Enhanced Performance Analysis of a Hierarchical Polling-based MAC Access Scheme for WBAN

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***Abstract*—An enhanced performance analysis of a hierarchically structured access scheme for a Wireless Body Area Network (WBAN) is carried out in this paper. The access scheme uses the polling technique in each hierarchy level. Sensor nodes from first level are provided with infinite size buffers and both first and second levels use exhaustive polling technique. The study is done through computer simulation and mathematical models. Initially, the results of computer simulation are compared to the mathematical modeling. In spite of some approach used in mathematical modeling, the both results are very close. Next, to overcome the sensibility of second level to the input load of first level the performance analysis is carried out using different transmission rates for first and second levels.**

Keywords-hierarchical polling; computer simulation; wireless body sensor network.

I. INTRODUCTION

In Wireless Body Area Network (WBAN), sensors are placed in various parts of the body and measure vital signs, such as temperature, blood pressure, heartbeat, etc., and transmit these data to an external device. The sensors can be placed on the skin or be implanted under the skin, and communication with the external device is always wireless, which ensures greater mobility and comfort to patients with WBAN. When a sensor is equipped with processing and data transmission capabilities will be denoted sensor node and the external device as sink node in this paper.

In the deployment of sensors in the body, certain requirements must be considered, as the short distance transmission, low power consumption and very small dimension of a sensor. These features provide a low level of radiation, longevity in use the sensor without battery replacement and providing comfort for users [1].

When multiple sensor nodes begin to transmit packets simultaneously, collisions occur and packets must be retransmitted, wasting energy. Thus, the MAC must be designed to avoid collision and operate efficiently to reduce energy consumption. One of the MAC access schemes presented in the literature uses the polling technique for data collection of sensors [2]. In the presented work, the sensors are divided into groups and each group has a sink node that collects data from sensors using the polling technique. To collect the data from sink nodes, there is another node called master that collects the data, also using the polling technique. This structure was denoted hierarchical MAC access based on polling technique [2] and the performance of this scheme has been studied theoretically using mathematical models.

In the theoretical models presented in [2], some approaches were used for the analysis of second level of hierarchy and the accuracy of models must be verified. The purpose of this article is twofold. Firstly, the analysis of the proposed structure in [2] is carried out through computer simulation to validate the theoretical model. Secondly, to overcome the sensibility of second level to the input load of first level is proposed different transmission rates for first and second levels and its performance analysis is carried out.

The paper is organized in six sections. In Section II related work is described. The concepts related to MAC access scheme based on hierarchical topology are presented in Section III. The developed computational simulator and the analysis of the results are discussed in Section IV. In Section V the performance analysis using different transmission rates for first and second levels is carried out. Finally, the main conclusions are presented in Section VI.

II. RELATED WORK

To fulfill the MAC protocol requirements for WBAN such as low power consumption, quality of services and security many proposals have been presented in the literature. The main standard for WBAN the IEEE 802.15.6 proposes general guidelines and it is not concerned with a specific type of access. Thus, many MAC scheme proposals can be implemented. Some proposals are compatible with IEEE 802.15.4 as presented in [6] denoted BAN MAC protocol which is a low power, designed for star topology. Upon receiving the data from the sensors, this MAC protocol dynamically adjusts the protocol parameters to improve energy conservation in sensors with low energy level.

Many proposals are based on Time Division Multiple Access (TDMA) access technique [4][5][8][9]. Each of the proposals explores some special features based on medical needs. For instance, in [4] to deal with the light and heavy loads in normal and urgent situations, a context aware MAC is proposed. To guarantee Quality of Service (QoS) of a WBAN, a MAC protocol based on random access technique is proposed in [9]. In the proposal presented in [8], the heart beating is used for the purpose of clock synchronization. In [5], the beacon used for wake-up sensor nodes is used for battery charging, increasing the network life time.

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Some proposals are based on polling access technique [2][7][10][11]. In [7] the MAC scheme based on flexible polling, guaranteeing QoS for WBAN is proposed. In the proposed MAC scheme the urgent traffic has high priority and is served before the normal traffic. The performance of MAC scheme based on polling in [10] is studied under different types of On-Off sources. The hierarchical polling based MAC scheme and its performance study are presented in [2][11]. The study is carried out using mathematical modeling and some approaches are used. Since the performance study of this paper is also to analyze the scheme by computer simulation and without approaches the hierarchical scheme will be detailed in next section.

