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Impact of Current Consumption on Battery Energy in IEEE 802.15.4 for Wireless Sensor Networks with Different Sensor Motes

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Abstract— Current consumption is a key aspect for evaluating the performance of a Wireless Sensor Networks (WSNs). This paper investigates the battery energy consumed for the different current draw parameters: transmit mode, receive mode, sleep and idle mode keeping other parameters like: initial energy and power supply same for all motes. This paper concludes that there is trade-off for the use of various motes at different types of devices in IEEE 802.15.4 WSNs.

Keywords— 802.15.4; WSN; Telos; MICAz; Z1; Epic Core; GTS End Device; CAP End Device; PAN Coordinator.

I. INTRODUCTION

IEEE 802.15.4 protocol provides real-time guarantees by using the Guaranteed Time Slot (GTS) mechanism, which is quite attractive for WSNs [1]. The IEEE 802.15.4 / ZigBee are designed for low-rate and small size Wireless Personal Area Networks (WPANs). The IEEE 802.15.4 Medium Access Control (MAC) protocol has the ability to provide very low duty cycles (from 100% to 0.1%), which is particularly interesting for WSN applications where energy consumption and network lifetime are main concerns [2]. In WSN deployments, reliably reporting data while consuming the least amount of power is the ultimate goal and the traditional IEEE 802.11 standard is developed with no energy minimization mechanisms which are necessary for those 802.15.4, designed for low-rate wireless applications [7]. In fact, when operating in beacon-enabled mode, i.e. beacon frames are transmitted periodically by a central node called PAN (Personal Area Network) Coordinator for synchronizing the network, The IEEE 802.15.4 protocol allows the allocation/deallocation of GTSs in a superframe for nodes that require real-time guarantees. Hence, the GTS mechanism provides a minimum service guarantee for the corresponding nodes and enables the prediction of the worst-case performance for each node’s application.

In particular the basic framework of IEEE 802.15.4 permits up to 10 – meter communications with a transfer rate of 250 kbps, although this parameter can be decreased even more (down to 20 kbps in the 868/915 MHz band) to enable a lower power consumption in the ZigBee nodes. IEEE 802.15.4 – compliant transceivers, which operate in the Industrial, Scientific and Medical (ISM) radio bands are designed to be simpler and more economical than the modules from other WPAN standards like: Bluetooth. The main attractiveness and also the main challenge of IEEE 802.15.4 WSN is its potentiality to set up self-organizing networks capable of adapting to diverse topologies, node connectivity and traffic conditions. Typical applications of 802.15.4 WSN usually consists of tens or hundreds of simple battery powered sensor nodes which periodically transmit their sensed data to one or several data sinks (PAN Coordinator).

IEEE 802.15.4 technology was conceived to minimize the power consumption of these sensor nodes. For this purpose, the activity of the nodes must be reduced up to a minimum so that they can remain most of the time in a sleep (low-power) state. Therefore, a node just has to be active in order to sense and transmit data for a small fraction of time. The general objective is to maximize the lifetime of the battery in nodes and consequently the lifetime of the sensor network. In order to predict the battery lifetime of the devices in a practical implementation of IEEE 802.15.4 WSN, we must characterize the current which is drained (consumed) from the battery during the different operations imposed by the dynamics of IEEE 802.15.4 communications, especially those which relates to the activation of radio transceiver.

In this paper we have simulated and presented the effects of varying the current consumption in WSN motes keeping all other parameters same in all scenarios except the current draw in a mote in each scenario. Comparing the results of different scenarios for different type of devices permits to conclude that there is trade-off for the use of various motes.

This paper is organized as follows: Section II reviews the existing literature on the characterization of IEEE 802.15.4. Section III gives the brief system description. Section IV presents and discusses the results. Finally, the Section V summarizes the main conclusions of the paper.

II. RELATED WORK

Ever since the release of IEEE 802.15.4 in 2003, many researches have been done to evaluate its performance in different environments, including software, hardware and analytical analysis. Initially in [1] authors have proposed an accurate simulation model with focus on the implementation of GTS mechanism. Additionally and most importantly the authors have proposed a novel methodology to tune the protocol parameters so that better performance of the protocol can be guaranteed, both concerning maximizing the throughput of the allocated GTS as well as minimizing frame delay.

