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Guaranteed time slot trade-off in QOS improvement with IEEE standard 802.15.4 for wireless sensor networks at the MAC layer

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Abstract

The performance of wireless sensor networks (WSNs) with IEEE standard 802.15.4 at different types of devices can be improved with the appropriate utilization of guaranteed time slots (GTSs) in superframe at the media access control (MAC) layer. GTS implementation at the MAC layer enhances quality of service (QoS) by providing guarantee for delivery in time to the data collected at real time by the reduced functional device (RFD) from the surroundings to be transmitted to the fully functional device (FFD). Results prove that trade-off has to be done in implementing GTSs for various network performance parameters like queue size, queuing delay, CSMA medium access delay, CSMA transmission failures, and network output load to improve QoS.

Keywords

Wireless sensor network (WSN), Guaranteed time slot (GTS), IEEE 802.15.4, Superframe, Fully functional device (FFD), Reduced functional device (RFD).

IEEE standard 802.15.4 due to its flexible features such as low data rate, low power consumption, and low cost makes it most suitable for WSNs (Koubaa et al., 2007). Furthermore, ZigBee protocol (ZigBee Specifications ■) based upon the physical and MAC layers of IEEE standard 802.15.4 completes the protocol stack for building low rate-wireless personal area networks (LR-WPANS). Physical layer of IEEE standard 802.15.4 because of its low data rate, low power consumption, and robustness is suitable for most of the WSN applications. Additionally, the MAC layer with its feature of Superframe makes 802.15.4 even more suited for WSN applications. The Superframe structure is possible only with the use/implementation of beacons as it is the time interval between two successive beacons. If the beacons are not used in WPAN, then GTSs cannot be implemented and guarantee of service (GoS) cannot be provided to the real-time data. The mechanism of allocating the time slots in advance from the superframe to the real-time data sensed by the sensor nodes (SNs) is called GTS mechanism.

The IEEE 802.15.4 protocol because of its suitability to WSNs has made several researchers to work on this protocol (Jurcik et al., 2007; Koubaa et al., 2005a, 2005b, 2006a, 2006b, 2006c, 2006d; Koubaa, Alves, Attia and Nieuwenhuyse, 2006; Koubaa, Alves, Nefzi and Song, 2006, 2007; ZigBee Specifications ■; IEEE 802.15.4 OPNET Simulation Model ■; Cunha et al., 2007; Huang et al., 2006; Chen et al., 2008; Li et al., 2008; Hameed et al., 2008; Lee, 2006; Zhang et al., 2008; Tao et al., 2006; Zen et al., 2008; Lee, 2005; Jurick and Koubaa, 2007; Gholamzadeh and Nabovati, 2008). Most of these research works are on evaluation or performance improvement of one or other characteristic of 802.15.4 standard. Jurcik et al. (2007) have evaluated the performance of IEEE standard 802.15.4 for GTS feature and have also highlighted its applicability. Koubaa et al. (2007) have explained the suitability of 802.15.4 in terms of power efficiency, GTSs, and scalability for WSNs. Koubaa et al. (2006c) have evaluated the performance of 802.15.4 for real-time applications using GTSs. Koubaa, Alves, Attia and Nieuwenhuyse (2006) have synchronized ZigBee cluster-tree network by proposing collision-free beacon frame scheduling algorithms. Koubaa et al. (2006a) evaluated the performance of slotted CSMA/CA in the case of broadcast transmissions. Koubaa et al. (2006b) have proposed alternates for GTS as a function of delays. Chen et al. (2008) have developed an accurate analytical model using the Markov chain model for evaluating CSMA/CA in IEEE 802.15.4. Li et al. (2008) have enhanced reliability of 802.15.4 by reducing the packets dropped. Hameed et al. (2008), Lee (2005, 2006), Zhang et al. (2008), Tao et al. (2006), Zen et al. (2008) have researched on analysis, investigations, and performance evaluation of 802.15.4. Koubaa, Alves, Nefzi and Song (2006) have evaluated different parameters of 802.15.4 on the basis of queuing strategies: FIFO and priority queuing. Koubaa et al. (2006d) have modeled a cluster-shaped WSN to guarantee minimum service to each and every node in the network. Koubaa et al. (2005a) have characterized IEEE 802.15.4 standard with respect to its suitability for WSNs. Gholamzadeh and Nabovati (2008) have proposed techniques that reduces the power consumption by WSNs.

This paper has analyzed the GTS mechanism in 802.15.4 standard for conversion into WSN from WPAN. For this, three different networks with the same configurations are developed: a network in which all the nodes have the GTS feature, the network in which none of the nodes have the GTS feature, and finally, a network in which half of the nodes have the GTS feature and remaining half do not have this feature. Finally, the performance of these networks is analyzed at PAN coordinator – fully functional device (FFD), and end device – reduced functional device (RFD).

In this paper, the first section surveys and details the prominent research works on 802.15.4 standard. The second section describes the system setup. The third section compares and analyzes the performance metrics at FFD and RFD in three different networks with the same configurations. Finally, the fourth section gives the conclusions on this paper.

