AN EFFICIENT DISTRIBUTED SLOTTED MULTI-HOP WIRELESS MAC PROTOCOL FOR INTERNET OF THINGS

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AN EFFICIENT DISTRIBUTED SLOTTED MULTI-HOP WIRELESS MAC PROTOCOL FOR INTERNET OF THINGS

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LIST OF ABBREVIATIONS

ATS	Average TimeSync
ATSP	Average Time Synchronization Protocol
BTS	Broadcast Time Synchronization
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
CDA	Clock Discipline Algorithm
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
DMTS	Delay Measurement Time Synchronization
DTSP	Distributed Time Synchronization Protocol
ETS	Efficient Time Synchronization
ETA	Elapsed Time on Arrival
ERP	Election Reelection Procedure
FIA	False Ticker Isolation Algorithm
FBS	Feedback-Based Synchronization
FTSP	Flooding Time Synchronization Protocol
FDMA	Frequency Division Multiple Access
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things

LSO	Least Significant Octet
LSLR	Least Square Linear Regression
LTS	Lightweight Time Synchronization
LDA	Load Distribution Algorithm
2LTSP	Long term and Large scale Time Synchronization Protocol
LOTS	Low Overhead Time-Sync
MMTS	Maximum Minimum Time Synchronization
MTS	Maximum Time Synchronization
MAC	Medium Access Control
NTP	Network Time Protocol
OSM	Own Slot Marked
PAN	Personal Area Network
PBS	Pairwise Broadcast Synchronization
PEP	Peer Evaluation Procedure
PC	Personal Computer
PETS	Power Efficient Timing Synchronization
RATS	Rapid Time Synchronization
RSP	Ratio-based Time Synchronization Protocol
RLS	Recursive Least Squares
RBS	Reference Broadcast Synchronization
RTS	Request to Send

RITS	Routing Integrated Time Synchronization
SLSO	Second Least Significant Octet
SN	Sensor Node
SATS	Simple Accurate Time Synchronization
SFD	Start of Frame Delimiter
TLSO	Third Least Significant Octet
TAA	Time Adjustment Algorithm
TP	Time diffusion Procedure
TDP	Time Diffusion synchronization Protocol
TDMA	Time Division Multiple Access
TSync	Time Synchronization
TPSN	Timing-sync Protocol for Sensor Networks
WMTS	Weighted Maximum Time Synchronization
WSNs	Wireless Sensor Networks

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PROTOKOL KAWALAN CAPAIAN MEDIA TANPA WAYAR BERBILANG HOP BERALUR TERAGIH CEKAP UNTUK INTERNET BENDA

ABSTRAK

Dalam Rangkaian Sensor Tanpa Wayar (WSN), Lapisan Kawalan Capaian Media (MAC) bertanggungjawab untuk menyelaras capaian nod deria (SN) kepada media. Aliran data masa nyata memerlukan penjadualan yang tepat supaya nod deria dapat mengakses media dan menghantar data tepat pada waktunya. Penjadualan penghantaran masa berslot diperlukan untuk mengakses media tanpa perlanggaran. Untuk mencapai perkara ini, nod deria perlu disegerakkan dan tahu mengenai tanggapan masa masing-masing. Walau bagaimanapun, penyegerakan masa memerlukan pertukaran mesej yang menyebabkan overhed yang tinggi. Protokol MAC yang dicadangkan, yang terdiri daripada algoritma untuk meminimumkan perlanggaran dan mengesan terminal tersembunyi, menghapuskan overhed mesej penyegerakan masa global. Ia menyegerakkan nod berasaskan slot masa dan mengurangkan pertukaran mesej dan kehilangan paket disebabkan oleh perlanggaran, di samping mengamalkan kaedah teragih lengkap. Algoritma yang dicadangkan menggunakan alamat IP nod deria untuk memulakan penyegerakan dan pengagihan slot antara nod. Hasil akhir eksperimen untuk protokol yang dicadangkan mengesahkan masa penumpuan setiap hop yang sangat pantas iaitu 3.62 saat untuk penyegerakan dan pengagihan slot, sebab kehilangan paket diminimumkan berdasarkan algoritma penantian masa yang novel, berbanding dengan CSMA yang digunakan oleh algorithma sedia ada. Ralat penyegerakan purata bernilai 0 (+/- 66.22μS) dicapai, yang merupakan ralat penyegerakan minima untuk protokol yang dicadangkan.

AN EFFICIENT DISTRIBUTED SLOTTED MULTI-HOP WIRELESS MAC PROTOCOL FOR INTERNET OF THINGS

ABSTRACT

In Wireless Sensor Networks (WSNs), the Media Access Control (MAC) layer is responsible for coordinating Sensor Nodes (SNs) as their access to the media. Real time data flow needs precise scheduling for sensor nodes to access the medium in order to send the data on time. Time slotted transmission scheduling is needed to access the media without collision. To achieve this, sensor nodes need to be synchronized and know about each other's notion of time. However, time synchronization requires message exchanges, which incur high overhead. The proposed MAC protocol, which consists of algorithms that minimizes collision and detects hidden terminals, eliminates the message overheads of global time synchronization. It synchronizes the node in terms of time slots and reduces the message exchange and packet loss caused by collision while being fully distributed. The proposed protocol uses IP addresses of sensor nodes for time slot assignment and synchronization among nodes. The final experimental results of the proposed protocol confirms a very fast convergence time per hop of 3.62 seconds for slot assignment and synchronization, since packet loss is minimized based on the novel waiting time algorithm, in comparison to CSMA used by existing algorithms. An average synchronization error of 0 (+/- 66.22μS) is achieved which is the minimum synchronization error for the proposed protocol.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Internet of Things (IoT) is a system capable of connecting all the things that need to have conversation directly or indirectly with its environment or even human being. Wireless Sensor Networks (WSN) have a considerable share in IoT. In WSNs, Sensor Nodes (SN) sense the environment and disseminate the collected raw data by the radio to a central computer directly or indirectly for further processing.

