MAC LAYER PROTOCOLS FOR LINEAR WIRELESS SENSOR NETWORKS: A SURVEY

RADOSVETA SOKULLU, EREN DEMİR
Department of Electrical and Electronics Engineering
Ege University
TURKEY
radosveta.sokullu@ege.edu.tr , eren.demir@ege.edu.tr

Abstract: - With the proliferation of new devices and connection technologies, the number and types of wireless sensor networks (WSN) applications have skyrocketed. This diversity has created the need to take a more systematic approach in defining the specifics and requirements of different types of WSNs. A major criterion is the topology of a WSN, which plays an important role in the trade-off between ensuring high performance and extending the lifetime of the network. In this paper we address a group of WSNs that require linear or chain topology, called Linear WSN (LWSN). Linear topology creates addition problems like increased delays, uneven load distribution between the nodes ("relay burden problem") but also provides unique possibilities to address the issues of delay control and energy efficiency at the media access (MAC) layer. Thus in our survey we present a overview of the latest MAC protocols, developed especially for LWSN, discuss their specifics and summarize the related research challenges and open research issues.

Key-Words: Wireless Sensor Networks, MAC Protocols, Linear Topology, Chain Networks, Energy Efficiency, Delay, Relay Burden Problem.

1 Introduction

In many environmental monitoring wireless sensor network applications, a sink gathers data from battery-operated sensors which are deployed on topologies that are mostly linear and this kind of networks are called "*linear wireless sensor networks (LWSNs)"* [1]. LWSNs are used in a number of specific application scenarios such as monitoring bridges [2], gas or oil pipelines [3] and roadside or highways (*e.g* accident detection on highways) [4]. Another interesting application scenario for LWSNs is related to railroad/subway operation and monitoring. Long freight train themselves have a linear structure by nature and sensor modules with external sensors can be deployed near or on the wheels where failures most commonly occur. For example acoustic sensors might be used to detect cracked or flat wheels, while a thermocouple might be used to detect overheated wheel bearings. The sensor modules relay sensor data and alert the base station, which is deployed on the locomotive [5,6,7].

A miner monitoring system, deployed in the confined environment of a coal mine can be used to keep track of the situation in the mine and the activities of the miners. It is an example of an ultra-sparse network with linear topology [8,9]. Underwater pipelines extend for hundreds of kilometers at depths reaching hundreds of meters and are subjected to high pressure. At such depths, it is really difficult to perform maintenance activities. So, LWSNs can be used for monitoring underwater pipelines [10,11,12]. In greenhouse agriculture, LWSNs can be very useful to monitor crop's growing environment. After measuring and transmitting crop's environmental parameters to farmers, they can make decisions based on the data to improve yields and quality [13]. Another LWSN application example is the case of a speleologist going deep down into the bowels of the Earth, who can deploy the wireless network in order to maintain a communication channel with the outside world [14]. In [15], a lightweight lap time measurement system based on wireless sensor nodes that are linearly deployed for Alphine skiing is presented. Another application example of LWSNs is Parking Sensor Network (PSN) which is a special form of WSN. It is rapidly attracting attention around the world and is regarded as one of the first implemented urban services in smart cities (*i.e "*Smart Santander") [16].

Among the numerous applications of sensor networks, monitoring systems for electric cable, boats in a watercourse, smart grids, borders and production line are other examples of linear wireless sensor networks [17,18,19,20].

It is obvious that the number of applications requiring LWSN is continuously increasing. That is why a growing number of researchers are turning to investigating the specifics of these networks and proposing new, more tailored solutions for increasing their efficiency and performance. This paper aims to provide a systematic overview of the recent developments in the area and discusses some of the most recent and promising MAC protocols specifically developed for LWSN.

The paper is organized as follows. In Section 2 we describe LWSNs with their specifics, objectives and challenges and define a general network model of LWSNs. In Section 3, we review the characteristics and operation of some recent MAC protocols for LWSNs and conclude with pointing out the major research challenges in this area.

2 Linear Wireless Sensor Networks

2.1 Network Model

The topology of a WSN is determined by the positions of the sensor devices that belong to the network. In general, a LWSN is composed of n sensors and one base station (sink) arranged along a line. Such a network may be referred to as *simple linear network, chain type network or one-dimensional network*. The authors of [21] give two different definitions for the network topology model of a LWSN.

Model definition 1:

A *simple linear network* is a connected non-cyclic graph where each node has exactly one neighbor or two distinct neighbors. The two nodes with only one neighbor are referred to as the *endpoints* of the network.

Model definition 2:

A *(N,d)-linear network* is a linear network containing *N* nodes, each able to communicate with nodes up to d hops away and shown in Fig. 1. The nodes of such a network are denoted by $n_1, n_2, \ldots n_N$ where nodes n_1 and n_N are the endpoints and node n_i is located between node n_{i-1} and n_{i+1} for $1 < i < N$.

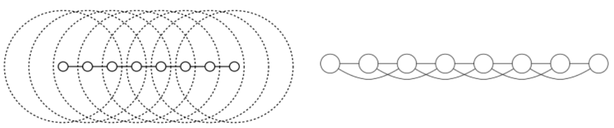

Fig. 1. A (8,2) linear sensor network.

Depending on their role in the transmission process the nodes can be divided in three categories: (1) Source node, (2) Relay node, (3) Sink node. In some of the applications [22] there is only a single source node (at one end of the chain) and a single sink node (at the opposite end of the chain) while all intermediate nodes only relay the data packets created by the source node. However, in most cases, more than one node or even all nodes serve as source/relay nodes. Thus, each node has to transmit both its own data packets and the ones coming from its upstream neighbors. In this case downstream shows the direction towards the sink, while upstream is the direction away from the sink node.

