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# Impact of network architecture and aggregation process on bandwidth allocation in wireless sensor networks

by

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**Abstract:** Assigning bandwidth to sensors in a Wireless Sensor Network (WSN), while using Time Division Multiple Access (TDMA) protocol, remains an important problem. Even if many solutions were proposed in the literature, nevertheless, and since 2013, we are mainly focused on the critical study and the improvement of Masri's approach published in *Telecommunication Systems* journal. In this paper, we introduce an extended version of our previous approaches (see Tarek Azizi and Rachid Beghdad, 2013, 2014, 2016) based on three fundamental concepts: network architecture, TDMA protocol, and data aggregation, in order to assign the maximum bandwidth to all sensor nodes. Three solutions will be presented in detail: Spiral-Based Clustered Data Aggregation (SBCDA) architecture, Tree-Based Clustered Data Aggregation (TBCDA), and Tree-Based Clustered Wireless Sensor Network (TBC-WSN). Aggregating data can reduce the number of the packets transmitted to the sink. This is the reason why, in the three approaches here described, each cluster head (CH) collects and aggregates received packets from its child nodes, before transmitting the resulting packet to its parent, until the data reaches the sink node (base station). With a number of simulations, we will demonstrate that our approaches are very competitive with Masri's proposition, and also with two other recent works.

**Keywords:** data aggregation, TDMA, bandwidth, superframe length, time slot, tree-based and spiral-based architecture

## 1. Introduction

Due to their potential usage in defense as well as in pervasive commercial and scientific applications, wireless sensor networks are becoming an active topic of research (see Kahn, Katz and Pister, 1999). Recently, many wireless sensor networks have been designed and deployed for numerous kinds of applications (see Ning Xu, 2002).

Many systems challenges still remain to be resolved (see Jianlin Mao, Zhiming Wu and Xing Wu, 2007) like the limited communication bandwidth of the sensors or energy, which is an essential problem, since sensors are usually battery-powered, and in some emergency applications, a short time of data collection is also required. In order to satisfy the above requirements, TDMA is a good choice towards such data gathering sensor networks. Saving energy is done by eliminating collisions, avoiding idle listening, entering inactive states where other sensors transmit their packets, bounding the delays of packets, which is important for the time-driven data aggregation (see Xu et al., 2012) and guaranteeing reliable communication, being maintained by TDMA protocol, as a collision-free access method.

Clustering in WSN (see Dasgupta, Kalpakis and Namjoshi, 2003) is the process of grouping the sensor nodes in a densely deployed large-scale sensor network. An issue is consitituted by the question of selection by the user of some more energy-powerful nodes in the network, meant to act as a Cluster-Heads, while other simple nodes act as cluster-members only (see Nandini, Patil and Patil, 2010). It was proven that this concept can be exploited in some access protocol like TDMA.

Another concept that can be used in TDMA protocol is data aggregation (see Heidemann et al., 2001, and Intanagonwiwat, Govindan and Estrin, 2000). The idea is to combine the incoming data from different child nodes, eliminating redundancy, minimizing the number of transmissions, and thus saving energy. This paradigm shifts the focus from finding short routes between pairs of addressable end-nodes (address-centric) to finding routes from multiple sources to a single destination that allows in-network consolidation of redundant data (data-centric) (see Krishnamachari, Estrin and Wicker, 2002).

The last concept that will be exploited by this study to optimize the bandwidth allocation, using TDMA, is the WSN architecture. For example, in Tree based Data Aggregation Techniques, nodes are organized in a tree topology, where the sink node is represented as a root. All the intermediate nodes perform the aggregation and transfer the resulting aggregated data to the root. Energy efficient tree construction is the main aspect of the tree-based approach (see Thangaraj and Punitha Ponmalar, 2011). We have already exploited this kind of architecture for bandwidth allocation and this leads to good results (see Azizi and Beghdad, 2014).

The problem of bandwidth allocation has been considered in a wired network and cellular network with the use of various multiplexing approaches, such as Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA). Using the allocated TDMA slots, the scheduled access period is used by the sensor nodes according to the reserved bandwidth (see Chitnis et al., 2009). Bandwidth resource allocation and scheduling is a challenging problem in WSNs. In the following, we will address the problem of bandwidth allocation among traffic classes by introducing a TDMA protocol with data aggregation in tree and spiral based architectures.

In this paper, we will present an extended version of our three already proposed solutions: Spiral-Based Clustered Data Aggregation (SBCDA) architecture, Tree-Based Clustered Data Aggregation (TBCDA) and Tree-Based Clustered Wireless Sensor Network (TBC-WSN) (see Azizi and Beghdad, 2013, 2014, 2016). By performing many more simulations, we will be able to demonstrate that our approaches remain better than the compared recent methodological proposals.

First of all, we will compute the superframe length (in order to define the bandwidth, which will be reserved for each sensor node in the network) when sensing is done by any node and simultaneous transmissions are performed by the same-level clusters and 3-hops-away levels. We will consider two different network architectures, ”tree” and ”spiral”, with and without data aggregation, the most complete case being where any sensor node in the network senses data and intermediate nodes are also sensing, aggregating and transmitting data.

When generating new clusters in a specified architecture (tree or spiral), each cluster has two kinds of sensors, cluster head, ”CH”, and cluster member, ”CM”. In the case of spiral architecture each cluster has only two sensors, corresponding to CH and CM.Second, after completing the cluster formation, all CMs of 3-hops-away clusters can concurrently transmit data to their respective CHs without inter-cluster collision.

The major difference between the proposed work and some works, reported in the literature, is that the proposed approach outperforms the existing techniques in terms of bandwidth allocation, in other words, the bandwidth reserved for each sensor node in the network is maximized by grouping sensors in order to transmit their packets at the same time and in the same time slot. Maximizing bandwidth leads to reduction of the superframe length, calculated during the execution of the scheduling algorithm.

The further sections in the paper are organized as follows. In Section 2, the existing methods of bandwidth utilization are presented. In Section 3, the TDMA protocol and bandwidth allocation are discussed and the bandwidth reservation is described. In Section 4, the proposed methods, TBC-WSN, TBCDA, and SBCDA are presented as a combination of superframe length computation, aggregation, and TDMA protocol. Performance of proposed methods is analyzed theoretically in Section 5 and simulation results are explained. Section 6 concludes the paper.

## 2. Related work

In wireless sensor networks, TDMA-based MAC layer protocols are used due to their efficiency.

Mammeri (2005) dealt with the problem of mapping QoS parameters and established conditions for the guarantee of end-to-end QoS. Another definition, related to QoS, presented in Frolik (2004), where it is seen as the network lifetime, is that it is the duration, for which the desired QoS is maintained.

Wassim Masri and Zoubir Mammeri (2010) present QoS support in WSN while highlighting the QoS mapping issue, a complex process, in which QoS parameters are translated from level to level and the authors present a case study of a TDMA tree-based clustered WSN, where network density at the user level is mapped to bandwidth at the network level. In Azizi and Beghdad (2014), we present a new approach, combining data aggregation with TDMA protocol in Tree-Based Clustered Data Aggregation WSNs (TBCDA), by minimizing the large number of transmitted packets to the sink node.

Phan Van Vinh and Hoon Oh (2016) discuss the problem of limited available energy and bandwidth, this problem being inherent in a wireless sensor network, and they present a method (MCMAC) of using multiple channels and a way to optimize the size of the sharable slot.

