Smart GTS Allocation Algorithm for Industrial Wireless Sensor Networks Emergency Messages Transmission

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Abstract: This paper presents the research on application of wireless sensor networks (WSNs) in wind power generation system and highlights an important issue associated with the deadline for the delivery of messages among nodes based on IEEE 802.15.4E standard. Due to the limits of standard and the power system application requirements, this research proposes a smart GTS (S-GTS) allocation algorithm which is based on Urgent/Important Matrix. This proposed algorithm promotes the utilization of CFP in a superframe, which can reach 94.64%. And over seven GTSs can be allocated in a superframe, there are only seven GTSs can be used in the standard. Additionally, this paper proves the value of BO and SO upper bound is 6 for the WSN application in power system. Moreover, when BO = SO =2, the network delay of S-GTS is 13.44ms, which perform better than 16-time-slot mechanism (58.08ms) and i-GAME mechanism (61.44 ms).

1 Introduction

Wireless Sensor Networks (WSNs) technology have been applied broadly in many places, and offer certain advantages over conventional networks, such as low power wireless communication, low power micro-controllers and sensors. In industrial applications, WSNs have been used as a substitute for the traditional industrial wired communication systems, for example in process automation or monitoring and control since they offer the easier installation, removability and lower maintenance cost [1]. Because the wireless sensor nodes can be installed the inside of rotatable device, and acquire more accurate vibration data and other operation performance parameters. These parameters can offer more reliable and accurate monitoring results.

However, different applications require the different network delay; for example, the data transmission delay range is from 20ms to 100ms for voltage and current data transmission in the power system. Although, the Beacon-enabled mode is defined by IEEE 802.15.4E standard which can be used for real time transmission. Additionally, the real time packet exchange is in the Guaranteed Time Slots (GTSs) of active superframe. However, the standard only permits the content of GTS information in four consecutive beacon frames. Even though there are up to seven GTSs are allocated in the Contention Free Period (CFP) of one superframe. Therefore, the maximum real time packet transmission is constrained by the maximum number of the GTS [2]. These shortcomings limit the IEEE 802.15.4E standard network application. Especially, the industrial WSN application, there are massive nodes are placed in a monitored objective, and the considerable number of periodic real time packets need to be transmitted. So the standard GTS allocation has to be modified for meeting the industrial application requirements [3].

This paper is organized as follows. Firstly, in section 2 the IEEE 802.15.4E standard is reviewed; the relevant GTS allocation researched is discussed in section 3; the process parameters measurement requirements for wind turbine is mentioned in section 4; the S-GTS allocation mechanism is proposed in section 5; the urgent & important matrix for S-GTS priority is discussed in section 6; the evaluation and analysis are given in section 7; finally, the conclusion in section 8.

2 Overview of IEEE 802.15.4E standard

2.1 Data transmission model

There are three data transmission transactions in IEEE 802.15.4E standard namely, device data transfer to coordinator, the coordinator data transfer to the device, and the data transmitted between two peer devices. Only two transactions apply to the star topology, because the data exchange is regulated between the coordinator and the device. However, all three transactions are applied in the peer to peer topology, because data exchange can be occurred in any two nodes in the network [2]. In beacon-enabled communication network, when the end node needs to deliver packet to a coordinator, it has to obtain the beacon, and synchronize to the super-frame structure. So the data is delivered from the end device to the coordinator in the appropriate time slot. When a coordinator wants to transmit packet to an end node, and then this end device receives the beacon. If the message is pending, the end node would send a medium access control (MAC) command request. The coordinator ensures to receive the data request, and then the acknowledgment-frame and the pending-message frame would be transmitted in the next procedure.

2.2 Superframe Structure

The following terms and parameters can be referred to the IEEE 802.15.4E standard [2]. The superframe can be used for peer to peer communication in the low-rate wireless personal area (LR-WPAN). Superframe transmission duration is formed by active/inactive portion. In order to save the power energy, the coordinator and the devices would be sleeping in the inactive portion period until the end of super-frame duration. The active portion can be classified by three periods: a beacon, a contention access period (CAP) and a CFP. The active portion can also be divided into 16 equally spaced slots of duration time slots; and the length of time slot and the parameter for time slot of CAP are setup by the coordinator. The super-frame structure is shown in the following figure 1:

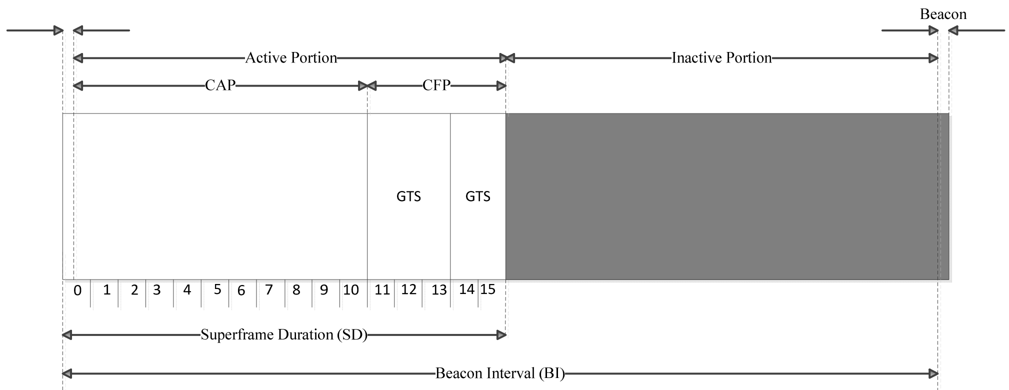

Figure 1: The Super-frame Structure [2]