System setup

Three different networks of standard – IEEE 802.15.4 are developed, i.e. With GTS – in which all the nodes have the GTS feature, without GTS – in which none of the nodes have the GTS feature and can handle non-GTS traffic only, and mixed – in which half of the nodes have GTS feature and remaining half are without GTS feature as shown below in Figure 1. Each network has one FFD (PAN coordinator), one analyzer, and 20 RFDs (end devices). These networks except the GTS feature are the same in all respects. IEEE 802.15.4 provides the GTS feature on the basis of superframe as explained below.

Structure – superframe

Superframe is the calculation of time interval between the two successive beacon frames, in which one indicates the beginning and the other marks the end of the superframe. Beacon frames are generated by the PAN coordinator after fixed intervals of time to advertise its personal area network and to synchronize all the nodes attached to it. Now, the time interval between two successive beacon frames constitutes Beacon interval (BI) which comprises of an active period and, optional, inactive period as depicted in Figure 2.

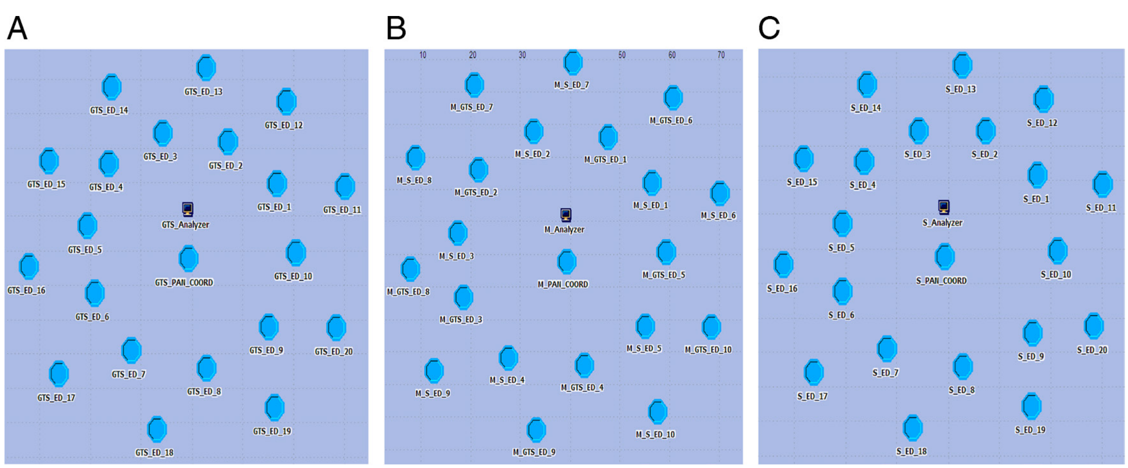

Figure 1: Networks – (A) With GTS, (B) mixed, (C) without GTS.

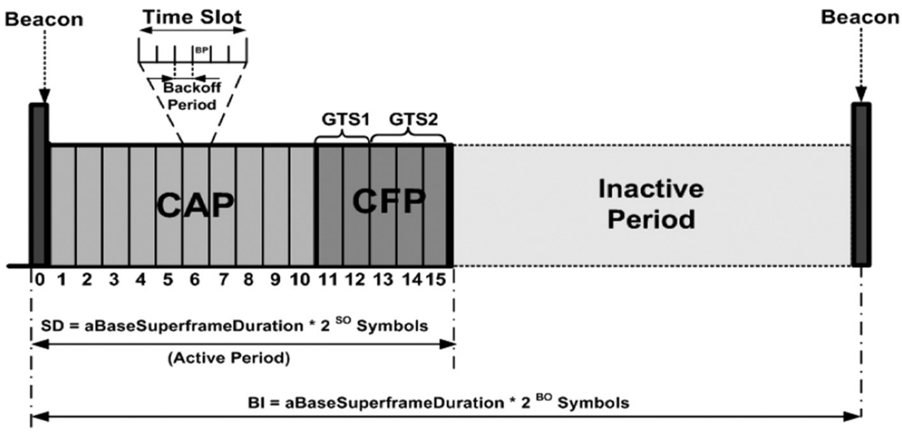

Figure 2: Superframe structure (Koubaa et al., 2007).

From the working of superframe, it can be concluded that if the GTS-enabled data are to be trafficked along with the non-GTS data, then the contention-free period (CFP) occupies at least one time slot (channel) and maximum of seven time slots in the CFP portion as follows:

$$0 < CFP \leqslant 7 \,\&\, CAP = 14 - CFP. \tag{1}$$

If only non-GTS data are to be trafficked, then:

$$CFP = 0 \,\&\, 0 < CAP \leqslant 14. \tag{2}$$

From (1), it is concluded that whenever GTS data are to be trafficked, specific numbers of time slots (sub-channels/bandwidth) are reserved for a specific period of time. During this time period, these time slots can only be used by the specific GTS data for which these are reserved or will remain idle if that data have finished being trafficked or is not being trafficked for one or the other reason. These time slots are released only after that specific data trafficking has finished. Therefore, no access mechanism works during this period, but only guarantee of service is provided at the cost of major resource bandwidth and the performance parameters like throughput, utilization, channel business, etc.

From (2), it can be concluded that if all 14 time slots (sub-channels) of superframe are accessed using CSMA/CA, i.e. without the use of GTS feature, then none of the time slots (sub-channel) will remains idle. Once it has finished trafficking data from one RFD, it can be immediately accessed by some other RFD using CSMA/CA mechanism.

