GTS Scheduling Scheme for Real-Time Communication in IEEE802.15.4 Industrial Wireless Sensor Networks

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Abstract

Background/Objectives: We have proposed an improved algorithm for the delay sensitive networks with bulk periodic data traffic. This kind of networks such as Industrial networks that should transfer the monitoring data has a high sensitivity to delay since these networks should work real-time. **Methods/Statistical Analysis:** Considering and studying the industrial network traffic model, a new adaptive centralized GTS scheduling algorithm is proposed focusing on real-time communication and reliability which are two important issues in industrial wireless communication. **Findings:** Wireless Sensor Network (WSN) is selected for implementing the industrial network. Industrial Wireless Sensor Network (IWSN) and IEEE802.15.4 standard is the most popular standard for WSN MAC layer protocol. In this paper considering the industrial network data types new GTS scheduling scheme for IEEE802.15.4 is introduced for the delay sensitive networks with bulk periodic data traffic. **Applications/Improvements:** Our proposed algorithm by adapting the characteristics of industrial networks and IEEE802.15.4 standard shows high gain in delay improvement.

Keywords: GTS Scheduling, Industrial Wireless Sensor Network (IWSN), IEEE802.15.4, Real-Time Communication

1. Introduction

Nowadays, wireless technologies might be of advantage in industrial environments. The IEEE802.15.4 standard[1] was finalized in October 2003 and specifies the characteristics of the physical layer and the MAC layer of a radio network stack. It is adopted as a communication standard for Low-Rate Wireless Local Area Networks (LR-WPANs). To achieve this standard such as low cost, low power, two-way wireless communication solution, it meets the unique requirements of sensors and control devices. Because of popular usage of this standard and its good specifications, investigations are made to use this standard for industrial applications which have more sensitivity in delay and reliability than ordinary networks. IEEE802.15.4 standard is week in real time and reliable communication[2,3].

IEEE802.15.4 has two non-beacon and beacon-enabled modes in the MAC. In the non-beacon mode all

the nodes can send the data using Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) at any time but in the beacon-enabled mode there is a coordinator which broadcasts the beacon to the ordinary nodes. In the beacon-enabled mode there is a coordinator which broadcasts the beacon to the ordinary nodes. The duration between two respective beacons is called Beacon Interval (BI) and contains the active region in which data transmissions are allowed (super frame) and the inactive region in which no data transmission would occur. The inactive region is mainly used for sleeping of the nodes for energy saving and longer life time of the nodes. IEEE 802.15.4 protocol also provides real-time guarantees by using Guaranteed-Time Slot (GTS) mechanism in beacon-enabled mode.

In this mode, as it is shown in Figure 1, each super frame is divided to sixteen equal time slots containing only up to seven GTSs. Each node can allocate up to two GTSs (one for receive and one for transmit), and one
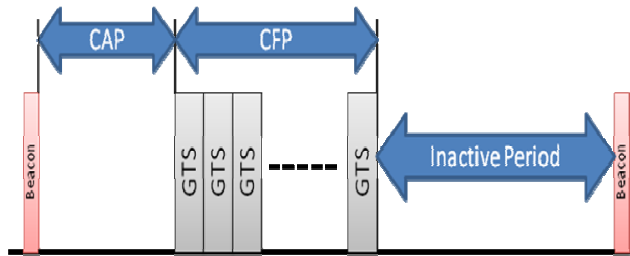
Figure 1. Beacon interval and superframe structure.

GTS may have more than one slot. The GTSs forming the Contention-Free Period (CFP) and the remaining time slots compose the Contention Access Period (CAP).

In this research we are going to add new features to this standard with some modification in order to improve real-time communication for industrial applications.