There are many different types of sensors that can be used in different places and applications. However, these sensors need a microcontroller to be driven and on the other side, the microcontroller drives actuators to do some tasks in response to sensor output. A very simple example can be temperature sensor which meters the temperature. On exceeding a fixed output range of sensors, microconroller order actuators (namely heater or cooler) to start functioning and keeping the temperature in range. By mounting transceivers on the sensor boards, actuators and sensors could talk to each other using wireless connection. If the number of SNs increases and become densely populated, it will cause some problems such as contention in accessing the medium. Among standard protocols defined for WSN, IEEE 802.15.4 and ZigBee can be named that make it possible to use hundreds or even thousands number of sensors in a sensor field (J.-S. Lee & Huang, 2006). Aforementioned protocols form a network of connected SNs called WSN and enable them to cooperate with each other to sense and send data to each other. Even in some cases, these SNs form an ad-hoc network which does not have a fixed structure. WSN protocol stack has 4 layers of physical, Medium Access Control (MAC), network, and application. IEEE 802.15.4 is responsible for physical and MAC while ZigBee is for network and application layers. SNs are scattered to a sensor field, then they sense the intended data and pass it to each other till it is delivered to sink node. Sink node can be connected to a Personal Computer (PC), another network, or even to satellite based on the application requirements.

WSNs are employed in different applications ranging from health (human, animal or plant), military (battle field monitoring or target tracking), security, commercial, (I. Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002), environmental monitoring (traffic), industrial sensing and diagnostics (supply chains), infrastructure protection (water distribution), disaster prediction (earthquake), context-aware computing (intelligent home) (Zhao & Guibas, 2004). Apart from mentioned applications the need for transmitting real time data such as voice and low rate video has grown up (Mangharam, Rowe, Rajkumar, & Suzuki, 2006); (Suh, Mir, & Ko, 2008); (Jasim & Çeken, 2015); (Usman et al., 2018); (Sousa, Dias, Ribeiro, Campos, & Ricardo, 2018); (Tsai, Huang, Chang, & Hussain, 2020). As it is clear from its name, real time data should be passed to the sink over a limited time. Since real time applications such as voice over WSNs, require high link utilization, minimum end to end packet delay and minimum packet loss, there had been many research conducted by researchers in the MAC layer to improve the bandwidth utilization which leads to improvement of link utilization and keeps the packet delay within limits that is acceptable for real time data. Another factor which is the most important one in WSNs is protocol efficiency in terms of message exchange as the SNs are, in many cases, battery powered.

MAC layer is the center of attention to improve the efficiency, since it is responsible for active period of SNs. Many different MAC protocols have been proposed to achieve the aforementioned criterion. The main four multiple access schemes which other schemes are derived from are listed below:

1. Carrier Sense Multiple Access (CSMA)
2. Frequency Division Multiple Access (FDMA)
3. Code Division Multiple Access (CDMA)
4. Time Division Multiple Access (TDMA)

CSMA functions very well when a huge number of SNs are deployed (I. F. Akyildiz, Melodia, & Chowdhury, 2007), but in multi-hop scenarios it imposes an exponential increasing delay to access medium (Farrag, Younis, & D'Amico, 2009); (Bianchi, Fratta, & Oliveri, 1996). It is not collision free. Hidden and expose terminals make it collision prone (due to broadcast nature of wireless communication). Overhearing and idle listening are other problems which lead to wasting SN resources (Nieberg, Dulman, Havinga, van Hoesel, & Wu, 2004).

FDMA is a collision free multiple access scheme. In topologies that clustering is needed, in order to overcome the inter-cluster hidden terminal, it is preferred to use multiple channels with different frequencies. But not all the radios support multi-channel communications and those support are more expensive and it is not the goal of WSNs (Demirkol, Ersoy, & Alagoz, 2006).

CDMA is another collision free multiple access scheme. It does not need any extra hardware and consequently is not a costly. However, high computation load in this scheme makes it inefficient for WSNs (Demirkol et al., 2006). Another problem is frequent listening to the channel which results in wasting resources too (Nieberg et al., 2004); (Ye & Heidemann, 2004).

TDMA is also a collision free multiple access scheme. This scheme does not have the previous schemes' constraints. No idle listening and over hearing, no specific hardware, and it does not have much computation complexity. It outperforms CSMA when latency is a concern (Cosar, Mahmood, & Björkbom, 2011); (Jakllari & Ramanathan, n.d.). However, it has limitations, which are time synchronization and scalability (I. F. Akyildiz et al., 2007) and time slot assignment. Time synchronization is very expensive in terms of message exchange and even before all the SNs get synced there is no promising mechanism or to access medium and deliver messages correctly and intact.

