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Improving Wireless Sensor Network Performance Using MAC Protocols

By

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ABSTRACT

Wireless sensor networks offers a wide range of applications that can be used in includes environmental monitoring, health structural monitoring, high end applications and security. However, WSN requires a constant power source. To operate efficiently various proposed MAC schemes have been proposed with the aim of achieving low energy consumption or high throughput depending on the application. This thesis proposes a scheme that offers both low energy consumption and high network throughput to enhance MAC protocols which are based on the theory of S-MAC protocol. The proposed scheme utilizes two control packets (particularly SYNC and RTS) and mix there functionalities in one control packet (shall be called SEEK) then this packet will be forwarded to the down stream nodes in a multi-hop fashion. Then apply this method on a MAC protocol that is based on S-MAC theory.

The simulation results show that it is feasible to achieve low energy consumption using the proposed algorithm presented in this thesis. In conclusion, this thesis has shown that it is feasible to manipulate the construction of control packets to achieve better operation for a MAC protocol.

ABSTRACT

WSN menyediakan pelbagai aplikasi yang boleh digunapakai didalam pengawasan alam sekitar, pengawasan struktur kesihatan, akhir tinggi permohonan-permohonan dan keselamatan. Walau bagaimanapun, WSN memerlukan sumber tenaga yang malar. Untuk beroperasi dengan lebih cekap, pelbagai cadangan skim-skim MAC telah dicadangkan dengan tujuan untuk mencapai penggunaan tenaga rendah atau daya pemprosesan yang tinggi bergantung pada permohonan. Tesis ini mencadangkan satu skim yang menawarkan penggunaan tenaga rendah disamping daya pemprosesan rangkaian yang tinggi untuk meningkatkan protokol-protokol MAC berdasarkan teori S-MAC protokol. Hasil simulasi itu menunjukkan bahawa ia boleh dilaksanakan untuk mencapai penggunaan tenaga rendah dengan menggunakan algoritma yang dicadangkan didalam tesis ini. Kesimpulannya, tesis ini telah membuktikan bahawa ia adalah boleh dilaksana untuk memanipulasi pembentukan dari mengawal bungkusan-bungkusan untuk mencapai operasi MAC protokol yang lebih baik.

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Dedication

To my parents, you were the source of this courage that I have to finish this work and to achieve the level that I am in. what ever I do will not be enough to repay for what you did to me through my life. Thank you.

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ACK : Acknowledge.

CTS : Clear To Send.

DC : Duty-Cycle.

MAC : Medium Access Control.

RTS : Request To Send.

SYNC : Synchronization.

WSN : Wireless Sensor Networks.

CHAPTER ONE

INTRODUCTION

1.1. Wireless Sensor Networks:

The recent climate change has a significant impact on our planet environment. Therefore, deploying sensor networks to monitor the environment is becoming important. With sensor networks deployed in strategic location can provide the scientific communities useful data to be analyzed and take action if necessary. Typical environmental applications of sensor networks include, but not limited to, monitoring environmental conditions that affect crops and livestock, biological, Earth, and environmental monitoring and many more. Monitoring hazardous environment like volcanic activities is one of the important applications for Wireless Sensor Network (WSN) [1]. WSN communicate wirelessly to pass and process information – see Figure 1-1.