The traffic load created in such a network can be defined as follows:

Let K_i denote the data packets generated by sensor X_i. Then, the total data load $L_{Dtotal}(n)$ in the network is given by Eq. (1).

$$L_{Dtotal}(n) = \sum_{i=1}^{n} Ki \qquad \text{Eq.(1)}$$

The utilization of a network of *N* nodes *U(n)* can be defined as the fraction of time the sink is busy receiving correct data packets, given by Eq. (2):

$$U(n) = \frac{L_{Dcorrect}(n)}{L_{Dtotal}(n)} \qquad \text{Eq.(2)}$$

where $L_{Dcorrect}(n)$ denotes the number of correctly received data packets by the sink.

2.2 Classification of LWSNs

LWSNs can be divided into the following groups:

***Single Line*:**

The simplest LWSN is a *one-level* network composed on *n* uniformly distributed identical sensor nodes and a sink node deployed along a straight geometric line. Such a network may also be referred to as *one-dimensional network* and as shown in Fig. 2. Such topologies are covered in [5,21,26,27].

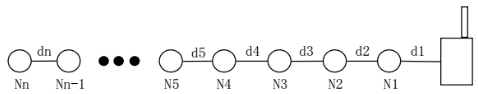

Fig. 2. One-dimensional LWSN.

***Chain Type*:**

Chain type wireless sensor network is another category of LWSNs where the nodes are placed in a semi-linear form [24] and an example of chain type WSN is shown in Fig. 3.

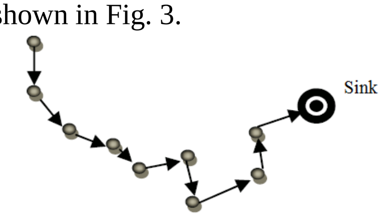

Fig.3. Chain of sensor nodes.

***Chain-Tree*:**

The data forwarding paths of a linear network can be modeled as a tree. Since a tree network can be reduced into equivalent multiline networks, this kind of network is called *Chain-Tree or Multiline LWSN*. In [4], the authors propose a long linear network topology called Long Thin Wireless Sensor Network (LT-WSN) based on ZigBee. In this topology, all nodes are FFDs and are divided into clusters as shown in Fig. 4. In each cluster, two new roles are defined: a cluster head and a bridge. Those nodes have to be manually selected among all nodes.

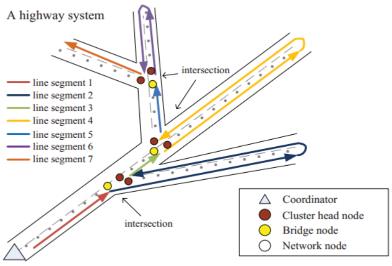

Fig. 4. An example of Chain-Tree Topology.

Hierarchical:

In LWSNs, directional transmission along the linear network creates significant latency if the end-to-end distance is long. Therefore, the number of relay nodes needs to be limited to control the overall latency. A hierarchical architecture of LWSN can balance between the number of relay nodes and the overall latency. In [1], the authors discuss LWSNs from hierarchic point of view. Three types of nodes are introduced which include basic sensor nodes (BSN), data relay nodes (DRN) and data dissemination nodes (DDN). The BSN nodes are responsible for sensing and collecting data which is transmitted to the nearest DRN nodes, which in turn perform the task of processing (*e.g* compression, aggregation) and communicating the collected information through a multi-hop process to the DDN nodes. The latter nodes, located at different intervals of the network communicate the information to the network control center (NCC). Another example is presented in [31], where the authors propose an innovative hierarchical multi-tier architecture for LWSN as shown in Fig. 5.

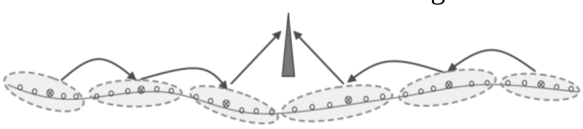

Fig. 5. A three-tier LWSN.

2.3 Specifics and Research Challenges.

Due to the nature of the LWSNs the data packets are relayed hop-by-hop in a chain-to-one pattern. Therefore, traffic load increases for the relay nodes closer to the sink. This also leads to increased packet collisions, congestion and loss and results in significant end-to-end latency. In turn this results in limited application fidelity at the sink or at worst to severe congestion, often node failure due to exhausted energy and finally collapse of the sensor network [18].

One of the major challenges in LWSNs is to ensure the end-to-end packet delivery relaying on a more limited number of relay nodes then other WSNs. Clearly, nodes closer to the sink end up forwarding or relaying more packets than nodes further away. Over time, this uneven load distribution, known as the "*relay burden problem*", results in a disproportionate share of energy consumption and leaves the "*close-in*" nodes with considerably less energy. Therefore the risk of prematurely terminating the network's lifetime is greatly increased. At the same time, these nodes cannot afford long sleep times because they must be alert, in *idle listening* mode, to carry out their relaying function [29]. That is why more intelligent methods for traffic load distribution must be applied in order ensure and prolong the network lifetime.

Due to the linear topology of the network data delivery is more exposed to failure in LWSNs than in classic WSNs. A single node failure can totally disturb the communication process in the network which is an obvious weakness of LWSNs. Nodes can fail due to battery exhaustion, hardware failures, and natural or intentional damage. This kind of failures may cause drastic problems so innovative recovery solutions need to be considered at the MAC layer since there are no alternative routing possibilities to the sink. Furthermore, consecutive faulty nodes form holes which may cause the LWSN to be divided into multiple disconnected segments and failure of overloaded nodes closer to sink may cause terminating the network's lifetime. Some interesting approaches related to failure recovery in LWSNs have been proposed in [25, 32].

