T-TMAC: Energy Aware Sensor MAC Protocol for Health-care Monitoring

Youssouf Zatout[1,2], Eric Campo[1,2]and Jean-François Llibre[1,3]
[1]Université de Toulouse; UPS, INSA, INP, ISAE, UTM, F-31703 Blagnac, France
[2]CNRS; LAAS; 7 Avenue du Colonel Roche, F-31077 Toulouse, France
[3]CNRS; LAPLACE; 2 rue C. Camichel, F-31071 Toulouse, France
{zatout,campo,llibre}@iut-blagnac.fr

***Abstract*—Wireless sensor networks (WSN) have received much attention during the last few years especially with regard to energy consumption. Many Medium Access Control (MAC) protocols were proposed to minimize the energy consumption in WSN, however they cannot be applied in all application contexts. Healthcare monitoring is an important application requiring adapted MAC protocol. This paper presents a new MAC protocol, called T-TMAC, based on simple mechanisms that organize data exchange and reduce collisions in many-to-one architecture. It includes maintenance mechanisms that permit mobility management and topology reconfiguration, which are needed for healthcare. We evaluated the performance of the protocol by analytical model. We propose also real prototyping using Imote2 platforms. We studied the impact of position of nodes and sleep modes on energy and delay. The results emphasize the interest of the protocol.**

***Index Terms*—Wireless Sensor Network (WSN), Healthcare Monitoring, MAC Protocol, Energy Saving, Performance Evaluation.**

I. Introduction

Over the past decade, the aging of population has lead to an increasing of the elderly [1]. Therefore the number of frail or dependent people has grown steadily in the world. The deployment of new systems which reduce the hospitalization costs by maintaining people at home is a real challenge. Nowadays, new remotely managed systems and domestic devices (sensors and actuators) are being developed [2, 3] to facilitate and improve the quality of healthcare at home, and to reduce the cost of this dependence.

Wireless sensor network (WSN) is a promising technology for a wide range of potential applications including healthcare monitoring [6]. In fact, they are characterized by their ease of deployment and their self-organization, which is an advantage for monitoring persons with risks and their living environment. Their benefits for healthcare include: continuous recovery of physiological data, medication management, motions and shocks detection (fall of a person), localization, diagnosis and early intervention for various diseases, observation of the living environment (recording the activities), monitoring of health status during training and sports, etc.

Wireless sensors are usually powered by batteries with limited capacity and the autonomy varies widely following the use. Replacing / recharging the batteries by the elderly / patients can be difficult (large number of sensors, etc.), expensive (charging forgotten), and sometimes impossible (particularly for intra body sensors). The ideal would be to extend their lifetime for several months or even for few years, to collect and relay medical data permanently to a management center or to a remote medical center (hospitals or doctors).

Many works were conducted to extend the lifetime of sensor nodes using techniques of recovering energy from ambient sources such as solar (photovoltaic) and vibrational energy [4]. However, the energy recovered (in home environment) stills limited and must be extended by other effective means.

Furthermore, many energy conservation techniques reducing power consumption of sensors are proposed at each layer in the networking stack: from the physical layer and modulation techniques, to the application layer and the development of specialized power-control tools [5]. In this paper we focus on energy-efficient MAC layer. The rest of the paper is organized as follows: related work is presented in Section II. We describe the protocol and its principle phases in Section III. We provide the analysis and the implementation of our protocol in sections IV and V. We conclude the paper in Section VI.

II. Design of MAC Protocols

Reducing power consumption at the MAC layer can be very significant [3, 5, 6, 7]. Approaches at this layer turn the wireless transceivers off when it is not necessary to transmit or to receive data. Several protocols based on this mechanism have been developed under IEEE-802.15.4 standard [8]. However, this technique requires a mechanism that synchronizes sensors between each other and organizes data exchanges.

They are three main categories of MAC protocols: contention based protocols such as: B-MAC, S-MAC and WiseMAC [9-11]; TDMA based protocols such as TRAMA [12], and Hybrid protocols such as Z-MAC [13]. In this paper, we present a MAC protocol that combines the strengths of slotted and contention channel access, while offsetting their weaknesses for healthcare monitoring needs.