From an allocation point of view, the concept of a GTS allocation is similar to a Time Division Multiple Access (TDMA) time slot allocation. A reserved amount of bandwidth is periodically granted for a given data flow. The amount of bandwidth is determined by the duration of the time slot and its periodicity. However, the IEEE 802.15.4 GTS mechanism is more flexible than a classic TDMA since the GTS duration may be dynamically adjusted by setting adequately the parameters of the IEEE 802.15.4 super frame, whereas a TDMA time slot duration is, in general, fixed for a given network configuration.

Many researches for investigating the standard and evaluating and improving its performance has been performed[4,5]. In general, IEEE 802.15.4 allocates GTS on a First Come First Serve (FCFS) basis. But it has problems such as bandwidth wastage, no delay tolerance and moderate throughput[6]. In[7,8] proposed implicit GTS allocation mechanism, henceforth referred to as iGAME algorithm. It can support higher bandwidth utilization and can allow the sharing of GTS among many devices. However, iGAME cannot guarantee a GTS slot if the delay guarantee is less than beacon interval. Also, the authors have assumed that the flow characteristics of all the devices are provided prior to scheduling itself. The GTS requests are transmitted in the CAP period itself. However, if the number of GTS requesting devices increases tremendously, then the chances that a device transmits its GTS request in the CAP is much less. This form of starvation is not addressed by iGAME.

The performance of the explicit GTS allocation in IEEE 802.15.4 has been evaluated[9]. That work proposes a delay bound analysis of an explicit GTS allocation. It also analyzes the impact of the beacon and super frame orders on the throughput, delay and power efficiency of a GTS allocation. It works under two constraints. First of all, the number of nodes requesting the GTS must be higher than seven and secondly the deadline associated with each GTS message is smaller than the beacon interval.

In[10,11] have addressed multi cycle polling scheduling in field bus networks. These papers have contributed to the schedule ability analysis of a set of periodic tasks with deadlines equal to periods under Rate Monotonic (RM) and Earliest Deadline First (EDF) scheduling policies, where the nodes polled are different from one cycle to another. In both approaches, the idea consists in finding the minimum cycle, called primary cycle, which corresponds to the greatest common divisor of all task periods, and computing the number of time slots needed to transmit periodic traffic inside each cycle, if the task set is schedulable. The last step consists in executing tasks according to their priorities (using RM or EDF) in each primary cycle. In[12] proposed a new GTS scheme which utilizes the CFP more efficiently than the standard scheme by dividing the CFP into 16 equally sized sub slots. With smaller slots, CFP utilization in the new scheme is better than that in the standard scheme. In[13] proposed a dynamic GTS (D-GTS) allocation algorithm to reduce wasted bandwidth. To reduce the wasted part of GTS allocation, they proposed to allocate a D-GTS in the back off period unit rather than a super frame slot unit.

Recently, Pervasive usage of wireless technology leads to working on reliability and real-time communication which can be mentioned as wireless weakness against wired communication for reliable and delay sensitive communication. In[14] used a network coding mechanism for transmitting data which enhances the reliability of the network. Furthermore, reducing the number of transmissions and receptions in network nodes results in the reduction of energy consumption. This method has been proposed for optimizing the parameters of reliability and energy consumption in multimedia WSNs. However this method is investigated in multimedia applications which have high traffic. In industrial network the data size is not voluminous.

In this paper, considering the situation of industrial network traffic pattern, an algorithm for scheduling of GTS slots to the nodes is presented in order to reduce delay.

2. Proposed Algorithm

Industrial network duty is to transfer the monitoring and control data between the sensors and actuators and the control room as a commander. Since this research is working on the industrial network, studying the specifications and the data types in this network can help for better modifications in order to have better performance.

Real-time and reliable communication is vital in industrial networks because the data is important how ever since the data is not massive (for example monitoring data and alarms are usually small packets) the bit rate is not as important as the real-time and reliability.

Two main data categories can be defined in industrial network. The first data type is the monitoring data. The sensors will send the data to the commander (Monitoring room) and the monitoring data will be analyzed in the central control room (Logging and profiling the data, analyzing the condition) and in the situation which a change in the plant is needed, the control room (commander) should send a command or control message to an actuator.