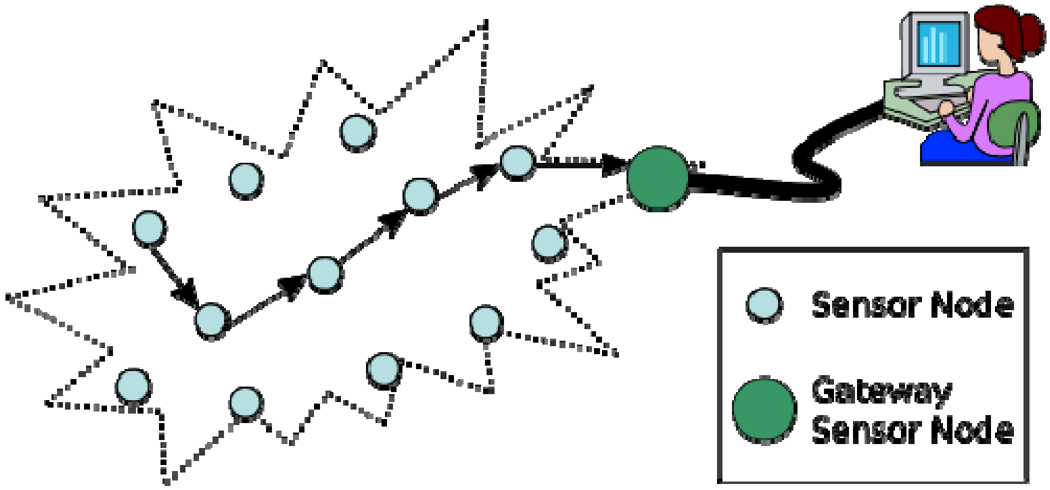

Figure 1-1: Wireless Sensor Networks

These sensor networks are deployed far away from the nearest permanent energy source available which make them depending on their own energy source to provide the needed information.

However, wireless sensor networks have a major problem, that is, “network life time”. Since WSN uses batteries, it does them in terms of storage, and processing power. Limited capabilities results in limited information efficiency. Current available technology on-shelf allow us to produce sensors that consumes as little power as 100mW which means that the sensors can remain operational efficiently (depending on the application and the deployed nodes own capabilities) for about 10 months. Yet the life time of the network can be extended for further than 10 months. Some researchers proposed methods includes energy harvesting, solar energy and vibration energy. But these methods can only provide a small amount of energy to power these sensors, typically 20mw or less [2, 3]. Maintenance and recharging these sensors is not a good option, and it will increase the expenses to keep the network alive and operational. Another alternative is to use energy efficient information processing and transacting algorithms to manage the network operation. We envisage that efficient routing and Medium Access Control (MAC) Protocols can help resolve this problem.

Information processing and routing is a technique used widely when it comes to provide a longer life time operation in wireless sensor networks however these techniques lacks the integrity as it has to compensate between either providing an energy efficient operation with the lack of high throughput or vice versa [4, 5].

One of the major levels of tweaking in networking systems is to manipulate the timing when to deliver particular packets at a precise times to achieve efficient operation. From the literature provided most of the available approaches consider the main purpose of manipulating information processing technique is to achieve better energy consumption in the nodes while sacrificing the system throughput quality and robustness [5].

MAC protocols controls when to send and receive distinguished packet between different nodes in a network. It controls the network interface when to establish the connection or the transaction between two or more hosts. Manipulating the operation of a MAC protocol can give its effect in terms of energy consumption and message delay between nodes [6].

Different MAC protocols were defined for WSN because of its application dependency. MAC protocols have to compensate between providing energy efficient consumption with the availability of decent throughput to make the system dependable [6, 7].

Energy efficient MAC protocols design has to overcome some challenges when it is meant for WSNs. These challenges includes but not exclusively: **Collisions**, which happens when two nodes try to enter the wireless medium at the same time. **Over-emitting**, when the source node is sending DATA but the destination node is in sleep mode.

This thesis proposes a MAC protocol scheme that can achieve efficient operation by compressing two control packets (SYNC+RTS) in one packet and shall call it (SEEK). This idea is derived from Traffic Energy Efficient MAC protocol (TEEM) [8] and another approach by Rajesh et al. [9] to decrease control packet overhead. The scheme will be discussed in detail in chapter 3.

1.2. Problem Statement:

1. Wireless sensor networks have a limited operation life time because of using their own energy storage (batteries).
2. The available MAC protocols suffer from either lack in energy consumption or latency problems.
3. WSNs are application dependent which affect on the design of any MAC protocol makes them vary in operation between low energy consumption with low throughput or vice versa.

1.3. Objectives of Research:

The objectives of this research are listed below:

1. Provide a MAC scheme that can achieve both energy efficient consumption and delay guarantee operation.
2. Enhance the operation of Sensor-MAC (S-MAC) [10] by adding the proposed scheme to achieve efficient network operation.
3. Enhance the Operation of Simple Energy Aware MAC (SEA-MAC) [11] as it is an improvement on S-MAC and to prove that the proposed scheme can be used to enhance the operation of MAC protocols that follows S-MAC basic operation.