In [14], we developed a possible runway based on the "event driven" approach. Simulation results showed on the one hand its advantages in terms of the early detection of anomalies and emergencies. On the other hand, they showed some limitations regarding to energy consumption. In [15], we presented a primary mobility aware protocol based on "sleep/active" mechanism. In this paper, we extend this approach by two key elements: a) Improving maintenance mechanisms, b) Real prototyping of the protocol.

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III. T-TMAC Protocol Design

A. Assumptions and Network Architecture

We propose a heterogeneous and centralized WSN architecture described in Figure 1. The sensor nodes are organized into groups: Medical (M), Coordinator (C), Video (V) and *Sink* (S). The network architecture is composed of three tiers (Each tier has its own characteristics and requirements): (M, C), (C, V) and (V, S). A sensor node may interact with other nodes in inter-tiers or intra-tiers to achieve the common goal (healthcare monitoring). This type of architecture offers many advantages in terms of capacity, coverage, and reliability compared to single tier Ad hoc networks as described in [16]. Medical nodes collect and relay physiological medical data (temperature, ECG, etc.), and Video nodes collect and relay ambient data (image, humidity, etc.).

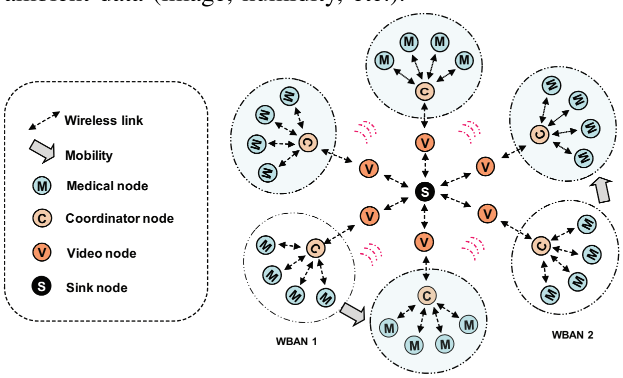

Figure 1. Global network architecture for healthcare monitoring at home

We summarize below the main characteristics retained for this architecture: (i) Low density of sensors: the deployment area of the global network is relatively small; we are conducting this study in the case of a house. (ii) The Wireless Body Area Network (WBAN) has a cluster / star topology that consists of (M) and (C) nodes. (iii) Video nodes are stationary, while the WBAN nodes are mobile. (vi) Video nodes act as relay nodes (forwarding data received by (C)). (vii) The traffic pattern is periodic: "many-to-one" (from the bottom to the top $(M) \rightarrow (C) \rightarrow (V) \rightarrow (S)$, managed by the *Sink*. The data flow is initiated by (M) node. (v) (C) node is associated with only one video node at a time following multi-hop transfer to reach the *Sink*. Thereafter, we propose the appropriate mechanism for mobility management. To enhance the lifetime of sensors, three principle assumptions are considered.

- *Data aggregation:* (C) node aggregates medical data of its WBAN, (V) node can aggregate data from multiple Coordinators within range.
- *Power tuning:* we propose to adjust the power transmission (TPL: Transmission Power Level) of each sensor node in the architecture while maintaining hop-by-hop connectivity between: $(M), (C), (V)$ and (S), as shown in Figure 1. This leads not only to limit the over-consumption of energy but can also leads to limit interferences between nodes [5].
- *Sleep / active schedule:* nodes operate under activity / inactivity mode. (M) and (V) nodes can turn off their radio during sensing data.

B. Structure of T-TMAC

To organize the data exchange between sensors in the three tier network we propose simple mechanisms that fit the application needs. The sensors of each level follow a dynamic scheduling (on / off). They wake up when needed and sleep the rest of the time. The scheduling is organized level by level as follows: in level 1 between Medical nodes (M) and their associated Coordinator (C), in level 2 between Coordinators (C) and Video (V), and finally in level 3 between Video nodes (V) and *Sink* (S).

1) T-TMAC Superframe: We consider an access method close to the IEEE-802.15.4 protocol with some modifications. Indeed, we adapt the parameters setting of the Superframe according to the requirement of each tier taking into account the sleep / active scheduling. In the first tier, the communications between (C) and (M) nodes are organized into Superframes managed by the coordinator. The Superframes are delimited by Beacons sent by the coordinator, within it provides information about synchronization, GTS (Guaranteed Time Slot) allocation, etc. The first Superframe (Superframe 0) may not contain CFP (Contention Free Period). In fact, there will be only CAP (Contention Access Period) for initialization (cf. section 2) where medical nodes compete to associate to the Coordinator and reserve some GTSs (cf. section 4). The other Superframes (*1* to *n*) contain only CFP period and remove the CAP. Figure 2 shows the parametrized Superframe.