From (1) and (2), we conclude that in 802.15.4, channel(s) can be reserved forehand to guarantee services to a particular application which constitutes GTS mechanism and is the core of WSNs but only by compromising its performance in terms of throughput, utilization, etc. As the slots are reserved in advance for the data fetched from the surroundings to be transmitted, this leads to the wastage of overall resources by reserving them in advance and then keeping them idle till the data arrives, just to provide the GoS to the data to be trafficked. Whole of this process reduces the overall throughput, utilization, etc., as the resources like channel are kept idle for long durations till the data arrives. On the contrary, channel could have been used for the ordinary data, had it been not reserved for the GTS data. According to (1), maximum of 07 slots are reserved for the GTS utilization i.e. 07 slots can be idle at a time just to provide the GTS to the data to be trafficked by the sensor node. According to (2), all the 14 data carrying slots are free to transmit the data any time, received from the surrounding which in turn increases the utilization of the resources like channel utilization. Simulation setup along with its parametric values for the GTS slot utilization in three different networks, i.e. with GTS, mixed and without GTS, is given below in Table 1.

Furthermore, the working of all three networks can be summarized as shown in Figure 3.

Results and comparisons

Here, the results are presented and compared for the significant parameters of WSNs at MAC layer like network output load, CSMA medium access delay, CSMA transmission failure, queue size and queuing delay for FFD and RFD.

Table 1. Parametric values for PAN coordinator and end devices in three different networks.

	PAN coordinator				End device			
Device type	Mixed				Mixed			
Parameter/network	With GTS	With GTS	Without GTS	Without GTS	With GTS	With GTS	Without GTS	Without GTS
Acknowledged traffic parameters								
MSDU interarrival time (sec)	Exponential (2)							
MSDU size (bits)	Exponential (912)							
Start time (sec)	0.1							
Stop time (sec)	180							
Destination MAC address	Broadcast				PAN coordinator			
Unacknowledged traffic parameters								
MSDU interarrival time (sec)	Exponential (2)							
MSDU size (bits)	Exponential (912)							
Start time (sec)	0.1							
Stop time (sec)	180							
CSMA parameters								
Maximum backoff number	4							
Minimum backoff exponent	3							
IEEE 802.15.4								
Device mode	PAN coordinator				End device			
MAC address	Auto assigned							
WPAN settings								
Beacon order	3							
Superframe order	2							
PAN ID	0							
Logging								
Enable logging	Enabled							
GTS settings								
GTS permit	Enabled		Disabled		Enabled		Disabled	
Start time (sec)	0.1		Infinity		0.1		Infinity	
Stop time (sec)	180		Infinity		180		Infinity	
Length (slots)	2		0		2		0	
Direction	Receive		Transmit		Transmit		Transmit	
Buffer capacity (bits)	10,000		1000		1000		1000	
GTS traffic parameters								
MSDU interarrival time (sec)	Exponential (2)		Constant (1.0)		Exponential (2)		Constant (1.0)	
MSDU size (bits)	Exponential (912)		Constant (0.0)		Exponential (912)		Constant (0.0)	
Acknowledgment	Enabled		Disabled		Enabled		Disabled	