III. Hierarchical Polling

The concept of hierarchical topology for WBAN was first presented in [3]. The idea was to minimize the fading of signals due to constant movement of the patient using WBAN. The sensor nodes have short ranges, typically less than 1 meter, and the transmission power is very low so that the fading of signals can be constant. In the work presented in [3], the sensors were divided into groups and each group is attended by an intermediate node using technique based on TDMA. The intermediate nodes are served by other hub node that also uses the TDMA technique.

In the work presented in [2], it was also used the concept of hierarchical topology, however, the technique of data collection is based on polling. In this proposal, sensor nodes of the first level are also divided into groups and the sink nodes collect the data from each group using the polling technique and in the second level, the master node collects all the data from sink nodes using also the polling technique. The hierarchical polling concept applied in a human body is illustrated in Figure 1.

The sensors, such as electroencephalography (EEG), electrocardiography (ECG), temperature (TPR), etc., are placed on the upper part of the body and are polled by the sink 2 which is attached to the arm, as shown in Figure 1. The sensors like motion (MTN), electromyography (EMG), glucose (GLC), etc., placed on the lower part of the body are polled by the sink 1 attached in a belt. The master node that polls the sink nodes can be a cellular phone or a device placed near the body. This device has connection to the internet so that the sensor data can be processed in a hospital or showed to a physician for diagnosis.

The communication protocol used to exchange information between the sensors and the sink node in a group works briefly as follows, noting that all communication is done wirelessly. The sink node transmits a broadcast packet containing the number of sensor node (a number that uniquely identifies the sensor node), that is, an authorization for a sensor node to transmit the data. This authorization packet contains in its header enough bits for the synchronization in the sensor node. After recognition of its number, if a sensor node has packets to transmit, begins the transmission. After transmission, the sensor node waits for confirmation packet in case of the need for retransmission. If the sensor node has no packets to transmit, the transceiver remains switched off to save power. The sink node recognizes that a sensor node is off waiting a small time interval after transmission of the authorization packet. If data do not arrive from the investigated sensor node, the sink node concludes that the sensor node has no data to transmit and begins to investigate the next sensor node in the sequence.

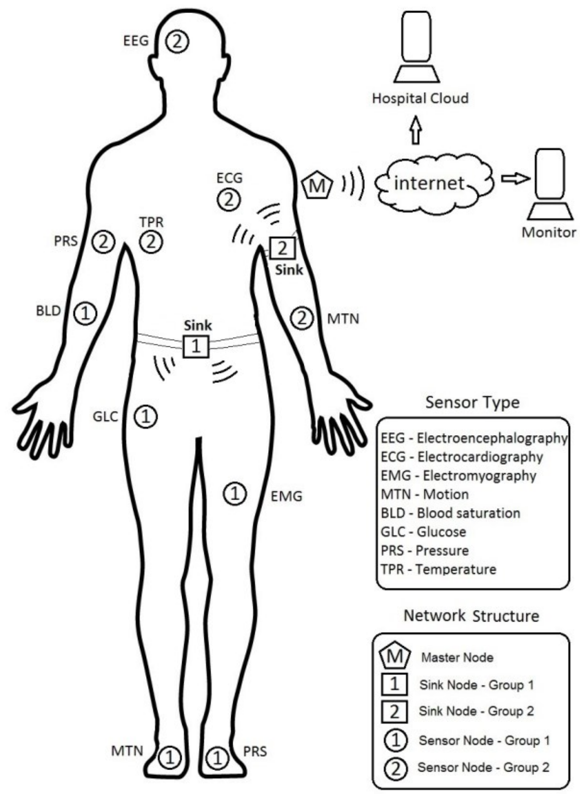

Figure 1. Hierarchical polling concept applied in a human body.

In this communication scheme, virtually all communication functions are in sink node and only the transmission function is assigned to the sensor node, in order to save its energy.

This same communication protocol described above can be used in the second level when the master node investigates sink nodes to obtain the data. Probably for a WBAN, only two levels are sufficient.