A TDMA scheme can be centralized or distributed. In distributed TDMA, each SN synchronizes and assigns its own resources and communicates with 1-hop neighbors. In contrast, in centralized TDMA, the synchronization and resource assignment of each SN is managed by a central coordinator (Bang & Lee, 2020). Since distributed TDMA, in comparison with the centralized TDMA, is a better choice for the constrained resources of the WSNs (Ahmad & Hanzálek, 2017), this work focuses on the distributed scheme, which is more appropriate for multi-hop scenarios too.

1.2 Research Motivations

A recent research that considered WSN as the most important element of IoT, underwent an intensive experiment to compare existing WSN standards namely: LoRaWAN, WiFi, BLE and IEEE 802.15.4 (Del-Valle-Soto, Valdivia, Velázquez, Rizo-

Dominguez, & López-Pimentel, 2019). That research believes that IEEE 802.15.4 outperforms the other mentioned standards when end to end delay and message overhead are the concerns. Realtime data flow applications or delay sensitive applications of WSNs such as monitoring in health area, forest fire detection or radiation monitoring at nuclear plant needs relatively bounded delay to convey packets with minimum packet loss (Takale & Lokhande, 2018). Imagine in aforementioned areas, not receiving the intact data or late reception of data can lead to disasters as messages contain sensitive data. Since delay is one of the main concerns of real time data flow applications, IEEE 802.15.4 can be a better candidate for the current research.

SNs which are operating under IEEE 802.15.4 standard are currently used at anytime and everywhere offering many services and create smart environments to facilitate human life. Since all things in IoT should communicate and share the same resources (most importantly the communications channel or medium), many studies focus especially on MAC layer (Ben Yaala & Bouallegue, 2016). Because of broadcast nature of WSNs, sharing and managing the same medium is not a simple task. IEEE 802.15.4 provides two topologies of star and peer to peer. In star topology, Personal Area Network (PAN) coordinator(s) are responsible for handling other SNs in its vicinity. Therefore, imposing single point of failure to the network (Rashid, Pecorella, & Chiti, 2020). On the other hand, peer to peer topology provides more flexibility for the network. PAN coordinator(s) can exist in peer to peer topology, but removing it and letting all SNs have exactly the same functionalities can improve the performance and eliminate the single point of failure (Carbajo & Mc Goldrick, 2017); (Gholami, Taboun, & Brennan, 2019); (Ullah, Said, Sher, & Ning, 2020) which is called distributed ad-hoc mode. A recent research (Gardašević, Katzis, Bajić, & Berbakov,

2020) provides a comprehensive comparison on how the 802.15.4 standard can reduce the cost of implementation and energy consumption of health care monitoring and how 802.15.4 standard is and will be used in a wide range of medical and health care area. It also categorize the time slotted 802.15.4 as a highly reliable standard with reliability of 99.999%. The time slotted version of 802.15.4 is reducing the collision which leads to a higher throughput.

SNs also tend to spend less energy to be alive for a longer period of time and losing packets caused by collision leads to less link utilization and finally results in wasting more energy. Hidden terminal or exposed terminal problems are seen in multi hop topologies. Peer to peer or distributed ad-hoc mode coupled with time sharing scheme can help in minimizing the collision problem as shown by (Kamimura & Tomita, 2017).

According to the discussion in Section 1.1, distributed TDMA is a promising multiple access scheme for multihop topologies, to maximize the bandwidth utilization and conveying data in bounded and limited time with no collision (Jakllari & Ramanathan, n.d.); (Cosar et al., 2011); (Peng, Liu, Wang, & Zeng, 2020). However, it needs stringent time synchronization and slot alignment among the SNs. A vast number of time synchronization algorithms are proposed and many of them are expensive in terms of message exchange (Mathioudakis, White, Harris, & Merrett, 2008) (Gotzhein, 2020), which results in consuming drastic energy too.

Configuration steps needed for multihop distributed TDMA scheme that are based on synchronizing the SNs' clocks are time synchronization, time slot assignment and time slot alignment or re-synchronization as shown in Figure 1.1. After time synchronization is achieved and all SNs have the same notion of time, they still do not know when to access the medium. Therefore, they need a proper time slot assignment algorithm to assign time slot numbers to them in order to access the medium without contention. Most of the slot assignment algorithms in the literature assume that all network SNs are synced in terms of time (Soua et al., 2012); (Bhatia & Hansdah, 2013); (Zeng et al., 2014). Care should be taken that time synchronization and time slot assignment algorithms are two separate algorithms and each of them has its own overhead and results in protocol inefficiency which is not desirable.