The personal area network (PAN) coordinator sends the beacon periodically in the Beacon Interval (BI). And the beacon is the beginning of each Super-frame which is sent by the PAN coordinator. Moreover, this beacon includes the super-frame duration and the allocated information for this period. Once the devices obtained the beacon of the super-frame, they would do the allocated mission until the end of super-frame duration. The values of macBeaconOrder (BO) and macSuperframeOrder (SO) are used to define the structure of super-frame. And the MAC PAN Information Base (PIB) attribute macBeaconOrder defines the interval at which coordinator should transfer its beacon frames. And macSuperframeOrder defines the length of the active portion of the superframe which includes the beacon frame. Therefore, the beacon interval (BI), the superframe duration (SD) and Slot can be calculated based on the values of aBaseSuperframeDuration, aBaseSlotDuration, macSuperframeOrder and macBeaconOrder according to equation (1), (2) and (3):

$$BI = aBaseSuperframeDuration * 2^{macBeaconOrder} \quad (1)$$

$$SD = aBaseSuperframeDuration * 2^{macSuperframeOrder} \quad (2)$$

$$\text{Slot}=\text{aBaseSlotDuration}*2^{\text{macSuperframeOrder}} \quad (3)$$

In above formulas, the macBeaconOrder should be in the range of $0 \leqq \text{macBeaconOrder} \leqq 14$ range. If macBeaconOrder=15, the coordinator would ignore the request from devices. The value of macSuperframeOrder would be ignored too. So the following inequation can be obtained:

$$0 \leqq \text{macSuperframeOrder} \leqq \text{macBeaconOrder} \leqq 14$$

When macBeaconOrder=0, it means constant aBaseSuperframeDuration=960symbols which is the shortest length of superframe; and aBaseSlotDuration=60symbols which is the minimum time slot. If macSuperframeOrder=15, the superframe should be in inactive portion after the beacon. So PAN Coordinator has to satisfy the inequation $0 \leqq \text{macSuperframeOrder} \leqq \text{macBeaconOrder} \leqq 14$, when the superframe is used.IfmacBeaconOrder=macSuperframeOrder =15 is setup, the superframe is not applied, and the unslotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism is based on the CAP which is used to access the channel [4].

The length of aBaseSuperframeDuration is equal to 960 symbols which in defined in IEEE 802.15.4E standard. In 2.4 GHz frequency band, each symbol represents 4 bits. In this paper, 2.4 GHz frequency band is used, because it is most popular band. The length of superframe duration can be obtained from 15.36ms to 251.66s, when SO and BO are equal to 0 and to 14. It is easy to find out the length of time slot increases exponentially with SO. If the packet size is constant, the waste of bandwidth will be increased with the SO increment. According to the IEEE 802.15.4E standard, one allocated GTS is able to transmit more than one frame. Additionally, when the SO is increased by one, the TS (Time Slot) Duration is incremented double. For a given SO, only a little part duration of time slot is used for data frame transmission. Because the utilization of the GTS is based on the maximum burst size and the arrival of data frames.

When the SO =10, the duration of the time slot is nearly equal to 1 second, which may consistent to transmit up to a bulk of 208 aMaxPHYPacketSize (1016 bits) bit-long unacknowledged frames (about 211kbits) with a long inter frame space (IFS) [2]. However, the node device hardware is constrained, therefore, it is impossible to expect that the sensor node can generate 211 kbits data in one second. For instance, an end node has to send traffic with a maximum burst size of 32 kbits, and an average arrival rate of 10 kbps, which can't produce more than 42 kbits per second. So the bandwidth utilization cannot exceed 42 kbps. Although, Multi-channel Superframe algorithm can be applied for inter-cluster communication, and the different channels are used in the communication among the coordinators [5]. However, in this research, the same channel is applied among the coordinators communication.

3 Relevant Researches in GTS Allocation

The GTSs are only allocated in CFP with First Come First Serve (FCFS) algorithm which is described by IEEE 802.15.4E standard. Additionally, the active portion of superframe is separated into 16 slots of equal duration. However, the CFP is limited in the remaining time slots following the CAP and up to the end of the active portion of the superframe. And there are at most seven allocated GTSs for PAN coordinator, although a GTS can be formed by more than one slot. However, when all the slots are used, the other nodes will not access to GTS slots. This issue is called as starvation problem [6]. Therefore, the IEEE standard also brings some limitations, such as inefficiency in energy consumption, bandwidth under-utilization, high latency, high packet loss rate, unfairness in GTS allocation.

Previously, some standard improvements have been made by some researchers. A revised GTS allocation scheme has been proposed by Cheng et al. [7]; CFP is separated into 16 equally sized time slots. And this new scheme is enable to offer more frames within the CFP in superframe duration, and better than in the standard scheme. However, the time slot duration is increased with the incremented Superframe Order (SO) has not been considered in paper [7]. J. Song and colleagues proposed a dynamic GTS allocation scheme for improving GTS utilization, such as, allocates a dynamic GTS in the backoff period unit. The disadvantage is that the standard frame format needs to be changed [8]. Y. Huang and colleagues proposed an AGA allocation scheme (Adaptive GTS), low latency and fairness are considered in this scheme, which includes device classification phase and GTS scheduling phase. And a last GTS usage feedback is used for the priority assignment in a dynamic fashion. During the GTS scheduling period, GTSs resources are used adequately by each device based on their priorities. The experiments proved that the proposed AGA scheme performs better than the standard scheme in wait time and fairness. However, during the GTS scheduling period, the GTSs are given to each device in a non-decreasing order of their priorities [9]. Anis Koubaa and colleagues have proposed i-GAME scheme for bandwidth utilization improvement. In this mechanism, a GTS can be shared by different nodes. Additionally, the traditional round robin approach is used for scheduling, and it is fairer to share the given bandwidth for each node. However, the message scheduling is not considered in this paper [10].Chewoo Na and colleagues put forward an online optimal GTS scheduling, however, GSA only adjusts the schedules of GTSs, and the BO and SO adjustments are not considered in GSA [11].Nam-Tuan Le et al. proposed Unbalanced GTS allocation Scheme (UGAS), this method promotes the bandwidth utilization efficiency based on the mini-time slot. However, this paper also focuses on the time slots scheduling [12].Seong-eunYoo et al. put forward a distance-constrained real time offline message scheduling algorithm for periodic real time messages scheduling in CFP. Meanwhile, superframe is defined by generating standard specific parameters. However, this is not online scheduling [3].Most of previous researches focus on improving the utilization of GTSs, and only Lee et al. mentioned emergency data transmission [13]. This paper concentrates on combination of GTSs allocation schedule and the real-time message schedule for emergency message in CFP.