E. Casilari et al. [2] presents an empirical characterization of battery consumption in commercial IEEE 802.15.4/ZigBee motes. This characterization is based on the measurement of the current that is drained from the power source under different 802.15.4 communication operations. The measurement permits the definition of an analytical model to predict the maximum, minimum and mean expected battery lifetime of a sensor networking application.

In [3] O. Landsiedel et al. predicts the accurate power consumption in wireless sensor networks. The authors [4] have empirically characterized the battery consumption in commericial 802.15.4/ZigBee and this characterization is based on the measurement of current that is drained out from the power source under different operations of 802.15.4 communications. In [5] authors have defined a duty cycle in order to allow the devices to achieve efficient energy consumption. The behaviour of 802.15.4 MAC, especially the performance of CSMA/CA algorithm, has been analytically modeled in different papers such as [6] – [7] for beacon – enabled and/or beaconless 802.15.4 networks. The accuracy of all these models, normally based on two – dimensional Markov chains, is evaluated by simulations. Authors [8] have implemented a decentralized power aware approach for data fusion application to increase the WSN lifetime. In [9] R. K. Panta et al. have presented a detailed study of the relationship caused by low power link layer duty cycling mechanism used in WSNs, additionally QuickMAC – a novel duty cycling protocol for WSNs has been implemented. The consumption in beaconed networks is also characterized in [10]; in this paper authors present their own measurements of power consumption of a CC2420 transceiver. The authors of [11] propose a method to tune the contention control of slotted CSMA/CA aiming at maximizing power saving and throughput; The study, which is evaluated by simulations utilizing the battery model of a commercial radio module, defines a specific metric to calibrate the battery efficiency; However, the model neglects the energy consumption that takes place for specific operations of radio module (e.g. in the backoff intervals). J.M. Cano-Garcia & E. Casilari have focused on the current demanded by a sensor node in a simple beaconless star topology when the CSMA contention algorithm introduces idle times in the activity of radio transceiver in [12]. The study in [13] suggests the use of battery state in the 802.15.4/ZigBee nodes as a metric for AODV (Ad Hoc on Demand Distance Vector) routing algorithm typically employed in ZigBee mesh topologies. The paper [14] investigates the effects of employing a cryptographic mechanism on the power consumption of beacon-enabled 802.15.4 networks. The mean energy consumption per transmitted byte is computed assuming that a battery mode of radio module [15] is not compatible with 802.15.4 standard.

In [16] W. Du et al. have implemented an energy model for WSNs which estimates the energy both for the hardware components of the individual nodes and whole of the sensor network. In [17] authors have proposed the comprehensive simulation study by addressing the impact of IEEE 802.15.4 MAC attributes (BO, SO and BE) on the performance of slotted CSMA/CA in terms of throughput, average delay and success probability. Here the concept of utility, which is defined as a combination of two or more metrics, enables to determine the optimal offered load for achieving the best trade-off between all combined metrics. Koubaa et al. [18] have explored the most relevant characteristics of IEEE 802.15.4 protocol for WSNs and have presented the most important challenges regarding the time-sensitive applications and have also provided some timing performance analysis of the IEEE 802.15.4 that unveils some directions for resolving the previously mentioned paradoxes including power efficiency. Authors of [19] have presented a methodology that provides a Time Division Cluster Scheduling (TDCS) mechanism based on the cyclic extension of RCPS/TC (Resource Constrained Project Scheduling with Temporal Constraints) problem for a cluster-tree WSN, assuming bounded communication errors. Authors of [20] have proposed a power efficient superframe selection method that simultaneously reduces power consumption and enables to meet the delay requirements of real-time flows allocating GTSs. In [22] K. Witheephanich et al. have developed an explicit Generalized Predictive Control (GPC) strategy for WSN power control that addresses practical constraints typically posed by health care problems. In [23] – [26] datasheets of various motes have been accessed to compare their performances.