IV. Performance Analysis

For the performance analysis the hierarchical polling scheme can be modeled as shown in Figure 2.

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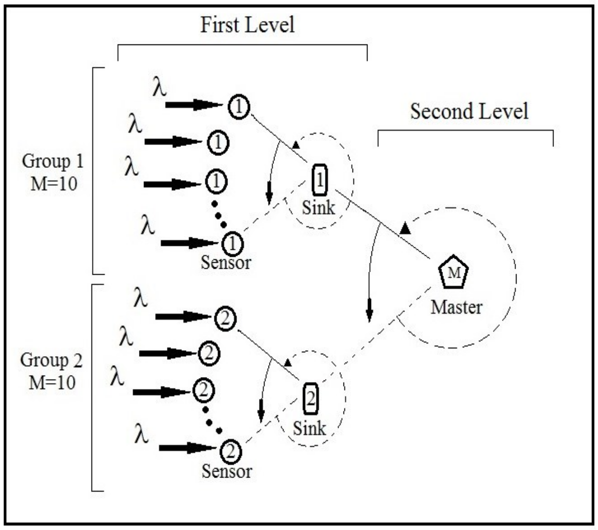

Figure 2. Hierarchical polling model for performance analysis.

As can be seen in Figure 2, the first level of the hierarchy is constituted of a number of sensors divided into groups, and each group is polled by a sink. The arrows represent the packets generated by each sensor with rate λ packets/s. In the second level the sink nodes are polled by the master node.

Based on the network model presented in Figure 2, a simulation program in Java language was developed for performance analysis of hierarchical polling scheme.

The input parameters of the simulation program are mean packet size of E{X} = 900 bits, the link capacity of R_1 = 20 kbps, packet transmission time of 900 / 20k = 45 ms (milliseconds), authorization packet transmission time of 4.5 ms and the packet synchronization time of 2 ms. These parameters are used to perform comparison with the theoretical model presented in [11].

A packet generated at each sensor follows a negative exponential distribution of mean 1/λ. To ensure that the statistics are collected under a statistical equilibrium, the first 10,000 packets are discarded at each sensor node.

The input load, S_1, is defined as

$$S_1 = \frac{M\lambda E\{X\}}{R_1} \tag{1}$$

where M is the number of sensors, λ is the average packet arrival rate, E{x} is the average packet size and R_1 is the channel capacity.

As a performance criterion, it is used the average transfer time of packets defined as the average waiting time of packets in the queue added to average packet transmission time in each sensor node. Another performance parameter is the average cycle time defined as the average time to inspect all sensor nodes in a cycle.

It was considered that the buffer for storing packets has infinite size, that is, lossless and the discipline of service is exhaustive, meaning that the buffer is completely emptied when it is inspected.

The central part of the algorithm used in the simulation is detailed in appendix A, after the references.

In a real case, the proposed body sensor network can monitor different biological signals such as temperature, pressure, among others, as shown in Figure 1. Since the sensors of a WBAN have short-range transmission capabilities due to energy saving, the communication signals among sensors and the sinks for some cases can be very impaired. Thus, two sinks placed in different positions to improve the communication capabilities are proposed in this paper, as shown in Figure 1.

The network structure of developed simulation program is based on the standard IEEE 802.15.6 in capability and function. The network structure of the simulator operates in a star topology and in accordance with the polling protocol. The polling network has a centralized node that controls the packet transmission and avoids collisions of packets as demonstrated in [14].

The developed simulator has the flexibility of adding new parameters to obtain the results, as is shown in appendix A, where a screen of simulator is presented.

Figure 3 shows simulation results and comparison with theoretical results in first level for mean transfer time. It can be observed that the results obtained in the simulation are close to the theoretical up to the load of 0.5. For load greater than 0.5, the simulation and theoretical curves are diverging, but considering that the load is high and the polling scheme is already operating in unstable condition, different results for simulation and theoretical are expected.