4 Process Parameters Measurement Requirements for Wind Turbine

In wind power generation systems for the wind turbine conditional monitoring purposes, so many process parameters have to be measured, such as acceleration, velocity, displacement, current, and voltage, and so on [14].The technique of acceleration measurement can illustrate the vital information for wind turbine condition monitoring.

Table 1: Measurement requirements for different value [15]

Quantity	Base Unit	Accuracy	Bandwidth	Sensitivity	Range	Signal Type
Acceleration	m/s^2	5%	0-20Hz	$2v/g^2$	+/-2g	Analogue, pulse, Data
Vibration	m/s	5%	3-20kHz	100mv/g	+/-2g	Analogue
Revolution per minute (RPM)	RPM/Hz	1%	3Hz RR^2	--	0-3000 RPM	Pulse
Shaft position	degree	5%	3Hz RR^3	--	0-360 degree	Analogue, pulse, Data

(Note: Gravitational Constant g=9.81 m/s2, Refreshing Rate (RR), the allowable refreshing rate minimum 3 values of the RPM per second.)

For the acceleration measurement, the acceleration parameters of vibration have to be collected for wind turbine tower and nacelle, and so on. The acceleration sensor or accelerometers are popular for the oscillation, velocity and displacement measurement. To evaluate and predict the condition of bearing and gearbox in rotated condition, vibration measurement is the most effective method. And shaft revolution per minute (RPM) measurement can offer the shaft speed and information about some of the characteristic values related to condition monitoring of bearing and gears. Additionally, the absolute position measurement of the shaft is important for specialized algorithms of spectral analysis. The requirements of condition monitoring and fault identification are shown in table1 [15].

5 Proposed Schedule

5.1 Motivation

In wind farm data transmission, the transmission time is the delay for transferring a process value from sending node to receiving node, there are three intervals are defined in the IEC 61400-25 standard:

T_a: the time duration is the sending node transfer the process value,

T_b: the time duration for the network message transmission,

T_c: the time duration is the receiving node for the value process logic.

The interval T_b is based on the network structure and is not related to an attribute of the hardware device. For a node transmission testing, only output and input latencies can be obtained in these three interval time. T_a and T_c are obtained from the measured latencies, therefore, the output and input latency can be obtained with equation (4) and (5) respectively [16]:

$$\text{Output latency} = \text{estimated input processing time} + \text{estimated } T_a \quad (4)$$

$$\text{Input latency} = \text{estimated output processing time} + \text{estimated } T_b \quad (5)$$

The total required data transmission time in WSN can be illustrated in figure 2, which shows function f_1 of sending node send the message to the function f_2 of the sink node. And the T_a, T_c and T_{total} can be obtained by the formulas (10), (7) and (11) respectively.

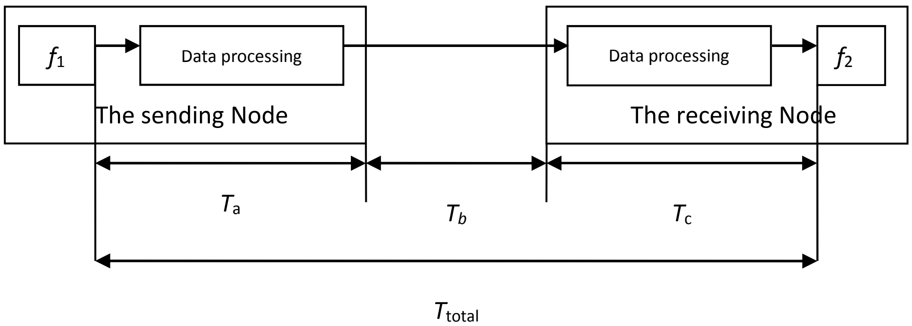

Figure 2: Message Total Transmission Time

The sink node receives data from different end nodes (from 1 to N), and these data will form a data flow. Due to the capacity of the sink node and the network performance requirements, the queue overflow condition is not allowed for each end node and the sink node. And the M/M/1 queue is used to describe the message processing in the devices, like Figure 3 shows.

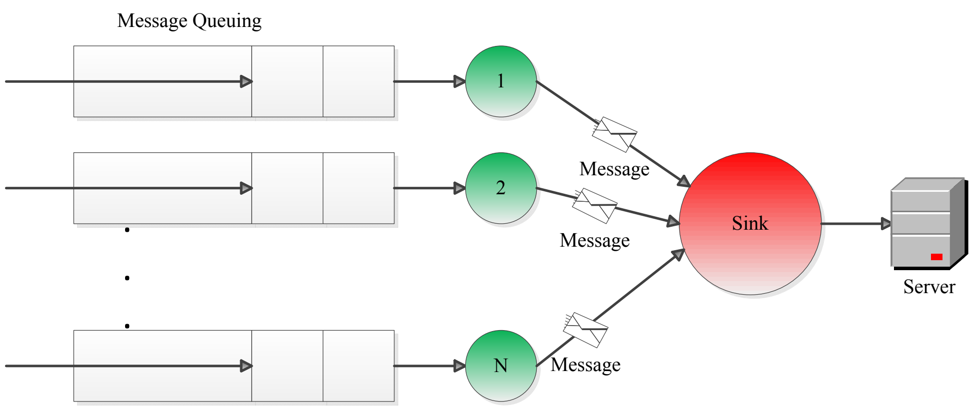

Figure 3: Message Queuing Model

The first M of M/M/1 queue represents the arrivals are determined by a Poisson process, the second M represents job service times have an exponential distribution, 1 represents one CPU of the device. The data arrival rate is λ which is equal to the data generation rate, μ_2 is the service rate of the sink node; N_2 is the buffer size of the sink node. According to the queuing theory, the state probability of system P_f can be obtained in the steady-state [17]:

$$P_f(N_2;N) = \frac{\rho_2^{N_2}(1-\rho_2)}{1-\rho_2^{N+1}}(\rho_2 \neq 1) \qquad (6)$$