1.4. Significance of the Research:

It is envisaged that the proposed scheme will provide the opportunity to study Data delivery security and quality of service (QoS) areas and applications in this multidiscipline area of research that can enhance the operation of WSNs to solve for example security issues in data delivery or add more computation abilities to these nodes, and to apply applications that require both delay guarantee and energy consumption.

1.5. Thesis Structure:

The next chapter will demonstrate a background about the technology and will give brief examples of the available MAC protocols provided by the literature. Chapter three will discuss the proposed approach and the algorithm of the approach and will provide a comparison case study between S-MAC [10] protocol and SEA-MAC [11] protocol. The results are discussed in chapter four and five. Chapter six will discuss conclusions and some issues in this field that could help in enhancing the proposed approach operation and then future work will be proposed.

CHAPTER TWO

BACKGROUND AND LETRATURE REVIEW

2.1. Background

As mentioned in chapter one, a sensor network consist of sensors connected in a way that sense and communicate with each other. It is an infrastructure comprised of sensing (measuring), computing, and communication elements that gives an administrator the ability to instrument, observe, and react to events and phenomena in specified environment.

WSNs usually consist of a large number of low-cost, low-power, multifunctional (or uni-functional) wireless devices deployed over a geographical area in an ad hoc fashion and with or without careful planning (this depends on the application mainly whether it is related to a real-time applications or non-real-time application). Individually, these devices have limited resources and have limited processing and communication capabilities. The cooperative operation behavior of these sensing devices gives a significant impact on a wide range of applications in several fields, including science and engineering, military settings, critical infrastructure protection, and environmental monitoring [12].

Networking distributed sensors are used in military and industrial applications and it dates back at least to the 1970s. back then the systems were primarily wired and small in scale. wireless technologies and low-power Very Large Scale of Integration (VLSI) design became feasible and emerged in 1990 and after that researchers began envisioning and investigating large-scale embedded wireless sensor networks for dense sensing applications [13].

One of the earliest research efforts in this direction is the use of Low-power Wireless Integrated Micro-sensors (LWIM) project at the University of California, Los Angeles

(UCLA) funded by Defense Advanced Research Projects Agency (DARPA) [1]. The LWIM project focused on developing devices with low-power electronics in order to enable large, dense wireless sensor networks. This project was succeeded by the Wireless Integrated Networked Sensors (WINS) project, in which researchers at UCLA collaborated with Rockwell Science Center to develop some of the first wireless sensor devices. Other early projects in this area, were also primarily in academia, at several places including MIT, Berkeley, and USC. Figure (2-1) is an example of a sensor node.

Figure 2-1: University California at Berkeley (UCB) Rene Motes used by the Laboratory of Experimental Computer Sciences (LECS).

Wireless sensor networks promise an invaluable interconnection between physical environment world and virtual information environment because of the amount of the application and fields that are being applied in. Figure 2-2 describes a typical sensor node in details with the basic contents [1].