In this paper, we have compared and characterized the current consumption in IEEE 802.1.5.4 using different motes (like: Z1, Epic Core, MICAz and Telos) under the same set of operations. The ultimate goal is to prove simulatively that certain motes are better as compared to others when a particular parameter is to be taken into consideration.

III. SYSTEM DESCRIPTION

Simulative model of IEEE 802.15.4/ZigBee implements Physical and Medium Access Layer defined in IEEE 802.15.4 standard and application layer defined by ZigBee. The OPNET® Modeler has been used for developing four variants of 802.15.4 i.e. Epic Core, MICAz, Telos and Z1. Each variant (scenario) contains ten GTS enabled nodes and ten non-GTS nodes. GTS nodes can handle only the acknowledged GTS traffic while the non-GTS nodes can only handle unacknowledged non-GTS traffic. All four scenarios are same in each and every respect except for the battery parameter: current draw (current draw in transmit, receive, idle and sleep modes).

A. Scenarios

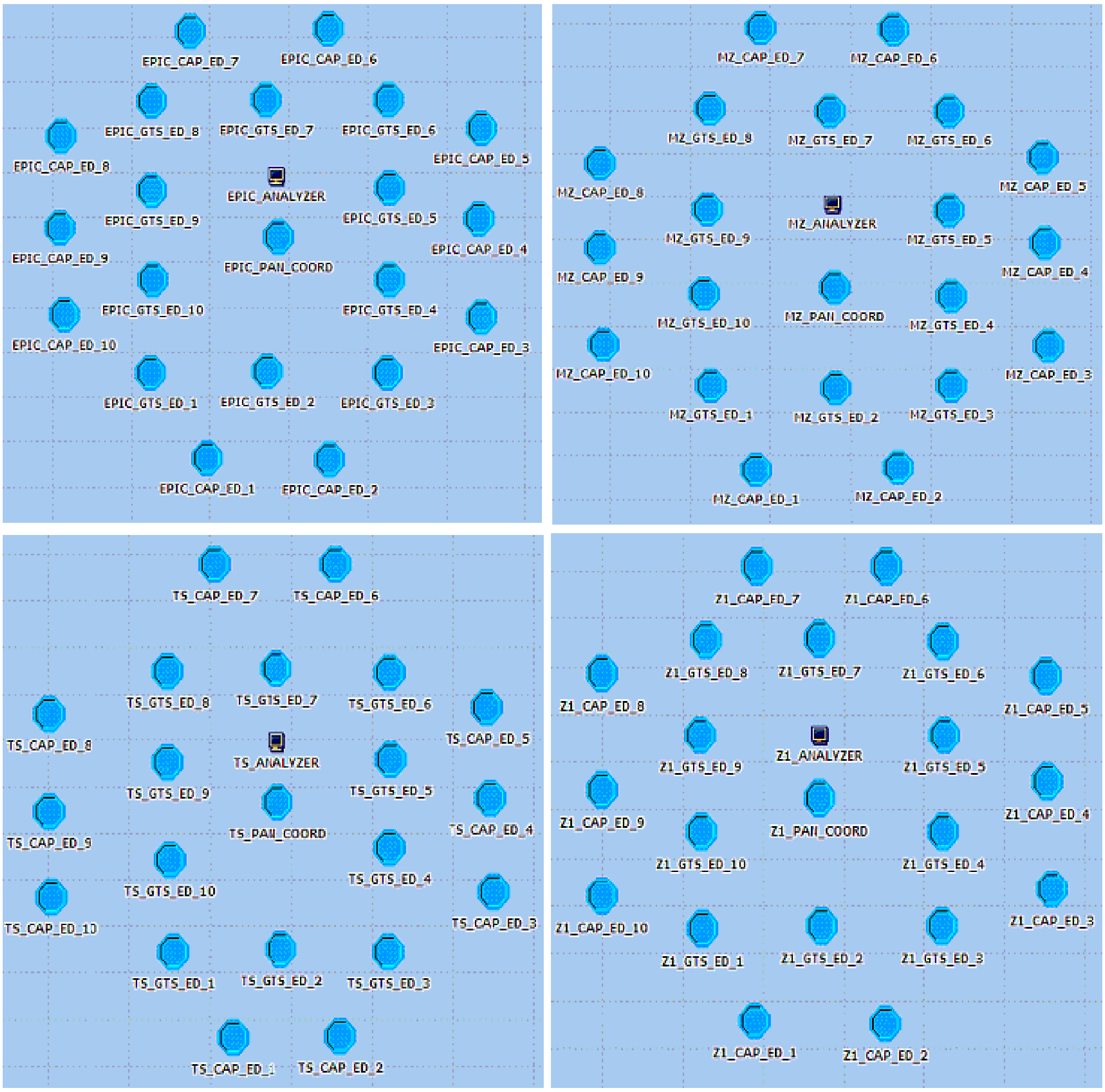

Fig. 1 Network Scenarios (a) Epic Core (b) MICAz (c) Telos (d) Z1

Fig. 1(a) shows the Epic Core scenario which contains one PAN Coordinator, one Analyzer and twenty end devices (ten GTS enabled and ten non-GTS enabled), similarly fig. 1(b) shows MICAz scenario, fig. 1(c) shows Telos scenario and fig. 1(d) shows the Z1 scenario. PAN Coordinator is a Fully Functional Device (FFD) that can support three operation modes, serving as:

- ✓ A *Personal Area Network (PAN) Coordinator*: the principal controller of the PAN. This device identifies its own network, to which other devices may be associated.
- ✓ A *Coordinator*: provides synchronization services through the transmission of beacons. Such a coordinator must be associated to a PAN coordinator and does not create its own network.
- ✓ A simple *Device*: a device which does not implement the previous functionalities.

End device is a Reduced Functional Device (RFD) operating with minimal implementation of IEEE 802.15.4 protocol. They do not need to send large amounts of data and associate with a single FFD at a time.