Another type is alarm data. In this approach the sensor only will send the packet (alarm packet) when its data has get upper or lower than a pre-defined value.

This two categories work in different manner and their traffic has complete different profile. In the monitoring data, mostly the sensors will send their data in a periodic manner which means they will send their measured quantity in a constant intervals but at the other side the alarms do not have a specified time and in any time an alarm can be arisen.

The majority of the traffic in an industrial network is the monitoring part because of the number of monitoring sensors and their traffic profile which produce constant data. (A monitoring sensor can also produce an alarm but for simplicity we consider the separated nodes for monitoring and alarm. It will not make any problem in our analysis because it is possible that the source of 2or more traffic be just one node in practice. We consider separated nodes for separated traffic just for simplicity). Since the bulk traffic is due to monitoring data which has periodic manner, managing this part is in our focus.

In industrial applications, it is important that the data received correctly and as soon as possible in the monitoring room. According to this specification of the industrial networks and simplicity, in this paper, transmission of this kind of data is in spotlight. Data packets are acknowledged and IEEE802.15.4 supports retransmission as reliability factors but in industry applications reliability with real-time transmission is meaningful. Ignoring retransmissions and assuming that in CFP period the packets will receive to their destination errorless, the coordinator node should manage the GTS slots, in such a way that all constrains about the sensors' data would match. Knowing that getting a GTS slot needs to send a successful request packet to the coordinator and the request should be sent during the CAP period, shows that the GTS just can be dedicated in the beacon Interval next to the first CAP region which the request is sent successfully (if the coordinator has an empty GTS slot to allocate). It will be concluded that with this algorithm the data will be delayed at least one beacon interval. This algorithm is suitable as a general method because the coordinator is not aware about the time when data of a node is generated so the node should request for a GTS slot when it has data. As described before in industrial applications, monitoring data is produced periodically so the time of production of the next data can be calculated accurately. Using this feature we propose a new method that the nodes that has periodic data do not follow the standard protocol and with a little change which is completely easy to implement, get a better result which means reduce the delay of the nodes' data.

For formulating the problem, T_i shows the intervals between producing the data of node i. As a reliability parameter D_i is considered maximum acceptable delay for ith node. If the node i expresses these two parameters to the coordinator, it can calculate the time of future generated data of that node.

$$\text{Kth data production time} = KT_i + T_{o1} \qquad (1)$$

Where T_{o1} is the beginning offset time from the t = 0 for node i. For having more flexibility in reducing the energy consumption by minimum duty cycle, the super frame order and the beacon order will adaptively choose which is possible in the standard. BI_j represents the jth beacon order and SD represents the super frame duration. According to the above parameters the nth super frame duration is:

$$\sum_{j=0}^{n-1} BI_j < \text{nth sup erframe} < \sum_{j=0}^{n-1} BI_j + SD_n \qquad (2)$$

$$BI_j = \text{Base sup er frame Duration} * 2^{B0_j}$$

$$SD_n = Base\ super\ frame\ Duration * 2^{SO_n}$$

As the inactive period will force some limitations on real-time transmission, in this paper we discard this opportunity of IEEE802.15.4 which is mainly used for energy saving in ordinary wireless sensor networks so the sensors' data can be sent more quickly. For neglecting the inactive period BO=SO.