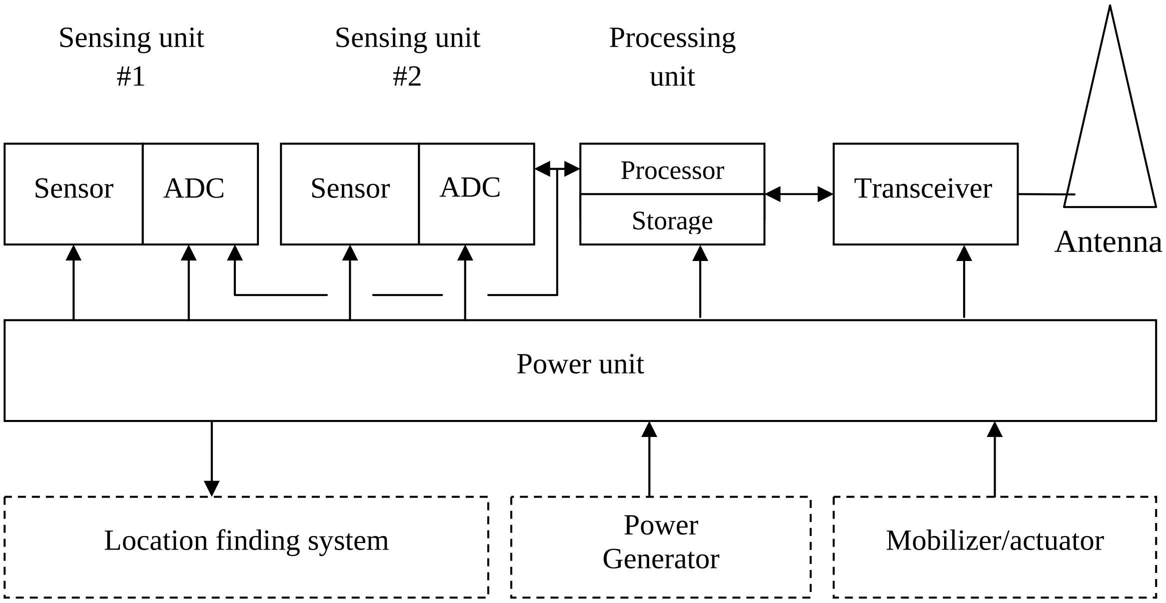

Figure 2-2: Typical sensing node [1]

As it is observed that the sensor node has a computing and processing module with a sensing module and a networks interface which is in this case a wireless transceiver.

There are four basic components in a sensor network:

- An assembly of distributed or localized sensors.
- An interconnecting network (usually, but not always, wireless-based).
- A central point of information clustering.
- A set of computing resources at the central point (or beyond) to handle data correlation, event trending, status querying, and data mining.

In this context, the sensing and computation nodes are considered part of the sensor network; in fact, some of the computing can be done in the network itself. Because of potentially large quantity of data collected, algorithmic methods for data management play an important role in sensor networks.