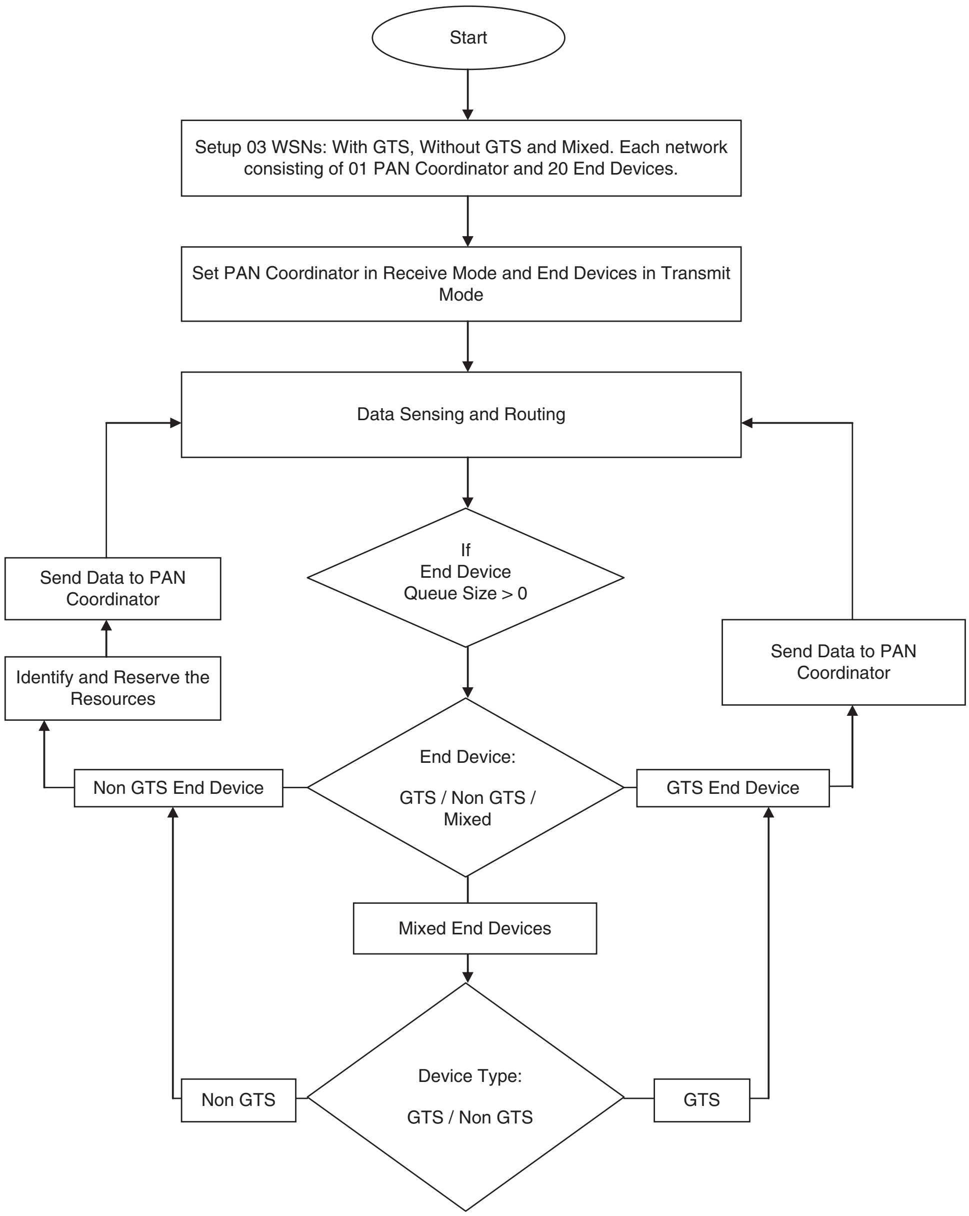

Figure 3: Flow Chart: Working of GTS, non-GTS, and mixed sensor networks.

Network output load

Figure 4A shows that the network output load at the PAN coordinator is 67,510.22, 60,802.81, and 49,234.42 bits/sec for without GTS, mixed, and with GTS networks, respectively. Network output load is minimum at the PAN coordinator in case of all GTS nodes because according to superframe, some slots are always reserved for the real-time data in order to ensure GoS according to: $0 < CFP \leqslant 7$ and $CAP < 14$. Since some slots are always reserved, network output load is minimum in case of with GTS nodes at the PAN coordinator (Koubaa, Alves, Nefzi and Song, 2006) (1). It has been comparatively analyzed that network output load is maximum in Without GTS network because no bandwidth reservations are made for any type of device and all the superframe 14 slots are used for the data transmission in accordance with: $CFP = 0$ and $0 < CAP \leqslant 14$ (Koubaa, Alves, Nefzi and Song, 2006) (2).

Figure 4B at the end device compares the network output load to be 244,581.7, 141,382.2, and 147,322.3 bits/sec for with GTS, without GTS, and mixed

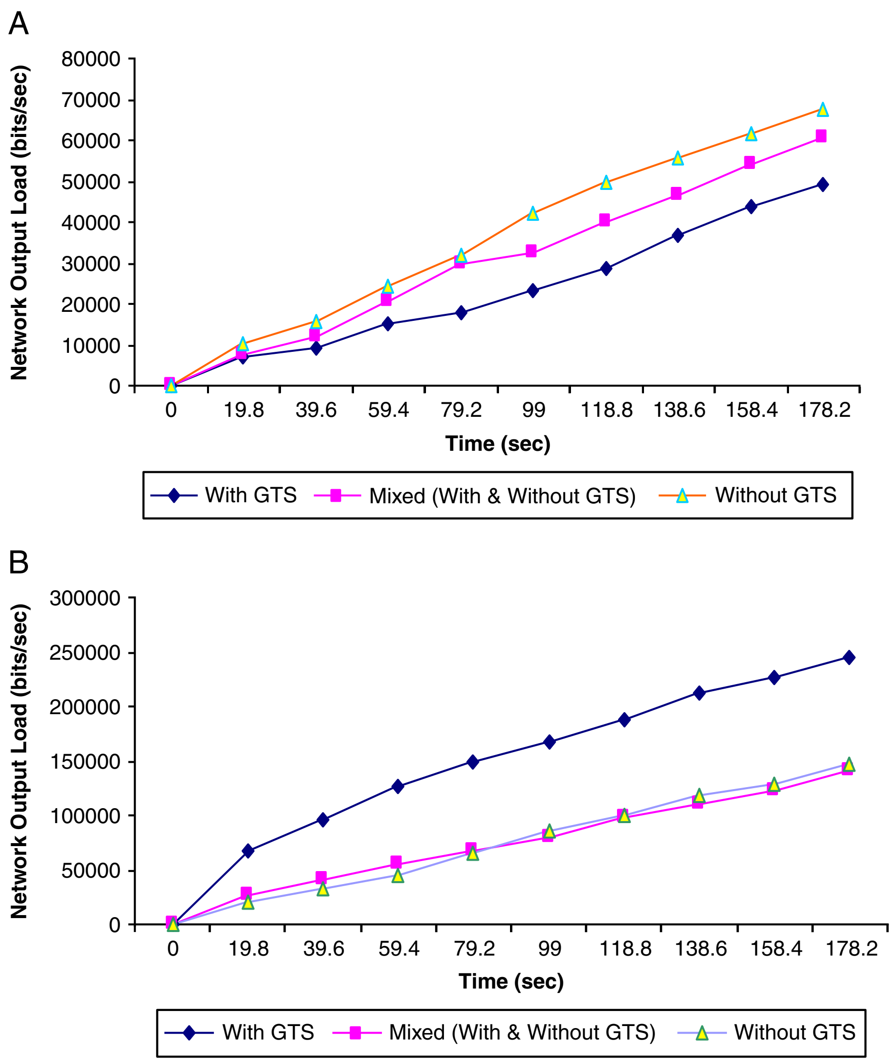

Figure 4: Network output load: (A) PAN coordinator (B) End device.