In LWSNs, it is also difficult to deal with the accumulation of the traffic produced by each node. Nodes closer to the sink tend to be more congested than the others, channel access becomes more difficult which leads to buffer overflow and packet drop. As a result both packet loss and end-to-end latency is additionally increased [30]. One possible solution can be assigning bigger buffers to the nodes closer to the sink. However this simple approach is not always a viable solution since most WSN nowadays use off-the-shelf components with standard characteristics. Such a solution would require bringing heterogeneity in the network which would increase the implementation cost.

Another important issue in LWSNs is energy consumption. Due to the linearity of the network and the traffic congestion created in the nodes close to the sink, there is an unbalanced energy consumption profile in the network. Also, the nodes

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in the network can experience exposed and hidden terminal problems which induce high latency and frame collisions. Thus, techniques for balancing the energy consumption should be considered while ensuring data traffic is being delivered within an accepted delay margin [28]. An interesting approach to dealing with the exposed and hidden terminal problem is presented in [34]

In addition, there are some potential benefits LWSNs may be able to offer. For example, nodes know their neighbors' position and can schedule packet transmission beforehand and regulate the duty cycle accordingly. This has been used by a number of researchers [33,39]. In most cases nodes are deployed at equal distances which creates advantages positioning and synchronization [6]. Random node deployment along a line or chain provides advantages in formulating clusters, which has been used in some studies to introduce hierarchy in the network in order to regulate the load and the energy consumption. On the other hand, since the topology is already known, additional control overhead for network discovery is minimal. Thus, well known techniques like flooding are not required in LWSN.

As routing solutions are very limited in LWSN, many researchers focus their attention and efforts on the MAC layer to solve the issues described above. Thus in the next section we present an overview of some recent and promising MAC protocols designed specifically for LWSNs.

3 MAC Protocols for LWSNs.

In the literature we can find some examples of MAC protocols that are specifically aimed for linear topologies.

In [33], authors propose a hard real-time MAC protocol with realistic assumptions for a random linear network, where sensors are deployed randomly along a line. The goal is to guarantee message delivery before certain deadline. There are four phases (initialization, switching, unprotected and protected mode) of the protocol. The initialization phase's goal is to organize the network nodes into cells so that all nodes of a cell can communicate with all nodes of the two neighboring cells. In this phase, the sink node emits *CC(i)* message, creating cell *i*. All nodes that receive this message emit another *CC* message according to a timer called $backoff_{initialization}$ which is proportional to their distance to the sender. The furthest will emit first. During this backoff time, each node records the number of *CC* messages it has received, the time of reception of the last one and the number of the last created cell. When emitting a *CC* message, a node also starts $timer_{last}$. If it expires before receiving any new message, the node knows it is the last node of the network, and sends out an *END* message. *END* message informs the sink node the initialization phase has ended. At the end of this phase, each node will know *I* the cell it belongs to, and *R* its position inside the cell. Also, it is assumed that each node knows its absolute position *A*.

After the initialization, run time can start in unprotected mode which offers near optimal speed for message transmission towards the sink (Fig. 6). If a collision occurs in unprotected mode, the network switches to protected mode. This mode guarantees collision-free functioning with bounded transmission times and shown in Fig. 7. It uses the cell based organization created during initialization phase. The overall idea is to reserve 5 cells ahead (*i.e.* towards the sink) of the sending node before sending the alarm message, using signaling messages. Once reserved, a cell cannot generate new alarm message which may cause collision. After reservation, the ALARM message which can be any of length is transmitted in unprotected mode.

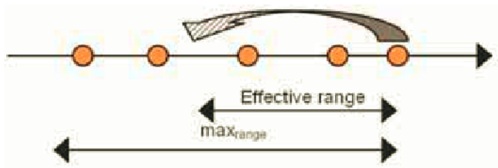

Fig. 6. Unprotected mode

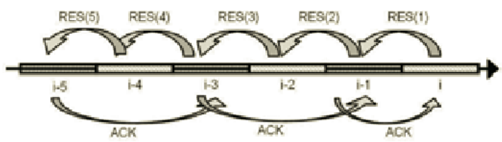

Fig. 7. Protected mode

It is up to the sink to switch back to unprotected mode. Switching back to unprotected mode yields very good transmission times. The sink decides based on the rate of arriving alarms: if there are few, the network is considered not congested and switching back should not lead immediately to collision. Switching is physically done using a jamming message *JAM*. Each node emits this JAM message once when it hears another *JAM* message or detects a collision. Simulations has been used to quantify the speed of the protocol and results has shown that a hybrid approach (using protected & unprotected mode) provides good performance and can be very attractive for real-time linear networks.

DiS-MAC [34] is a Directional Scheduled MAC protocol which guarantees collision-free communication between synchronized sensor nodes

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arranged in a linear topology. It uses the advantages of directional antennas, increased spatial reuse, higher gains, longer ranges between communicating nodes and eliminates the interference and collisions by pointing the radio beam in the desired direction. This protocol has been implemented for highway monitoring. In DiS-MAC, each node is equipped with one transceiver and a directional antenna with a single beam of high gain in a particular direction, and a lower gain back lobe in the opposite direction.