A new TDMA-based MAC protocol (MC-LMAC), which aims at maximizing the data transmission parallelism with two channels, is described by Phan Van Vinh and Hoon Oh (2015), where the authors include two key schemes, a channel allocation scheme and a slot allocation scheme.

The major demerits of those approaches is the low rate bandwidth reservation, which bears directly on data freshness, accuracy, fairness, and latency, due to the longer size of the superframe calculation.

Our contributions (see Tarek Azizi and Rachid Beghdad, 2013, 2014, 2016) focus on maximizing the bandwidth reserved for each sensor node in the network. We present the SBCDA, TBCDA architectures approach combining data aggregation (and TBC-WSN without data aggregation) with TDMA protocol in WSNs for improving connectivity and avoiding inter-cluster collisions, and for increasing the bandwidth reserved for each sensor node, by computing the length of the superframe generated by all sensor nodes in the network.

So, the challenge here is to implement all the approaches cited in Table 1, in order to establish that our solutions are highly competitive against the approaches considered from the literature. In addition to that, note that all the results that will be presented here were not published before.

Table 1: Summary of related work

| Authors | Title | Bandwidth | Freshness | Accuracy |
|---|---|---|---|---|
| Tarek Azizi, Rachid Beghdad | ”Maximizing Bandwidth In Wireless Sensor Networks Using” TDMA Protocol” | Much more bandwidth reservation | More fresh | Medium accuracy |
| Wassim Masri, Zoubir Mammeri | ”Mapping density to bandwidth in tree-based wireless sensor networks” | More bandwidth reservation | Fresh data | Medium accuracy |
| Tarek Azizi, Rachid Beghdad | ”Mapping density to bandwidth in tree-based wireless sensor networks” | More bandwidth reservation | More fresh | Medium accuracy |
| Tarek Azizi, Rachid Beghdad | ”Bandwidth Assignment in a Cluster-based Wireless Sensor Network” | More bandwidth reservation | Fresh data | High accuracy |
| Phan Van Vinh and Hoon Oh | ”Optimized Sharable-Slot Allocation Using Multiple Channels to Reduce Data-Gathering Delay in Wireless Sensor Networks” | More bandwidth reservation | Fresh data | High accuracy |
| Phan Van Vinh and Hoon Oh | ”O-MAC: an optimized MAC protocol for concurrent data transmission in real-time wireless sensor networks” | More bandwidth reservation | Fresh data | Medium accuracy |

## 3. TDMA protocol and bandwidth allocation

### 3.1. TDMA protocol in WSN

In the TDMA protocol, nodes share the available bandwidth in time through the ”bandwidth sharing method”. The available bandwidth is divided among the frames (see Dawood Khan et al., 2012), and each frame is divided into time slots. On the other hand, energy and fast and efficient query response is another issue in the WSN (see Christian Nastasi et al., 2010).

In the design of an efficient TDMA protocol for wireless sensor network, the following attributes must be considered (see Amrita Ghosal et al., 2011):

- Energy efficiency: it is often very difficult to change or recharge batteries for the sensors.
- Scalability and adaptability to change: any change in network size, node density, and topology, should be handled effectively by TDMA protocols.
- Latency: the detected events in WSN applications must be reported to the sink in real time for an immediate appropriate response action.

- Fairness: it is important to guarantee that the sink node receives information from all sensor nodes fairly, while bandwidth is limited in many WSN applications.

In the TDMA Based MAC protocol, the network is assumed to be formed as clusters. Each one of these clusters is managed by a Cluster Head (CH). The CH collects the information from its child nodes within its cluster, carries data merging, communicates with the other CHs and finally sends the data to the sink. This CH performs the assignment of the time slots to its child nodes (see Ghosal, Halder and Dasbit, 2011).

### 3.2. Bandwidth allocation issues

#### 3.2.1. Variable bandwidth

In reality, many factors moght affect the effective bandwidth, reserved for each sensor. This fact, though, cannot be reflected by the current problem formulation with a constant shared bandwidth as constraint. The computational approach, proposed in this paper, is capable of adapting to the dynamics in the bandwidth, according to the superframe length.

#### 3.2.2. Bandwidth allocation in TDMA protocol

In the TDMA protocol, nodes share the available bandwidth in time through the 'bandwidth sharing method'. The available bandwidth is divided among the frames (see Ghosal, Halder and Dasbit, 2011), and each frame is divided into time slots. The number of time slots of the TDMA frame depends on the length of the frame that we call superframe TDMA. The length of the data transmitted during a time slot depends on the length of the time slot and the transmission bit rate of this network.

## 4. Network model and problem statement

### 4.1. Network model and definitions

In practical terms, we consider a WSN consisting of 58 homogeneous sensor nodes $1, 2, ..., 58$ and the sink node 0. We assume that our network works without inter or intra-cluster interference, and all of the sensor nodes are similar and sense the same kinds of phenomena (temperature, for example). We adopt a perfect data aggregation model and TDMA-based scheduling protocol. This network is characterized by:

- *Network type*: we assume that our network architecture is both hierarchical "tree-based" and "spiral-based".
- *Synchronization of sensors*: the time synchronization of the network can be carried out by applying a synchronization algorithm (see Römer, Blum and Meier, 2005), or by sending a signal from the sinks or other entity capable of reaching all sensors (see Stojmenovic and Olariu, 2005).

We define a round (or reporting period) as a TDMA schedule period consisting of time slots, equivalent to the duration of the process of gathering data from all nodes to the sink. At each time slot, all senders and their corresponding parent nodes are scheduled in the active state, while the remaining nodes are in the "sleep" state. The length of this round is the "superframe length", which we intend to calculate. We consider in this paper simple aggregation functions (such as min, max), through which multiple input packets can be aggregated into a single output packet.

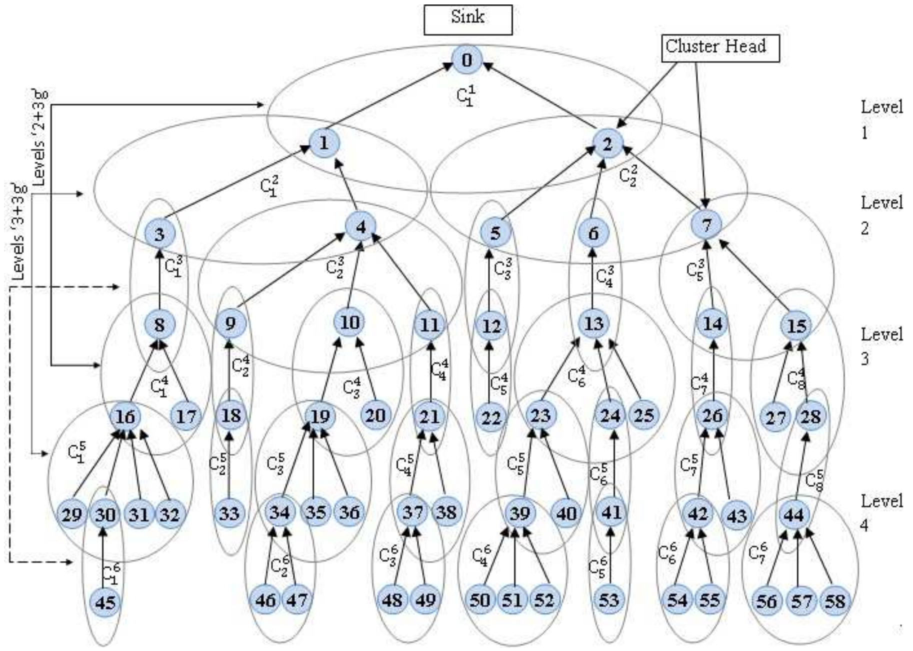

Figure 1: Tree-based clustered sensor network

### 4.2. Problem statement and notations

In order to highlight the relationship between network density and bandwidth reserved for each sensor node in the network, and between superframe length, round and packet size, we took a tree-based and spiral-based clustered sensor network (see Figs. 1, 2, 3, 4), as a pattern. As a model, illustrated in these figures, our network architecture covers any kind of trees and spirals, and our network could have any number of nodes in its respective clusters, irrespective of its depth. Leaf nodes sense data and forward them to their parent nodes in each cluster, which in turn aggregate and forward them to their parent nodes until the data reach the sink. In this article, we compute the number of time slots needed in the superframe for each sensor node in the network to perform their activity.

