A survey on time division multiple access scheduling algorithms for industrial networks

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Abstract

In recent years, wireless networks have been widely adopted in industrial applications such as monitoring and control because of their flexibility and low cost. However, wireless networks use shared medium which require appropriate Media Access Control (MAC) protocols to manage the shared medium. Time Division Multiple Access (TDMA)-based MAC protocols, which are collision free are predominantly used in industrial networks. To achieve the stringent requirements of reliability and timeliness in industrial applications, proper scheduling of the nodes accessing the shared channel is essential. A number of TDMA scheduling algorithms have been proposed in the literature but there is no study that have analyzed and compared the algorithms to help designers of new algorithms with basic information of the existing algorithms. The objective of this study is to provide basic findings that should be used by researchers looking for TDMA scheduling algorithms for industrial applications. To achieve the objectives of this article various categories of the TDMA scheduling algorithms that have been implemented in various industrial networks mostly Industrial Wireless Sensor Network (IWSN) which is widely deployed have been presented. Comparison of the various categories of the scheduling algorithms using reliability and delay as performance metrics which are crucial in industrial applications have been done. It was noted that hybrid TDMA scheduling algorithms have improved performance compared to distributed and centralized algorithms in random networks. Designing and testing of hybrid TDMA scheduling algorithms in the emerging industrial wireless networks such as LoRaWAN are recommended future work.

Keywords Industrial networks · TDMA · Scheduling algorithms · IWSN · MAC

1 Introduction

Industrial wireless networks differ from traditional wireless technology in the sense that, wireless technology deployed in industrial application such as factory and process automations should meet the hard requirements such as real time, determinism and reliability [1]. The requirements may vary depending on the application domain; For example, in process automation which is mainly composed of monitoring/supervision, closed loop control, interlocking and control, the requirements vary from less sensitive to reliability of 99.999% [2]. Low-latency

requirements are more demanding in industrial automation especially in motion control applications [3].

According to [4], there have been evolutions of industrial networks from Fieldbuses [5], real-time Ethernet (RTE) [6], and a number of wireless networks [7]. These communication technologies varies from being star, mesh or single hop network topology that can be used in industrial communication [8]. In recent years, wireless communication networks such as WirelessHART [7], ISA 100.11a [9] and the Wireless network for Industrial Automation—Process Automation (WIA-PA) [10] has been widely deployed in industrial networks due to their flexibility and low installation and maintenance cost. However, most of the

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wireless communication systems use a shared channel which require Medium Access Control (MAC) protocols to manage the transmission of packets, retransmission of damaged packets, and resolution of collisions among stations [11]. Therefore, a MAC protocol is considered as an important enabler for efficient network operation and good performance in wireless communication.

There are various types of MAC protocols that can be used in wireless communication technologies such as TDMA, Code Division Multiple Access (CDMA) and Frequency Division Multiple Access (FDMA). However, the MAC protocol in proposals for applications in industrial automation have been dominated by the TDMA protocol [12–14]. TDMA MAC protocols have several advantages such as collision, overhearing, and idle listening avoidance hence energy efficient. In TDMA protocol, the channel is divided into a number of time slots that can be used by each node to transmit data in a periodic fashion [15]. Therefore, an efficient scheduling for the slot allocation is necessary to achieve the benefits of the TDMA MAC protocol.

There is a number of TDMA scheduling algorithms that have been proposed in literature but there is no study performed to classify and compare, the algorithms for industrial wireless networks. The absence of this study may impose difficulties for researchers who are looking for efficient TDMA scheduling algorithms to be used in newly developed industrial wireless networks. In this paper therefore, different TDMA scheduling algorithms that have been used in various industrial wireless networks have been presented. The performance of the scheduling algorithms has been extensively reviewed and compared using delay and reliability as the performance metrics. It was noted that it is challenging to have an algorithm that satisfy both reliability and timeliness requirements which are crucial in industrial wireless networks. Therefore, hybridizing two algorithms to obtain an efficient algorithm is a recommended way of optimizing the scheduling algorithm for better performance in the industrial networks.

The rest of the paper is organized as follows; the general overview of TDMA-based MAC protocols is presented

in Sect. 2, the TDMA scheduling algorithms for industrial networks in Sect. 3, comparison of the different TDMA scheduling algorithms for industrial networks in Sect. 4 and lastly conclusions and future work in Sect. 5.