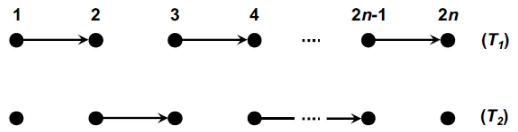

Fig. 8. DiS-MAC topology and operation

Channel access in DiS-MAC is divided in two phases (Phase I and Phase II). Each phase has duration of T_1 and T_2. (optionally $T_1 = T_2 = T$). When the system is in Phase I, only the nodes in positions 2n-1 on the chain are allowed to transmit for a time interval T_1 where n corresponds to each node's position on the chain as shown in Fig. 8. Similarly, during Phase II, the rest of the nodes (*i.e.* the ones located at 2n points) on the chain can access the channel and transmit their packets. During a *scheduling cycle* that lasts for *2T* all nodes have been in two possible states, transmitting or receiving and packet transmission occur simultaneously.

Compared to contention based protocols DiS-MAC does not use RTS/CTS packets and the use of directional antennas provides a solution to the collisions and hidden terminal problems and also avoids the control packet overhead. In addition, per hop latency is minimized as there is no backoff mechanism and the latency can be approximated by *2T*. However, the main focus of the paper is throughput rather than the delay. Simulations have been done under three main scenarios: only the first node acting as source, all nodes generating packets and all nodes generating packets and these packets are forwarded to a final destination defined by the probability *q*. Results show that the protocol provides stable and reliable links between nodes. However, larger payloads results in more errors and degradation of the system performance. The authors suggest that in case the transmission of large packet is required, the incorporation of channel coding and data fragmentation techniques should be considered with Dis-MAC.

LC-MAC (Long-chain MAC) [18] is a duty cycle medium access control protocol that exploits a mechanism for relay nodes booking in advance and transmitting in a burst manner in order to reduce the end-to-end delivery delay in a long-chain sensor network scenario without sacrificing energy efficiency. There are three steps involved. The first step is the location detection and it is like an initialization phase. At the beginning of initialization relay nodes detect neighboring relay nodes. The relay node which only has one neighboring relay node will set itself as an end point of the long-chain. This end node is noted as R_n and is shown in Fig. 9. Then, R_n will send a Location Detect Package (LDP) including its address to its neighboring relay node. The neighboring relay node that gets the LDP will add its address into this package and send it to another neighboring relay node. The LDP will be relayed and finally reach the sink. The sink sends the LDP with address table back along the route it came (Fig. 9). As a result, relay nodes can get their location information.

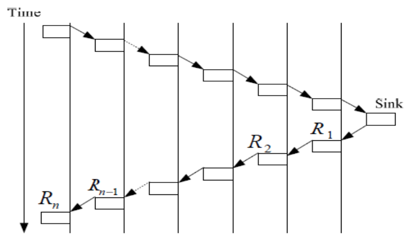

Fig. 9. Distance detection mechanism of LC-MAC

During the second step super SYNC message passing is done. Every relay node will create a Staggered Wakeup Schedule (SWS) for relaying super synchronization (SSYNC) message. The SWS for a relay node is calculated according to the node's location. For a relay action, it doesn't include RTS(ready to send) or CTS(clear to send), because every relay node follows the SWS to transmit SSYNC, so collision can be avoided. SSYNC relay action is shown in Fig. 10.

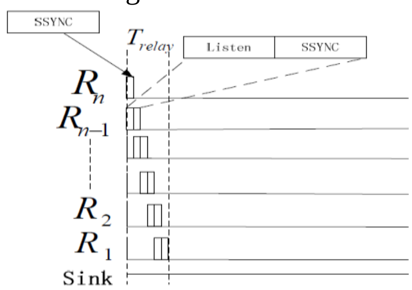

Fig. 10. SSYNC relay action of LC-MAC

The SSYNC is composed of a transmission information part and a registration part. The transmission information part includes a sleep schedule and address information. The registration part is divided into n fractions for n relay nodes. Each fraction has a space *p* bits to register the

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number of packets which are going to be send. Once the endpoint is confirmed, the length of SSYNC is fixed. Any relay node getting SSYNC will update it. After the second step, every relay node gets the information about the number of data packets belonging to each relay node. Then, every relay node will calculate the time point to wake up and relay the data packets. It is also a staggered wake up. At the last step the burst transmission occurs for the network. The SSYNC frame structure and an example of burst transmission is shown in Fig. 11. The authors evaluate the performance of LC-MAC through simulation, comparing LC-MAC with S-MAC and S-MAC with adaptive listen mode [35]. Results show that LC-MAC performs much better than S-MAC with more than 99% decrease in latency, a small amount decrease in energy consumption and a better throughput in heavier traffic for long-chain scenario.

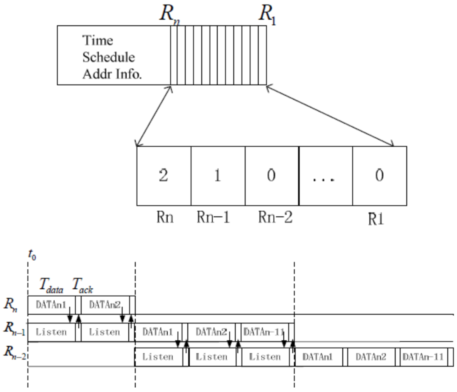

Fig. 11. SSYNC framework and burst transmission with staggered wakeup.