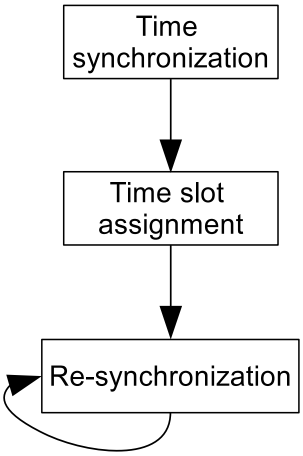

Figure 1.1: Configuration Steps of TDMA MAC Protocols

When SNs have just started up and are trying to synchronize with each other, in many proposed time synchronization or time slot assignment algorithms, the easiest way to access medium and delivering their messages is via CSMA (He et al., 2014); (Elsharief, El-Gawad, & Kim, 2018); (Rana & Saini, 2017); (Elsharief, Abd El-Gawad, & Kim, 2018) as it does not need preliminary setup or other coordination. However, CSMA is not able to handle collision caused by hidden and exposed terminal (P. Huang, Xiao, Soltani, Mutka, & Xi, 2013); (Cao, Yang, Ding, Qian, & Zhi, 2013);

(Shin, Kim, & Lee, 2017); (Khandish, Lee, Park, & Suk, 2018); (Gamal, Sadek, Rizk, & Ahmed, 2019).

Collision caused by hidden terminal is minimized in CSMA by means of Request to Send (RTS) and Clear to Send (CTS) messages, but in WSNs to reduce message exchange and improve protocol efficiency these handshaking messages are eliminated (R. Huang et al., 2015); (G. Shi & Li, 2017). Hidden terminal problem affects packet loss, energy consumption and link utilization too.

One of the key factors to have collision free TDMA is to keep the network globally synced. It means that all SNs should have the same notion of time. This entails all the SNs or a part of them change their timing information continuously and based on the precision required. Sending messages imposes the most inefficiency to the resource-constrained WSN (Kaur & Kaur, 2013); (Djenouri & Bagaa, 2016) that leads to shortening the SN and network lifetime which is not desirable.

It should be noted that many of time synchronization algorithms are not distributed (they follow local or global reference node) and if the reference/master node stops functioning, network will lose the synchronization, at least for a while, till another reference node is selected (Swain & Hansdah, 2015). This problem affects the robustness of the algorithms against node failure and in case of re-configuring, network should experience idle time. Convergence time of time synchronization algorithms is another factor that in some algorithms is high (Maróti et al., 2004); (Schenato & Gamba, 2007); (Swain & Hansdah, 2015); (Elsharief, El-Gawad, & Kim, 2018); (Elsharief, Abd El-Gawad, & Kim, 2018). Achieving network-wide time synchronization delays the time when the WSN is ready to perform data transmission tasks of the SNs and this is of the order of some minutes in some algorithms (Elsharief, El-Gawad, & Kim, 2018); (Elsharief, Abd El-Gawad, & Kim, 2018). If the time synchronization process is long and it should be performed frequently, it will imposes more inefficiency during re-synchronization process (PalChaudhuri et al., 2004); (Benzaïd, Bagaa, & Younis, 2017); (Skiadopoulos et al., 2019).

If a TDMA based protocol bypasses the time synchronization process it will be highly improved in terms of convergence time, possible message overhead and message collision.

1.3 Research Questions

According to the mentioned research motivations above this thesis raises three research questions as below:

- How to reduce or minimize the message collision in order to improve delivery of network configuration messages in a multihop environment?
- How to design an enhanced multi-hop distributed/decentralized MAC protocol based on time sharing approach without requiring extensive global time synchronization?
- How to reduce the overhead of re-synchronization and to avoid interrupting normal data forwarding process for the proposed multi-hop time sharing distributed MAC protocol?

1.4 Research Problems

Based on the research background, this thesis considers the problems listed below that will be addressed by this work.

- Lack of an efficient mechanism for successful delivery of configuration messages for time synchronization and time slot assignment algorithms during the initial configuration phase.
- Lack of an algorithm for allocating and synchronizing Distributed TDMA time slots without performing global time synchronization
- Lack of a multi-hop distributed TDMA MAC protocol which performs time slot re-synchronization with low overheads.

1.5 Research Objectives

In answer to the research questions and problems mentioned above, this work targets three objectives as below:

1. To propose a low-loss packet delivery mechanism for preliminary configuration messages that detects hidden terminal and does not let the SNs to remain in the loop of collision.
2. To enhance distributed-TDMA algorithms to perform slot assignments for slotted multi-hop transmission without requiring initial global time synchronization which has improved convergence time.

3. To propose an efficient time-slot synchronization algorithm which does not disrupt data forwarding functionality while re-synchronizing.

1.6 Expected Contribution

- This work expects to minimize and reduce the message overhead by proposing a novel waiting time that allows medium access with less collision. The proposed protocol is able to detect the collision caused by hidden terminal without exchanging extra messages. This will lead to reduced packet loss.
- The proposed protocol removes global time synchronization and its corresponding overheads, therefore a much faster convergence time is expected.
- Time slot re-synchronization/re-alignment process in th propose protocol is not interrupting the main functionality of the network which is data forwarding. Therefore, less message overhead and idle time is expected.

1.7 Scope

The scope and focus of the proposed protocol is listed below.

- This work only focuses on multi-hop protocols that use single shared channel for multiple access and time slotted algorithms.
- The network topology assumes a many-to-one multihop scenario where many SNs send data to a single sink located inside the network.
- The number of messages exchanged will be used as the metric to evaluate overhead and protocol efficiency in the proposed protocol.

- The proposed protocol will be evaluated by both means of simulation and testbed experiments. Feasibility of the protocol will be tested by testbed (maximum 8 SN) and physical scenarios. At the same time the result obtained from the simulator can be verified.