networks, respectively. It is comparatively observed that output load is maximum in with GTS nodes as some bandwidth is always reserved for data (real-time) from the surroundings according to $0<CFP<8$. In addition to that end device communicates only to the PAN coordinator and not to any other device in the network; therefore, only the traffic of that particular device is to be handled as a result of which there are least delays, retransmission attempts and minimum retransmission failures (Jurick and Koubaa, 2007) (1). Also, it has been comparatively observed that network output load is least in Mixed scenarios because half of the nodes are GTS enabled and remaining half are non-GTS which results in a mixture of GTS and non-GTS traffic as a result of which there are comparatively more collisions, more delays, jitters and requires comparatively more number of retransmission attempts and also out of the 14 slots of superframe used for data transmission some are always reserved for real-time applications, therefore comparatively less output load (1).

Figure 4A, B) analyzes that network output load is minimum at FFD if all the nodes connected to it are GTS enabled. On the contrary, the network output load is maximum at the RFD if it is GTS enabled.

CSMA medium access delay

Figure 5A depicts that the CSMA medium access delay at the PAN coordinator is 15.49391, 5.169278, and 0.971008 sec for with GTS, mixed and without GTS networks, respectively. CSMA medium access

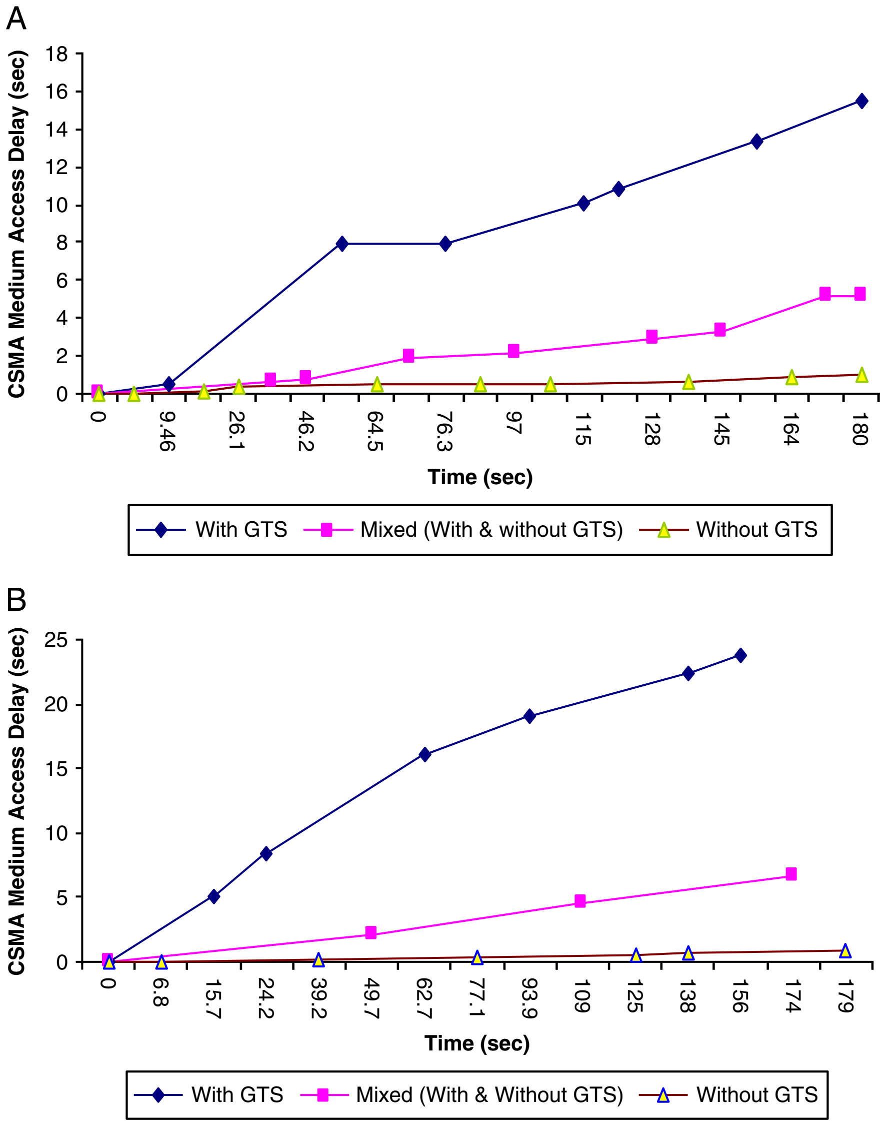

Figure 5: CSMA medium access delay: (A) PAN coordinator (B) End device.

delay is maximum in with GTS network as all nodes are GTS feature enabled, i.e. according to the superframe structure at each node CFP>0 and thereby reducing the CAP slots in accordance with the relation 14 – CFP as a result of which the delays are maximized (Koubaa et al., 2006a; Hameed et al., 2008) (1). It has also been observed that delays are minimum in case of without GTS network as all nodes are non-GTS and no superframe slot reservation is done, i.e. CFP=0 and all the data carrying 14 slots can be used for data transmission without idleness (Koubaa et al., 2006a; Hameed et al., 2008) (2).