In [5], authors apply the RTS/CTS (Request To Send/Clear To Send) mechanism of IEEE 802.11 [37] to the unslotted CSMA/CA algorithm of IEEE 802.15.4 [38], in a linear sensor network. The CSMA/CA procedure has shown to be an effective approach to increase throughput in shared medium environments. Also, the RTS/CTS mechanism is used to reduce the effects of collisions caused by the hidden terminal. The authors point out the benefits of combining these two mechanisms for reducing packet drops. They also argue that the combination helps reduce collisions as well.

The algorithm of the protocol can be summarized as follows. When a node has a data frame to send, it first attempts to send a RTS with unslotted CSMA/CA. If the channel is detected idle in at most five attempts, the pending frame can be sent and the receiver replies by sending a CTS without backoff. Otherwise the current frame is dropped in order to fight against the medium overload. When the sender receives the CTS, it sends the data frame directly. Finally, the receiver sends an acknowledgement (ACK) as soon as the data frame transmission ends. RTSs and CTSs contain the maximum duration of the whole exchange. When a RTS is transmitted, a timer is started at the sending entity with a duration of $t_{RTS} + 2t_{TA} + t_{CTS} + t_{DATA}$, where t_{RTS}, t_{CTS} and t_{DATA} are the time to transmit a RTS frame, a CTS frame and the data frame respectively and t_{TA} is the turn-around time. The length of the data frame is included in the fields of RTS and CTS frames. When a node receives a RTS or CTS concerning another node, a timer is also started with duration depending on the length of the pending frame. Unslotted CSMA/CA stops decrementing its backoff counter. Once the timer has expired, unslotted CSMA/CA continues reducing the original backoff. Also, there is a tradeoff between the duration required to send RTS/CTS and the length of the data frame. For small data frames, the benefit of RTS/CTS mechanism is reduced.

The authors propose a *leaky shift register* model which is shown in Fig. 12. Packets flow from left to the right, hence the name *shift register*. With this model, some frames can be dropped or lost, hence the name *leaky register*.

In this model, there are three reasons for a node to drop or lose packets: Medium overload, FIFO overload and Retransmission credit exceeded

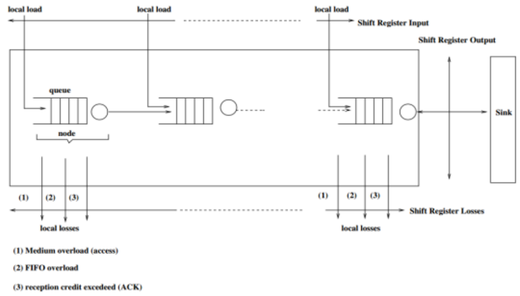

Fig. 12. The leaky shift register model.

(ACK), the main one being traffic overload. The authors focus on the evaluation of the leaky shift register. They study the relationship between the register parameters (the local traffic load, the number of nodes and the size of the node queue) and the leaks of the register with and without the RTS/CTS mechanism. In the leaky shift register, forwarded packets become increasingly important as they get closer to the sink. Simulation results show that the number of dropped packets decreases significantly with RTS/CTS, as well as the load of the queues, at the cost of a slight increase in delay.

CMAC-T [13] is a chain-type medium access control protocol based on tokens and is designed and implemented for monitoring crop’s growing environment. The protocol is combined with access

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on demand and stationary distribution of time slots. It uses two main types of frames, beacon frame and data frame. Beacon frames are responsible for the synchronization between adjacent nodes and assigning channel permission. Frame length is stable. It includes two bytes. The first one stores token information and the other one stores the number of nodes in the network. Token is different in different periods. Each node, except uploading its own data, has to transmit other node's data. So the length of data frame is changeable for different nodes. Data frame also includes the node's ID and alarm information. Alarm information is one bit indicating that the node has low power level.

In CMAC-T, synchronization is done by using beacon frames. The sink node periodically sends a certain number of beacon frames. After waking up from sleeping state, nodes in the network randomly receive a beacon frame containing a time slice and token information, which can determine whether nodes get the communication authority. If the get it, they finish synchronization and later complete data transmission between adjacent nodes. Otherwise, they will continue to sleep. In this way, the network not only avoids data collision in data transmission, but also reduces the power consumption (Fig.13). The authors state that CMAC-T has been applied in a greenhouse and has satisfied the requirements of high reliability and low power consumption.

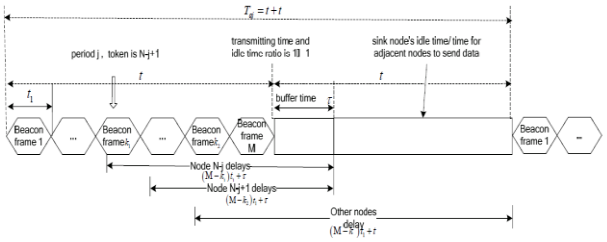

Fig.13. Synchronization and communication process of CMAC-T.

MFT-MAC (Multi frame transmission MAC) [39] is a contention-based duty cycled MAC protocol using a synchronized approach. It uses a control frame called PION that considers the number of DATA frames to be transmitted to the next node in order to improve the energy efficiency and reduce the end-to-end delay. MFT-MAC forwards multiple data frames over the multi-hops in a single duty cycle in order to reduce energy consumption without sacrificing the end-to-end delay. The protocol is well suited for data collection applications in which sensor nodes have to reach the sink node through multi-hops in a chain topology. There are three periods in a single cycle: SYNC, DATA and SLEEP. Nodes synchronize their clocks with the required precision in the SYNC period. In the DATA period, the source node contends with its neighbors and setups a forwarding path using the control frame for sending the data to the sink node in the SLEEP period. SLEEP period is the actual data transmission period but only the next hop node wake up according to the schedule created in DATA period and the other nodes sleep in this period. The control frame PION is similar to the RTS/CTS mechanism and solves the hidden terminal problem. PION includes all fields of RTS/CTS and the final destination address, the hop count and the number of multi frames. In the SLEEP period the nodes wake up at some specific time in order to receive the multi frames and then go back to sleep after transmitting data frames of its own plus received from the previous node. The number of DATA frames transmitted in the SLEEP period is determined using the number of PIONs transmitted in the DATA period. If the number of nodes in the chain is greater than the number of PIONs, the transmission should be continued in the next cycle. The operation of MFT-MAC is shown in Fig. 14. Authors compared the MFT-MAC with DW-MAC [40] and R-MAC [41] protocols which use an adaptive duty cycle. Results show that MFT-MAC is superior to the DW-MAC and R-MAC in regard to average power consumption, average end-to-end delay and throughput.