- The proposed protocol assumes constant rate of real time data transmission, and not bursty/event driven data streams.

- The proposed protocol assumes an error free or low noise channel to study the behavior of the protocol.

- The proposed protocol focuses only on the multihop MAC layer issue and end-to-end routing is managed by upper layers of the network stack, which is not the focus of this thesis.

1.8 Thesis Organization

In this chapter an introduction and background of the research was given as well as introducing the problem together with the objectives of the research. In Chapter 2 related work of this research is reviewed, advantages and disadvantages of them is analyzed and reported. Chapter 3 proposes the novel MAC protocol and Chapter 4 proves the validity of proposed protocol experimentally. Chapter 5 discusses the results achieved in Chapter 4 and Chapter 6 proposes future directions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In Chapter 1, an introduction about current work as well as motivation, research question, objectives, expected contributions and scope of the work was presented. Before reviewing the literature, this work elucidates some problems that affect the MAC protocols.

The well known issue of SNs is the power consumption. Why it is important is because in many applications SNs are not mains powered and use batteries to function. When the battery is depleted, they need to be substituted by another which is not feasible in certain applications such as battlefields and disaster monitoring. Hence, researchers attempt to reduce energy consumption of the SNs as much as possible to extend their lifetime. One effective way to achieve this goal is to let the SNs go to sleep mode when they are idle and not functioning. Therefore, they only need to be awake when they need to send and receive data. However, it will be problematic especially when two or more than two SNs in each other's transmission range send their data exactly or almost at the same time. Certainly their data collide and the intended receiver will not be able to receive the intact data. The collision problem influences both packet loss and bandwidth and at the same time medium will be occupied without delivering information. The main problem in this work is to ponder **how to reduce the overhead imposed to the network in terms of message exchange and collision which at the same time reduces the convergence time**.

According to the explanations in Section 1.1 distributed TDMA can cope with collision and is suitable for realtime data flow as it can guarantee a bounded delay and latency. However, Prerequisite of using TDMA is to make SNs have the same notion of time (time synchronization), however, is expensive in terms of message exchange.

Consider the situation that the synchronization process is successfully done and all network nodes are synced with a reasonable accuracy. Now, SNs should possess their own time slot to start functioning in that specific portion of time. **There should be a mechanism and algorithm to assign time slots to the SNs with minimum message exchange and collision.**

This chapter reviews the literature to the state of the art which is how to synchronize the SNs' clocks and distribute the wireless medium among SNs. The other literature for this research is the algorithms that assign time slots to the SNs in the network. As mentioned earlier, distributed TDMA is a good candidate to be employed in this work. Distributed TDMA is a promising algorithm that commits a collision free communication and let the data be transferred from the source to the sink node in a bounded portion of time. However, according to previous works, SNs' clocks need to be precisely synced, tick in unison and unique time slots (in two-hop neighborhood) should be assigned to the SNs too. Therefore, this chapter, reviews, classifies and evaluates time synchronization and time slot assignment algorithms proposed by researchers in the following sections. In the end a discussion and a comparison table about existing algorithms is conducted too.

2.2 Definition of a Multi-hop Wireless Sensor Network

a multi-hop wireless sensor network is a type of network in which the sensor field is larger than radio range of single SN. Therefore, to reach some destination a SN can use other SNs as relays. Since the transceiver is the major source of power consumption in a SN and long distance transmission requires high power, in some cases multi-hop routing can be more energy efficient than single-hop.

2.3 Classification Criteria for Time Synchronization Algorithms

This work classifies existing time synchronization algorithms based on three criteria of structure, synchronization interval and message overhead. Each class is further expanded into sub-classes which are listed and described below:

Structure is defined as how SNs form the network and if there is any specific SN(s) (root node, cluster head, and so forth) acting differently from other SNs. A thorough literature inspection reveals that existing surveys classify the structure of the network to be centralized and decentralized/distributed (Anceaume & Puaut, 1997); (van Greunen & Rabaey, 2003); (Bojic & Nymoen, 2015). However, in this work, structure is classified as centralized (there is one SN as root or master that controls the synchronization process and all the SNs get synced with the clock of that SN), semi-distributed (there are more than one SN in the network that are responsible for synchronizing the whole network) and finally, fully-distributed (all SNs act the same, and there is no specific SN).

Synchronization interval refers to the frequency of the synchronization process.