B. Parametric Description

Parametric values for the different types of devices in all scenarios are same except for the battery parameters (as shown in the table 1). E.g. parametric values of the PAN Coordinator acknowledged traffic like: MSDU Interarrival time, MSDU size, start time, stop time etc. are same in all four scenarios and the battery parameters like: current draw in ‘Idle mode’ (1.0, 20, 545 and 426) µA, is different for each scenario.

TABLE I

PARAMETRIC VALUES OF PAN COORDINATOR, GTS AND CAP DEVICES IN DIFFERENT SCENARIOS

Scenario	Epic Core			Micaz			Telos			Z1		
Device Type / Parameter	PAN Coord	GTS	CAP	PAN Coord	GTS	CAP	PAN Coord	GTS	CAP	PAN Coord	GTS	CAP
Acknowledged Traffic Parameters												
MSDU Interarrival Time (sec)	Exponential (1.0)											
MSDU Size (bits)	Constant (912)											
Start Time (sec)	0.1											
Stop Time (sec)	180											
Destination MAC Address	Broadcast	PAN Coord		Broadcast	PAN Coord		Broadcast	PAN Coord		Broadcast	PAN Coord	
Unacknowledged Traffic Parameters												
MSDU Interarrival Time (sec)	Exponential (1.0)											
MSDU Size (bits)	Constant (912)											
Start Time (sec)	0.1											
Stop Time (sec)	180											
CSMA Parameters												
Maximum Backoff Number	4											
Minimum Backoff Exponent	3											
Battery												
Current Draw Receive Mode (mA)	**19.7**						**21.8**			**18.8**		
Current Draw Transmit Mode (mA)	**17.4**						**19.5**			**17.4**		
Current Draw Idle Mode (μA)	**1.0**			**20**			**54.5**			**426**		
Current Draw Sleep Mode (μA)	**9.0**			**1.0**			**5.1**			**20**		
Initial Energy	**2 AA Batteries (1.5 V, 2300 mAh)**											
Power Supply	**2 AA Batteries (3V)**											
IEEE 802.15.4												
Device Mode	PAN Coord	End Device		PAN Coord	End Device		PAN Coord	End Device		PAN Coord	End Device	
MAC Address	Auto Assigned											
WPAN Settings												
Beacon Order	7											
Superframe Order	3											
PAN ID	0											
Logging												
Enable Logging	Enabled											
GTS Settings												