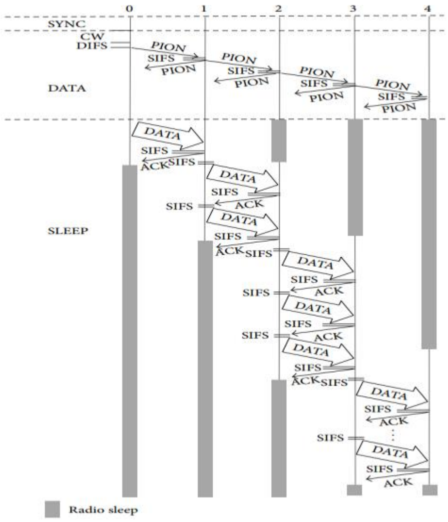

Fig. 14. The MFT-MAC operation.

AC-MAC/DPM (Adaptive Coordinated MAC protocol based on Dynamic Power Management) [42] focuses on reducing the number of transceiver state switches. It guarantees low delay, high throughput and reduced energy consumption when the traffic load is high. In order to reduce the energy consumption due to transceiver state switching between idle and sleep, AC-MAC/DPM uses Dynamic Power Management [43] mechanism. The basic principle of the protocol is to control the value

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of T_i which is the duration between transition to sleep state and active state. The protocol calculates a value called R_i which is the number of new duty cycles according to sensor' traffic load. The number of packets queued at the MAC layer is an indication of the traffic load. A node announces the value of R_i through the RTS/CTS packets. On receiving RTS/CTS packets, all nodes either within one-hop of the transmitter or the receiver, may follow the same new duty cycle during one basic cycle time. One node accepts only one R_i value within one basic cycle time. The algorithm for deciding the number of chances of communications within one basic duty cycle is shown in Fig. 15. The authors compare the AC-MAC/DPM with the S-MAC protocol. They

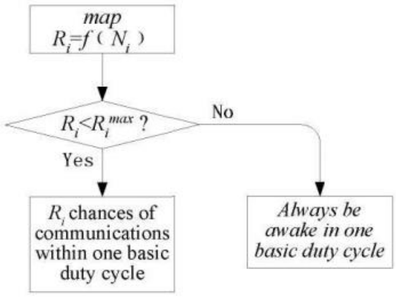

Fig.15. Algorithm for determining the chances of communication within one basic duty cycle.

the end-to-end delay of packets in a multi-hop linear topology. The results show that when the traffic load is high AC-MAC/DPM can be more efficient than S-MAC in terms of delay and energy.

WiWi [14] is a contention-free MAC protocol based on synchronous multi-hop transmission along a chain of independent nodes. Devices are displaced in order to build up a linear (or curvilinear) strip. WiWi recalls some DiS-MAC features; in particular both protocols avoid interferences between simultaneous transmissions by alternating transmissions between adjacent nodes. However, WiWi does not require directional antennas; it provides bidirectional communication over a single RF channel. The communication between WiWi nodes is synchronous, based on fixed size packets and follows a staggered pattern. The downstream data flow proceeds downwards from the head of the chain to the tail. Every node resynchronizes its clock upon the start of the incoming down-stream packets. Once a node is synchronized with the downstream flow, its activity pattern is receive-transmit-idle-transmit-receive-idle (R-T-I-T-R-I) regardless its position in the chain. The upstream flow follows the same principle of passing messages along the chain, but between the reception of a packet and its forwarding, the node waits 4 time slots in order not to collide with the downstream one and it is shown in Fig. 16. Moreover, WiWi nodes

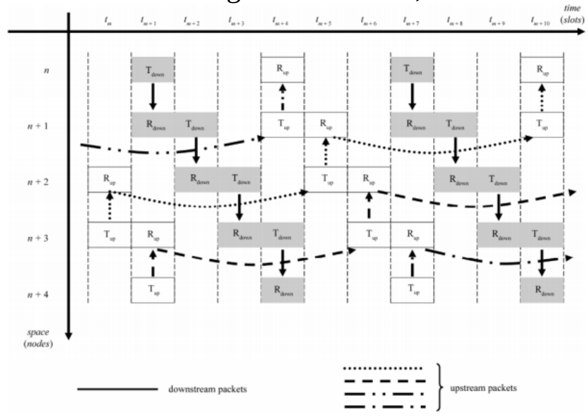

Fig. 16. Bidirectional staggered transmission.

require no explicit addressing because within the range of transmission there is only one receiving node (*i.e* the next hop for the packet). The authors argue that WiWi provides deterministic and predictable latency and throughput in both directions. However, in this protocol power consumption is not considered.

4 Conclusion

In this paper we have addressed a specific group of WSN, the linear WSN. We have summarized their characteristics and challenges and provided an in-depth overview of recently proposed MAC protocols that aim to solve these specific challenges.