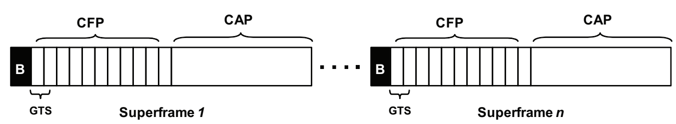

Figure 2. T-TMAC *Superframes*

The number of reserved GTS depends on the type and the length of data. In the CAP period (called later "Reporting" period), the coordinator sends the collected data to (V) node to which it is associated. This later, reports data to the *Sink*. During this period, medical nodes can turn off their radios (sleep mode).

2) Principle phases of the protocol:

Initialization: Its principle role is to synchronize the four groups of heterogeneous nodes between each other for mutual recognition, and to organize data transmission that will be used in the data collection phase. During this phase, the network is created level by level according to a top-down messages transfer from (S) to (M). At the end of network creation, collection phase begins in bottom-up sense from (M) to (S) with periodic data transfer.

Data Collection and topology reconfiguration: This phase takes place immediately after the topology creation. It represents the crucial phase of the protocol. In one hand it allows relaying medical data hop by hop to reach the *Sink*, according to the schedule defined in the creation phase. In other hand, it includes mechanisms for topology maintenance and reconfiguration (cf. section C).

3) Organization of Data Exchange: Both phases operate in different ways. Figure 3 describes for each data flow, the different messages exchanged between active nodes per level. Initially, the *Sink* node initiates the topology creation by sending "S_Beacon" message to Video (V) node. This later sends an association request message "ASC_RQ" to the *Sink*, which accepts the request by sending "ASC_ACK" message. Thus, the node (V) is associated with the *Sink*. Then, the association between (V) and (C) nodes begins. The node (V) sends "B_Beacon" message to node (C), followed by the exchange of "ASC_RQ" and "ASC_ACK" messages whose finalize their association. Then the initialization of the WBAN network starts between (M) and (C) nodes with the exchange of "C_Beacon", "ASC_RQ" and "ASC_ACK" messages. After setting up the WBAN network, the data collection begins. The node (M) collects data, builds the first data message "DATA" and sends it to its associated Coordinator (C). Then (C) responds with acknowledgment message "ACK". "DATA" message will be then relayed by (C) to (V), and finally relayed by (V) to the Sink (S), with the exchange of "DATA" and "ACK" messages. As shown in Figure 3, after receiving the "ACK" message, nodes can turn to sleep mode to save energy.

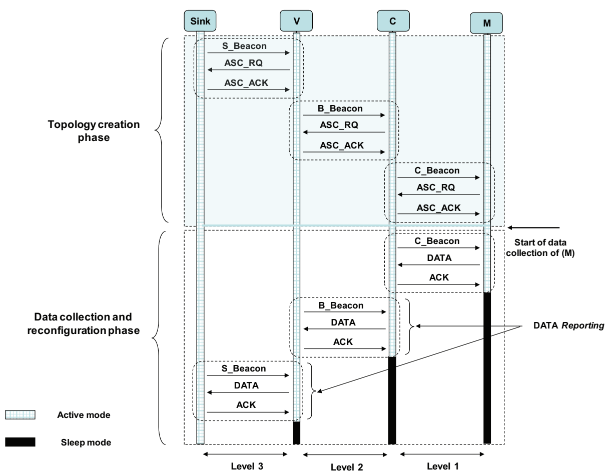

Figure 3. Principle mechanisms of the protocol

- *Medium access:* to minimize collisions in the three tier architecture we manage the medium access as follows: we use "Data reporting" period to manage "inter-tier" interactions between nodes belonging to different levels (nodes report data (by level) as shown in Figure 3. However, it is necessary, to assign the appropriate access method to minimize collisions between nodes belonging to the same level. In fact, we propose a hybrid access:

  - Slotted access for M and C nodes (WBAN): it provides a guaranteed access and a reduced delay for medical data.

  - Contention access for (C, V) and (V, S): this is appropriate for mobility.