GTS Permit	Enabled	Disabled	Enabled	Disabled	Enabled	Disabled	Enabled	Disabled
Start Time (sec)	0.1	Infinity	0.1	Infinity	0.1	Infinity	0.1	Infinity
Stop Time (sec)	180	Infinity	180	Infinity	180	Infinity	180	Infinity
Length (slots)	2		2		2		2	
Direction	Receive	Transmit	Receive	Transmit	Receive	Transmit	Receive	Transmit
Buffer Capacity (bits)	10,000	1000	10,000	1000	10,000	1000	10,000	1000
GTS Traffic Parameters								
MSDU Interarrival Time (sec)	Exponential (1.0)							
MSDU Size (bits)	Constant (912)							
Acknowledgement	Enabled							

IV. RESULTS AND DISCUSSIONS

In the following subsections we present the obtained results by varying the sensor motes in IEEE 802.15.4 four different scenarios and keeping all other required parameters (TABLE I) same in all scenarios. In this section we present the results for Fully Functional Device (FFD) PAN Coordinator and Reduced Functional Devices (GTS and CAP).

A. Battery Energy Consumed at the Fully Functional Device (PAN Coordinator)

Fig. 2 shows that the energy consumed by the battery at the PAN Coordinator is: 12.30983, 10.30983, 9.066223 and 7.26554 joules if we use Telos, MICAz, Epic Core and Z1 motes respectively.

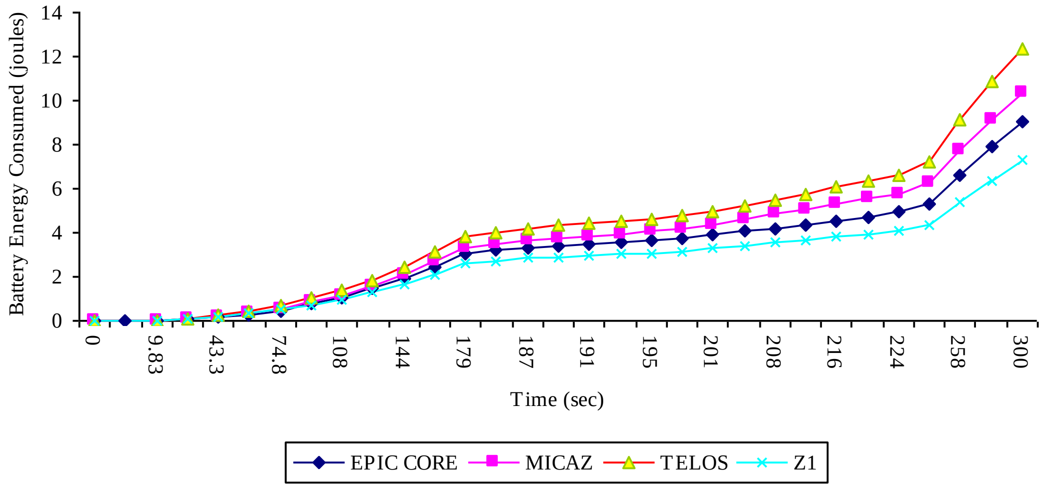

Fig. 2 Battery Energy Consumed at the Pan Coordinator

It is observed that minimum energy is consumed by the Z1 mote because according to the implementation:

/* **Transmit/Receive Mode** */

```
consumed_energy= (battery.current_tx_mA * milli) * tx_time * battery.power_supply;
consumed_energy= consumed_energy + (battery.current_idle_microA * micro) * duration * battery.power_supply;
```

/* **Receive Mode** */

```
consumed_energy= (battery.current_rx_mA * milli) * rx_time * battery.power_supply;
consumed_energy= consumed_energy + (battery.current_idle_microA * micro) * duration * battery.power_supply;
```

From these modes (transmit & receive) it is analyzed that consumed energy is directly proportional to current consumed for transmission and current consumed for reception i.e.

consumed energy α tx_mA α rx_mA (Eq. 1)

where
tx_mA: current in transmission mode (mA).
rx_mA: current in reception mode (mA).