References:

[1] I. Jawhar, N. Mohamed, and D. P. Agrawal, "Linear wireless sensor networks: Classification and applications," *J. Netw. Comput. Appl.*,pp. 1671-1682, September 2011.

[2] S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser and M. Turon, "Health monitoring of civil infrastructures using wireless sensor networks," in *IPSN07: Proceedings of the 6th international conference on Information processing in sensor networks.* ACM Press, 2007, pp. 254-263.

[3] I. Stoianov, L. Nachman, S. Madden and T. Tokmouline, "PIPENET: A wireless sensor network for pipeline monitoring," in *ACM IPSN*, 2007, pp. 264-273.

[4] Y.C.L. Meng-Shiuan Pan, Hua-Wei Fang and Y.C. Tseng, "Address assignment and routing schemes for zigbee-based long-thin wireless sensor networks," in *IEEE Vehicular Technology Conference' 08 Spring* 2008, pp. 173-177.

[5] M. Zimmerling, W. Dargie, and J. M. Reason, “Localized power-aware routing in linear wireless sensor networks,” in *Proceedings of the 2nd ACM International Conference on Context-awareness for Self-managing Systems*, CASEMAN’08, New York, 2008 pp.24-33.
[6] Nan, Wang, et al. "Research on linear wireless sensor networks used for online monitoring of rolling bearing in freight train." *Journal of Physics: Conference Series.* Vol. 305. No. 1. IOP Publishing, 2011.
[7] Shafiullah, G.M.; Azad, S.A.; Ali, A.B.M.S., "Energy-Efficient Wireless MAC Protocols for Railway Monitoring Applications," *Intelligent Transportation Systems, IEEE Transactions* on , vol.14, no.2, pp.649,659, June 2013
[8] Li, M. and Liu, Y. 2009. “Underground coal mine monitoring with wireless sensor networks”. *ACM Trans. Sensor Netw., 5, 2, Article 10* (March 2009), 29 pages. DOI = 10.1145/1498915.1498916.
[9] A. Kumar, K. Singh, D. Bhattacharya, “Coal Mining Safety Monitoring Using WSN,” *International Journal of Scientific Engineering and Technology, Volume No.2 , Issue No.10,* 2013, pp. 979-981.
[10] Yang Xiao, Miao Peng, John Gibson, Geoffrey G. Xie, Ding-Zhu Du, Athanasios V. Vasilakos, "Tight Performance Bounds of Multihop Fair Access for MAC Protocols in Wireless Sensor Networks and Underwater Sensor Networks", *IEEE Transactions on Mobile Computing*, vol.11, no. 10, pp. 1538-1554, Oct. 2012.
[11] N. Mohamed, I. Jawhar, J. Al-Jaroodi, and L. Zhang, “Sensor network architectures for monitoring underwater pipelines,” *Sensors*, vol.11, no.11, pp. 10738- 10764, 2011
[12] Y. Xiao. “Underwater Acoustic Sensor Networks”. CRC Press, 2010.
[13] Tong Sun, Xi J. Yan, Yan Yan. "A Chain-type Wireless Sensor Network in Greenhouse Agriculture". *Journal of Computers*, 2013, 8(9) pp. 2366-2373.
[14] D. Caneva and P. Montessoro, "A Synchronous and Deterministic MAC Protocol for Wireless Communications on Linear Topologies," *Int'l J. of Communications, Network and System Sciences*, Vol. 3 No. 12, 2010, pp. 925-933.
[15] Hyung-Bong Lee, Ki-Hyeon Kwon, Lae-Jeong Park, Tae-Yun Chung, and Qishi Wu, “A Lightweight Lap Time Measurement System for Alpine Ski Sport Using a TDMA-Based Linear Wireless Sensor Network,”*International Journal of Distributed Sensor Networks*, vol. 2012, Article ID 674380, 15 pages, 2012.
[16] Trista Lin, Hervé Rivano, and Frédéric Le Mouël, “How to choose the relevant MAC protocol for wireless smart parking urban networks ?,” In *Proceedings of the 11th ACM symposium on Performance evaluation of wireless ad hoc, sensor, & ubiquitous networks* (PE-WASUN '14). ACM, New York, NY, USA, 1-8., 2014.
[17] T. Watteyne, I. Augt’e-Blum, and S. Ubt’eda, “Dual-mode real-time mac protocol forwireless sensor networks: a validation/simulation approach”. International Conference on Integrated Internet Ad Hoc and Sensor Networks, 138(2):2, May 2006.
[18] Chen Fang, Hao Liu, LiLi Qian, "LC-MAC: An Efficient MAC Protocol for the Long-Chain Wireless Sensor Networks", *CMC, 2011, Communications and Mobile Computing, International Conference on, Communications and Mobile Computing, International Conference* on 2011, pp. 495-500.
[19] F. Salvadori, C.S. Gehrke, A.C.D. Oliveira, M.D. Campos, and P.S. Sausen, "Smart Grid Infrastructure Using a Hybrid Network Architecture", *presented at IEEE Trans. Smart Grid, 2013,* pp.1630-1639, 2013.
[20] T. Karveli, K. Voulgaris, M. Ghavami, and A. H. Aghvami, “A collision-free scheduling scheme for sensor networks arranged in linear topologies and using directional antennas,” in *Proceedings of the 2nd International Conference on Sensor Technologies and Applications (SENSORCOMM '08),* pp. 18–22, Cap Esterel, France, August 2008.
[21] http://eprint.iacr.org/2014/288.pdf
[22] El-Darymli K., "Amplify-and-Forward cooperative relaying for a linear Wireless Sensor Network," Systems Man and Cybernetics (SMC), IEEE International Conference on , vol., no., pp.106,112, 10-13 Oct. 2010
[23] D. Dudek, C. Haas, A. Kuntz, M. Zitterbart, D. Krüger, P. Rothenpieler, D. Pfisterer, S. Fischer, “A wireless sensor network for border surveillance,” *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems*,Berkeley California, Nov. 04-06, 2009.
[24] Sumithra S., Aruldos Albert Victoire T., “An energy efficient linear chain-based clustering routing protocol for wireless sensor networks,” *Journal of Theoretical and Applied Information Technology*, May 2014, Vol. 63 No.3 pp. 654-664, 2014.