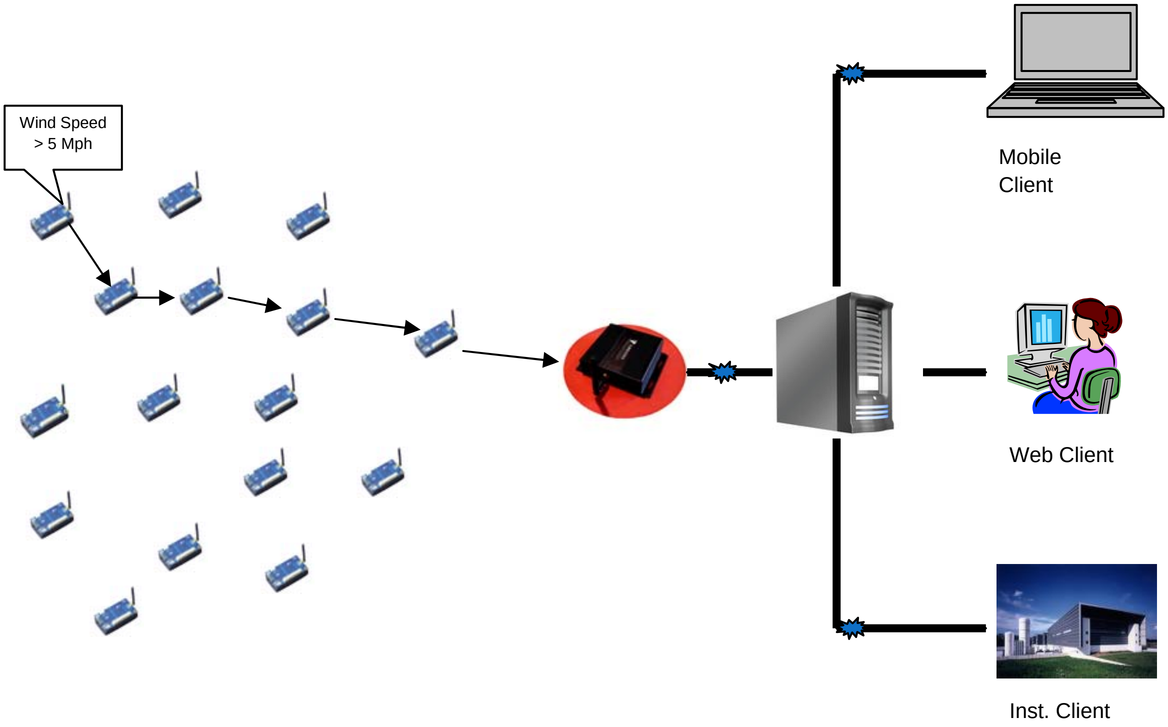

Figure 2-3: An example of sensor networks

Sensor networking is a multidisciplinary area that includes but not exclusive to radio and networking, signal processing, artificial intelligence, database management, systems architectures, resource optimization, power management algorithms, and platform technology (hardware and software, such as operating systems) [1].

Table 2-1: Research disciplines of wireless sensor networks

Research Discipline	Literature available in percentage
Deployment	9.70%
Target tracking	7.27%
Localization	6.06%
Data gathering	6.06%
Routing and aggregation	5.76%
Security	5.76%
MAC protocols	4.85%
Querying and databases	4.24%
Time synchronization	3.64%
Applications	3.33%
Robust routing	3.33%
Lifetime optimization	3.33%
Hardware	2.73%
Transport layer	2.73%
Distributed algorithms	2.73%
Resource-aware routing	2.42%
Storage	2.42%
Middleware and task allocation	2.42%
Calibration	2.12%
Wireless radio and link characteristics	2.12%
Network monitoring	2.12%
Geographic routing	1.82%
Compression	1.82%
Taxonomy	1.52%
Capacity	1.52%
Link-layer techniques	1.21%
Topology control	1.21%
Mobile nodes	1.21%
Detection and estimation	1.21%
Diffuse phenomena	0.91%
Programming	0.91%
Power control	0.61%
Software	0.61%
Autonomic routing	0.30%

2.1.1. Energy-efficient design:

Once deployed, it is often infeasible or undesirable to re-charge sensor nodes or replace their batteries as this leads to inefficient costs effects. Thus, energy conservation becomes crucial for sustaining a sufficiently long network lifetime. Among the various techniques proposed for improving energy-efficiency, cross-layer optimization has been realized as an effective approach. Due to the nature of wireless communication, one performance metric of the network can be affected by various factors across layers. Hence, a holistic approach that simultaneously considers the optimization at multiple layers enables a larger design space within which cross-layer tradeoffs can be effectively explored.

Yet the energy constrained miniatures must operate in a way that keeps fair consuming between sensor nodes to reach efficient network productivity. In practice, it will be necessary in many applications to provide guarantees that a network of unattended wireless sensors can remain operational without any replacements for several years. Hardware improvements in battery design and energy harvesting techniques will offer only partial solutions. This is the reason that most protocol designs in wireless sensor networks are designed explicitly with energy efficiency as the primary goal [13].

2.1.2. Applications of Sensor Networks

Sensor networks have been used in high-end applications such as radiation and nuclear-threat detection systems, ‘‘over-the-horizon’’ weapon sensors for ships, biomedical applications, habitat sensing, and seismic monitoring. More recently, interest has focusing on networked biological and chemical sensors for national security applications; furthermore, evolving interest extends to direct consumer applications. Existing and potential applications of sensor networks include, among others, military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, process control, inventory management, distributed robotics, weather sensing, environment monitoring, national border monitoring, and building and structures monitoring [1].

2.2. MAC Protocols for WSN

MAC is the second layer after the physical layer in the Open System Interconnection (OSI) model in networking systems, this layer controls how to establish the connection of the media and synchronize the timing when to send or receive data between two ends.

An essential characteristic of wireless communication is that it provides an inherently shared medium. All MAC protocols for wireless networks manage the usage of the radio interface to ensure efficient utilization of the shared bandwidth. MAC protocols designed for wireless sensor networks have an additional goal of managing radio activity to conserve energy. Thus, while traditional MAC protocols must balance throughput, delay, and fairness concerns, WSN MAC protocols place an emphasis on energy efficiency as well [13].

MAC layer affects the energy efficiency mainly through the adjustment of transmission scheduling and channel access. A common way to do that is via sleep scheduling from a long time scale, or time-division multiple access (TDMA), from a short time scale perspective. Similar to the shutdown technique of CPUs, sleep scheduling also explores the energy *vs.* response time tradeoffs in wireless communication. From previous studies, the response time is translated to network or application layer transmission delay or throughput.