- *Maintaining synchronization:* during the data collection phase, the network must operate under a regular schedule to ensure the transit of the data between levels 1, 2, and 3 in order to reach correctly the *Sink*. To this end, we propose that Coordinator, Video and *Sink* nodes send periodically Beacon messages. These messages have a crucial role because they permit to resynchronize nodes (to prevent the clock drift phenomenon) while keeping the data exchange hop by hop.

- *Slots request by (M):* the activity periods of (M) nodes may differ depending on the data size (temperature, fall detection, ECG, etc.). Indeed, if a medical node wants to send more than one packet in an activity period, we propose that it sends a request to its associated Coordinator. In fact, during initialization, (M) nodes request a certain number of slots (subsequently appointed GTS in Section 1) via ASC_RQ message. Then the response will be indicated in C_Beacon message (with the number of allocated slots), for use in the collection phase. However, in Data collection phase, the request could be integrated in DATA message, and the response will be in the C_Beacon message (in the next cycle). This mechanism responds to the dynamic behavior of network.

- *Reliability:* to reduce collisions / transmission errors that could occur during the two phases, it is necessary to retransmit all messages (the number of retransmissions is parametrized) including Beacon messages (except acknowledgments). This leads to increase the reliability of the data exchange.

- *Traffic model:* we assume that the traffic model made in the Data collection phase is periodic with the same period throughout the network. Each node (M) is the origin of one or more data packets in each period (one data flow). (M) nodes can also aggregate all medical data in one packet (the maximum size of PPDU in IEEE 802.15.4 is 127 bytes). To meet the energy needs of the sensors, the activity period should be optimized and reduced as much as possible.

C. Complementary Mechanisms for Topology Maintenance

We have improved the topology maintenance with new mechanism. Sending Beacon messages periodically offers other advantages that meet the application requirements. Particularly, they can be used for mobility management, re-allocation of new slots for WBANs, and topology re-configuration: addition of new sensor, and removal of a sensor (depleted battery, sensor breakdown, etc.). Actually, each level has a manager node that takes decisions while an event occurs: (C) node for tier 1, (V) node for tier 2 and (S) node for tier 3.
The mobility of a person has an impact on communications of tier 1 and tier 2: (i) In tier 1, when 2 WBANs are situated in the same range, to reallocate new slots, the (C) node sends C_Beacon message containing the new allocated slots. (ii) In tier 2, the link between (C) and (V) could be interrupted: node (C) should re-associate with a new (V) node (we can use the initialization mechanism via the exchange of B_Beacon, ASC_RQ and ASC_ACK messages). Then the new (V) node relays the received data to the Sink (via DATA and ACK messages).

IV. Dimensioning and Performance Evaluation

A. Analytical Model

The delay and energy consumption are the most important performance criteria for the application. Below we evaluate the performance of the protocol in the two phases: initialization and data collection. We used three important parameters: network size, transmission interval and data size.

• *Initialization phase analysis:* The first association phase between all medical nodes and the Coordinator is represented by the duration D :

$$D = T_{C\_Beacon} + \sum_{i=1}^{n_M} D_{ASC}(i) \ (1)$$

Where $D_{ASC}(i)$ is the association duration of one node i and n_M the number of medical nodes. Then, let $D_{ASC}(i)$ is the mean association time of node i with the (C) of its WBAN:

$$D_{ASC}(i) = T_{cs} + T_{ASC\_RQ} + T_{ASC\_ACK} \ (2)$$

T_{cs} is a random duration before each node i sends its *"ASC_RQ"*. To reduce collisions, each node initially senses the channel during a random duration T_{cs} uniformly distributed in the interval $[0, T_f]$, where T_f is the maximum of the duration. For the sake of simplicity, we consider in a similar manner to [10] the mean value of T_{cs}: $T_{cs} = \frac{T_f}{2}$ (3)

- When the other medical nodes hear the first *"ASC_RQ"* they must wait for a time equal to $(T_{ASC\_RQ} + T_{ASC\_ACK})$ before starting to draw again a random duration T_{cs}.
- The number of reserved GTS (reserved by (M)) depends on the kind and the length of data.

