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A GTS Scheduling Algorithm for Voice Communication over IEEE 802.15.4 Multihop Sensor Networks

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Abstract

The recent increase in use of the IEEE 802.15.4 standard for wireless connectivity in personal area networks makes of it an important technology for low-cost low-power wireless personal area networks. Studies showed that voice communications over IEEE 802.15.4 networks is feasible by Guaranteed Time Slot (GTS) allocation; but there are some constraints to accommodate voice transmission beyond two hops due to the excessive transmission delay. In this paper, we propose a GTS allocation scheme for bidirectional voice traffic in IEEE 802.15.4 multihop networks with the goal of achieving fairness and optimization of resource allocation. The proposed scheme uses a greedy algorithm to allocate GTSs to devices for successful completion of voice transmission with efficient use of bandwidth while considering closest devices with another factor for starvation avoidance. We analyze and validate the proposed scheme in terms of fairness and resource optimization through numeral analysis.

Key words: LR-WPAN, wireless sensor network, GTS, voice communication

1. INTRODUCTION

Wireless sensor networks (WSNs) and personal area networks (WPAN) have gained an incredible aspect from the perspectives of researchers during the past few years. Researchers are focusing their interest and attention on the feasibility of the transmission of voice packet over sensor networks [1]. The particular IEEE 802.15.4 standard is a suitable network component to be utilized since it has low-cost, low energy consumption and long lifetime maintenance of the network. In [2], the authors discussed the possibility of transmitting short-distance voice over ZigBee technology with the restriction of a very small number of nodes.

The IEEE 802.15.4 MAC protocol performs in two modes which are the non-beacon enabled and beacon enabled modes. In the non-beacon enabled mode, the IEEE 802.15.4 uses carrier sensing multiple access collision avoidance (CSMA/CA). In the beacon enabled mode, the protocol supports a type of time division multiple access (TDMA) which is known as guaranteed time slots (GTS) mechanism. However, there is a problem when it comes to efficient allocation of GTS due to its conventional first come first served (FCFS) method.

In this paper, we propose a GTS allocation scheme that can support voice traffic in a multihop star topology. Our proposed scheme allocates GTS in an efficient and fair way. This scheme considered the number of intermediate nodes, the nodes identification and the waiting delay to allocate GTS. The goal of our proposed scheme is to minimize bandwidth waste in voice packet transmission by prioritizing farther nodes and to provide fairness of resource allocation. The analysis of the proposed scheme results showed that the fairness improved in the network.

The remaining of the paper is organized as follow: in section II we give a brief overview on IEEE 802.15.4 standard and related work. Section III presents the proposed scheme, followed by section IV where we perform numerical analysis to validate the scheme and finally section V concludes the paper.

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2. BACKGROUND: REVISED IEEE 802.15.4 STANDARD AND RELATED WORK

The IEEE 802.15.4 MAC protocol has low-energy consumption within a short-distance [3] and its beacon-enable mode which is our domain of interest provides a contention-free GTS mechanism where the PAN coordinator periodically broadcasts the beacon to all the devices in the network to support time-critical data deliveries. The beacon, used for synchronization provides the superframe format. As shown in Fig.1, there are two portions in the superframe: the active one, equally divided into 16 time slots is composed of the contention access period (CAP) and contention free period (CFP). In the CAP, a slotted CSMA/CA mechanism is used to access the channel while in the CFP the PAN coordinator allocates the GTS to the devices to transmit data. During the inactive portion, being unable to transmit data, nodes are in an energy saving mode. In [4] the details about how the PAN coordinator specifies the structure of the superframe are given.