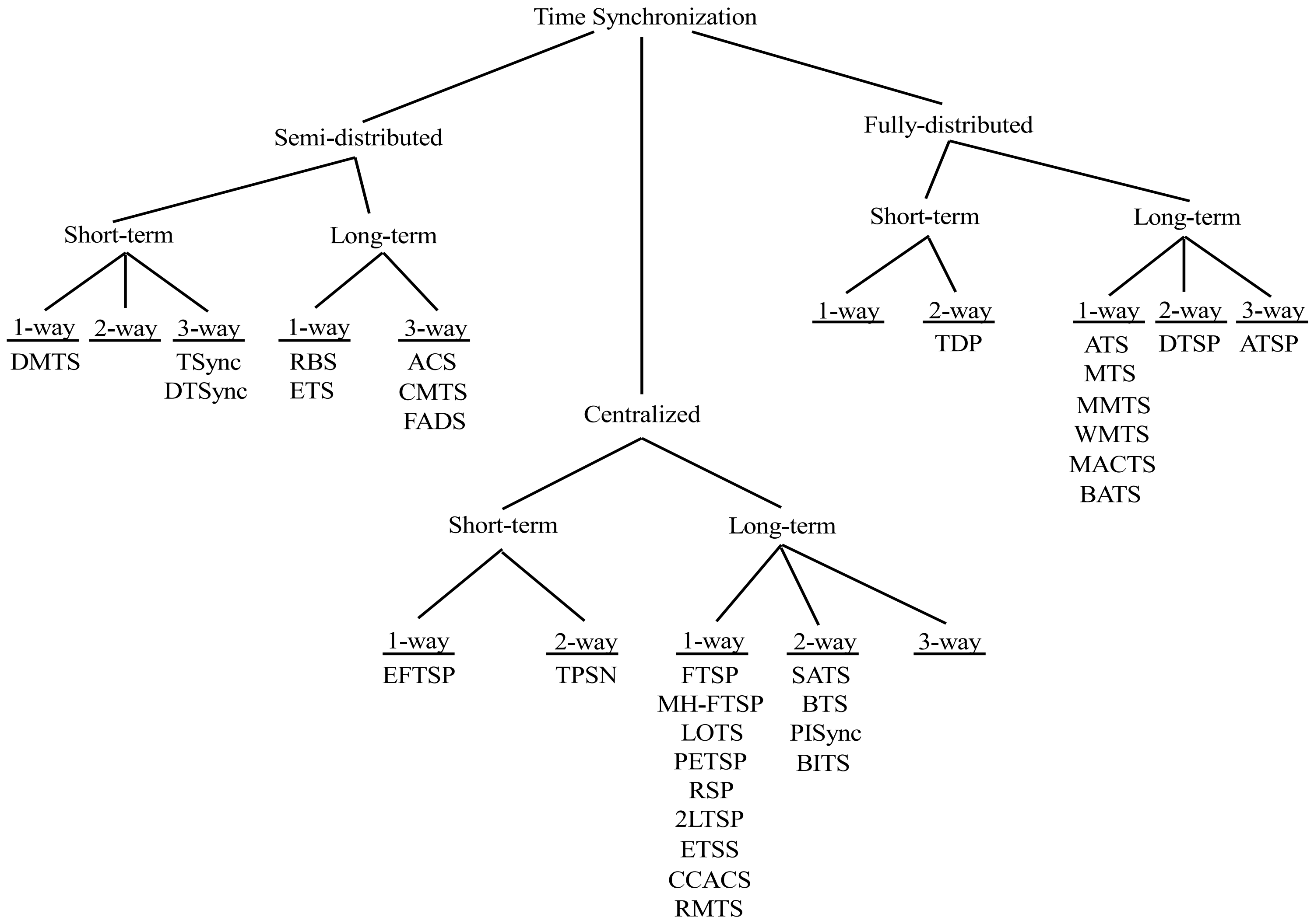

Figure 2.1: Classification of Time Synchronization Algorithms

It is important for algorithms to prolong the synchronization intervals (Anceaume & Puaut, 1997); (Khediri, Nasri, Samet, Wei, & Kachouri, 2012); (Swain & Hansdah, 2015); (Bojic & Nymoen, 2015) as multiple messages are exchanged during each round of synchronization. Therefore, the sub-classes of this class are short term (algorithms only compensate the offset) and long term (algorithms compensate both the offset and the drift).

Message overhead refers to the number of messages exchanged between any pair of SNs (regardless of packet loss) in order for one of them (slave) to get synced with the other one (master). Existing reviews normally classify algorithms as 1-way (unilateral) and 2-way (bilateral) (Sadler & Swami, 2006); (Y.-C. Wu, Chaudhari, & Serpedin, 2011), but algorithms that exchange three messages to get synced exist too. Therefore, sub-classes of this class are one-way (one message is sent from the master node only), two-way (two messages are sent from two SNs (master and slave nodes) consecutively) and three-way (two messages from the master node and one message from slave node are sent). A taxonomy diagram is shown in Figure 2.1.

2.4 Time Synchronization Limitations

It is worth mentioning that time synchronization involves setting the timer value of the SNs in such a way that they show the same value with acceptable accuracy (accuracy is application based) at the same moment and during the whole time they are functioning. When SNs are deployed in a sensor field, they start functioning and their timers start counting too, but not exactly at the same time, specifically in multi-hop scenarios where not all the SNs are in each others' transmission range. In another word, they capture different timer values at the same times. Proposed algorithms attempt to find this phase difference by exchanging messages and achieving network-wide synchronization which is called offset compensation. However, this message exchange generates some constraints and difficulties for the time synchronization process known as message delay uncertainties.

Message delay factors are 1- Send Time, 2- Access Time, 3-Transmission Time, 4- Propagation Time, 5- Reception Time and 6- Receive Time (Ganeriwal et al., 2003). Send Time, Access Time, and Receive Time are not deterministic. Propagation delay is negligible as it is less than 1 μs for 300 meters (Maróti et al., 2004)(Rhee, Lee, Kim, Serpedin, & Wu, 2009). The two remaining factors which are Transmission Time and Reception Time can be measured and are more deterministic. Therefore, non-deterministic factors of the message delay should be estimated. These uncertainties are usually estimated and measured by the time-stamping mechanism at both side of sender and receiver. To keep the network synced, the process of message exchange and time-stamping should be carried out frequently, since the oscillator of the SNs, which generates the clock ticks, drifts away over time from 1μs to 100μs per second (Elson et al., 2003); (Meier & Thiele, 2005); (Sommer & Wattenhofer, 2009); (Kim, Hong, Hur, & Eom, 2010).