For the rest of the paper, the following notations are used for convenience, to calculate the superframe length (see Masri and Mammeri, 2010):

$C_i^h$: denotes the cluster number $i$ at level $h$.
$CH(x)$: returns the Cluster Head of cluster $x$,
$CH^{-1}(x)$: returns the cluster, which has $x$ as Cluster Head,
$Ch(x)$: returns the number of all child nodes in cluster $x$,
$S(x)$: is a Boolean variable qual to 1 if child nodes in cluster $x$ sense data and 0 otherwise,
$Nc(h)$: returns the number of clusters at level $h$ :

$$Nc(h) = \begin{cases} 1, & \text{if } h = 1 \\ \\ \sum_{i=1}^{Nc(h-1)} Ch(C_i^{h-1}), & \text{if } h \neq 1 \end{cases}$$

$L(x)$: returns the number of leaf nodes, whose ancestor is the $CH$ of cluster $x$, (here $H$ means the tree depth),

$$L(C_i^h) = \begin{cases} Ch(C_i^h), & \text{if } h = H \\ \\ \sum_{j=\sum_{k=1}^{j-1}(Ch(C_k^h))+1}^{\sum_{k=1}^{j} Ch(C_k^h)} L(C_j^{h+1}), & \text{if } h \neq H \end{cases}$$

$Ns(x)$: returns the number of all sensing child nodes, whose ancestor is the $CH$ of cluster $x$ (with $Ns(0) = 0$),

$$Ns(C_i^h) = \begin{cases} Ch(C_i^h), \quad \text{if} h = H \\ \\ S(C_i^h) \times Ch(C_i^h) + \sum_{j=\sum_{k=1}^{i-1}(Ch(C_k^h))+1}^{\sum_{k=1}^{j} Ch(C_k^h)} L(C_j^{h+1}), \ \text{if} h \neq H. \end{cases}$$

### 4.3. Superframe length calculation

According to our example (Fig. 1), nodes "19" and "20" are in the same cluster $C_3^4$, so they are in the same neighborhood, while nodes "8" and "9" cannot hear each other (they are not in the same cluster). In general case, where each time slot is reserved for one and only one sensor node to transmit its packet, we compute the superframe length when sensing is done by all nodes, and no simultaneous transmissions are performed between clusters. As we notice in Fig. 5, the superframe is composed in this case of 3 parts (squares of three different colors [no colors, please!!!!]): 22 time slots for aggregating and transmitting 22 flows from 22 cluster child nodes of levels '3' and '6', 21 time slots for aggregating and transmitting 21 flows from 21 cluster child nodes of levels '2' and '5', and 15 time slots for aggregating and transmitting 15 flows from 15 cluster child nodes of levels '1' and '4'. The length of the TDMA superframe in the tree-based clustered network with a depth equal to $H$ is obtained by the following formula:

$$Length = \sum_{i=1}^{H} \Big[ \sum_{j=1}^{NC(i)} Ch(C_j^i) \Big] \tag{1}$$

where $H$ denotes the tree depth, i.e. the number of levels in the network. From formula (1), we can see that there is enough space in the superframe for node flows to be sent simultaneously to each other as depicted in Fig. 6.

### 4.4. Proposed approaches

In this paper, we will compute the superframe length when sensing is done by any node and simultaneous transmissions are performed by same-level clusters and 3-hops-away levels. We will consider the most complete case, where any sensor node in the network senses data and intermediate nodes are also sensing, aggregating and transmitting data.

#### 4.4.1. Tree-based Clustered Wireless Sensor Network (TBC-WSN)

In order to practically compute the length of our TDMA superframe and to understand the relationship between the density changes and the bandwidth reserved for each node, we illustrated in Fig. 1 an example of running TDMA without collisions in a tree-based WSN (TBC-WSN). The problem here is: how to run the TDMA with the nodes of different levels without any collision? For example, nodes 3, 5, 18, 19, 21, 25, 26, and 27 can run simultaneously the TDMA, and so on...

In the following, we will introduce our extended formula (2), which is meant to improve over the the Masri's one (see Masri and Mammeri, 2010), in terms of bandwidth allocation. The superframes, calculated by the proposed formula (2), avoid collisions, caused by simultaneous transmission of nodes in the same cluster on one hand, and allow many more sensors to communicate with each other in each slot time on the other hand.

$$\begin{aligned}Length &= [\max_{i=1}^{Nc(2)}\{Ns(C_i^2+1)\}]\\ &+\Big[\max_{i=1}^{Nc(2)}[(\max_{i=1}^{Nc(2)}\{Ns(C_i^2)\});(\max_{i=1}^{Nc(2)}\{Ns(C_i^1)\})-(\max_{i=1}^{Nc(2)}\{Ns(C_i^2)\}+1)]\Big]\\ &+[\max_{i=1}^{Nc(3)}\{Ns(C_i^3)\}],\quad \forall C_i^h, i\in(1,Nc(h)), h\in(1,H).\end{aligned} \tag{2}$$

Figure 5 shows that, from formula (2), the superframe length is composed of three parts:

$[\max_{i=1}^{Nc(2)}\{Ns(C_i^2+1)\}]$: represents the maximum number of all child nodes that do sensing, whose ancestor is among the child nodes of level 1 $\{Ns(C_i^2)\}$

plus one for the sensor itself,

$\Big[\max\limits_{i=1}^{Nc(2)}[(\max\limits_{i=1}^{Nc(2)}\{Ns(C_i^2)\});(\max\limits_{i=1}^{Nc(2)}\{Ns(C_i^1)\})-(\max\limits_{i=1}^{Nc(2)}\{Ns(C_i^2)\}+1)]\Big]$: is the maximum among the number calculated by $\max\limits_{i=1}^{Nc(2)}\{Ns(C_i^2)\}+1$, and the sum of all child nodes that do sensing, whose ancestors are the child nodes of level 1 $\{Ns(C_i^2)\}$, except for those accounted for in the last formula.

$[\max\limits_{i=1}^{Nc(3)}\{Ns(C_i^3)\}]$: represents the maximum number of all child nodes that do sensing, whose ancestor is among the child nodes of level 3 $\{Ns(C_i^3)\}$. In addition, there is no collision here.

### 4.4.2. Tree-based Clustered Wireless Sensor Network with data aggregation (TBCDA)

In order to increase the bandwidth reserved for each sensor node and to limit the problem of collisions among sensors, we propose a communication architecture where nodes operate in TDMA.