Z1 mote consumes least current during transmission/reception as compared to the other motes (TABLE II). Being a FFD, a PAN Coordinator has to handle the traffic of all types from whole of the network i.e. most of the time is consumed in transmissions and receptions. It remains idle or goes to sleep for a very short period of time, so the major current characteristics that effect the battery consumption at the PAN Coordinator are current consumption in transmission and reception modes [Eq. 1]. Therefore Z1 mote consumes least energy at the PAN Coordinator. Also it has been observed that energy consumed is maximum in case of Telos Mote because the current consumed during transmission/reception is maximum (TABLE I) as compared to other motes [Eq. 1].

B. Battery Energy Consumed at the Reduced Functional Device (GTS End Device)

Fig. 3 indicates that the energy consumed by the battery at the GTS End Device is: 7.673145, 6.488002, 2.744401 and 1.343695 joules for Epic Core, Z1, Telos and MICAz motes respectively.

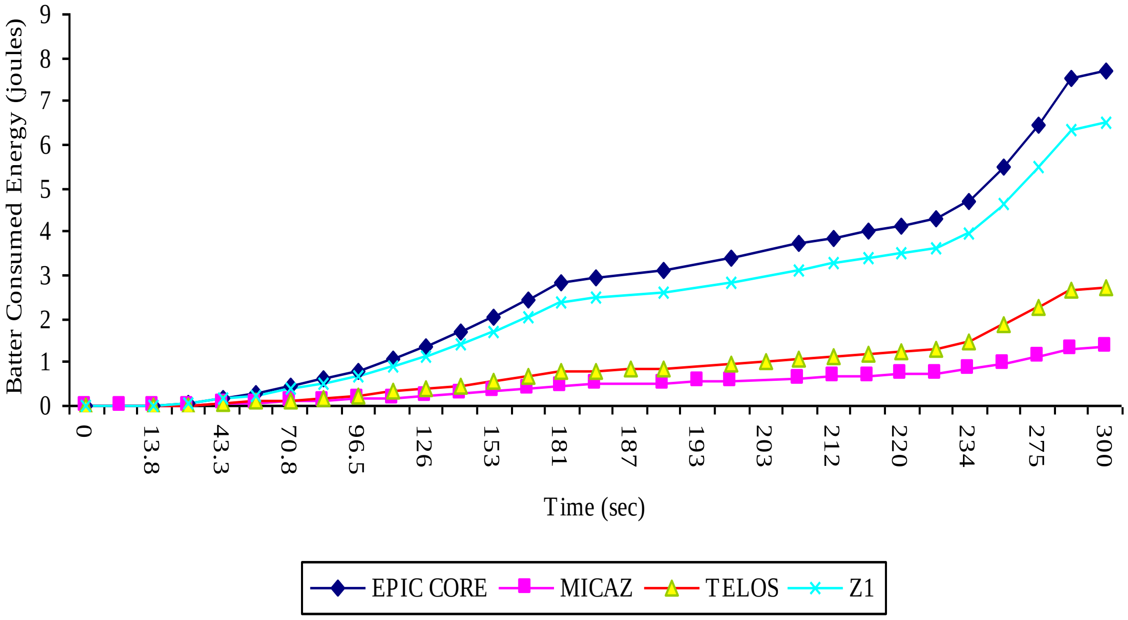

Fig. 3 Battery Energy Consumed at the GTS End Device

It is observed that minimum energy is consumed in case of MICAz mote because as per implementation:

/* **Sleep Mode***/

consumed_energy= (battery.current_sleep_microA * micro) * sleep_duration * battery.power_supply;

consumed energy α battery.current_sleep_microA (Eq. 2)

where
battery.current_sleep_microA is the current consumed by battery in sleep mode (µA).

MICAz mote consumes least current in the sleep mode as compared to the other motes (TABLE III). Since GTS end device has to remain in the sleep mode for a most of its life and has to periodically wake-up and transmit/receive data to/from the PAN Coordinator, so the current consumed in sleep mode plays a major role in the energy consumed by the battery at the end device [Eq. 2]. Also it has been observed that energy consumed at the GTS end device is maximum in case of Epic Core mote because GTS end device reserves required bandwidth for a particular data transmission/reception in advance i.e. it spends time either sleeping or transmitting/receiving and only small fraction of time in idle mode. Therefore it consumes more energy as compared to the other motes [Eq.1, Eq. 2, TABLE IV] especially in case of sleep mode Epic Core consumes 9.0 µA which is less than 20 µA of Z1 mote but in receive mode Epic Core consumes 19.7 mA of current but Z1 consumes only 18.8 mA.