And then $\rho_2 = \dfrac{\lambda}{\mu_2}$ is named by utilization factor of sink. According to equation (6) and Little's formula, the buffer time of the sink T_c can be obtained:

$$T_c = \frac{\rho_2^{N_2+1}(N_2\rho_2 - N_2 - 1) + \rho_2}{\lambda(1-\rho_2^{N_2})(1-\rho_2)} \qquad (7)$$

And probability of sink in the idle state is π_0 :

$$\pi_0 = 1 - \rho_2 \qquad (8)$$

The end node service rate is μ_1, the real service rate is μ_{1r} :

$$\mu_{1r} = \pi_0 \mu_1 = (1-\rho_2)\mu_1 \qquad (9)$$

The buffer time of the end node T_a can be obtained:

$$T_a = \frac{\rho_{1r}^{N_1+1}(N_1\rho_{1r} - N_1 - 1) + \rho_{1r}}{\lambda(1-\rho_{1r}^{N_1+1})(1-\rho_{1r})} \qquad (10)$$

And then $\rho_{1r} = \dfrac{\lambda}{\mu_{1r}}$ is named by utilization factor of end node, N_1 is size of the end node buffer.

Therefore, the message transmission total time can be:

$$T_{Total} = T_a + T_b + T_c \qquad (11)$$

The total data transmission delay should be less than the required transmission delay in the power system application, Table 2 lists examples of the voltage and the current data transmission allowed delay in different classes for power system [18]. Based on above research, it is easy to find out the IEEE 802.15.4E can't meet the data transmission requirement of power system, if without any modification.

Table2: Data Transmission Time Limitation in Power System [18]

Data Type	Required Rank	Time(ms)
Voltage	P1	100.0
Current	P1	100.0
Voltage	P2	20.0
Current	P2	20.0
Voltage	P3	20.0
Current	P3	20.0

And this paper concentrates on the emergency GTS allocation research, in order to satisfy the delay requirement of the various emergency packet flows, especially the WSN data transmission delay can meet the IEC61850 standard requirements in power system and more than seven end nodes can use GTS in a superframe.

5.2 Smart GTS Mechanism

Based on the above research, it is easy to find out that the smaller time slot of CFP can offer the more efficient bandwidth utilization and the smaller SO and BO value offer the low delay. In order to offer the low delay in the emergency message transmission, this paper assumes that the value of SO and BO are low, such as BO=SO=0, 1 or 2. When BO and SO are equal to 0, the inactive portion of the superframe can be eliminated. Additionally, in order to ensure coordinators can receive others' beacons and have their active periods overlapped with each other, the value of the BO should be larger enough than the SO value. The reason is that the value of BO and SO effect on the number of coordinators and the length of aBaseSuperframeDuration. When the BO= SO+1, the active period duration would be half of the Beacon Interval duration and then one BI can have two active periods in maximum [11]. Hyeopgeon Lee et al. have used the EDG (Emergency Data Slot) for emergency data transmission in cluster tree WSNs. However, guaranteed bandwidth of the EDG is assumed enough bandwidth for the emergency data, and the different data arrival rates are not considered [14]. Xiaoying Lei et al. proposed a GTS allocation for emergency data transmission; however, they just considered the low-rate WPAN (Wireless Person Area Network) condition [19]. Yuemin Ding et al. proposed a new traffic scheduling algorithm which focuses on time-critical industrial periodic message and decides the values of network and node parameters for GTS. However, the emergency data transmission condition is not considered [20]. Naoki Hayashi et al. present the consensus problems and consider a branch-and-bound GTS scheduling algorithm for non-preemptive communication tasks under the modified IEEE 802.15.4E standard [21].

In this paper, a new GTS mechanism is proposed for emergency messages communication in order to meet wireless sensor network applications requirements in power system. A beacon-enabled mode and cluster-tree topology is assumed for proposed network operation. This proposed S-GTS allocation algorithm focuses on the emergency message communication efficiency and the network delay, especially, more than seven nodes can use GTS for the real time data transmission at the same time and the deadline of each emergency message matches the power system requirements. Moreover, this mechanism is compatible with IEEE 802.15.4E communication standard.

In order to accomplish these objectives, the standard time slot has to be changed according to the message flow length. Firstly, the CFP is divided into a few smaller time slots, these new time slots form some blocks which are based on the number of S-GTS request. These new time blocks are classified by two type blocks, one is emergency block for the emergency message, and another one is non-emergency block for normal GTS message. Based on the message flow length, each block delivers message in sequence which is formed the sensor order, such as Emergency Message GTS (EM-GTS) for sensor 1 until sensor N. And each sensor node uses the new time slot for data transmission. During all blocks for one superframe, the same sensor order will be repeated in the following block until the data has been transmitted completely. In the emergency block, the sensor order depends on the message priority.

5.3 Emergency Message GTS Request

In this paper, this proposed mechanism uses Emergency Message GTS for the emergency message transmission. The GTS Characteristics field has added two fields based on the reserved space. The following figure 4 is illustrated for the EM-GTS Request format and the GTS Length field [2]. The proposed S-GTSs use the reserved 6^{th} and 7^{th} bit in the GTS characteristics frame; these two bits represent Emergency Type and Priority respectively, which are embedded into the S-GTS allocation request. When end nodes have to send emergency message to the PAN Coordinator, the emergency type would be set 1 in the GTS request frame. And then the EM-GTS Request is sent to the coordinator first. This EM-GTS Request includes the MHR (MAC header), the Command Frame Identifier and the GTS Characteristics.

Octets: 7	1	1
MHR Fields	Command Frame Identifier	GTS Characteristics

Bits: 0-3	4	5	6	7
GTS Length	GTS Direction	Characteristics Tpye	Emergency Type	Priority

Figure 4: Modified GTS characteristics field Format

The proposed GTS Characteristics field includes the following parts:

1. The GTS Length field includes the number of superframe slots which is needed for S-GTS allocation.

2. The GTS Direction field should be 1 for the receive-only GTS; in contrast to, 0 is for the transmit-only GTS.

3. The Characteristics Type field value is 1 means that the Characteristics refer to a GTS allocation; or the Characteristics Type field value is 0 means that the Characteristics refer to a GTS deallocation.