We propose a formula, (3), which allows us to calculate the superframe length (see also Fig. 7).

$$Length=\sum_{d=1}^{3}\max_{\substack{h\in\{d+3g\}\\ g=0\ldots H}}\Big\{\max_{i=1}^{Nc(h)}\{Ch(C_i^h)\}\Big\}. \tag{3}$$

From formula (3), we can deduce that the superframe length is composed of three different parts, according to index $d$, as also illustrated in Fig. 7, where:
The first part is composed of all sensor nodes of levels $(1+3g)$, where $g=0,\ldots,H$ (i.e. levels 1, 4, 7, etc.). The length of this part is the maximum number of child nodes of all $(1+3g)$-level clusters (in this case we obtain 3-time slots):

$$d=1:\quad \max_{\substack{h\in\{1+3g\}\\ g=0\ldots H}}\Big\{\max_{i=1}^{Nc(h)}\{Ch(C_i^h)\}\Big\}. \tag{4}$$

The second part is composed of all sensor nodes of levels $(2+3g)$, where $g=\emptyset,\ldots,H$ (i.e. levels 2, 5, 8, etc.). The length of this part is the maximum number of child nodes of all $(2+3g)$-level clusters (in this case we obtain 4-time slots):

$$d=2:\quad \max_{\substack{h\in\{2+3g\}\\ g=0\ldots H}}\Big\{\max_{i=1}^{Nc(h)}\{Ch(C_i^h)\}\Big\}. \tag{5}$$

The third part is composed of all sensor nodes of levels (3+3g), where $g = \emptyset, ..., H$ (i.e. levels 3, 6, 9, etc.). The length of this part is the maximum number of child nodes of all $(3+3g)$-level clusters (in this case we obtain 3-time slots):

$$d = 3 : \quad \max_{\substack{h \in \{3+3g\} \\ g=0...H}} \left\{ \max_{i=1}^{Nc(h)} \{Ch(C_i^h)\} \right\}. \tag{6}$$

### 4.4.3. Spiral-based Clustered Wireless Sensor Network with data aggregation (SBCDA)

We calculate the superframe length and the bandwidth assigned to each sensor node in the network, where CHs perform data aggregation in a TDMA scheduling algorithm. We took as an example the case illustrated in Figs. 2, 3, 4 to better understand the mechanism of calculation of our TDMA superframe length and how the changes in density affect directly the bandwidth reserved for each node.

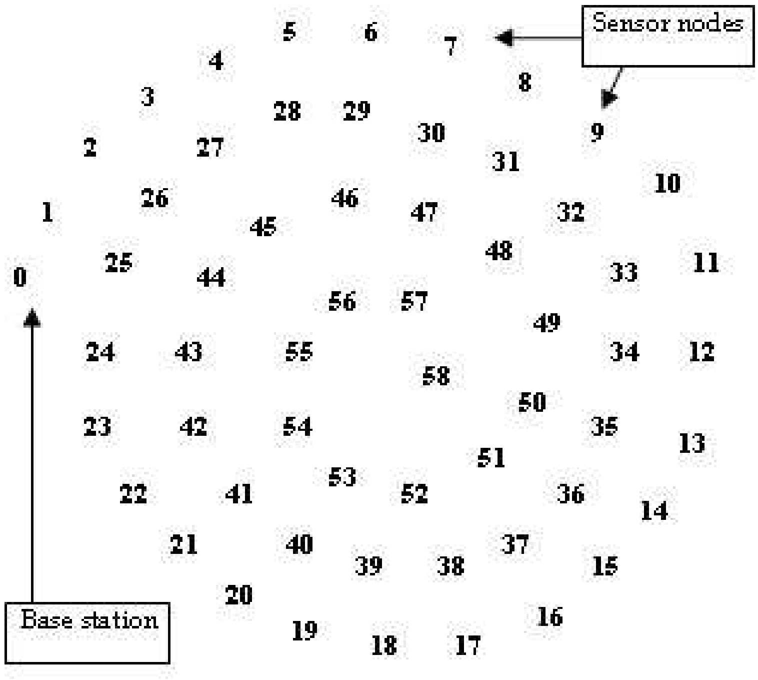

Figure 2: Proposed network model

According to our example, nodes ID19 and ID20 are in the same cluster, so they are in the same neighborhood, while nodes ID8 and ID10 cannot hear each

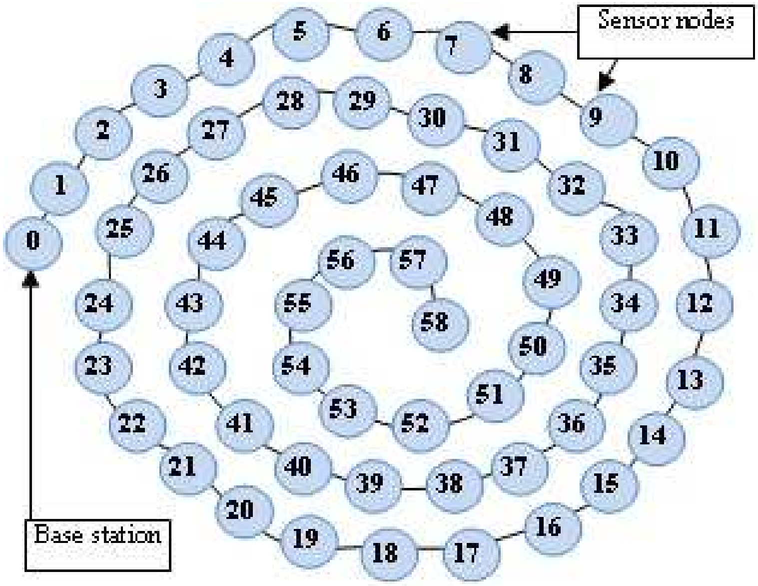

Figure 3: Spiral-based network model

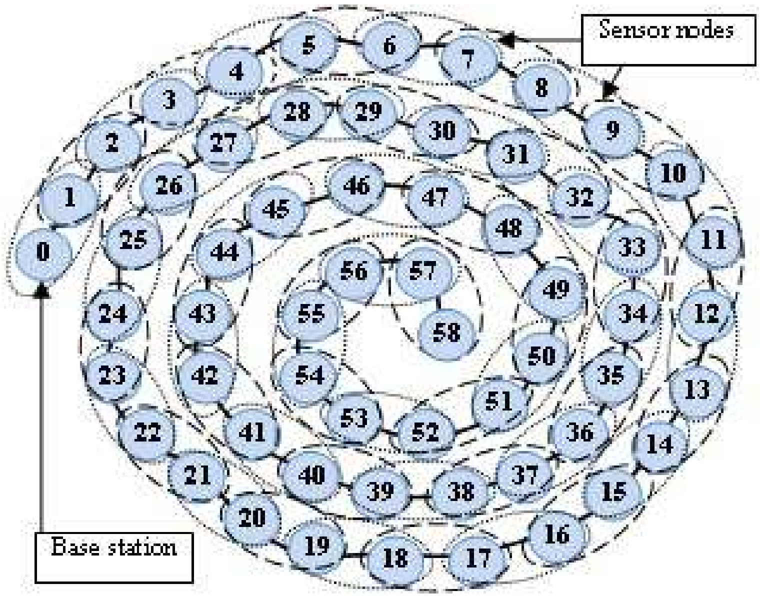

Figure 4: Spiral-based clustered sensor network

other (they are not in the same cluster). For each cluster, there is a Cluster Head (CH), which aggregates data received from its child nodes and relays it to its parent node.