Conventionally, a GTS is consisted of at least one time slot which is allocated to the requesting wireless device. As shown in Fig.1, the first GTS consists of three time slots, the second GTS consists of two time slots and the maximum number of GTSs that can be allocated in a superframe is seven. Studies on IEEE 802.15.4 MAC protocol envisioned the star topology which seems to be dominant and suitable for WSNs. In Fig.2, it consists of nodes, routers and a PAN coordinator which is responsible for GTS allocation. The PANC coordinator determines the length of the CFP in a superframe which depends on the GTS requests and the current available capacity in that superframe. In such a topology the devices that request new GTS allocation send a GTS request to the PAN coordinator during the CAP which in turn first checks if there is an available capacity. Provided that there is sufficient bandwidth, the PAN coordinator determines a device list for GTS allocation in the next superframe based on a FCFS fashion. However this scheme does not provide efficiency or fairness of resource allocation and is subject to bandwidth wastage; and it is worst when it comes to voice communication.

Here, though the MAC protocol of the conventional scheme can support voice communication, it is inadequate to support voice traffic having bidirectional characteristics and in a multihop structure the performance degrades due to the increase of the transmission delay and packet loss ratio. Several GTS allocation scheme researched in IEEE 802.15.4 domain to support voice traffic with low latency [5]. In [6] J. JUNG proposed the Virtual-cut through GTS allocation scheme for voice traffic which allocates GTSs for guaranteed minimum delay. The participating devices are allocated GTSs as in the stepping stone method and showed low end-to-end delay and packet drop ratio. The dynamic GTS allocation scheme in IEEE 802.15.4 by multi-factor proposed in [4] improves the utilization of GTS bandwidth; the allocation is determined by the data size, the delay time and the utilization of GTS time slot but voice packets were not taken into account. Considering a multihop star topology, in this paper we proposed a greedy scheme allocation where GTS requesting nodes priority depends basically on three factors: intermediate hops count, requesting feedback of nodes from previous superframes based on their identification and the waiting delay of unlucky nodes. GTSs are allocated to devices for successful completions of voice transmission in a stepping stone scheme meaning the intermediate nodes of a requesting node are also served GTS slots to optimize the resource utilization in one superframe duration.

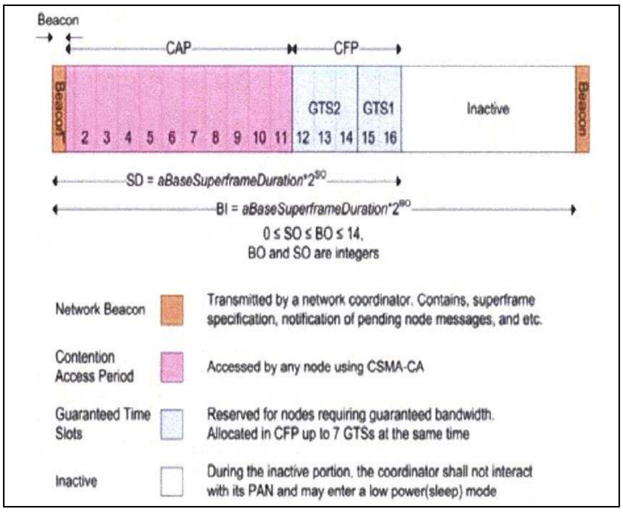

Fig.1 Superframe structure in IEEE802.15.4

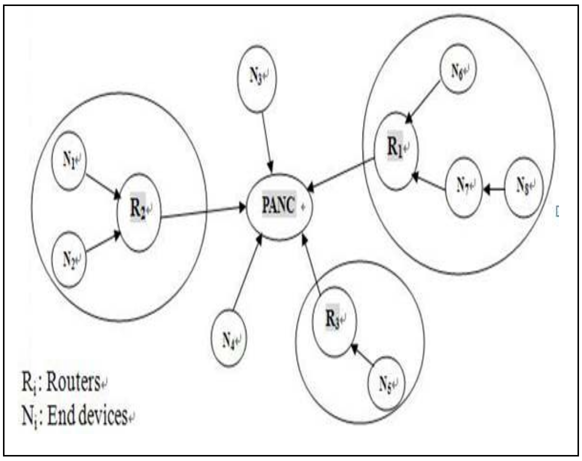

Fig. 2 Example of star topology multihop network

3. PROPOSED ALLOCATION SCHEME

A. System model

The objective of this section is to explain our proposed scheme for supporting voice over IEEE 802.15.4 multihop networks with consideration of bandwidth utilization and fairness. The basic idea defines the priority considering three perspectives. The most determinant one takes into account the nodes requesting from farther distance from the view of the PAN coordinator. The second one concerns the requesting feedbacks of nodes in the previous superframe and lastly to overcome the starvation problem we defined the waiting delay for GTS requesting nodes that could not be allocated because of their overall lower priority value.