4. The Emergency Type field should be set to 1 if the emergency message transmission, or 0 if the general GTS data transmission.

5. The Priority field should be set to 1 if the most important emergency message transmission, or 0 if the general emergency message transmission.

5.4 Mini-Time-Slot for Emergency Message GTS

In order to meet the power system requirements, SO is equal to BO with the low value, such as SO=BO=0, 1 or 2. When the CFP and the number of GTS are confirmed, the data transmission delay will be confirmed too. And the mini-time-slot length can be ensured by formula (12):

$$D_{mTS} = D_{message} + D_{IFS} \qquad (12)$$

$D_{message}$ is the length duration for the message transmission, D_{IFS} is the duration required by one node after delivering or receiving a message. And only D_{mTS} is based on the message stream parameters, which do not vary with any other parameters. The mini-time-slot allocation mechanism is shown in the following code. Therefore, the minimal CAP length (440 symbols) is reserved, and the length of the CFP is maximizing. According to the value of the CFP length duration (D_{CFP}), the number of the mini-time-slot can be obtained by formula (13):

$$N_{mTS} = \left\lceil \frac{D_{CFP}}{D_{mTS}} \right\rceil \tag{13}$$

Mini-Time-Slot Allocation Mechanism

```
if the device using standard IEEE 802.15.4E then
    GTS slot size = Superframe Duration /16
else
    GTS slot size = D_mTS = D_message + D_IFS
end if
Calculate data transmission duration in GTS
if device using proposed IEEE 802.15.4E then
    if number_of_GTS_slotsrequired <number_of_remained_slot then
        reserved = 01
        request GTS according to proposed GTS slot size
    else
        reserved = 02
        request GTS according to standard GTS slot size
    end if
else
    request GTS according to standard GTS slot size
end if
```

5.5 Block Allocation

Message transmission of nodes is arranged into the blocks, which include *n* delivery opportunities for the sensors. The number of the blocks (N_{Block}) can be described as a function of D_{CFP} and T is the packet stream periodicity:

$$N_{Block} = \left\lfloor \frac{D_{CFP}}{T} \right\rfloor \qquad (14)$$

The first Block 1 starts at the first mini-time-slot that starts just after CAP. In order to reduce the delay for the emergency message transmission, this paper defines the Block1 as the emergency Block (red B1 as figure 5 shown), which can transmit emergency message for several end nodes. If the emergency message hasn't been transmitted completely in the Block1, the subsequent Block will be used to ensure the emergency message can been sent completely. If one superframe hasn't transmitted the emergency message completely; the subsequent superframe would transmit this emergency message, and ensure the emergency message has been transmitted completely. The following figure 5 illustrates the structure of the Emergency Message GTS in one CFP.

When any end node needs to send emergency message to coordinator, the EM-GTS request will be sent out by end nodes. The EM-GTS will be allocated immediately following the CAP; which is shown in the Figure 5. If more than one node sends EM-GTS request, the Coordinator allocates up to the entire CFP slot for the Emergency Message transmission. Additionally, EM-GTS is allowed to occupy more than one slot period, each EM-GTS request will be given an order value based on its Priority.

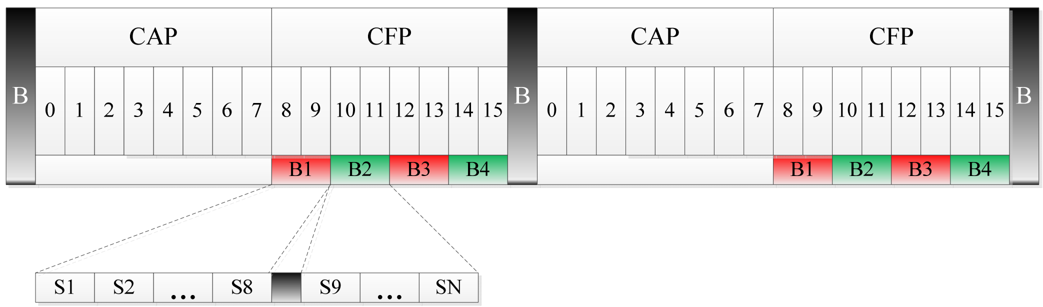

Figure 5：Emergency Message Allocation

The Emergency Message GTS allocation process can be described by the following steps:

1. A sensor node needs to send emergency message to a Cluster Head node, and the EM-GTS request will be sent by sensor node.
2. The Cluster Head checks the EM-GTS request frame format, if the Emergency Type field and the Priority field are both 1, the EM-GTS1 period will be allocated; if the Emergency Type field is 1 and the Priority field is 0, the EM-GTS2 period will be allocated, which is just after the EM-GTS1. If the Emergency Type field is 0 and the Priority field is 1, and the general GTS1 will be allocated which is after the EM-GTS; if Emergency Type and Priority field are both 0, this GTS will be allocated after GTS1 and named by GTS2.
3. And then the Cluster Head sends the same EM-GTS request to the PAN Coordinator.

6 The Urgent & Important Matrix for Priority

In this paper, if a CFP period of superframe is regard as personal time table, great time management means managing time slot effectively and achieving the specific Industrial Wireless Sensor Network application requirements. In order to reduce the stress of having too many tight deadlines, the important activities and the urgent activities should be distinguished [22]:

Important activities: it means an outcome causes the accomplishment of aims.

Urgent activities: it requires instant concentration, and is always connected with the accomplishment of someone else's aims.

The Urgent/Important Matrix is a powerful solution which is popular for priorities thinking, and it can help people to overcome the natural tendency to focus on urgent activities, and concentrate on the really important activities.