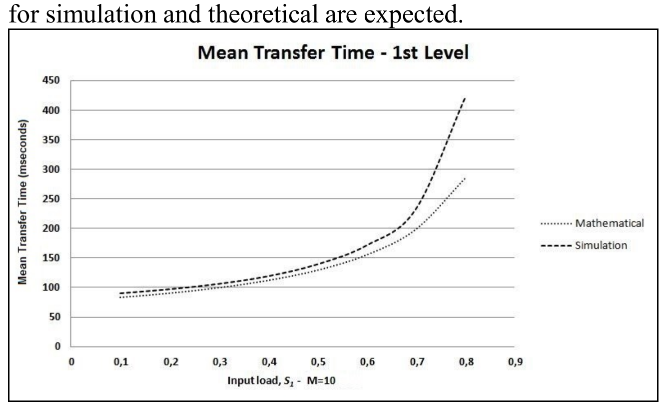

Figure 3. Packet mean transfer time of first level.

Figure 4 shows results for mean cycle time in first level. In this case, for the input load ranging from 0.1 to 0.6 the results obtained in the simulation are very close to the theory. For load greater than 0.6 the same phenomenon observed for mean transfer time occurs, that is, the curves are divergent.

For the analysis of second level it must be observed that in the exhaustive polling technique, the packets are stored in the buffer at each sensor node and wait its turn to be attended, and when a sensor node is polled, all packets are transmitted, so that the packets arrival to the sink node in burst.

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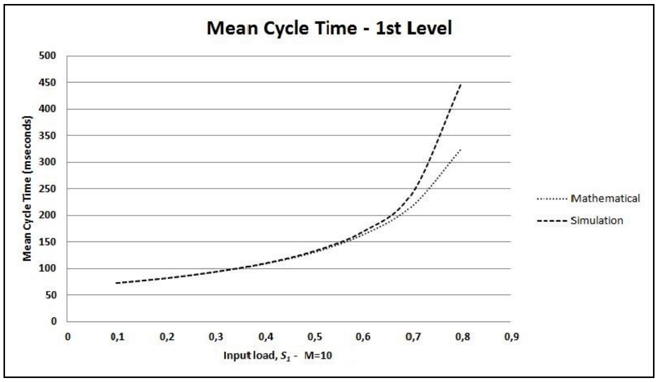

Figure 4. Mean cycle time of first level.

But, in the case of theoretical model, the negative exponential distribution of packet arrival at input of sink nodes is assumed [12]. In the case of simulation, the negative exponential distribution is assumed only at output of a sensor node. Figure 4 shows the comparison of results obtained by simulation and theoretical means for mean transfer time. It can be observed the both curves are very close, meaning that the approach used in theoretical model is very reasonable.

The curves of Figure 5 also show that the polling system, for given parameters, cannot operate with the load greater than 0.3 because the transfer times become prohibitively large, meaning that the waiting time of packets at each sensor node buffer is too large.

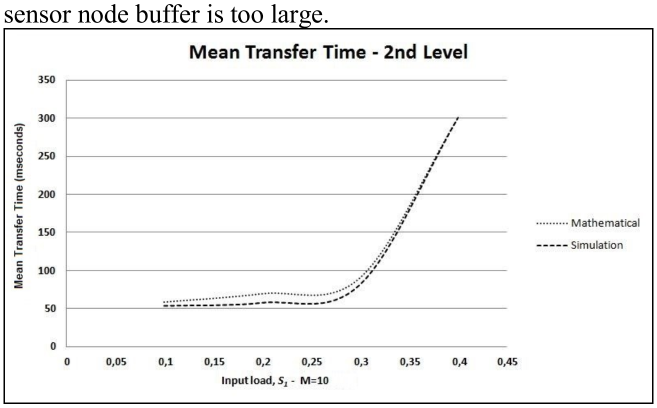

Figure 5. Packet mean transfer time of second level.

Figure 6 shows the behavior of the curves for mean cycle time. The curves show that for load up to 0.3 the mean cycle values are very close but some divergence for load above 0.3 can be observed but it is not significant.

It can also be observed that for load above 0.3, a small increment of input load, a large mean cycle time is obtained, approaching to the infinity quickly, showing the second level high sensitivity to the input load.

The general conclusion is that in order to have stable operation in the first and second levels of the hierarchical polling scheme with the given parameters, the system must operate with a load lower than 0.3.