2 TDMA- based MAC protocols overview

In TDMA-based MAC protocol, the total time duration of communication is divided into a fixed number of timeslots which are configured into time-frames that repeat periodically [16]. Each node in the network is allocated a fixed number of time-slots and is allowed to transmit only in the allocated time-slots in each frame. The division of the time slot is commonly done using scheduling algorithms that determine efficient and optimal schedules for each node in the network. Based on the nature of the algorithms used in the TDMA protocol, [17] have classified the TDMA protocols in three groups; Centralized, distributed and hybrid protocols.

In Centralized TDMA protocols, a central entity such as Base Station (BS) or Access Point (AP) centrally schedules different slots to different nodes in the network. Every node uses these time-slots for data communication. Examples of centralized TDMA protocols include Bit-map-assisted MAC Protocol [18], which is mostly applied in event-driven applications. More examples of the centralized MAC protocols can be studied in [17].

In Distributed TDMA protocols, scheduling is done by the nodes themselves based on the local information that they have. There is no need of any centralized entity as in centralized TDMA MAC protocols. Self-organizing medium access control for sensor networks (SMACS) [19] is one example of a distributed MAC protocol which can be applied in applications with low bandwidth utilization. Other examples of distributed TDMA MAC includes Power Aware Clustered TDMA (PACT) [8], Distributed Randomized TDMA algorithm DRAND [20] and Deterministic Distributed TDMA(DD-TDMA) [21]. The major differences between centralized and TDMA algorithms are depicted from [17] and presented in Table 1.

Table 1 Differences between centralized and distributed TDMA scheduling algorithms

Centralized TDMA	Distributed TDMA
Time slot allocation is managed by a central entity or base station	Time slot allocation is managed by individual nodes in the network
The central entity must have a prior knowledge of the entire topology to create the schedules for each node	Does not require the knowledge of the topology to create the schedule
Efficient bandwidth utilization	Bandwidth is not efficiently utilized as the nodes needs to send HELLO message regularly to update their status to neighbor nodes
More overhead and obsolete information for node mobility scenarios.	Can adapt easily with topology changes
Not reliable as all the information are carried by one central node which can cause unreliability when failure occur	Data can still be transmitted using alternative paths when a failure occur in the network

Some researchers have combined centralized and distributed algorithms to form hybrid TDMA scheduling algorithms that have increased performance. For example Ref [22] have hybridized the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms to enhance the searching capabilities in terms of total time and energy for data collection. Other examples of hybrid TDMA scheduling algorithms have been presented in [23–25]. Hybrid algorithms have improved performance compared to centralized and distributed TDMA algorithms in terms of either energy efficiency, fairness, delay, and throughput.

In addition, for proper operation of the TDMA MAC, neighboring nodes need to agree on boundaries of time slots and therefore a clock synchronization algorithm is needed [13]. The synchronization should be lightweight enough to avoid increasing the delays and bandwidth utilization. There are different synchronization algorithms that have been used in traditional networks such as Continuous Clock Synchronization (CCS) algorithm [26], Dynamic CCS (DCCS) [27] and hybrid algorithm [8, 23, 28]. Most of these algorithms consider only the clock offset problem and cannot be used in the harsh industrial environment. The synchronization algorithms appropriate for industrial networks should consider the delay, reliability and energy efficiency requirements of the industrial application. Therefore, modified algorithms such as the ones proposed in [29–31] can be used in industrial networks.

3 TDMA scheduling algorithms for industrial networks

The successful transmission of a packet between two nodes in an industrial network is affected by environmental factors, such as noises and multipath propagation, which can corrupt a packet and cause the transmission to fail. The transmission failure can also be caused by access contention problem among neighboring nodes in data link layer scheduling. These transmission failures cannot be tolerated in industrial application and therefore reliable and low latency scheduling algorithms are required. However, maximizing the reliability and minimizing the transmission delay are two conflicting performance objectives in industrial networks. Although various efficient scheduling algorithms have been proposed to be used in wireless networks, most of them concentrate on reducing the transmission latency [10] or minimizing the communication cost [11]. Scheduling algorithms should be able to reduce collisions and the number of time slots while being adaptive to the link dynamics to provide reliable communication. In addition, the algorithms should meet the energy efficiency requirements of the industrial applications.