Frequent time synchronization has two main deficiencies according to this work. First, it imposes message overhead as frequent message exchange should be carried out. Second, it occupies the channel and does not let SNs transmit their data during the synchronization period. Therefore, estimation of oscillator drift or clock drift leads to consuming less energy and prevent channel occupation (Anceaume & Puaut, 1997);

(Khediri et al., 2012). Estimation of the drift is not as easy as the offset. Clock drift should be measured over time and takes some synchronization intervals. Data points should be recorded and in many cases, statistical analysis is carried out to measure oscillator or clock drift. Consequently, it is better to measure and compensate both offset and drift in addition to measuring message delay uncertainties to have a more precise time synchronization algorithm (Chao et al., 2007); (Sheu et al., 2008); (Chen, Yu, Zhang, Chen, & Sun, 2010).

2.5 Time Synchronization Algorithms in WSNs

In this section, the most famous and important synchronization algorithms in WSNs are classified and shortly reviewed. An evaluation table in addition to a short discussion will also be presented at the end of this section.

2.5.1 Reference Broadcast Synchronization (RBS) (Elson et al., 2003)

RBS eliminates the non-deterministic parts of the critical path shown in Figure 2.3 proposed by (Mock et al., 2000). In fact, it eliminates sent time and access time at the sender side. In RBS, a master node sends out a non-stamped message to the slave nodes, then they stamp the message according to their own local clock and start negotiating with their neighbors to find the best estimation through the Least Square Linear Regression (LSLR). Figure 2.2 illustrates the multi-hop scenario of RBS. As can be seen, there are some SNs (A, B, C, and D) that play the role of master nodes. Big circles in Figure 2.2 determine the transmission range of master nodes. At first, master nodes should get synced, and only then the message can be exchanged with slave nodes. If one of the master nodes fails, the remaining SNs in the overlapped areas can assist in the synchronization process. In RBS, a large number of messages are exchanged in each cycle of synchronization and this results in high chance of collision. RBS isolates the medium access delay as it believes that it does not affect the RBS process, however, the collision leads to longer convergence time and wasting more energy.

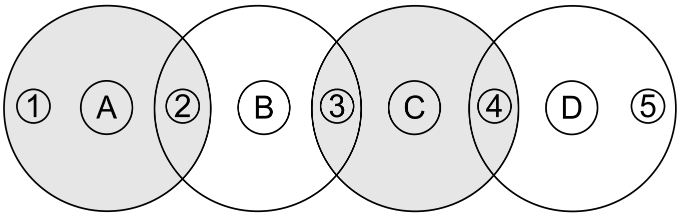

Figure 2.2: Multi-hop RBS Elson et al. (2003)(modified)

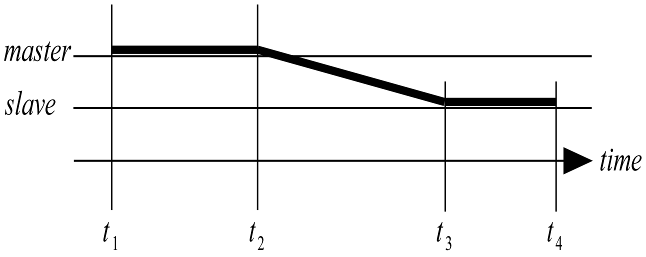

Figure 2.3: Time Critical Path (Mock et al., 2000)

2.5.2 Adaptive Clock Synchronization (ACS) (PalChaudhuri et al., 2004)

ACS uses the technique employed in RBS. However, after receiving n number of messages, it calculates the slope of the line formed by the data points (using linear regression) and returns it back to the sender in addition to a point on that line. It uses random delay to decrease the chance of collision at receiver sides. Afterwards, The master node composes all these slopes together, and broadcasts a packet containing its relative clock drift slope to all the receivers. By doing this, the receivers access information related to their neighbors. Therefore, the number of message exchanged is drastically alleviated. ACS reduces message overhead, but it loses accuracy. There is a trade-off between the number of message exchanged and accuracy. In multi-hop scenario, still a considerable number of the messages are exchanged, and the chance of collision is high in spite of using random delay.

2.5.3 Efficient Time Synchronization (ETS) (Wehbi et al., 2008)

ETS is the revised version of RBS which improves the accuracy and extends the synchronization frequency of RBS. In the multi-hop scenario, ETS creates a hierarchy by some selected SNs that have already got synced by other SNs. These selected SNs are called local references and are responsible for broadcasting synchronization messages. Unlike RBS, non-reference nodes do not exchange any messages and only record the time included in the messages they receive from local references. When enough data points are recorded, they apply a linear regression to measure clock offset and drift. ETS reduces the communication overhead which will eventually improve the network lifetime too. In ETS, there is no guarantee for a hierarchy of selected SNs to be synced well due to the reasons such as hidden or expose terminal.