As the beacon mode of IEEE 802.15.4 is slotted first the time should be considered in a discrete manner. So every time quantity should map to the beginning of the next slot. This new discrete parameters can be calculated using the Expression (3). represent ceiling function in this formula.

$$T_j^* = \sum_{i=0}^{n-1} BI_i + \left\lceil \frac{T_j - \sum_{i=0}^{n-1} BI_i}{\frac{BI_n}{16}} \right\rceil * \frac{BI_n}{16} \quad (3)$$

Where T_j is the time in continuous manner and T_j^* is its mapped time to the beginning of the next slot. We will define discretion delay as the difference between these two parameters.

$$Discretion\ Delay = T_j^* - T_j = \left(\sum_{i=0}^{n-1} BI_i + \left\lceil \frac{T_j - \sum_{i=0}^{n-1} BI_i}{\frac{BI_n}{16}} \right\rceil * \frac{BI_n}{16} \right) - T_j \quad (4)$$

According to the IEEE 802.15.4 standard at least the first nine slots should dedicated to the CAP and in this paper for reliability and analytical purposes the periodic data is going to be transmitted in CFP period. In each beacon, based on the number of data, the coordinator dedicates the slots from the end of super frame. This may force extra delay for the data. So in this paper we assumed that in each beacon the coordinator dedicate all 7 GTS slots so the first CFP data can be sent in 10'th slot. The Figure 2 shows a template of each super frame in our method in this paper.
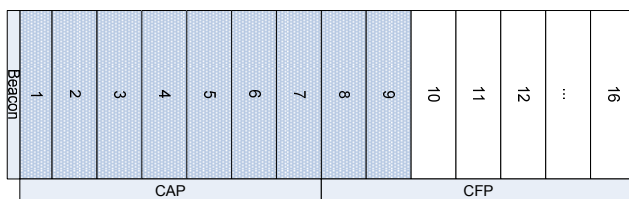

Figure 2. Template of each superframe in our algorithm.

Reminding that the coordinator knows the time of data generation of each node, it can predict the situation of further super frames. First for the simplicity, consider the situation of scheduling a super frame which contains just one data. At this simplified situation two conditions may occur.

1. T_j^* is in the CAP region.
   As shown in Figure 3 the red slot is the actual time and the green slot is the scheduled time
2. The T_j^* is in the CFP region.

Figure 4 shows the case that the data is generated in slot 11 which can be directly n the CFP. Now the following expression can calculate the scheduling delay forced to this packet because of the standard limitation.

$$Scheduling\ Delay = \max\left\{ T_j^*, \sum_{i=0}^{n-1} BI_i + \frac{BI_n}{2} \right\} - T_j^* + (T_j^* - T_j) \quad (5)$$

In a real situation which more than one data can exist for transmitting in the nth beacon, GTS slots will schedule in the FCFS manner according to the time of the data generation but this procedure is just for the same priority data which means that the first CFP will dedicate to the first data generated. This simple procedure will be performed just if the next data matches its tolerable delay in the case it will be sent in the second GTS, otherwise the data with less tolerable will schedule first. The tolerable delay will show the priority of the data and in the same
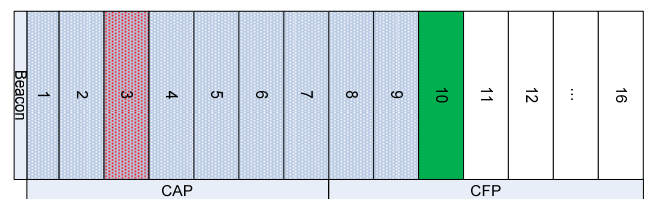

Figure 3. Simple scenario with single data in superframe generating in CAP region.
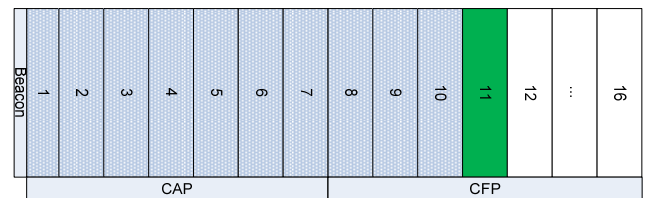

Figure 4. Simple scenario with single data in superframe generating in CFP region.

condition the data with higher priority should schedule first. Figure 5 is showing a graphical example for 3 data slots.