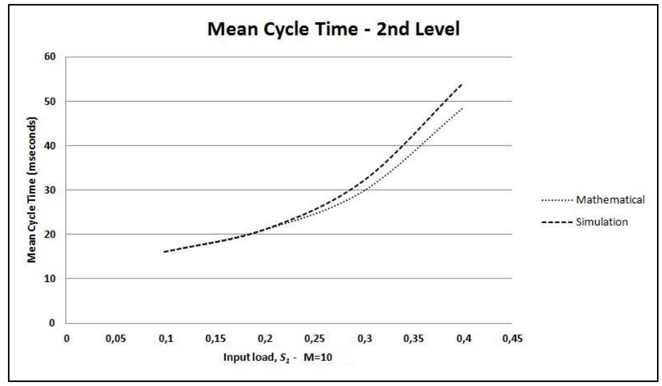

Figure 6. Mean cycle time of second level.

It can also observed that for input load above 0.4, a small increment of the load, both transfer and cycle times have exponential values as can be seen in Figures 5 and 6, meaning a high sensitivity of the second level to the input load.

V. ENHANCED CAPACITY OF SECOND LEVEL

As seen in section four the second level has high sensitivity to the load of first level. To improve the performance of second level a higher link capacity can be used in this level. The use of low link capacity in first level is convenient because the sensors are implanted under skin or placed very close to the skin, so that low frequencies devices can avoid any damage to human body. The hierarchical structure studied in this paper can use different capacities for first and second levels to improve the performance of system.

To show the performance of second level using different capacities a theoretical analysis is carried out.

Since there is no loss in first level, the performance model for second level will be as shown in Figure 7 [11].

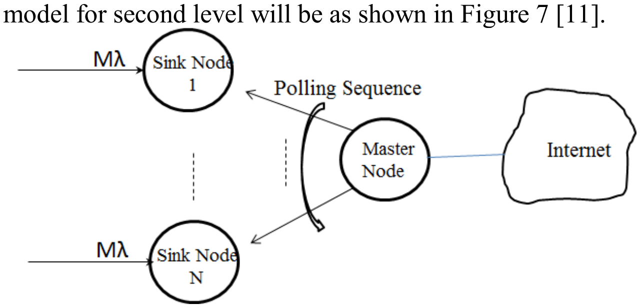

Figure 7. Second level performance model for infinite buffer case.

The mean cycle time for this case is given by

$$\mathrm{T}_{c2} = \frac{N w_x}{(1 - S_x)}, \tag{2}$$

where N is the number of sink nodes, w_x is the walk time (packet authorization transmission time plus synchronization time) and S_x is given by

$$S_x = \frac{NM\lambda E\{X\}}{R_x} = NS_1 \frac{R_1}{R_x} \qquad (3)$$

where R_1 is the transmission capacity of first level, R_x is the transmission capacity of second level and S_1 is given by (1).

The stability condition is given by

$$S_x < 1 \Rightarrow NM\lambda E\{X\} < R_x. \qquad (4)$$

The queuing time in a buffer of second level is given by [11]

$$E\{W_2\} = \frac{Nw_x(1-S_x/N)}{2(1-S_x)} + \frac{S_x E\{X\}}{2R_x(1-S_x)}, \qquad (5)$$

for deterministic packet length.

The packet transfer time for the second level is given by

$$E\{T_2\} = \frac{E\{X\}}{R_x} + E\{W_2\}. \qquad (6)$$

Assuming the capacity of 20 kb/s for first level and for the second level the following capacities will be assumed: 40 kb/s, 100 kb/s and 250 kb/s. In the literature the most frequent capacities cited are 19.2 Kbits/sec and 38.4 Kbits/sec used in Mica2Dot [12], and 250 Kbits/sec used in MicaZ [12][13]. These capacities are always used in first level in cited references. An advantage of the hierarchical structure is that the capacities of first and second levels can be uncoupled, so that a higher link capacity can be used in second level.

TABLE I. PARAMETERS FOR SECOND LEVEL.