From Fig. 4, each group of two sensors forms a cluster, so, sensors ID58 and ID57 are in cluster C158, sensors ID57 and ID56 are in cluster C157, and so on, until we reach the base station (ID0), which is in the cluster C11 with sensor ID1.

The current section focuses on a new architecture, based on spiral-based clustered WSN using data aggregation (SBCDA). CHs of 3-hops-away clusters can operate (send their packets) at the same time, which means that our new superframe has three parts, if we apply formula (7), as this is shown in Fig. 8:

$$Length = \sum_{d=1}^{3} \max_{\substack{h\in\{d+3g\}\\ g=0\ldots H}} \left\{ \max_{i=1}^{Nc(h)} \{Ch(C_i^h)\} \right\}. \tag{7}$$

If we take $d = 1$; $d = 2$ or $d = 3$;

$$\max_{\substack{h\in\{d+3g\}\\ g=0\ldots H}} \left\{ \max_{i=1}^{Nc(h)} \{Ch(C_i^h)\} \right\} = 1. \tag{8}$$

So, whatever the network density, our superframe generated in all cases is always equal to three,

$$Length = \sum_{d=1}^{3} \max_{\substack{h\in\{3+3g\}\\ g=0\ldots H}} \left\{ \max_{i=1}^{Nc(h)} \{Ch(C_i^h)\} \right\} = 3 \tag{9}$$

**Network latency**

Network latency, also known as end-to-end latency, is the amount of time it takes for a packet to cross the network from a sensor node to the destination (sink node). The delay could be considered a synonym for latency. Latency and bandwidth define the speed and capacity of a network.

In this approach, sensors can use the medium to transmit their packets as shown in Figs. 8, i.e. packets of node $ID_1$ can reach the sink after one time slot, and packets of sensor $ID_{58}$ are transmitted in the 58th time slot, while the duration of the time, in which the packets are transmitted between the sensor $ID_{57}$ and the sink node is 58 time slots.

So, we can generalize our latency formula as packets of each sensor node can reach the sink after:

$$Rt = (id + ((Nbs - id)\mathrm{mod}3)) \star Ts(\text{time unit}) \tag{10}$$

where $Rt$ is the response time, i.e. the whole time duration it takes the sensed events transmitted as a packets from source (a sensor node) to the destination (sink), $Nbs$ is the number of all sensor nodes in the network, $Ts$ is the duration of the slot time and $id$ is the identifier of each sensor node ($id(ID_{57})$ is 57).

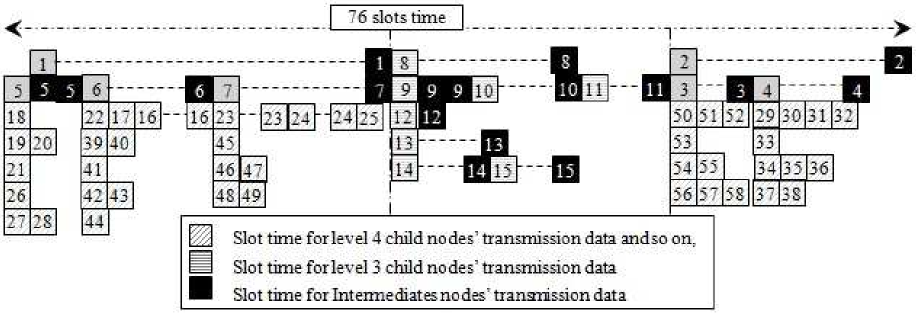

Figure 5: Reduced TDMA superframe

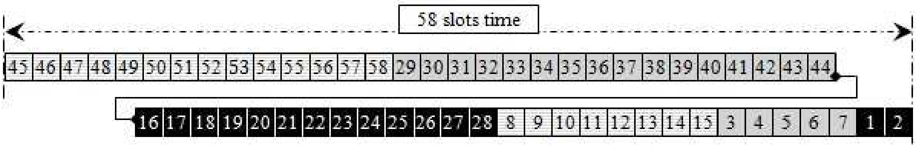

Figure 6: TDMA superframe with data aggregation in general case

### 4.5. Bandwidth allocation

In evaluation of network performance we are interested in the following quality of service metrics:

*Superframe length*: it is the period, during which all sensor nodes of the network transmit their frames to the base station, so they are ready to transmit again (round).

*Bandwidth*: the amount of traffic sent by each node in the network during the simulation time. This metric varies along the length of superframe calculated according to the network density (formula (11)), where $B(n)$ is the volume of bandwidth reserved for node $n$:.

$$B(n) = \frac{Ns(CH^{-1}(n)) + 1}{Length}. \tag{11}$$

*Network capacity*: the number of frames sent by all nodes in the network during the simulation. The higher capacity network can offer a better quality of service to a higher number of sensors.

*Stream capacity*: it is the sum of all traffic sent by any node in the network (frames generated by CMs or generated and received by CHs) and received by the base station during the simulation. This metric allows for studying the problem of appropriate sharing of bandwidth between nodes.

In the tree or spiral architecture with data aggregation, the bandwidth ratio B is calculated from formula (12):

$$B = \frac{1}{Length}. \tag{12}$$

Since each sensor node sends its packets in one and only one slot time, all the sensors share the same bandwidth ratio.