Consider the set T as below

$$T = \left\{ T_{(j,1)^*}, T_{(k,2)^*} T_{(l,3)^*}, \ldots \right\}, T_{j,1}^* \quad \text{is discrete time of}$$

transmission of node j which is the first data in the n'th BI and $T_{k,2}^*$ shows that the second data in nth BI dedicated to node k.

So the total delay for $T_{j,m}^*$ can be calculated in the following expression. (mth data in nth super frame).

$$\text{Total Delay} = \max \left\{ T_{j,m}^*, \sum_{i=0}^{n-1} BI_i + \frac{BI_n}{2} \right\}$$

$$-T_{j,m}^* + \frac{(m-1)BI_n}{16} \frac{1 - \text{sign}\left(T_{j,m}^* - \sum_{i=0}^{n-1} BI_i \right)}{2} \quad (6)$$

If the number of data which should be sent in the nth beacon becomes greater than 7, the additional data will be in the queue for the next super frame. For the data which will be kept in the queue the total delay can be calculated

$$\text{Total Delay} = \sum_{i=0}^{n+\left[\frac{m}{7}\right]-1} BI_i + \left(m - 7 * \left[\frac{m}{7}\right] - 1 \right) \frac{BI_n}{16} \quad (7)$$

Since the coordinator is going to decide about each BI and SD at the beginning of each beacon interval in a way that maximize the performance considering the delay constraint of the nodes' data, it calculates the sum of total delay for the data of all nodes that have data in that super frame. Also it calculates if extending the super frame by increasing the SO and BO will cause any node data that cannot match its tolerable delay. (Because the number of GTS slots in each super frame is fixed, extending its length will possibly increase the number of data in that super frame and queue delay will play more important role in the total delay expression).

Figure 6 shows a scenario which extending the super frame duration, can lead to lower delay. For clarity, just one data is shown in the Figure. If data production time is in the slots 1 to 8 of the second super frame in (a), it can be scheduled quicker in the extended super frame (b). The green slots show the first possible GTS slot for that data in each case.

Consider Total Delay$_{1,k}$ The sum of total delay of all data in the super frame with SO=K of node i. The Cost$_{so=k}$ is the sum of the total delay of all nodes for SO=K. (SO=0~14).

$$\text{Cost}_{so=k} = \sum_{i=1}^{\text{No. of Nodes}} \text{TotalDelay}_{i,k} \quad (8)$$

Consuming that the coordinator is a node with higher processing power and can calculate the costs all along the previous super frame, this procedure can be easily performed by coordinator. In the case the process unit is limited, the calculations for SO=1~3 have acceptable result.

3. Simulation and the Results

According to the introduced adaptive scheme for selecting Bo and SO parameters of the standard, coordinator can calculate the total delay of each data by the theoretical expressions derived. It will repeat this calculations for BO=1 to 3. And will select the best BO with lowest cost in the case the tolerable delay of all nodes match.
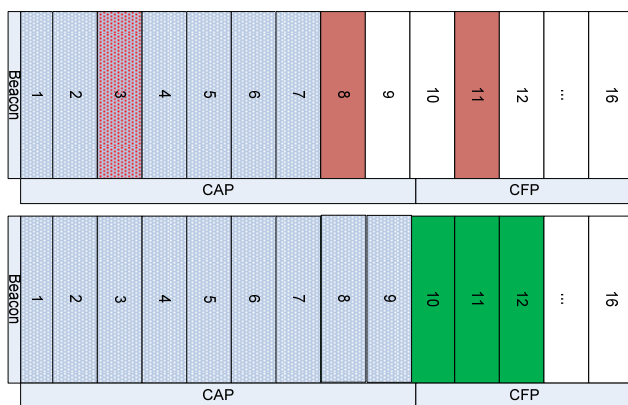
Figure 5. Scheduling of GTSs in a superframe with more than one data.