Capacity R_x Kbit/sec	Authorization Packet Time (ms)	Synchronization Time (ms)	Walk Time w_x (ms)
20	4.5	2	6.5
40	2.25	1	3.25
100	0.9	0.4	1.3
250	0.36	0.16	0.52

Table 1 shows the parameters used for second level. The packet authorization time in the first line of Table 1 is calculated considering that packet has 10 % of length of data packet (E{X} = 900 bits) and a transmission rate of 20 Kbit/sec, that is, 90 / 20 K = 4.5 ms. The synchronization time in first line of Table 1 is approached to 2 ms and the walk time is the addition of packet authorization time and synchronization time. The other values of packet authorization and synchronization times are calculated considering inversely proportional to the link capacities.

Using (5) and (6) and the parameters of Table 1, the mean transfer times for various link capacities of second level can be calculated as is shown in Figure 8. The figure shows that the performance limitation of second level using the same capacity of first level can be completely overcame using different capacities.

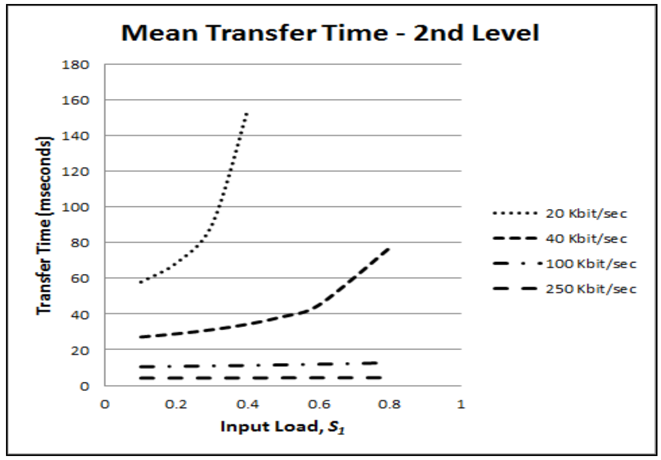

Figure 8. Performance comparison of transfer times for different transmission capacities of second level.

A Figure 8 shows using the double of first level capacity (40 Kbit/sec) the performance in relation to transfer times is much better. For the link capacity of 250 Kbit/sec the transfer time is very low and almost constant for any input load.

As shown in Figure 9 the curves of mean cycle times have the same behavior of mean transfer times. Using the double of link capacity of first level the cycle time of second level becomes stable, and for the capacity of 250 Kbit/sec the cycle time is almost constant for any input load.

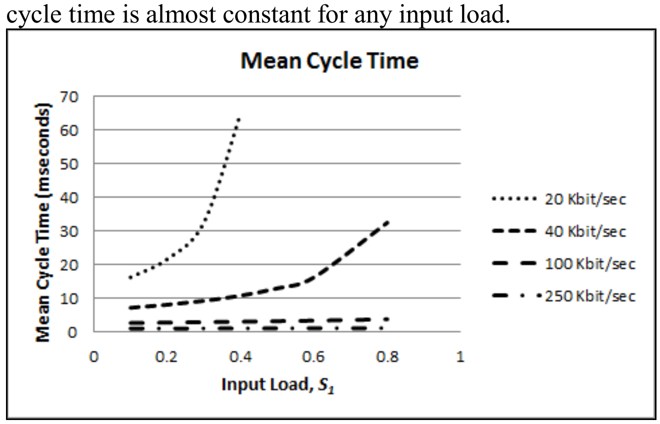

Figure 9. Performance comparison of cycle times for different transmission capacities of second level.

The results obtained in Figures 8 and 9 can be compared to the results presented in [2][11]. The performance study presented in [2][11] considered the same transmission rate of 20 Kbit/s in both first and second levels and as the result, the mean transfer and cycle times of second level were very sensitive to the input load. The second level could operate in stable condition if only less than 0.4 of input load was applied in first level. Figures 8 and 9 show that just doubling the transmission rate of second level, the input load can also be doubled to 0.8 for stable operation of second level. For higher transmission rates, the stable operation of second level is almost independent of load of first level.

VI. Conclusion

A MAC scheme hierarchy structured using polling-based technique was analyzed is this paper. The results obtained for mean transfer times by simulation in first level of hierarchy were compared to the theoretical results, showing good closeness for light loads and some divergence for high loads. For high loads, the polling system is operating in unstable condition so that some divergence is expected. The same conclusion was observed for mean cycle time in the first level. The results for mean transfer times of second level of hierarchy, in spite of some approach assumed in theoretical model for this level, showed a good closeness for both simulation and theory for all range of load. Thus, concluding that theoretical model is a good model. The results for mean cycle times of second level showed that for load up to 0.3 are very close but some divergence for load above 0.3 can be observed but it is not significant. It was also observed that for load above 0.3, a small increment of input load, a large mean cycle time is obtained, showing the high sensitivity of second level to the input load.