From the perspective of the OSI Reference Model (OSIRM), the MAC protocol functionalities are provided by the lower sublayer of the data link layer (DLL). The higher sublayer of the DLL is referred as the logical link control (LLC) layer. The subdivision of the data link layer into two sublayers is necessary to accommodate the logic required to manage access to a shared access communications medium. Furthermore, the presence of the LLC sublayer allows support for several MAC options, depending on the structure and topology of the network, the characteristics of the communication channel, and the quality of service requirements of the supported application. Figure 2-4 depicts the OSI reference model and the logical architecture of the DLL for shared medium access in wireless networks [1].

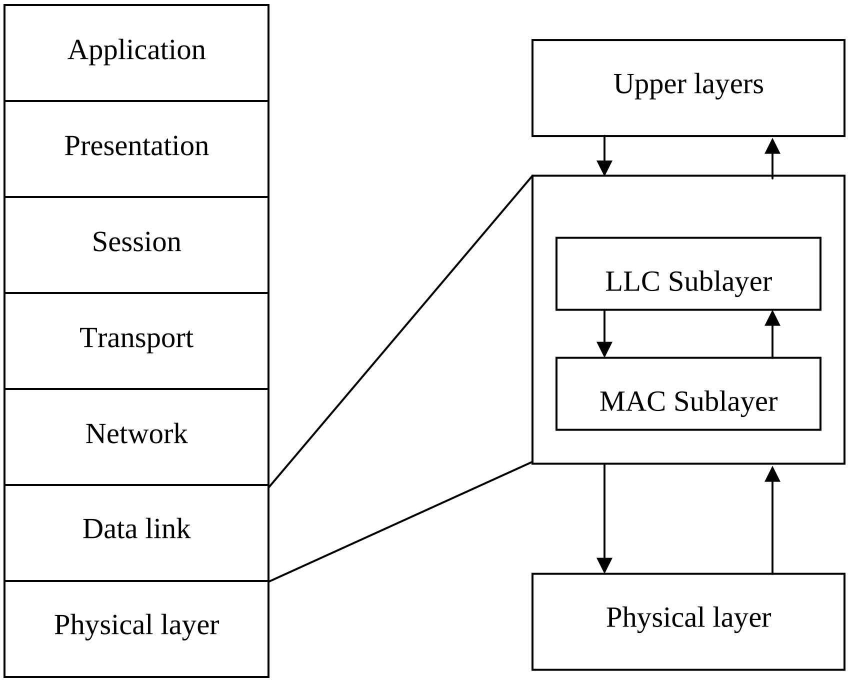

Figure 2-4: OSI interconnection reference model and Data Link Layer architecture [1].

For wireless sensor networks the literature provided a lot of protocols and divided it into two major categories:

1. **Contention Based MAC Protocols (CSMA carrier sense multiple access)**. The wireless nodes here contend to enter the medium of connectivity (which is the wireless medium in case of WSNs) and the winner node reserves the medium to itself until it finishes its operation. Examples for this kind of protocols are: IEEE 802.11 [10], S-MAC [10], T-MAC [14], R-MAC [15] and others.
2. **TDMA (time division multiple access) Based MAC Protocols**. The medium here is divided into time slots each node knows its time slot when to enter the medium and do its operation. One popular TDMA based MAC protocol for WSNs is ALOHA [16].

2.2.1. Design Challenges

Because of the nature of applications where WSNs are applied, MAC protocols faces a number challenges. In trying to determine the performance requirements of MAC protocols, the scope of research has been very broad includes traditionally, issues such as delay, throughput, robustness, scalability, stability, and fairness have dominated the design of MAC protocols. Following is a brief discussion of these performance metrics [1] :

2.2.1.1. Delay

Delay refers to the amount of time spent by a data packet in the MAC layer before it is transmitted successfully. Delay depends not only on the network traffic load, but also on the design choices of the MAC protocol. For time-critical applications, the MAC protocol is required to support delay-bound guarantees necessary for these applications to meet their QoS requirements.