The association duration of the other nodes can be written as follows:

$$D_{ASC}(i)_{i\neq1} = D_{ASC}(i-1) + \frac{T_f}{i+3} + T_{ASC\_RQ} + T_{ASC\_ACK} \quad (4)$$

Energy consumption: To calculate the energy consumption of the first node we can reuse the formula (2) by adding consumption corresponding to each mode (reception or transmission), then we obtain:

$$E_{ASC}(i)_{i=1} = e_{rx} \cdot (T_{cs} + T_{ASC\_ACK}) + e_{tx} \cdot (T_{ASC\_RQ}) \quad (5)$$

To calculate the total energy consumed we add the amount $(e_{rx} \cdot T_{C\_Beacon})$ that corresponds to the receiving of the Coordinator Beacon *("C_Beacon")* and e_{rx}, e_{tx} are respectively the energy consumed when receiving and transmitting data. The energy consumption of the other nodes during the association phase can be written as follows:

$$E_{ASC}(i)_{i\neq1} = e_{rx} \cdot [D_{ASC}(i-1) + \frac{T_f}{i+3} + T_{ASC\_ACK}] + e_{tx} \cdot (T_{ASC\_RQ}) \quad (6)$$

As shown in Figure 3, in the reporting period, (C) sends the collected data to (V) to which it is associated. During this period, medical nodes may turn off their radios (sleep mode) to save energy.

• *Data collection phase analysis:* It corresponds to the data sending and differs from the association, because during this time, medical nodes don't have to compete for the medium access, however they have to send *"DATA"* messages larger than *"ASC_RQ"*.

$$D_{DC} = T_{C\_Beacon} + T_{DATA} + T_{ACK} \ (7)$$

$$D_{Total} = T_{slots} \cdot \sum_{i=1}^{n_M} N(i) \ (8)$$

Where T_{slots} is the slot duration and $N(i)$ is the total number of slots allocated to medical node (i). To calculate the energy consumption in data collection we reuse the formula (7):

$$E_{DC} = e_{rx} \cdot (T_{C\_Beacon} + T_{ACK}) + e_{tx} \cdot (T_{DATA}) \ (9)$$

• *Other Superframes analysis:* In the same way, we can evaluate the upper *tiers* (C, V) and (V, S). The principle parameter that changes is the number of nodes per level (n_C, n_V). However, in data collection analysis, the T_{cs} duration must be added because (C) and (V) nodes compete for the medium access.

B. Hardware Implementation

• *Platforms used:* we have implemented T-TMAC in Imote2 hardware platform. The Imote2 transceiver operates at ISM 2.4 GHz frequency, 17.4 mA with (0 dBm) power output and it allows data rates of up to 250 Kbps. The micro-controller runs at $13-416$MHz. This device requires a supply voltage between $3.2-4.5$ Volts, and is powered by three $1.5V$ (AAA) batteries in series. The sensing unit includes: temperature, acceleration and humidity measurements. Two kinds of cards [14] may be embedded on Imote2 radio card: *Sensing card* and *Video card*.

• *Protocol implementation:* Figure 4 shows the implemented sensor network and Table 1 shows the measured real parameter values of the Imote2. Four important tasks are realized to build the network architecture and to test the network operations: power tuning, frames setting (S_Beacons, DATA, ACK, etc.), WBAN implementation (aggregation functions for (C), slots management) and Data forwarding.

PARAMETER	VALUE	UNIT
$S\_Beacon,\ B\_Beacon$	$11,7$	ms
$CBeacon$	$12,8$	ms
T_{ASC_RQ}	$12,2\,(M),\ 11,7\,(C,V)$	ms
T_{ASC_ACK}	$11,9\,(M),\ 11,7\,(C,V)$	ms
$T_{DATA(M)}, T_{DATA(C)}, T_{Data(V)}$	$13,7\,(M),\ 14,9\,(C,V)$	ms
T_{ACK}	$11,9\,(M),\ 11,7\,(C,V)$	ms
ST	$1083\,(M1),\ 450\,(M2)$	ms
e_{tx}	$74,2\,(92\,bytes)$	mA
e_{rx}	$97,2\,(92\,bytes)$	mA
e_l	$56,4\,(listening)$	mA
e_{px}	37	mA
$e_{px(sleep)}$	500	µA
e_{sgx}	$6,4\,(procOn:\ 43,4)$	mA
LED	$2\,(procOn:\ 39)$	mA
$Number\,of\,retransmissions$	3	/ o
$Tx\,power\,(M_1, M_2, C_1, V_1, S)$	$-25, -25, -10, -10, -10$	dBm