To overcome the sensitivity of second level to the input load a study using different and higher transmission capacities in second level was carried out. The study showed that using the double capacity in second level the polling system becomes stable for almost all input load, and for the capacity of 250 Kbit/sec the transfer times, as well cycle times are almost constant for any input load.

In future work, other models of sensor nodes reflecting real situations will be incorporated to the simulation program to study real capability of hierarchical polling-based MAC scheme.

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APPENDIX A

Figure 10 shows the main parts of the developed algorithm for simulator. The first step of the algorithm is the generation of the arrival times of packets using the negative exponential distribution and store in a attribute of class named Packet. Each newly generated packet is placed in a FIFO (First In First Out) queue that represents a Sensor. Two other attributes of this class are the sink and master clock times which are obtained during the simulation. The following step is the verification of sensor queues of Group1 in a polling sequence so that the packets of each queue can be served exhaustively. Each attended packet receives a clock stamp and is moved to the Sink1 queue. When all packets are served, the packets are in a FIFO sequence in the Sink1. Then the process goes to the next Group2 and same procedure of previous step is repeated so that the packets are stored in the queue of Sink2. The next step is the verification of sink queues of second level to serve the packets in the exhaustive polling sequence. Each attended packet receives a clock stamp and is sent to the Master queue. During the polling process the mean transfer and polling cycle times and other parameters are calculated.

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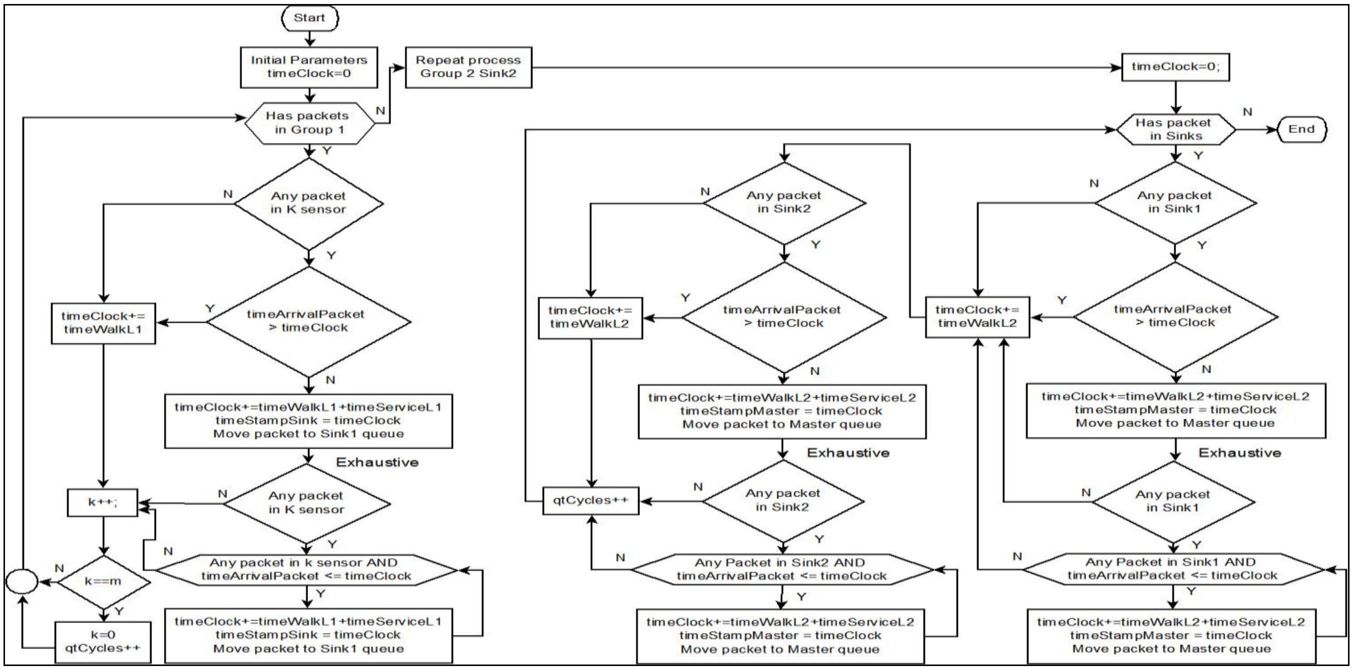