(a)

(b)
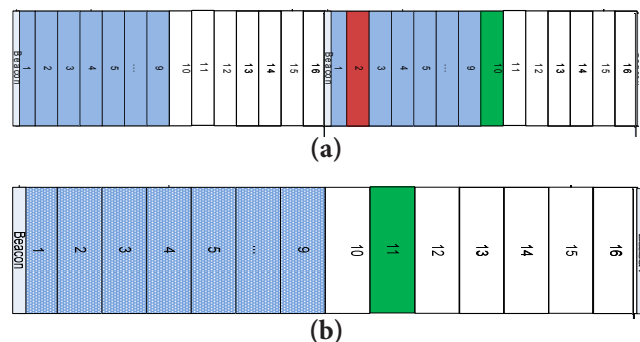
Figure 6. Comparison total delay of a data in two different BO and SO selection. **(a)** Considering two successive superframe with BO=SO=0. **(b)** Consider one superframe with Bo=SO=1.

We have used MATLAB for simulation and comparison of our proposed algorithm with the standard. For generality and better comparison the start time and data interval of each node is chosen randomly during each simulation[15]. For precise comparison, the same random data will use for both the standard and our algorithm so the result is not dependant to the initial random data. We have chosen the data interval greater than the base super frame duration so every node can produce at most only one data in every super frame. This limitation is because of the reliability of the network and prevention of instability. Otherwise having nodes with no limit traffic generation can lead the network to a congested situation. We have assumed that the data packets are small size and can be sent during just one slot. It is an acceptable assumption because in industrial network which we focus on that as a delay sensitive network the data is just monitoring data so the packet size is small.

Here are the assumptions in a brief.

- Consider periodic data generation traffic.
- Random start time for each node.
- Random data interval for each node.
- Packet size is small and can be sent during one slot.
- Base super frame Duration=15.36ms.
- BO=SO. Because the delay is so important in industrial network the inactive region is omitted.

The simulation has generated 500 data for each node and runs for 1000000 beacon interval so all the packets can be sent.

In this paper the delay definition is the time difference between the time the data is generated and the time the data is sent successfully. For better depiction of the effectiveness of the proposed algorithm the average delay improvement can be defined by the following formula.

$$\text{Average delay improvment} = \frac{\sum_{i=1}^{N} s\tan dard\ Average\ delay_i - Im\ proved\ Average\ I}{N} \quad (9)$$

Where,

N is the total number of nodes in the network, standard Average delay$_1$ is the average delay that node i have using the standard and Improved Average Delay$_1$ is the average delay that node i have using the our improved algorithm.

For investigating the effect of number of nodes on the average delay, the simulation has been run for different number of nodes and the results has been depicted in the Figure 7.
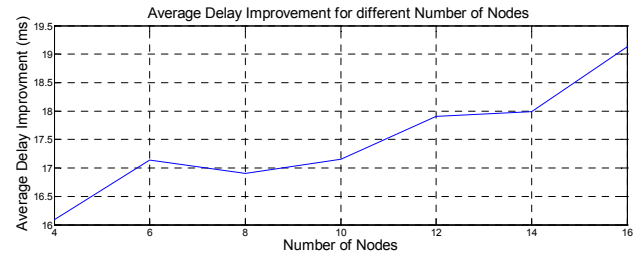

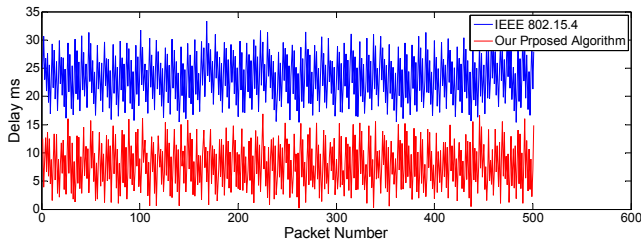**Figure 7.** Average delay improvement via number of nodes.

As shown in Figure 7, the improvement grows as the number of nodes grows. Growing the number of nodes will increase the network traffic. The number of nodes should be limited so the network does not get congested. In a congested network the queues of all nodes will grow as the time passes so the network will get unstable.