6.1 Urgent/Important Matrix

The Urgent/Important Matrix can be illustrated in figure 6, with the Importance's dimension and Urgency's dimension:

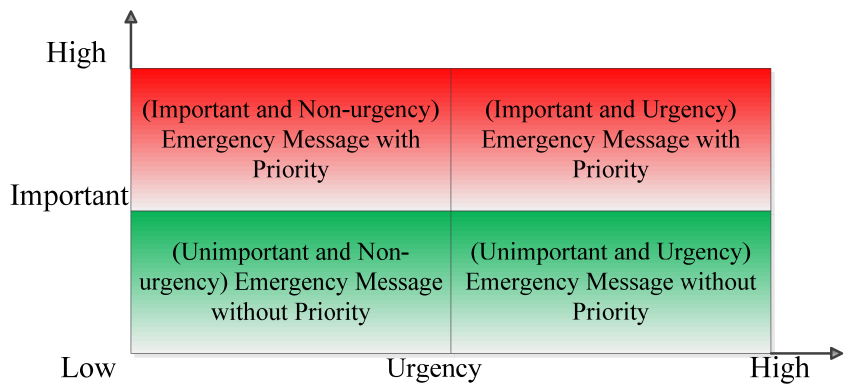

Figure 6: Urgent/Important Matrix

The following steps help Sink Node to utilize the matrix to rank message:

1. Firstly, based on the EM-GTS Request, each message has to be confirmed and arranged in the right part of the Urgent/Important Matrix.
2. Secondly, to assign Emergency/Importance to each message. This is a measure of how important the message is in the queue of sink node which is in order to meet system requirements and objectives.
3. Sink node allocates the Time Block for each end node which is based on the message value. If EM-GTS Request of one end node includes the Emergency Type value 1 and the Priority value 1, the Block1 with the low order number mini-time-slot will be allocated for this end node (as the

figure5 shown). If EM-GTS Request of one end node just includes Emergency Type value 1 and the Priority value is 0, the Block1 with the higher order mini-time-slot number will be allocated. If EM-GTS Request just includes priority value 1 and the Emergency Type value is 0, the Block2 will be allocated with the low order number mini-time-slot which is just after the Block1. If GTS Request of one end node includes Emergency Type value 0 and the Priority value 0, the Block2 with the higher order mini-time-slot will be allocated.

4. When emergency message can't be transmitted completely in the Block1, the following Block will be allocated for emergency message transmission until all emergency messages has been transmitted completely.

7 Evaluation and Analysis

In this section, an application case is referred to evaluate the proposed mechanism; the final results are compared with, L. Cheng's 16 mini-time-slots and A. Koubaa's i-GAME [6, 9]. Based on this application case, the data size and data rate can be confirmed. And each message packet includes the data obtained from 3-axis sensors (90 bits) packed into 12 bytes (16bit waste) [23]. The sensors are placed in the monitored components, as the figure 7 shown. The red circles represent sensors which are installed on the main components of Wind Turbine for data collection, after that, the collected data will be sent to the a server via a gateway.

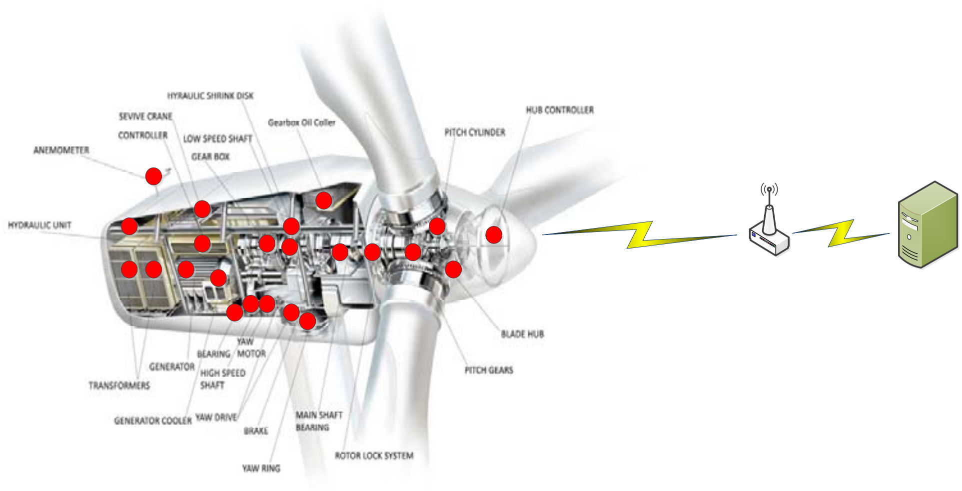

Figure 7: The WSNs Monitoring sub-system

In this paper, supposing the 3-axis sensor can collect three different operation parameters which include the vibration, temperature and the rotating speed of the monitored device. Additionally, IEEE 802.15.4E standard requires the Physical Layer header size and MAC Layer header size are 6bytes and 5bytes, respectively. Therefore, the total length of each message for transmission is 23 bytes. Additionally, based on the length of each message and the minimum short interframe spacing (SIFS) period, 29 bytes data has to be transmitted for each node in a data periodicity. The other message size is changed based on SO value, and several acquisition results are encapsulated into the same frame and the data rate can reach 250kbps in all schemes [24]. This proposed algorithm just considered the cluster tree topology network, as the figure 8 shown.

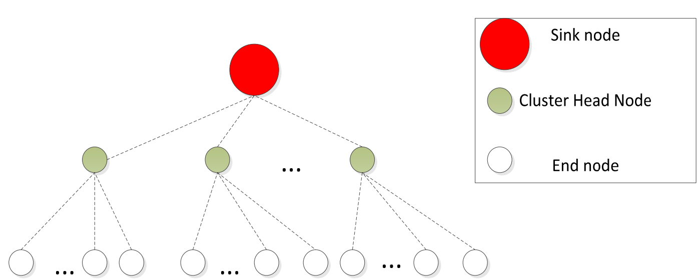

Figure 8: Network Topology

Based on power system data transmission requirements, the BO and SO value are restricted between zero and six. In order to meet the 20ms delay requirement in power system, BO=SO=2 is given, therefore, the scale of network is limited. Just as [25] provides the number of coordinators calculation formula, therefore, there is only one coordinator in this network. And each time slot is 3.84ms for CFP. This paper sets that CAP length is 2 time slots and the remained 14 time slots are equal to 53.76 ms for CFP duration. Assuming that there are fifteen end devices, they send the GTS request to coordinator, and eight devices need to use GTS for emergency message transmission (from Sensor 7 to Sensor 14, as figure 10 shown), and these eight end nodes use emergency message block for emergency message transmission in S-GTSs mechanism. In the following sections, S denotes sensor order, and B denotes Beacon, and the supposed condition will be evaluated in the different algorithms and the results will be compared.