Figure 5B compares the CSMA medium access delay at the end device to be 23.69137, 6.559795, and 0.881048 sec for with GTS, mixed, and without GTS networks, respectively. It is analyzed comparatively that CSMA delays are maximum in with GTS nodes for the same reason as stated in Figure 5A for with GTS network (Koubaa et al., 2006a; Hameed et al., 2008) (1). It has also been observed that delays are minimum in without GTS network, again for the reason stated in Figure 5A for without GTS network (Koubaa et al., 2006a; Hameed et al., 2008) (2).

Figure 5A, B analyzes that CSMA medium access delay at all types of devices for WSNs in 802.15.4 is maximum in with GTS nodes. On the contrary, it is minimum in without GTS networks for all types of devices in 802.15.4.

CSMA transmission failure

Figure 6A shows that the CSMA transmission failures at the PAN coordinator are 0.13536, 0.00384, and 0.0 for mixed, with GTS, and without GTS networks, respectively. It has been analyzed that transmission failures are maximum at the FFD in case of mixed network because it receives the data both from GTS enabled and non-GTS RFDs, which leads to the situations like medium not accessible and ultimately transmission failures occurs. Since, PAN coordinator communicates to all the devices in the network that suffers from maximum transmission failures because superframe slots are reserved according to the relation $0<CFP\leqslant 7$ and non-GTS devices keep on trying to transmit the data but it is possible only according to 14 – CFP (Koubaa et al., 2006a) (1). It is also analyzed that transmission failures are reduced to minimum in Without GTS networks as no superframe reservation takes place and all 14 slots can transmit the data if idle (Koubaa et al., 2006a) (2).

Figure 6B shows that the CSMA transmission failures at the end device are 3.397584, 0.46218, and 0.14688 for with GTS, mixed, and without GTS networks, respectively. It is comparatively analyzed that transmission failures are maximum in with GTS network as bandwidth or superframe slots are reserved in advance for the time sensitive data and are occupied till that data have been transmitted completely and in that particular time slot chances for the other data transmissions are 14 – CFP; therefore, maximum delays as channel is reserved in advance (Koubaa et al., 2006a) (1). It is also analyzed that transmission failures are reduced to minimum in without GTS networks as no superframe reservation takes place and all 14 slots can transmit the data if idle (Koubaa et al., 2006a) (2).

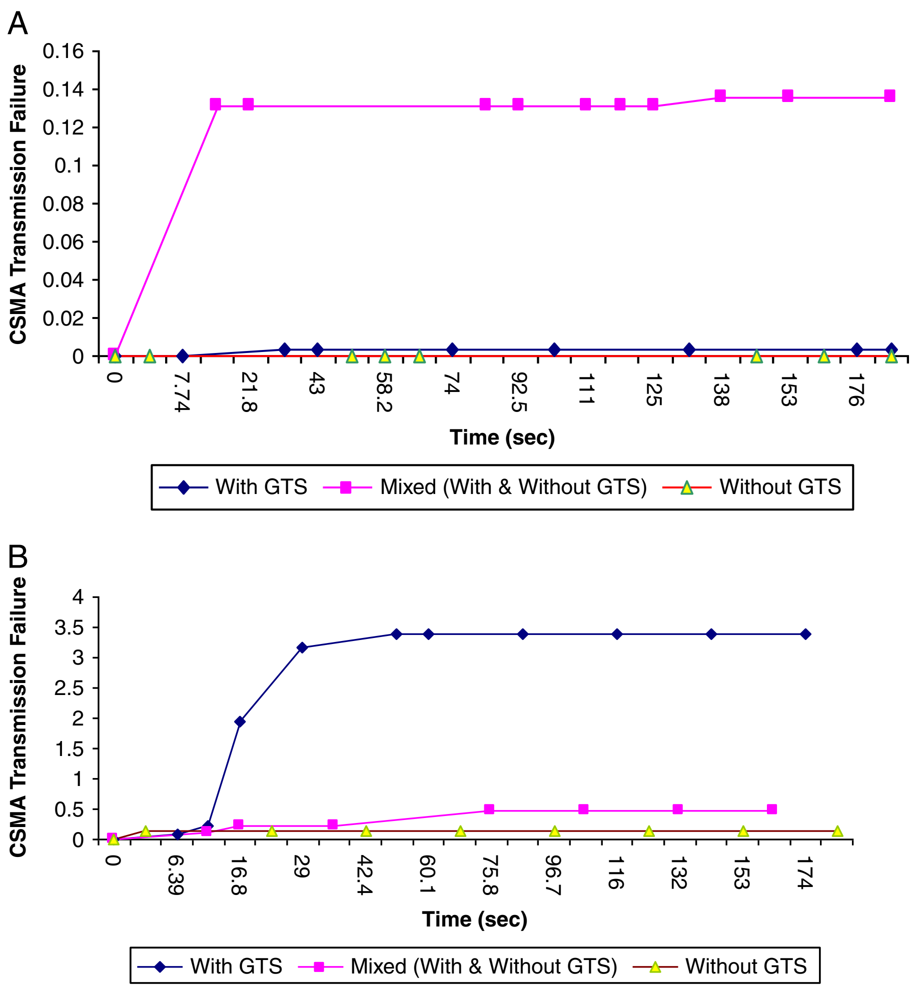

Figure 6: CSMA transmission failure (A) PAN coordinator (B) GTS end device.