For the priority parameters process we defined the intermediate hop count ratio for farther nodes consideration. The requesting feedback of nodes is evaluated with the identification of nodes which is a ***miss*** in case the node requests but it did not get a GTS or a ***hit*** in case the node has been served a GTS; and the waiting time of nodes that did not get allocation at the time they requested which is bound to their lower priority and the number of cycles.

In the proposed scheme, the GTS allocation is given to devices with higher priorities. The priority is established in non-increasing order; that is the devices with higher priority value get the GTS which is allocated in two phases: the classification and the scheduling phase. In the classification phase, the PAN coordinator classifies devices by considering first the device's position through its intermediate hop count ratio; after that the device's past GTS usage through its $\boldsymbol{i\_d}$ feedback (***miss*** or ***hit***) and the device's waiting time through the waiting delay factor is evaluated. In order to avoid starvation problem in the proposed scheme, a longer waiting time means that the priority increases for such node to get allocation.

B. Priority assignment

The PAN coordinator can control the behavior of each node in the network by using the classification parameters defined above and accordingly starts the priority process. Assuming that there are ***N*** nodes in the network, the priority value assigned to device ***n*** is ***Pn*** and the device which has higher priority value ***Pi*** is scheduled for GTS allocation. The PAN coordinator assigns priority to nodes based on the following calculation of the priority value where ***Pi*** is the overall priority value of a node.

$$\boldsymbol{Pi = h + \beta \times i\_d + \frac{m \times d}{SD}} \quad \textbf{(1)}$$

β is derived from the exponential weigh moving average scheme to manage the priority of devices, $0<\beta\leq 0.5$; and for a requesting node's feedback (***miss*** or ***hit***) we use an identification variable $\boldsymbol{i\_d}$ with $\boldsymbol{i\_d} = \begin{cases} 0 \text{ for } \boldsymbol{hit} \\ 1 \text{ for } \boldsymbol{miss} \end{cases}$; ***h*** is the ratio of intermediate hop count defined by ***n/ K*** with ***n*** equals to the intermediate hops count and ***K*** is the number of nodes in the corresponding subnet; ***d*** is the waiting delay of a node in a beacon interval. ***SD*** is the superframe duration and ***m*** is the number of cycles a device waited for GTS allocation.

Table 1

Device scheduling algorithm
Assume that there are K total devices in the WPAN
$P = \{Pn_1, Pn_2, \ldots, Pn_K\}$
Pnl is The largest priority value
M:Total number of time slot to be allocated
d = waiting factor
While there is a request for GTS **do**
check the waiting time factor of node i
if node **i** has waiting time factor **then**
add **d** to priority
else
evaluate intermediate hops count factor
if hop count factor is the largest
schedule GTS
remove Pnl from P
else
evaluate node id factor:
if node factor is hit
evaluate priority and schedule GTS
remove Pnl from P
else if router is busy or failed be allocated
evaluate waiting delay of unlucky nodes
else break
end while

The purpose of ***h*** is to set a relative high priority to requesting nodes that have more intermediate node count. The factor $\boldsymbol{\beta \times i\_d}$ regulates the fairness for nodes with lower priority particularly for nodes directly connected to the PAN coordinator that have zero as intermediate node count. $\boldsymbol{\frac{m \times d}{SD}}$ is the waiting time factor that increases the priority of nodes with repeated ***miss***. In case we have nodes with the same intermediate hop count ratio, their $\boldsymbol{i\_d}$ is considered which gives the feedback of past usage of GTS what is added to an eventual existing waiting factor and the PAN decision is made. The idea is to give chance to every node in the network requesting for GTS to get allocation. However if nodes have ***miss*** and have the same hop count ratio then the choice is made according to the value of their waiting delay factor and the remaining nodes are considered in the next superframe according to their waiting time status. By consequent, the nodes in waiting time status get higher priority in next beacon interval. The proposed allocation algorithm is described in Table 1.