2.5.4 Timing-sync Protocol for Sensor Networks (TPSN) (Ganeriwal et al., 2003)

TPSN is an NTP-like Mills (1991) algorithm which is able to be event driven in a multi-hop scenario combined with post-facto synchronization. Therefore, there are two solutions in the multi-hop scenario, but event driven scenario is out of scope of this work. The other scenario is based on hierarchy formation, involves all the SNs in the network and employs overhearing technique. In overhearing technique, a pair of SNs start the synchronization process and other SNs in transmission range of that pair can get sync without exchanging any messages. Figure 2.4 illustrates the overhearing technique. Reference node and SN A transmit messages to each other, SN B and C listen to the transmitted messages and get synced without sending any messages. Once the network nodes are formed hierarchically and level by level from the sink node, SNs start measuring the offset and delay by Eq. 2.1, which is illustrated in Figure 2.5. In Figure 2.5, SN A sends a message at time T_1 and the same message is received at T_2. A reply from SN B at T_3 is received at T_4 by SN A. Delay decomposition of TPSN was pointed earlier in Section 2.4. TPSN claims that by time-stamping at MAC layer, the send time, the access time and the receive time are removed. In the case of root breakdown in TPSN, a new root is needed to be selected which wastes both time and energy. It uses acknowledge message to make sure of existence of the SNs, but it increases the message overhead at the same time.

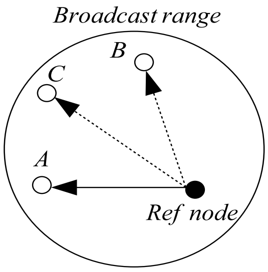

Figure 2.4: Synchronization Using Overhearing Technique

$$\begin{cases} \Delta(offset) = \frac{(T_2-T_1)-(T_4-T_3)}{2} \\ d(delay) = \frac{(T_2-T_1)+(T_4-T_3)}{2} \end{cases} \rightarrow T_2 = T_1 + \Delta + d \tag{2.1}$$

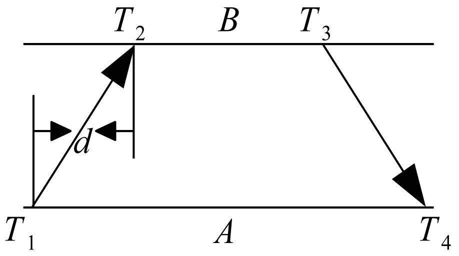

Figure 2.5: Offset and Delay for TPSN (Ganeriwal et al., 2003)

2.5.5 Flooding Time Synchronization Protocol (FTSP) (Maróti et al., 2004)

FTSP deals with uncertainties of radio such as Interrupt Handling Time, Encoding Time, Decoding Time and Byte Alignment Time. To remove the effect of the first three uncertainties, it stores multiple timestamps at both the receiver and the sender side. However, it uses the normalized version upon exchanging messages. It also uses the benefits of both TPSN (Ganeriwal et al., 2003) and RBS (Elson et al., 2003), but no extra steps for spanning tree formation exists and tree is formed during synchronization process. It measures the clock drift through previous consistent data points by linear regression as it believes that the offset between two SNs is linear. It has two scenarios of single reference and multiple references. In order to remove redundant messages in multiple reference scenario, FTSP uses some information embedded in the message and SNs memory for detecting redundant messages. The number of message exchange is high as a flood of messages is formed and in a populated network, chance of collision cannot be ignored.

2.5.6 Time Synchronization (TSync) (Dai & Han, 2004)

TSync uses two algorithms namely HRTS and Individual-based Time Request algorithm (ITR). HRTS is NTP-like Mills (1991) and is proposed in two different scenarios of single reference and multi-reference. In HRTS, the SNs get synced with a single reference, but the main difference with NTP is that it employs two different channels to reduce collision. Single reference broadcasts a message on a channel named common. A specific SN selected by the reference node replies on a clock channel. Eventually, another message is broadcasted with measured offset and delay. Hence, three messages are transmitted, but the second message is only transmitted by one SN at each level of hierarchy, so it is negligible. In multi-reference scenario, the SNs get synced with the reference node that has a level number lower that themselves. ITR is applied for those SNs that for any reason (collision, channel fading and so on), could not get synced with the reference node in HRTS. In ITR, a request message is issued by a SN to get synced to the reference indirectly (multi-hop). In this scenario, all the SNs along the path to the reference node, are switched to the clock channel specified in the request message. Therefore, the actual sync request is sent using the same method. Finally, the reference node sends back the timing information to the invoking SN. TSync has many particular SNs in the network in HRTS (references and particular SNs selected to be involved in synchronization process) which affects the robustness of the algorithm in case of node failure. Employing multichannel radios reduces the chance of collision drastically (hidden and exposed terminal problems are alleviated) and speeds up the convergence time, but multichannel radios are more expensive than single channel radios. It increases the scalability of the algorithm like the algorithm proposed in (Toscano & Bello, 2009).

2.5.7 Broadcast Time Synchronization (BTS) (Xu et al., 2006)

BTS also gets the benefits of both TPSN (Ganeriwal et al., 2003) and RBS (Elson et al., 2003). It first creates a breadth first spanning tree, and then the root node broadcasts