From Figure 6A, B, it is analyzed that CSMA transmission failures in 802.15.4 WSNs are maximum in case of mixed networks at the FDD and with GTS network at RFD. It has also been observed that CSMA transmission failures are minimum in without GTS networks of 802.15.4.

Queue size

Figure 7A shows that the queue size at the PAN coordinator is 9.250342, 6.503601, and 2.006762 packets for with GTS, mixed, and without GTS networks, respectively. It is observed that queue size is maximum in with GTS networks as the bandwidth is reserved in advance for a particular data transmission to provide GoS (Jurick and Koubaa, 2007). It has also been observed that queue size is shortest in without GTS networks as no part of the superframe is reserved, i.e. CFP = 0 and $0 < CAP \leqslant 14$ (2).

Figure 7B depicts that the queue size at the end device is 83.57478, 16.77362, and 4.695392 packets for with GTS, mixed, and without GTS networks, respectively. It is comparatively observed that queue size is maximum in with GTS network (Jurick and Koubaa, 2007). It has also been observed that queue size is shortest in without GTS network (2).

Figure 7A, B have compared and analyzed that queue size is longest in With GTS networks for all types of devices whether FFD or RFD in 802.15.4 WSNs, while it is shortest in without GTS networks,

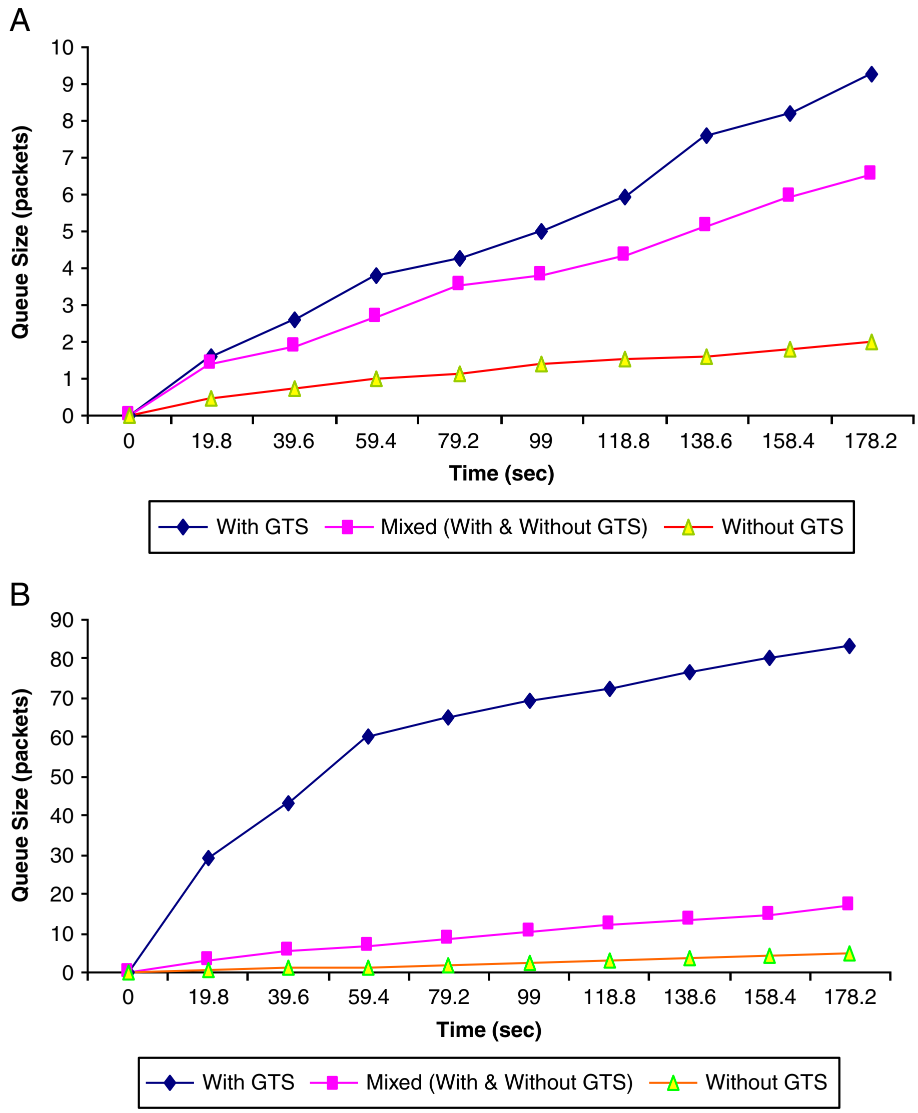

Figure 7: Queue size (A) PAN coordinator (B) End device.

irrespective of the device type: FFD or RFD in 802.15.4 WSNs.