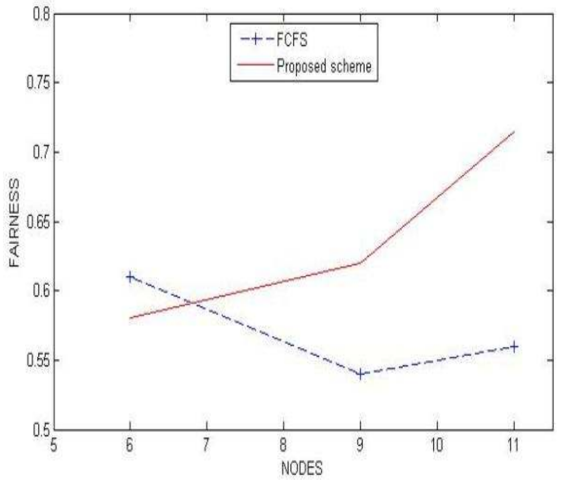

Fig.3 Fairness in the multi-hop network

4. EVALUATION AND DISCUSSIONS

Due to our limited resources we went through numerical analysis rather than simulation. As the priority determination emphasizes on farther nodes with slot allocation to their intermediate nodes, distant nodes on request are expected to realize full resource utilization. The analysis showed that average of nodes scheduled results from nodes that are located one or more hops apart from the PAN coordinator therefore achieving the optimization objective.

For the evaluation we considered the analytical model in [6] with a discrete time M/D/1 queuing system. We referred to the simulation parameters and values in Table 3 of [6]. The main metric of the numerical analysis is the fairness metric $\boldsymbol{F}$ described in [8] defined by

$$\boldsymbol{F} = \frac{\left(\sum_{i=1}^{N} Wi\right)^2}{N \sum_{i=1}^{N} Wi^2} \qquad (2)$$

where we considered $\boldsymbol{Wi}$, the average waiting time to be the sum of the delays $\boldsymbol{d}$ encountered by each nodes with $\boldsymbol{N}$ the number of nodes in the network. The bound of equation **(2)** is $0 \leq \boldsymbol{F} \leq 1$. The $\boldsymbol{F}$ value approaches 1 when the average delay of devices is close. Therefore, a large value of $\boldsymbol{F}$ implies that each device obtains the GTS bandwidth more fairly, and much probably, starvation will not occur. We made the assumption to simplify our analysis model in a star topology:

1. Only voice traffic over GTS is considered
2. All GTS transmissions are successful
3. For each cycle at least the half of nodes in t he network request GTS allocation

We performed the analysis on three different multihop star networks with the number of nodes equal to 6, 9 and 11. Each network was considered with 10 cycles. Requesting nodes are set randomly and according to the priority equation **(1)**, we allocated GTS to the node having the highest priority. Other nodes that did not get the GTS are delayed and their average waiting time of the nodes concerned were used to determine the overall fairness in the network which was 0.58, 0.62 and 0.72 for the star topology of 6, 9 and 11 nodes respectively. With the same analysis approach on the conventional FCFS scheme, the fairness value relatively dropped. As plotted on Fig.3 the fairness of the proposed scheme exceeded not only one half but also advanced the conventional FCFS scheme; more over it is increasing slightly with the increase of nodes in the network. This result validates the goal of our proposal which needs further investigation in a network simulation environment.

5. CONCLUSION

In this paper, we present a GTS allocation scheme to support voice traffic based on priority value without changing the frame format of IEEE.802.15.4 standard, with the goal of achieving efficient and fair allocation to nodes in a multihop networks. The formulas to evaluate the priority are derived in function of three factors which include the intermediate hop count ratio, request feedback and the waiting delay of nodes. Numerical analysis showed that the proposed scheme can improve effective fairness in GTS allocation and enhance bandwidth utilization. In addition, we proposed the algorithm for the deployment of the implementation. Our work needs simulation to validate the proposed scheme.

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