There are various types of TDMA scheduling algorithm that can be used in industrial wireless network with a look-up table [32] or a database that contain all information related to the topology and attached nodes in the network. The algorithms can be broadcast where the schedule is applied to the nodes in the network or link scheduling where the schedule is applied to the link connecting the nodes in the network. Tables 3, 4 and 5 summarizes the advantages and disadvantages of centralized, distributed and hybrid TDMA scheduling algorithms that have been implemented in industrial wireless networks. The Wireless Sensor Network (WSN) have been widely deployed in industrial applications which give it more credit to represent other industrial networks in this study. Most of these algorithms are either periodic TDMA MAC scheduling algorithms [46] and contention free as only one message is slotted to access the channel in each transmission time.

However, Dual-channel Multiple Spreading Factors (DMSF)–TDMA [47] is a scheduling algorithm deployed in LoRa network which is considered as emerging Low Power Wide Area Network (LPWAN) for industrial application. The algorithm is an improved version of Static TDMA (S-TDMA) algorithm for full duplex channel. It uses channel 2 for periodic data transmission and channel 1 for end nodes joining the network, time synchronization, urgent packets uploading and connectivity testing. The algorithm works by assigning time slots in different Spreading Factors (SFs). The algorithm performed better compared to S-TDMA and ALOHA in terms of decreasing the message delay.

Simulated Annealing (SA) [48] have been used in both traditional and industrial wireless networks due to its capability of solving the broadcast scheduling problem which is NP-complete. SA have shown better performance compared to genetic algorithms, mean field annealing, neural networks, factor graph and sum product algorithm, as well as sequential vertex coloring algorithm. It has been noted that when SA is used with the other algorithm (hybrid) an optimized algorithm that can be applied in industrial networks can be attained. For example, an energy efficient, low delay algorithm was attained by combining GA and SA [25]. Also combining Linear Programming (LP) and SA have resulted into an algorithm that minimize the delay and energy efficient [23].

The scheduling algorithms that specifically meet WirelessHART features have been presented in details in [49]. Conflict-Aware Least Laxity First (C-LLF) and Han Algorithms have been discussed with C-LLF considered as the optimal solution as it allocates all the time slot from first to the least. It also gives priority to nodes with deadlines and more interferences. However, the nodes with deadlines can sometimes miss the schedule resulting in failure of the algorithm. Other algorithms include, the Han algorithm and the Zhang policy which is not an actual algorithm

but rather a policy which establishes lower bound for the number of channels for time-optimal converge cast. The authors in [49] have also suggested other algorithms that can be considered to be used in the WirelessHART such as Distributed network Management scheme for Real-time applications (D-MSR), for real-time and reliable communications of industrial control applications. The other algorithms that can be considered for WirelessHART includes D-SAR and MRF-based multi-service node scheduling (MMNS). The traffic-aware message scheduling (TAMS) and contention window size adjustment (CWSA) algorithms have been implemented in ISA100.11a.

Segmented Slot Assignment (SSA) is an interesting algorithm presented in [56] that consider the assignment of slots to nodes that should retransmit during link or node failures in the network. SSA guarantees route-ordered scheduling while improving the retransmission efficiency using the shared slot efficiently. The principal of the algorithm is to assign the time slot to the re-transmitting node before its following hop to ensure that the super frame is delivered to the sink in its completion.

Some of the algorithms that have been used in the hybrid TDMA scheduling algorithms have different attributes that makes them suitable for industrial application. The different attributes for the various algorithms are presented in Table 2. Most the algorithms used in hybrid have been selected in a smart way to ensure that the benefits of the individual attributes are optimized and used for better performance. Therefore, the table can be used by designers of new algorithms to see which other algorithms can be combined depending on the need to get optimized scheduling algorithms for industrial applications. If the algorithm is not marked as conflict free that means conflicts may occur under special circumstances.

4 Comparison of the different TDMA scheduling algorithms for industrial networks

Different scheduling algorithms performed differently under different conditions. There are various parameters that have been used in the evaluation of the different scheduling algorithms including end to end delay in relation to the node positioning or number of nodes in the network [33, 35, 41], slot allocation duration in relation to number of neighbor nodes or period [37–39] and reliability in relation to period and number of nodes in the network.

To analyze the performance of the different scheduling algorithms under the different conditions, the number of nodes were chosen to be 100 which signifies the maximum number that were evaluated in [33, 53]. The performance of the TDMA algorithms given the maximum number of nodes should be interpreted as the worst case scenario and the algorithms should perform better in a network with smaller number of devices (< 100). Parameters in Tables 6, 7 and 8 from individual categories of the TDMA scheduling algorithms have been used.