Queuing delay

Figure 8A comparatively shows that queuing delay at the PAN coordinator is 11.59374, 8.521715, and 2.551126 sec for with GTS, mixed, and without GTS networks, respectively. It is comparatively analyzed that queuing delays are maximum in with GTS networks because queue size is larger due to the bandwidth reservation in advance (Koubaa et al., 2006a; Li et al., 2008). It is also analyzed that queuing delay is minimum in without GTS networks due to no bandwidth reservation in advance which leads to the smaller queue size and shorter delays (Jurick and Koubaa, 2007).

Figure 8B shows that the queuing delay at the end device is 47.25739, 14.41287, and 3.693047 sec for with GTS, mixed and without GTS networks, respectively. It has been analyzed that queuing delay is largest in with GTS networks (Koubaa et al., 2006a; Li et al., 2008). It is also comparatively analyzed that queuing delay is shortest in without GTS networks (Jurick and Koubaa, 2007).

Figure 8A, B has analyzed that queuing delay is largest in with GTS networks for all types of devices whether FFD or RFD in 802.15.4 for WSNs. Also, it is observed that queuing delay is shortest in Without GTS network for FFDs as well as RFDs in 802.15.4 WSNs.

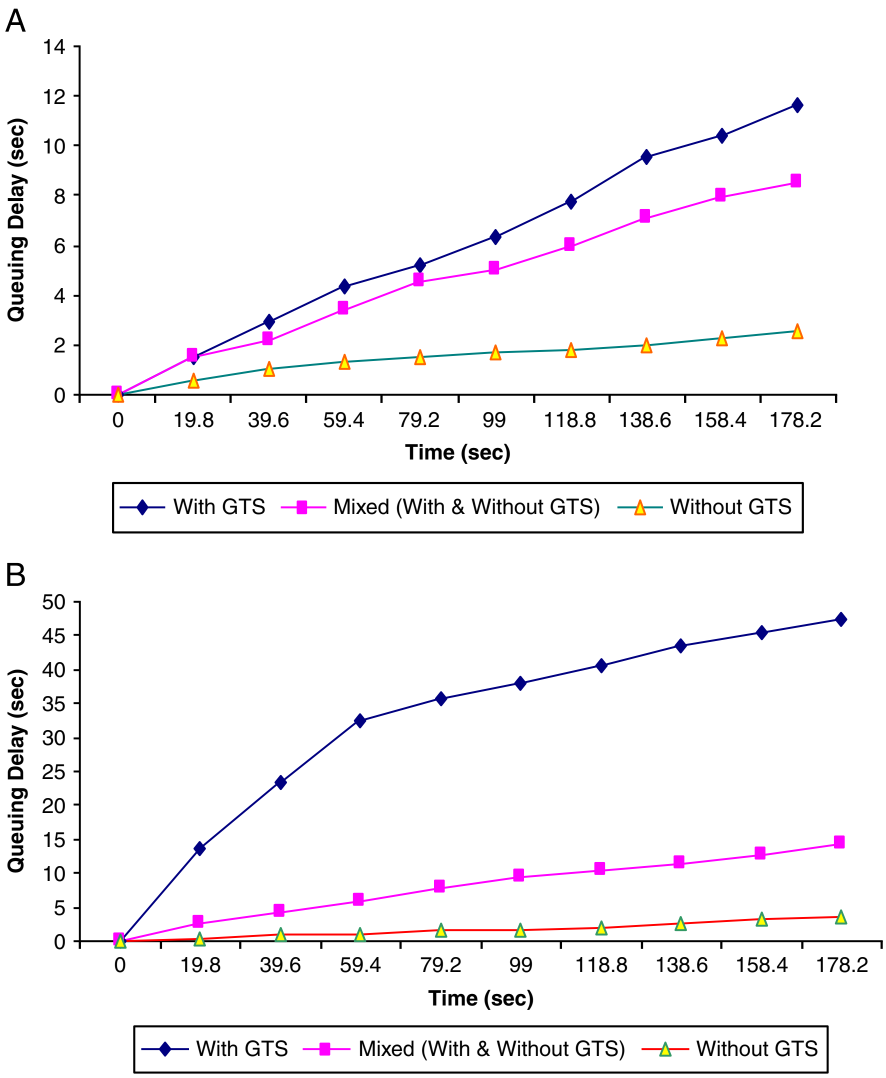

Figure 8: Queuing delay (A) PAN coordinator (B) End device.

Conclusions

Comprehensive evaluation of GTS mechanism in superframe reveals that at the MAC layer, for improving QoS in IEEE 802.15.4 WSNs, GTS mechanism at different types of devices in three different networks (with GTS, without GTS, and mixed) of IEEE 802.15.4 WSNs provides GoS to real-time data through superframe but by compromising the performance effecting parameters like queue size, queuing delay, CSMA media access delay, CSMA transmission failures, and network output load. It is concluded that at the MAC layer CSMA medium access delay at all types of devices for WSNs in 802.15.4 is maximum in with GTS nodes, i.e. if GTS mechanism is implemented on all nodes, also with the GTS the CSMA transmission failures are maximum at the RFDs. Furthermore, it is observed that the queue size and queuing delay are maximum in case of GTS implementation on all types of devices in 802.15.4 WSNs. Finally, it is proved that the network output load with GTS mechanism on FFD gives the reduced output, whereas at the RFD it gives the maximum output.

In conclusion, GTS mechanism improves the QoS by providing the GoS to data (real-time) through superframe, but only by compromising performance effecting parameters like queue size, queuing delay, CSMA media access delay, CSMA transmission failures, and network output load.

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