Figure 10. Overview of main algorithm developed for the performance analysis of hierarchical polling-based MAC scheme.

Figure 11 shows a screen of simulator where the changes of source/input values, process and output are possible. In the tab named “Source/Input” the initial values can be typed. They are: numbers of packets and sensors, the mean packet size in bits and the number of packets to be discarded before the statistics. In this tab, it is also possible to select the type of source packet generation distribution ("Negative Exponential" or "On/Off") as well as the transmission rates of first and second levels.

In the tab named "Process" the sensor buffer size can be set, what technique for packet service will be used and the system load range. In the tab named "Output", it is possible to select the result graphs for presenting at the end of the simulation process.

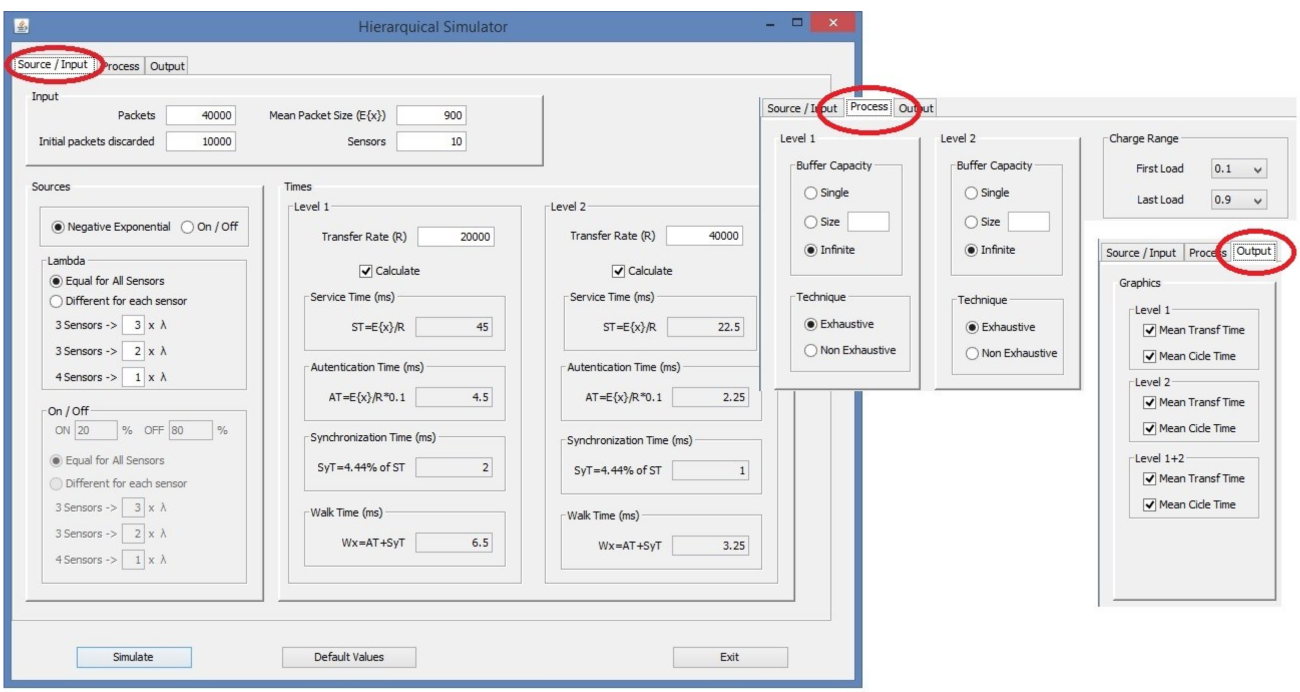

Figure 11. Overview of the simulator screen.