Although it was difficult to get a fair comparison that could be used to compare the performance of the various TDMA scheduling algorithms, the values of end to end delay for 100 nodes network, for both distributed, centralized and hybrid TDMA in [23, 34, 37, 45, 53, 54] are presented in Table 6. There were longer delay experienced by hybrid algorithms in allocating the time slot to the end devices which can increase the delay for the data to be transmitted to the sink node especially in networks whose transmissions are periodic. Distributed algorithms uses shorter times to allocate time slots to the end devices which causes shorter end to end delay which is more suited in triggered event transmissions.

The end to end delay for hybrid algorithms were smaller compared to both centralized and distributed algorithms as the number of devices increases in the

Table 2 Attributes of various TDMA scheduling algorithms

Algorithm	Minimized Delay	Energy efficiency	Adaptive	Conflict free
(PSO) [50]	√			√
Distributed, edge coloring based link scheduling algorithm [51]		√		√
Ref [52]		√	√	√
Ref [53]	√	√		√
Fast real-time scheduling [45]	√	√		
Genetic-Fix Algorithm [54]	√			
GA [55]	√	√		

Table 3 Centralized TDMA scheduling algorithms for Industrial networks

Algorithm	Description	Advantages	Disadvantages
Source aware scheduling (SAS) TDMA [33]	It assigns dedicated schedule to each link in the source path	It is adaptive such that it can respond quickly to maintain the shorter scheduling length during link dynamics	The delay is increased as the total number of time slots increase because no slots reuse.
Ref [34]	Allocate more than one time slots in a link depending on an upper bound of the link latency, link burstiness and interference	Guarantee minimum delay and 100% reliable packet delivery	The performance deteriorate in wireless networks with poor link quality
Breadth-first and depth first scheduling [13]	The network manager assigns time slots starting from the outmost sources. The time-slot assignment starts with sources getting the first slots, followed by the forwarders directly attached to sources, followed by forwarders directly attached to first wave forwarders and so on	It is energy efficient	Might cause a buffer problem
Depth-first scheduling [13]	The network manager assigns time slot using depth-first approach. The first time slot is assigned to the source the second time slot to the forwarder of the source and the third time slot to the second forwarder etc.	Avoid buffer overflows in the forwarders. Guarantee reliability	Long setup delay
Lagrange Relaxation based Aggregated Cost (LARAC) [35]	The path is computed using Dijkstra with an aggregate cost metric and labels the intermediate paths found as either infeasible or feasible	Improve the reliability even in the presence of dynamic interference	The schedule depends on the quality of the channel which can cause errors from channel to be propagated in the scheduling
Mixed criticality relative execution deadline TDMA [36]	Assign time slots based on the mixed criticality modes and relative execution deadline	Uses the limited slots and channels to improve the system reliability, the real-time performance and the criticality of flows	System reliability can not be guaranteed in interference situations

Table 4 Distributed TDMA scheduling algorithms for industrial networks

Algorithm	Description	Advantages	Disadvantages
Latency-Energy Minimization Medium Access (LEMMA) [37] RE-DRAND [38]	Time slot allocation considers interfering nodes and not the physical topology Uses priority control scheme and energy residue. Slot allocation is performed giving priorities to nodes with low energy residue It uses energy and topology (E-T) factor to create the schedules	Decreased delay Energy efficient. The authors recommend it as a solution to industrial monitoring	More energy is consumed, Not reliable It may result to increased schedule time when there is increased number of end devices
Energy-Topology(E-T-DRAND) [39]		It considers topology change as well as the energy factor in creating the schedule	It may result into transmission failure if the node with the least energy residue will not be prioritized
Parameterized Adaptive and Autonomous Scheduling (PAAS) [40] SchedEx [12]	Used in IoT Time Slotted Channel Hopping (TSCH) TDMA. Improved version of Incrementer that implements the packet buffer update in each schedule to ensure end-to end reliability by a controlled packet move delay	Minimize energy consumption and delays with increased reliability	Can only be used in networks with low offered traffic. Increased delay with large number of nodes in the network.
Distributed and dynamic coloring algorithm [41]	Used to provide real time, reliability, energy efficiency and link dynamics requirements of WIA-PA	Avoids industrial interference of other coexistence wireless networks by performing scheduling using the actual channel condition	The algorithm allow communication only when the channel is clear and no retransmission which can sometimes result in information lost
Distributed Neighborhood Information Based (DNIB) algorithm [42]	Allocates slots to nodes while minimizing the message complexity and schedule length	It is scalable and outperforms the DD-TDMA and DRAND	It relies on information in two-hop neighbors which can sometimes not be realistic
Self Organizing Time Division Multiple Access (STDMA) [43] Reconfigurable and Adaptive Time Division Multiple Access (RATDMA) [43]	Achieves scalability by deploying reused global frame Achieves scalability by creating multiple local TDMA frames grouped according to specific collaborative applications	Allows coexistence of devices with different control cycles Allows coexistence of both static and mobile devices	Increased packet losses under overlapping networks or poor clock synchronization Outperform STDMA under overlapping networks or poor clock synchronization

