. However, the overall performance of Scheme2 is superior.

Fig 8 describes the average energy consumption for nodes with data transmission. We can see, in the low load, the energy consumption of three protocols is relative close. When the load increases ("Interval" value decreases), the energy consumption also increases. The average consumption of the proposed Scheme2 protocol is higher than two others' with high data generating rate. It is because that Scheme2 needs more energy to ensure that the higher priority nodes to prior competed channel successfully. In low network load, the Scheme2 protocol can also conserve energy without urgent information transport.

5 Conclusions

In this letter, we propose a node-grouping superframe-division MAC protocol based on IEEE802.15.4 MAC protocol. For different events monitoring tasks in smart home, nodes are classified into three classes with priorities. A group of nodes with priorities is assigned to a P-slot in CAP. Two algorithms for slot division are proposed to reduce delivery delay, increase throughput, and conserve energy consumption. The proposed Scheme2 improves urgent information delivery efficiency and facilitates it first to be transmitted. Using the protocol, we can prevent the occurrence of fires, gas leakage or other security incidents and create a safe environment. The protocol also reduces the cost of dedicated security & control systems for smart home sensor applications. The performance evaluation shows that the proposed Scheme2 has lower delivery delay than IEEE802.15.4 MAC and Scheme1. Meanwhile, Scheme2 can conserve energy and increase throughput in low network load. This thesis is supported by "The 211 Project Central Special Fund of Hainan University".

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