[25] Nader Mohamed, Jameela Al-Jaroodi, and Imad Jawhar, “Modeling the Performance of Faulty Linear Wireless Sensor Networks,” *International Journal of Distributed Sensor Networks*, vol. 2014, Article ID 835473, 12 pages, 2014.

[26] Bischoff, R., Wattenhofer, R., "Analyzing connectivity-based multi-hop ad-hoc positioning," *Pervasive Computing and Communications, 2004. PerCom 2004. Proceedings of the Second IEEE Annual Conference* on , vol., no., pp.165,174, 14-17 March 2004.

[27] Z. Lotker, M.M. de Albeniz, S. Perennes., “Range-free ranking in sensor networks and its applications to localization,” in ADHOC-NOW, 2004.

[28] Bin He and Gang Li, “PUAR: Performance and Usage Aware Routing Algorithm for Long and Linear Wireless Sensor Networks,” *International Journal of Distributed Sensor Networks, vol. 2014*, Article ID 464963, 13 pages, 2014.

[29] H. Ozgur Sanli, R. Simha, “A Joint Design Approach for Communication Schedule and Layout of Wireless Sensor Networks”, *Proceedings of ICWN’05*, Las Vegas,NV,2005.

[30] Noori, M.; Ardakani, M., "Characterizing the traffic distribution in linear wireless sensor networks," *Communications Letters, IEEE*, vol.12, no.8, pp.554,556, Aug. 2008.

[31] Chang Wen Chen and Yu Wang, “Chain-Type Wireless Sensor Network for Monitoring Long Range Infrastructures: Architecture and Protocols,” *Int. Journal of Distributed Sensor Networks,* vol. 4, no. 4, pp. 287-314, 2008.

[32] Nader Mohamed, Jameela Al-Jaroodi, and Imad Jawhar, “A Cost-Effective Design for Combining Sensing Robots and Fixed Sensors for Fault-Tolerant Linear Wireless Sensor Networks,” *International Journal of Distributed Sensor Networks*, vol. 2014, Article ID 659356, 11 pages, 2014.

[33] Thomas Watteyne , Isabelle Augé-Blum , Stéphane Ubéda, “Dual-mode real-time MAC protocol for wireless sensor networks: a validation/simulation approach,” *Proceedings of the first international conference on Integrated internet ad hoc and sensor networks*, May 30-31, 2006, Nice, France.

[34] Karveli, T.; Voulgaris, K.; Ghavami, M.; Aghvami, A.H., "DiS-MAC: A MAC protocol for sensor networks used for roadside and highway monitoring," *Ultra Modern Telecommunications & Workshops, 2009. ICUMT '09. International Conference* on , vol., no., pp.1,6, 12-14 Oct. 2009.

[35] Wei Ye,Heidemann, J, Estrin D, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on Networking, June* 2004, pp. 493-506 VOL. 12.

[36] El Hadji Malick Ndoye, Frédérique Jacquet, Michel Misson, Ibrahima Niang., “Evaluation of RTS/CTS with unslotted CSMA/CA algorithm in linear sensor networks,” *NICST’2013, New and smart Information Communication Science and Technology to support Sustainable Development*, 18-20 September 2013, Clermont Ferrand, France.

[37] Dd “Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” ANSI/IEEE, Standard 802.11 R2003, 1999.

[38] “Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs),” ANSI/IEEE, Standard 802.15.4 R2006, 2006.

[39] EunJin Lee, Jeong Woo Jwa, and HeungSoo Kim, “MFT-MAC: A Duty-Cycle MAC Protocol Using Multiframe Transmission for Wireless Sensor Networks,” *International Journal of Distributed Sensor Networks*, vol. 2013, Article ID 858765, 6 pages, 2013.

[40] Y. Sun, S. Du, O. Gurewitz, and D. B. Johnson, “DW-MAC: a low latency, energy efficient demand-wakeup MAC protocol for wireless sensor networks,” *in Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '08)*, pp. 53–62, Hong Kong, China, May 2008.

[41] S. Du, A. K. Saha, and D. B. Johnson, “RMAC: a routing-enhanced duty-cycle MAC protocol for wireless sensor networks,” *in Proceedings of the 26th IEEE International Conference on Computer Communications (IEEE INFOCOM '07)*, pp.1478–1486, 2007.

[42] Feng Li , Yun Li , Weiliang Zhao , Qianbin Chen , Weiwen Tang, “An adaptive coordinated MAC protocol based on dynamic power management for wireless sensor networks,” *Proceedings of the 2006 international conference on Wireless communications and mobile computing*, July 03-06, 2006, Vancouver, Canada.

[43] A. Sinha, A.Chandrakasan. Dynamic power managerment in wireless sensor networks. Design & Test of Computers, 2001, 18(2): 62~74.