7.1 i-GAME allocation Mechanism

When BO=SO=2, it is easy to find out that each node message is transmitted during the standard time slot and 3.84ms each time slot corresponding to 16 time slots. There are fourteen time slots for CFP period allocation. Each sensor node data is allocated by i-GAME mechanism in each time slot as shown in figure 9:

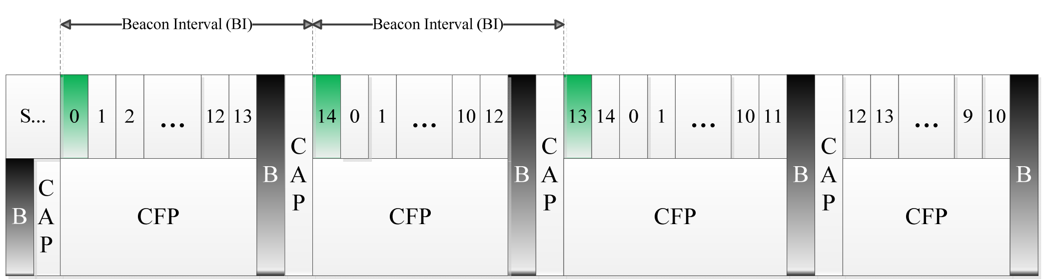

Figure 9: i-GAME allocation Mechanism

In this case, there are fourteen time slots which are 120 bytes bandwidth are used, each packet size is 29 bytes. Therefore, the CFP bandwidth utilization is 91.49%. And each end device data transmission delay is 65.28 ms.

7.2 16-mini-time-slot mechanism

The L. Cheng's 16-mini-time-slot is similar to the IEEE802.15.4 standard. However, the CFP's time slots are always separated into 16 small time slots, as the Figure 10 shows:

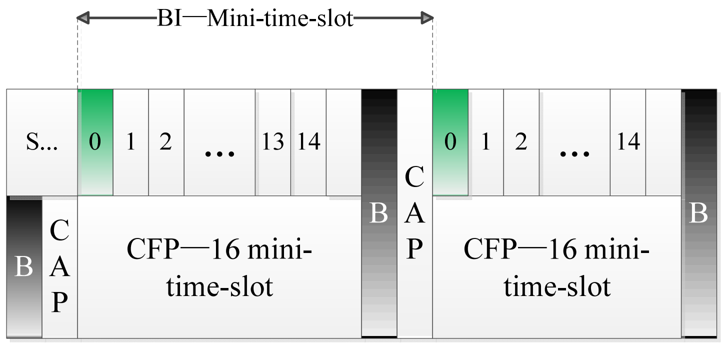

Figure 10: 16-mini-time-slot mechanism

The 16-mini-time-slot mechanism, When BO=SO=2, 14 standard time slots are separated into 16 smaller time slots. Each mini-time-slot is 3.36ms, and the CFP bandwidth utilization is 38.1%, and the data transmission delay for each node is BI minus one mini-time-slot that is equal to 58.08ms.

7.3 Smart GTS (S-GTS) allocation

In smart GTS (S-GTS) allocation scheme, when BO=SO=2 and each time slot is 3.84ms for 16 time slots. This paper sets that CAP length is 2 time slots and the remained 14 time slots are equal to 53.76 ms which divided as 56 mini-time-slots for the CFP division. Each mini-time-slot length is 60 symbols (fit for the IEEE standard requirement). In this allocation mechanism, the CAP length is set to a constant value (480 symbols). Because when CAP length value is 480 symbols, the CFP can be divided and represented with an integer for the number of the minimal time slot (60 symbols). And these mini-time-slots are organized into the continuous blocks, and each block is formed by mini-time-slots, each block length based on the number of the same type message. The figure 11 illustrates the S-GTS allocation. The Emergency Block No.1 will be used for the prioritized emergency message. Based on the length of each message and the minimum SIFS period, there will be 29 bytes data has to be transmitted for each node in a data periodicity. Each mini-time-slot can send 30 bytes message, so that there is an 8 bits gap between two messages.

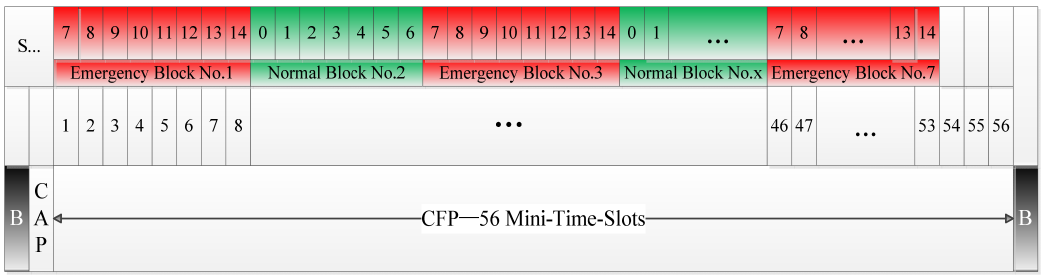

Figure 11: Smart GTS (S-GTS) allocation

In each superframe, the red block is used for emergency message transmission, and the green block is used for the non-emergency message transmission. If the message can't be transmitted completely in a superframe, the allocated blocks can be used circularly until the CFP resource has been run out. There are only three mini-time-slots (54, 55 and 56) are free for this case. These three free mini-time-slots can be reserved for the joined new end node. The utilization of each standard time slot is 96.67%, and the CFP bandwidth utilization is 94.64%. The delay for each node is between 11.52ms and 13.44ms, which meets the highest power system data transmission delay requirements.