C. Battery Energy Consumed at the Reduced Functional Device (CAP End Device)

Fig. 4 represents that the energy consumed at the CAP end device is: 9.566554, 6.469655, 4.007025 and 3.470106 joules for Telos, Z1, Epic Core and MICAZ motes respectively.

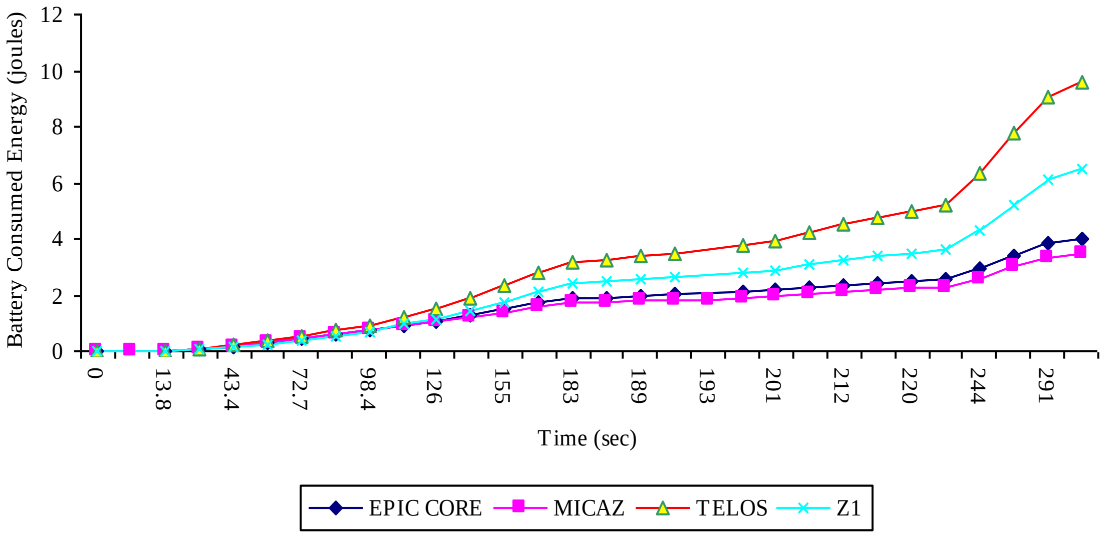

Fig. 4 Battery Energy Consumed at the CAP End Device

It is observed that minimum energy is consumed in case of MICAz mote at the CAP (non GTS) end device because CAP end device has to remain in the sleep mode for a most of its life and has to periodically wake-up and transmit/receive data to/from the PAN Coordinator, so the current consumed in sleep mode plays a major role in the energy consumed by the battery at the end device [Eq. 2]. Also it has been observed that maximum energy is consumed in case of Telos mote at the CAP end device because current in transmit and receive mode are more in case of Telos as compared to the other motes (TABLE I). Since CAP end device is a non GTS enabled i.e. it does not make any bandwidth reservations in advance for data transmission/reception, therefore no or minimum delays and CAP end device is in state of transmitting/receiving for most of its lifetime. Therefore current consumed in transmit mode and receive mode are the major contributors to the energy consumed by the battery in CAP end device [Eq. 1, Eq. 2].

V. CONCLUSION

This paper provides simulative characterization of current consumption in IEEE 802.15.4 sensor motes. The characterization takes into account energy consumed by the battery. Battery energy consumed concludes that Z1 mote at the PAN Coordinator and MICAz mote at the end devices consumes least energy. Therefore this paper concludes that there is trade-off for the use of motes in IEEE 802.15.4 WSNs if the battery energy consumed is to be taken into consideration as no single mote meets all the requirements of IEEE 802.15.4 for WSNs.

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