Table I
MEASURED PARAMETER VALUES

V. RESULTS AND DISCUSSION

Figure 5 shows the prototyping results for initialization and data collection phases. The graph on the left side shows the current consumption during initialization of each node $(M1), (M2), (C), (V)$ and (S). We see that it increases depending on the nodes position in the architecture. (M) and (C)

nodes are the larger consumers of energy. This is due to the waiting time that these nodes spent to receive their appropriate Beacon message (B_Beacon for (C) and C_Beacon for $(M1)$ and $(M2)$ (as shown in Figure 3). The graph on right side shows the current consumption of each node during data collection phase, during 1 hour of operation, with Deep Sleep period of 20 seconds. The results show clearly the advantage of the Deep sleep mode implemented on Imote2 platforms, to save the energy of all nodes.

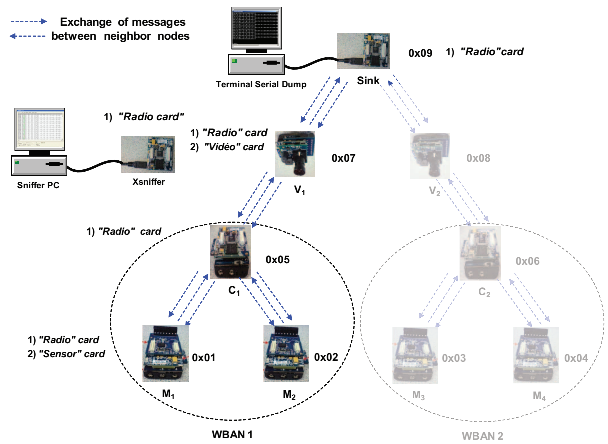

Figure 4. Implementation of the sensor network

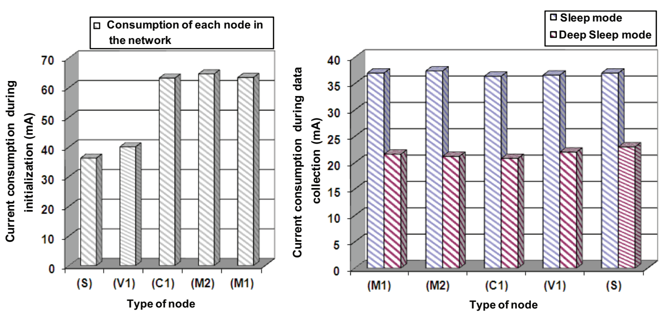

Figure 5. Prototyping results: initialization and data collection phases

We estimated analytically the average energy consumption (E_{ASC}) in initialization and Data collection phases. Figure 6 shows the comparison between analytical and real prototyping results, for one hour of operation of the network, with Deep sleep of 20 seconds (180 cycles). We added in the analytical calculation the values assigned for data sensing ($(M1)$: temperature and $(M2)$: all Data). We show that analytical results fit with the prototyping results.

VI. Conclusion

In this paper a new MAC protocol for healthcare monitoring is presented. Simple mechanisms based on sleep/active schedule are proposed for energy efficiency. We showed the advantages of data aggregation and allocation of slots in a multi-tiers architecture. The performance evaluation has been realized with an analytical model and with real prototyping on Imote2 platforms. The results fit very well. From all results, it seems that T-TMAC protocol provide a significant amount of energy saving. Our on-going work is focused on detailed modeling analysis and scenarii evaluation and on the comparison between T-TMAC and other MAC protocols such as IEEE 802.15.4. Other perspective of this work concerns extending the protocol with scalable slot allocation mechanism. This mechanism could be appropriate for large applications with dense number of nodes such as in the case of hospitals.

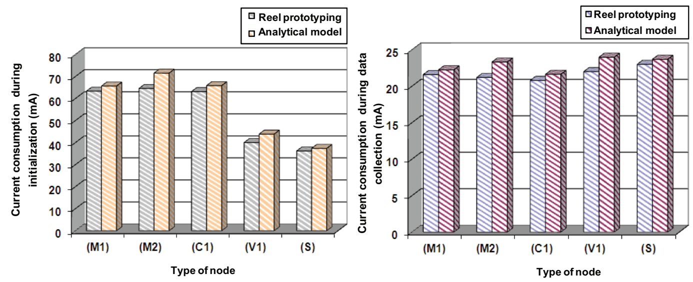

Figure 6. Comparison of results obtained by the two methods: current consumption by each node during initialization and data collection phases

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