Figure 7 completely shows real effectiveness of our algorithm in the improving the delay. For better depiction of the algorithm effect, Figure 8 and Figure 9 illustrate the delay and delay improvement of a sample node in a network with 4 nodes. 4 node network is selected since it has the lowest average delay improvement and as the number of nodes grow the average delay improvement will grow too. The reason of this improvement is that in the network with more nodes, the traffic will grow and the scheduling algorithm and adaptive SO selection algorithm can demonstrate its role more obvious.

Our proposed algorithm focuses on the periodic data but our algorithm will have a positive effect on the delay of alarms and the data packets which their generation time is not specified too. Considering that this kind of traffic is transmitted in the CAP region, using the proposed algorithm will omit the GTS request packets which according to the standard will send in CAP region. These requests are a bulk traffic for this region and by its omission the traffic in this region decreases considerably. The Delay in this region is also related to the network traffic in this region so, for showing this fact another simulation has been done using MATLAB to simulate the effect of the network via the traffic in the CAP region.

Figure 10 depicts the average delay for the packets that are sending in CAP region via the mean rate of generating the traffic in the nodes.
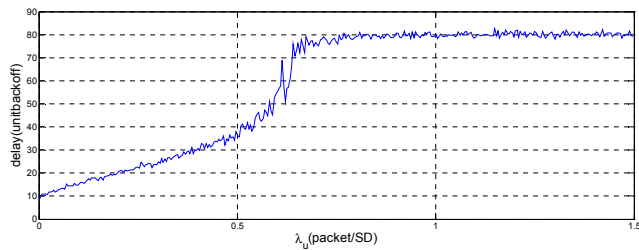
λ_u shows the mean rate of packet generation of each node in each superframe. So as the λ_u increases the traffic of a node in each superframe increases and therefore the

Figure 8. Delay of each packet (ms) in standard and our proposed algorithm.
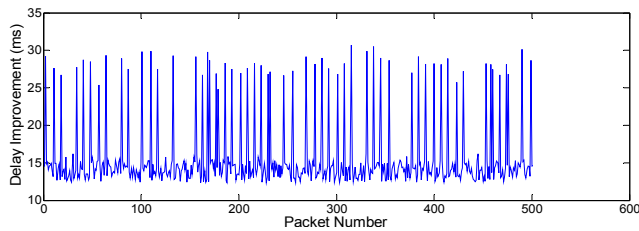
Figure 9. Delay improvement of each packet (ms).

Figure 10. Average delay in transmission in CAP region via the rate of generation of packets in nodes in each super frame.

traffic of the network will increase and it can be seen that for the λ_u above the 0.7 the network is getting saturated.

According to Figure 10 reducing the traffic in CAP region can lead to considerable average delay reduction, and in our improved algorithm with omission of the GTS request packets of the nodes that should be sent in CAP region, the traffic of CAP has reduced considerably and this will decrease the delay of the packets which should be send in this region.

4. Conclusion

We have proposed an improved algorithm for the delay sensitive networks with bulk periodic data traffic. This kind of networks such as industrial networks that should transfer the monitoring data has a high sensitivity to delay since these networks should work real-time. With studying the IEEE 802.15.4 standard structure and the characteristics of the industrial networks, the GTS request for all periodic data packets are omitted and the coordinator can calculate each node data time. Also an adaptive SO parameter selection is introduced which coordinator will select the best SO for corresponding super frame which leads to best performance.

The results show that our proposed algorithm without forcing a big change to standard (really easy to implement) and just by adapting to the characteristics of industrial networks has a high gain in delay improvement. The gain is related to the traffic so it is related to the data interval of the nodes and also the number of nodes producing periodic data. Also it is shown that omission of the bulk traffic of GTS request in CAP region results in considerable reduction of traffic in CAP region and it reduces the delay of data transmission in CAP region.

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