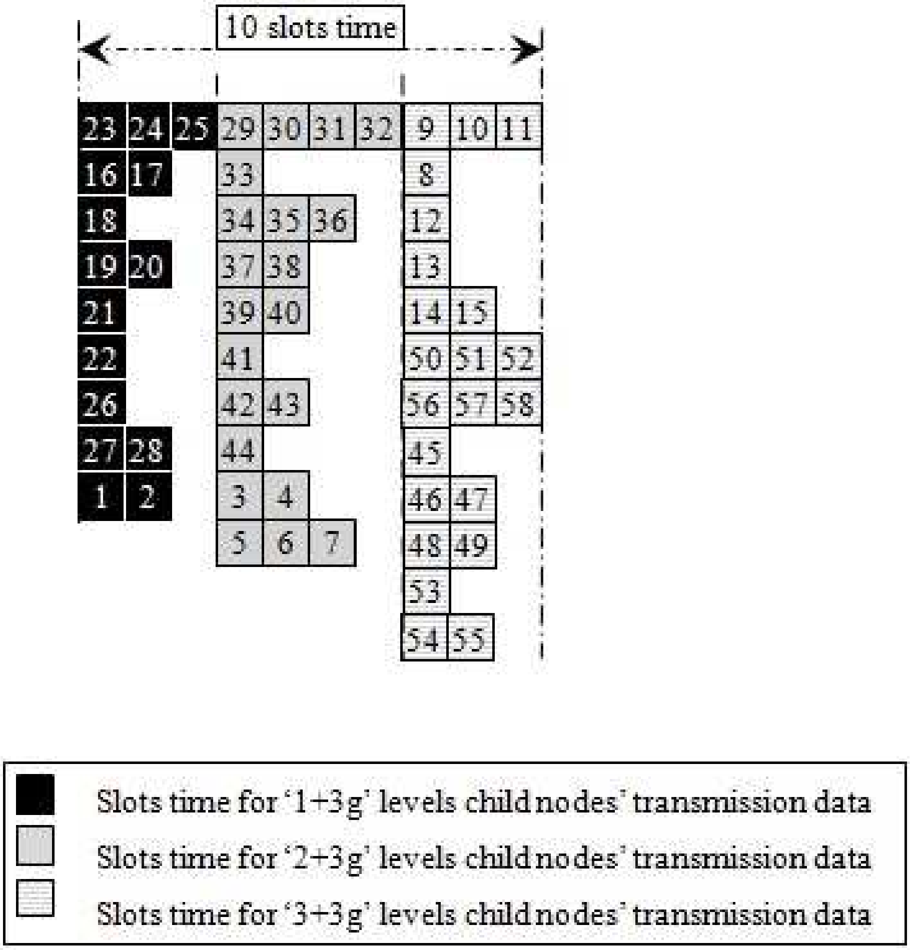

Figure 7: Reduced TDMA superframe with data aggregation

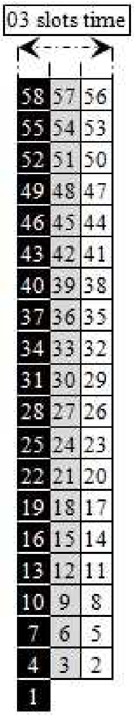

Figure 8: SBCDA superframe length computation

## 5. Performance study

Using OMNeT++ Simulator, we have conducted several simulations to verify the proposed formulas guaranteeing bandwidth.

Table 2: Simulation settings

| Settings | Values |
|---|---|
| Number of sensors | 58 |
| Packets size | 90 Bytes |
| Simulation duration | 150 s |
| MAC layer | TDMA |
| Channel bit rate | 9.6 Kbps |
| Length of slot time | 100 ms |

We study the impact of the active sensor number on the network performance (in terms of bandwidth). We calculated the number of active nodes deployed in the same area. We have identified the number of active nodes compared to the total number of nodes in each time slot. The degree of achievement of the aim of reducing energy consumption is assessed by reducing the number of active nodes at the same time.

### 5.1. Number of active nodes

A sensor node in the tree-based clustered TDMA protocol can be in one of three states: sleep, active (in reception mode), or active (in emission mode):

- Sleep mode: at the beginning of each activity period (after the synchronization phase, and also if the sensor node neither emits nor transmits data) some nodes are in the sleep mode.
- Active in reception mode: during the reception of frames (from an active neighbor), the node in sleep or active mode becomes passive (active in reception mode) and preserves its state until the beginning of the next period.
- Active in emission mode: in this mode, the node aggregates and sends data to its CH (or root) at the beginning of its assigned time slot.

The goal of reducing energy consumption is being attained by reducing the number of nodes active at the same time.

Figure 9 shows the evolution of this number for the here proposed approach and the one described by Masri and Mammeri (2010). We note that the approach described in by Masri and Mammeri (2010) extends the lifetime of the network better than the here proposed approach (if the network uses 100% of the total energy for our approach, the energy consumption, described by Masri and Mammeri (2010) is equal 93.18%.

When the size of the superframe increases, it is obvious that the number of time slots increases, whereas the number of active nodes per slot time decreases.

We can note that the number of active nodes per time slots is always higher for smaller superframe (e.g. in slot [1650ms, 1725ms] we have 3 nodes for TBC-WSN (76-time slots), 5 nodes for TBCDA (10-time slots) and 20 nodes for SBCDA (3-time slots)).

### 5.2. Relationship between network density and bandwidth

In Fig. 10, we compare the bandwidth of the general case superframe and that of the proposed approach, where the cluster $(C_2^4)$ has, initially, one child node $(Ch(C_2^4) = 1$, which is node 18), and cluster $(C_3^4)$ has two child nodes, i.e. $Ch(C_3^4) = 2$.

In this simulation, we increase the number of child nodes in this cluster gradually until reaching 3 sensors, i.e. $Ch(C_2^4) = 3$, and then further to $Ch(C_2^4) = 4, 5, 6, 7, 8, 9, 10$. Note that in this case, the bandwidth decreases gradually when more nodes are added. And we increase the number of child nodes in cluster $(C_3^4)$ gradually, that is, $Ch(C_3^4) = 3, 4, 5, 6$, and then yet further, i.e. $Ch(C_3^4) = 7, 8, 9, 10, 11$. Note that in this case, the bandwidth decreases gradually when more nodes are added, then it begins to decline more rapidly when the number of nodes exceeds 6 nodes in this cluster.

According to Fig. 10, the SBCDA approach provides better bandwidth compared to the other approaches. In fact, and according to formula (11), the length of superframe is the denominator of the bandwidth rate, if we reduce the superframe length, the ratio will increase, so, the bandwidth will increase, and vice versa.

### 5.3. Number of packets received by the root

In fact, the length of the superframe affects the number of messages collected by the sink node from its children, with a smaller superframe allowing the Base Station to collect more data than a larger one.

In practice, data freshness is evaluated through the number of packets received in each round, where receiving more data in a period depends on the superframe length, in other words, a smaller superframe allow us to aggregate and transmit more data (data in this context are fresh, as in our proposed approach) than a larger one.

According to Fig. 11 (a and b) our approach, TBC-WSN, perfoms better than the ones of Masri and Mammeri (2010), MC-MAC and MC-LMAC, in terms of the number of received packets. In addition, in Fig. 11 (c) our approaches, TBC-WSN and SBCDA, and also MC-MAC, performed better than the ones of Masri and Mammeri (2010) in terms of the number of received packets. Nevertheless, TBC-WSN remains better than MC-MAC. In fact, decreasing superframe length means increasing the guaranteed bandwidth allocated for each sensor node and so, increasing the number of received packets.

### 5.4. Relationship between superframe length, round and packet size

The duration of a "round" is directly related to the superframe length and it also depends on the packet size, so that changing one parameter does affect the others. For example, in order to increase data freshness (i.e. decrease the round duration), the superframe length should be reduced either by removing time slots (i.e. minimizing the number of nodes) or reducing the size of packets, allowed to be sent by each node (Fig. 12-a,b,c,d,e).

From Figs. 12 (a, b, c, d and e), we note that SBCDA and TBCDA perform better than the approach of Masri and Mammeri (2010). In fact, the smaller the superframe length, the bigger the allocated bandwidth.

So, reducing the superframe length means decreasing the round duration, increasing the data freshness and the number of the transmitted packets by each sensor node.

### 5.5. Relationship between network density and network throughput

As shown in Fig. 13, network throughput increases with increasing network density. We can see that TBC-WSN is better than the approach of Masri and Mammeri (2010), MCMAC, and MC-LMAC, in terms of network throughput.

On average, MC-LMAC achieves maximum throughput of 9 kbps and MCMAC of 27 kbps, whereas our TBC-WSN protocol can achieve maximum throughput of 29 kbps. In TBC-WSN, the size of the superframe is effectively reduced by enhancing and supporting parallel transmission. Therefore, TBC-WSN can achieve high performance in terms of network throughput and data collection time. Note that a node has always sufficient time to send collected data, since the time slot is assigned according to the node bandwidth demand.

### 5.6. Relationship between network density and superframe length

Figure 14 shows the simulation results of the size of a superframe (TBC-WSN, MCMAC, Masri and Mammeri, 2010, and MC-LMAC) for the changing number of nodes and the length of the tree topology.