Table 5 Hybrid TDMA scheduling algorithms for industrial networks

Algorithm	Performance Metrics
GA+ SA [25]	Minimize the total number of time slots, high energy efficiency and low delay
Linear Programming model+ SA [23]	Improves system response time and system operation time
PSO + SA [44]	Improves slot allocation time hence minimum delay
Ref [45]	Provides fast and efficient real time scheduling for WIA-PA
GA + PSO [22]	Minimize energy consumption and shorten the time required to complete a set of tasks.

Table 6 Approximate end-to-end delay of various TDMA scheduling algorithms in relation to network size

No. of Nodes	End-to-end delay (ms)		
	Distributed TDMA	Centralized TDMA	Hybrid TDMA
100	43.4627	1750, 80	6000
	Slot allocation duration (TDMA cycles)		
100	18	100	810
51–55	151, 225, 170	50	> 400

Table 7 Performance of the various TDMA algorithms in random networks [26]

No of Nodes	End-to delay(ms)		
	Distributed	Centralized	Hybrid (HA/GSA)
100	2451.4	2387.6	2327.7/2210.4
200	4786.5	4721.8	4611.9/4387.8
300	7523.4	7452.5	7385.3/6946.9
400	9468.2	9453.1	9295.4/8796.9

Table 8 Approximate reliability of various TDMA scheduling algorithms in relation to network Size

No of Nodes	Reliability		
	Distributed TDMA	Centralized TDMA	Hybrid TDMA
100	0.99	0.987	Appr. 0.99 + 0.98

random networks as shown in Table 7. This makes hybrid algorithms to be more suited in random networks. However the performance of different TDMA scheduling algorithms in random networks have been compared qualitatively in Fig. 1, with the parameters of interests being reliability and delay which are crucial in industrial applications. The numbers in the graph do not signify the actual performance of the algorithms but have been used for comparative purposes. The assumption is that if the algorithm has the best performance in the metric,

the score is set to 1, 2/3 for the second best and 1/3 for the last algorithm.

Hybrid TDMA scheduling algorithms have improved performance over centralized and distributed algorithms in random networks, the centralized algorithms were capable of producing schedules with minimum delay and guaranteed reliability when failures occur in the network. Also, it takes long time for centralized TDMA algorithms to adapt link dynamics at the central entity and updates the schedule for each node in the network. Moreover, there is a lot of overheads in centralized TDMA scheduling algorithms which consumes more energy. On the other end, the delay is increased especially with increased number of connected nodes in the network using distributed TDMA scheduling algorithm with high reliability than the centralized TDMA as shown in Table 8. It was therefore revealed that, balancing between reliability and timeliness is a challenge as the two performance parameters oppose each other. In addition, individual scheduling algorithms whether being centralized, distributed or hybrid have different performance depending on their applications albeit, better performances were attained with hybrid algorithms especially in random networks.

5 Conclusion and future work

The review of different TDMA scheduling algorithms used in industrial networks mostly IWSN have been presented. The classification of the various types of the TDMA scheduling algorithms and comparison of the different categories of TDMA scheduling algorithms using reliability and timeliness as the performance metrics have been presented. Most of the reviewed algorithms have been used in IWSN such as WirelessHART, WIA-PA and ISA100.11a which are dominating standards for industrial monitoring and control application. It was noted that, Hybrid TDMA scheduling algorithms have better performance compared to centralized and distributed algorithms in random networks. The hybrid algorithms are more appropriate for energy serving purposes although longer time can be used to allocate an optimal schedule to the devices.

Fig. 1 Comparison of TDMA scheduling algorithms performance in random networks

Therefore, designing and evaluating the performance of hybrid TDMA scheduling algorithms for improved energy efficiency is an area for future research. Also, evaluating the performance of the existing TDMA scheduling algorithms in the emerging industrial networks such as LoRaWAN will also be considered in the future work. Lastly the review of other schemes such as CDMA can also be considered in the future work.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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