7.4 CFP Bandwidth Utilization

There are two main advantages for S-GTS mechanism, such as the capability of dividing time slot divided into mini-time-slot and giving the priority for nodes emergency message transmission. Based on above results, the utilization of the CFP can be expressed:

$$U_{CFP} = \frac{T_{Data\_transmission}}{T_{CFP}} \qquad (15)$$

$T_{data\_transmission}$ is the time period needed for all messages delivery in CFP period. With the value of SO is increased, the CFP duration is increased as well. And the time slot of i-GAME and 16-mini-time-slots are increased, except the time slot of S-GTS maintains a constant. Based on the emergency message transmission scenario assumption, therefore, the utilization of CFP can be obtained, which can be illustrated by the figure 12.

In figure 12, it is easy to find out that the utilization of CFP is very efficient in the S-GTS mechanism; the utilization can maintains around 95%. The utilization of CFP is reduced with the increment SO in 16-time-slot mechanism and i-GAME mechanism. And the S-GTS mechanism performance is better than i-GAME mechanism and 16-time-slot mechanism in this case.

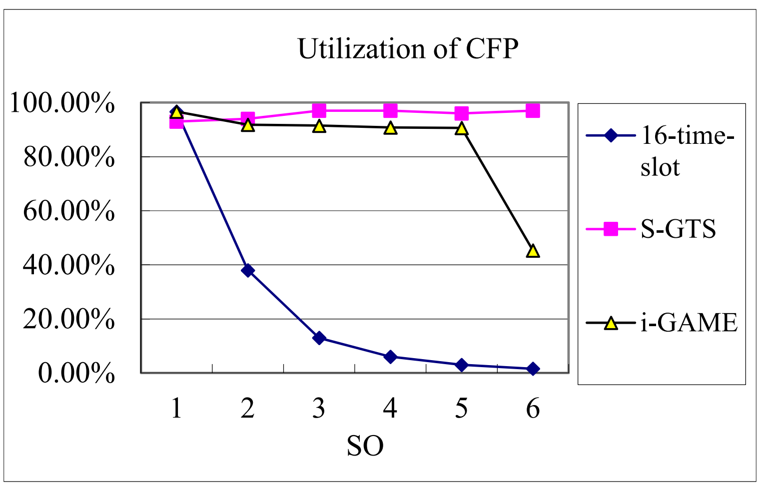

Figure 12: Utilization of CFP

7.5 Data Transmission Delay

In the S-GTS mechanism, the delay bound mainly based on the CAP duration and the block messages length. Based on the emergency message transmission scenario assumption, when SO is equal to 2, the delay of S-GTS is 13.44ms which performs better than 16-time-slot (58.08ms) and i-GAME (65.28 ms). With the value of SO is increased, the CFP duration and the time slot is increased as well. Therefore, when the data size of emergency message is given, the bandwidth of CFP will be occupied a fixed bandwidth. However, when the CFP duration is increased, the CFP bandwidth will be wasted. The following figure 13 shows a comparison of delay bounds for S-GTS, 16-time-slot and i-GAME when SO value is increased. However, the maximum value of SO is 6, which based on power system data transmission delay requirement is not over 100ms.

It is noticed that in figure 13, when SO value is less than 6, the S-GTS delay bound is quite stable. The reason is that S-GTS bandwidth can be used efficiently; moreover, the delay is mostly related to the duration of the CFP. In comparison, in i-GAME and 16-time-slot schemes, the delay bounds are increased exponentially with SO, because these delay based on the duration of the time slot. Based on above comparison, there is a comprehensive summary can be made by the following table3.

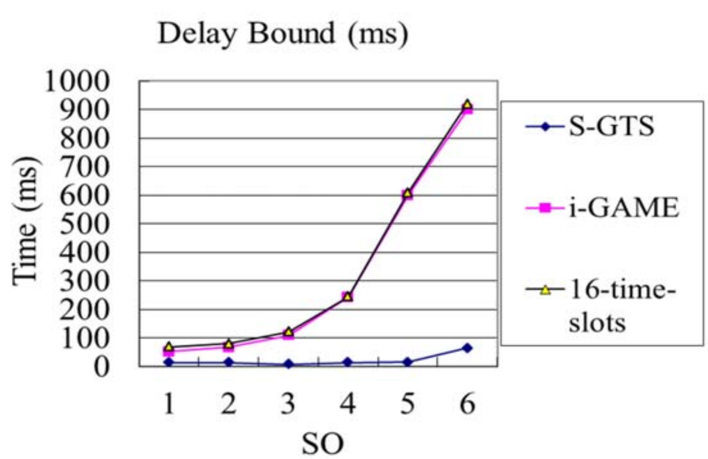

Figure13: Delay Bound

Table 3: The Main Advantages Comparison for Three Algorithms

	CFP Usage	Emergency Message Transmission Delay (SO=BO=2)	aBaseSlotDuration
S-GTS	CFP usage maintains reasonably constant with SO.	13.44ms	It maintains a constant 60 symbols with SO, which is equal to IEEE standard definition.
i-GAME	CFP usage decrease about half from SO=5 to SO=6.	65.28 ms	The time slot duration is always changing, when SO value is changed.
16-mini-time-slots	CFP usage decreases continuously with SO.	58.08ms	When SO=BO=0, the mini-time-slot will less IEEE standard definition.

8 Conclusion

In this paper, the S-GTS mechanism is proposed. The proposed mechanism has been tested, based on the result analysis the following can be concluded: 1) It is able to reduce the delay of the communication by utilizing maximized CFP in a beacon enable network. 2) The redefined mini-time-slots are based on the application requirements and the minimal standard time slot requirement, which can optimize the CFP bandwidth utilization and eliminate one time slot which is utilized by one device. 3) The utilization of CFP and the delay bound comparisons have been made, and the S-GTS mechanism performs better than other popular scheduling mechanisms for IEEE 802.15.4E standard. The S-GTS mechanism is able to meet the requirements of WSN application in power system. Additionally, this mechanism can offer more than seven devices to use GTS during one superframe.

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