We can see that the superframe size increases according to the increase of the number of nodes and the network length. In our approach, TBC-WSN, the superframe size attains the 120-time slot, less than MCMAC and MC-LMAC. So, by achieving the minimum superframe size, our approach leads to a better bandwidth ratio.

## 6. Conclusion

In this paper, we presented an extended version of our own approaches (see Azizi and Beghdad, 2013, 2014, 2016) in order to prove that these solutions are better than the recently forwarded approaches, in terms of bandwidth allocation in a WSN while using TDMA. The TDMA protocol avoids collision (a collision-free protocol) in transmitting packets by synchronizing the access of the sensors to the medium. Yet, in some protocols, this leads to interference due to slot reuse. In a decentralized environment, it is not easy to change the slot assignment in the context of traditional TDMA. We propose a new TDMA scheme for constructing the communication set during each time slot, based on the Max Child Nodes on each level of the network. Through a high number of simulations, we showed that our approaches are very competitive compared to the general scheme. In our three solutions we have to compute the superframe length. Once we have calculated the superframe length, we establish the relationship between this length for a given topology, expressed, on the one hand, in terms of density, and the bandwidth, on the other. We calculate the bandwidth rate allocated to each sensor, and we show how the position of the added node exerts a direct impact on the length of the superframe and hence on the allocated bandwidth.

In our approach, the superframe length is computed via formulas, while the scheduling of the superframe was done manually. Another possible way to take is to implement mechanisms that achieve the scheduling of the superframe automatically, while choosing for each node the optimal position in the superframe that maximizes the bandwidth ratio by parallelizing transmissions, whenever possible. Interferences between sensors and extending the network with new nodes are other issues that could be considered in the future research. The position of the newly added nodes should be also checked as to whether it causes new interferences, and thus should be taken into account when scheduling

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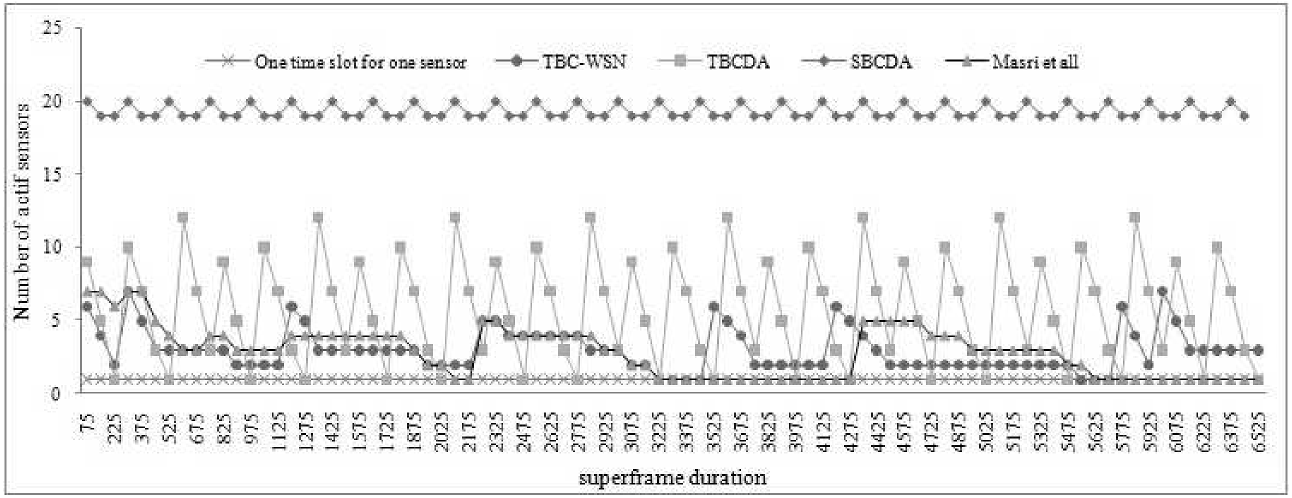


Figure 9: Number of active sensors in each period

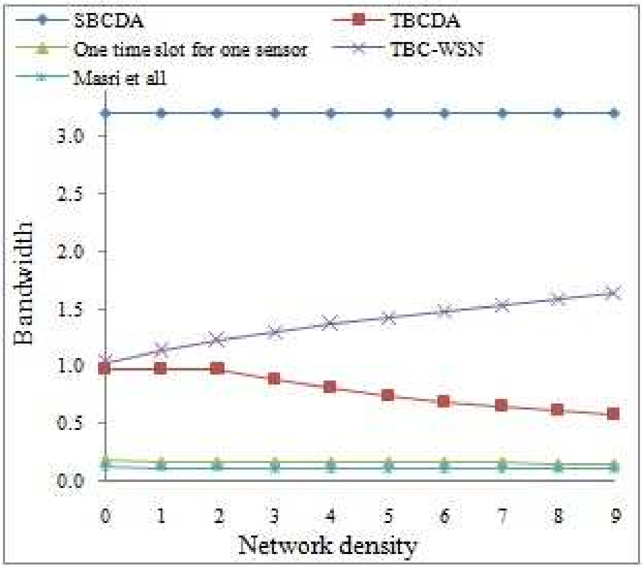
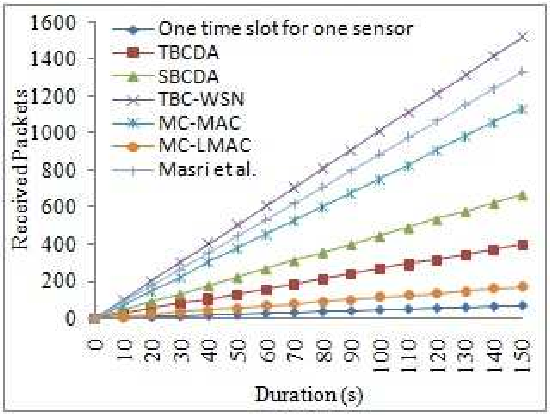
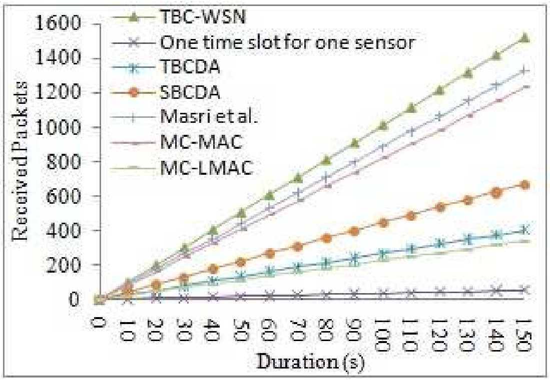


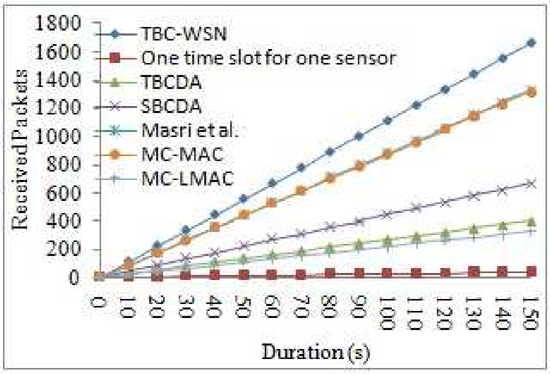
Figure 10: Network density vs. bandwidth



(a) Network density (50 nodes)

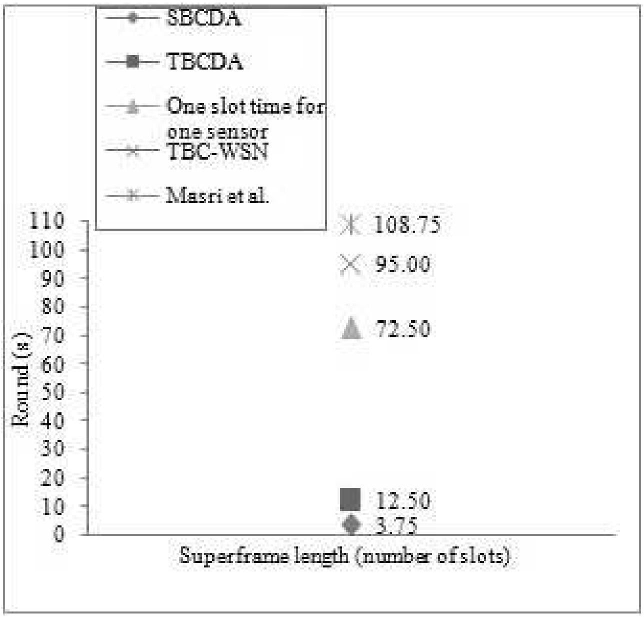


(b) Network density (75 nodes)

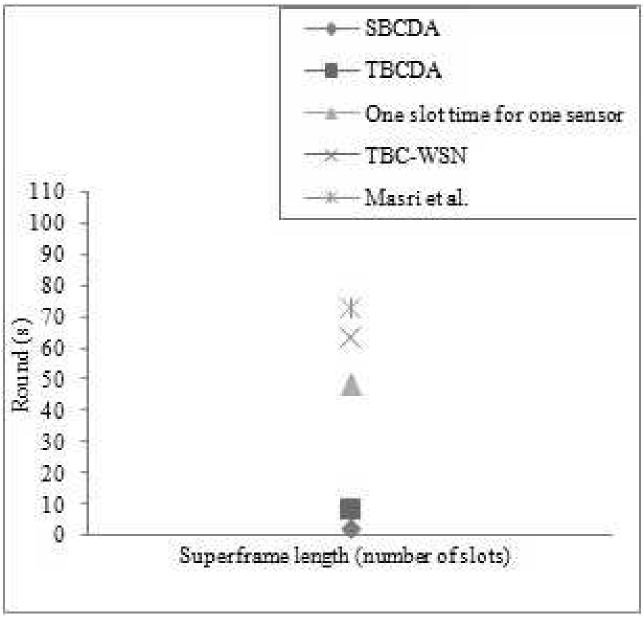


(c) Network density (100 nodes)

Figure 11: Number of packets received by the ROOT (BS)

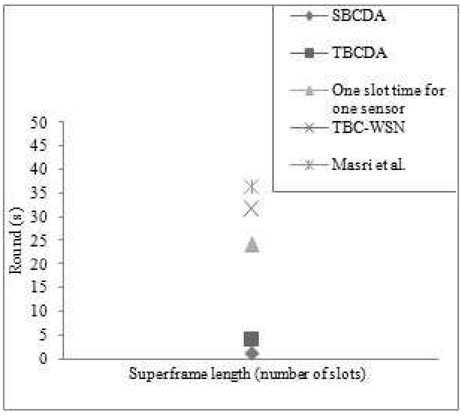


(a) Packets of 1500 bytes

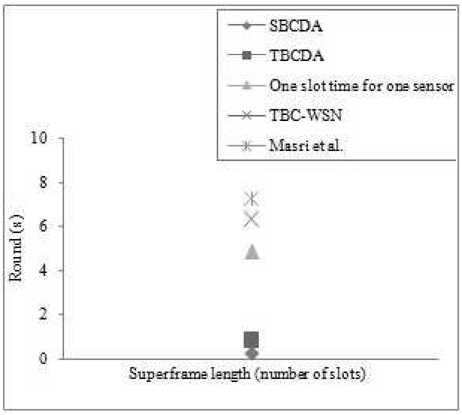


(b) Packets of 1000 bytes

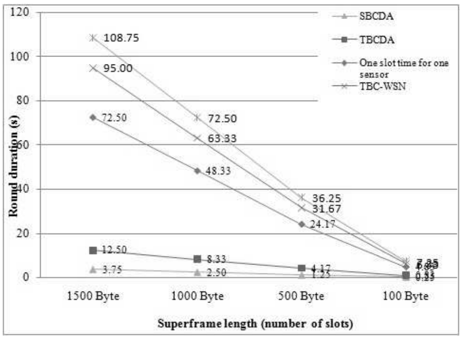
Figure 12: The relationship between superframe length, round and packet size



(c) Packets of 500 bytes



(d) Packets of 100 bytes



(e) superframe duration vs. packets sizes

Figure 12: (continued)The relationship between superframe length, round and packet size

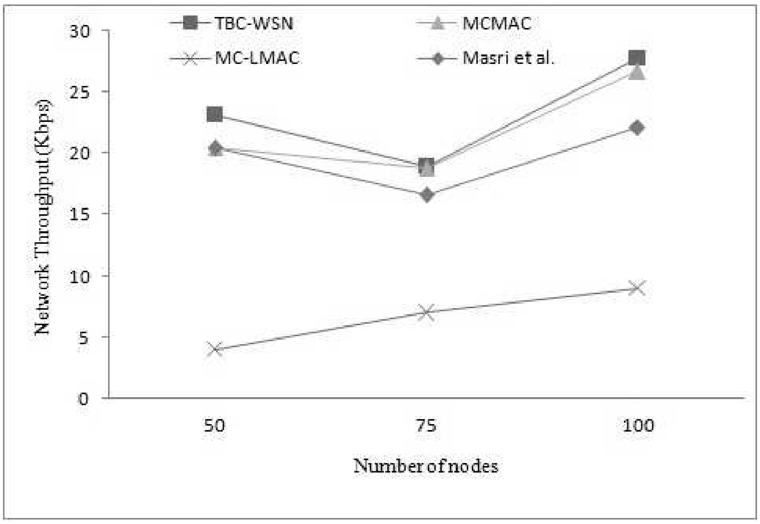


Figure 13: Network throughput according to network density

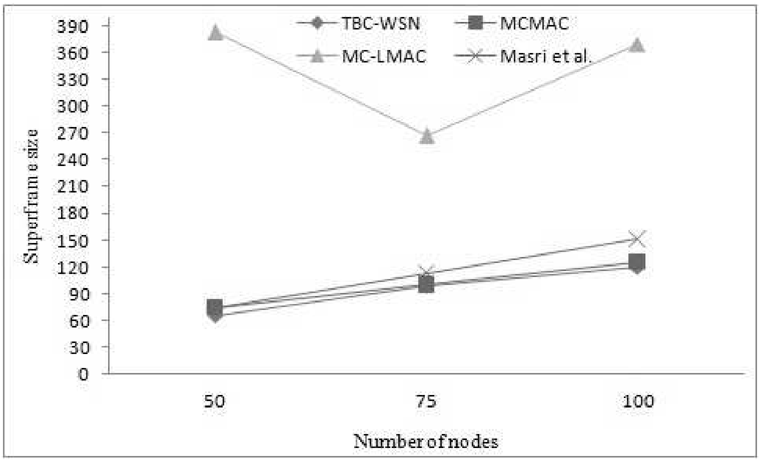


Figure 14: The size of a superframe according to the number of nodes