2.2.1.2. Throughput

Throughput is typically defined as the rate at which messages are serviced by a communication system. It is usually measured either in messages per second or bits per second. In wireless environments it represents the fraction of the channel capacity used for data transmission. Throughput increases as the load on the communication system increases. After the load reaches a certain threshold, the throughput ceases to increase, and in some cases, it may start to decrease. An important objective of a MAC protocol is to maximize the channel throughput while minimizing message delay.

2.2.1.3. Robustness

Robustness, defined as a combination of reliability, availability, and dependability requirements, reflects the degree of the protocol insensitivity to errors and misinformation. Robustness is a multidimensional activity that must simultaneously address issues such as error confinement, error detection and masking, reconfiguration, and restart.

2.2.1.4. Scalability

Scalability refers to the ability of a communications system to meet its performance characteristics regardless of the size of the network or the number of competing nodes. In WSNs, the number of sensor nodes may be very large, exceeding thousands and in some cases millions of nodes. In these networks, scalability becomes a critical factor. Achieving scalability is challenging, especially in time varying environments such as wireless networks.

2.2.1.5. Stability

Stability refers to the ability of a communications system to handle fluctuations of the traffic load over sustained periods of time. A stable MAC protocol, for example, must be able to handle instantaneous loads which exceed the maximum sustained load as long as the long-term load offered does not exceed the maximum capacity of the channel.

2.2.1.6. Fairness

A MAC protocol is considered to be fair in operation if it allocates channel capacity evenly among the competing communicating nodes without unduly reducing the network throughput. Achieving fairness among competing nodes is desirable to achieve equitable QoS and avoid situations where some nodes fare better than other nodes.

2.2.1.7. Energy Efficiency

A sensor node is equipped with one or more integrated sensors, embedded processors with limited capability, and short-range radio communication ability as discussed in Figure 2-2. These sensor nodes are powered using batteries with small capacity. Unlike in standard wireless networks, wireless sensor nodes are often deployed in unattended environments, making it difficult to change their batteries. Furthermore, recharging sensor batteries by energy scavenging is complicated and volatile. These severe constraints have a direct impact on the lifetime of a sensor node. As a consequence, energy conservation becomes of paramount importance in WSNs to prolong the lifetime of sensor nodes.

Ioannis Mathioudakis [17] presented the most energy wastage sources in MAC protocols for WSNs:

> **The first** source is caused by collisions, which occur when two or more nodes attempt to transmit simultaneously. The need to re-transmit a packet that has been corrupted by collision increases the energy consumption.
>
> **The second** source of energy wastage is idle-listening, where a node listens for traffic that it is not sent. In a sample fetching operation, a silent channel can be high in several sensor applications.
>
> **The third** source of waste is overhearing, which occurs when a sensor node receives packets that are destined for other nodes.

The fourth is caused by control packet overheads, which are required to regulate access to the transmission channel. Sending and receiving control packets consumes energy too, and less useful data packets can be transmitted.

The fifth source is over-emitting where the destination node is not ready to receive during the transmission procedure, and hence the packet is not correctly received.

Finally, the transition between different operation modes, such as sleep, idle, receive and transmit, can result in significant energy consumption. Limiting the number of transitions between sleep and active modes leads to a considerable energy saving.

The next section will demonstrate most of the recent proposed MAC protocols for WSNs.

2.2.2. Related Work

MAC protocols can be divided into two categories; that is contention based MAC protocols and TDMA based MAC protocols:

A popular contention based MAC protocol for wireless networks is the IEEE 802.11 which is the standard for WLAN applications. IEEE 802.11 performs well in terms of latency and throughput but it is not efficient in terms of energy consumption because of the idle listening problem. It has been shown that when the node is in idle listening state it consumes energy equivalent to the receiving energy and that is why this protocol is not suitable for WSNs applications [10].

Sensor-MAC, S-MAC is a contention based MAC protocol designed explicitly for wireless sensor networks proposed by Wei et al [10]. While reducing energy consumption is the primary goal of this design, the protocol also has good scalability and collision avoidance capability. It achieves good scalability and collision avoidance by utilizing a combined scheduling and contention scheme. It also achieves efficient energy consumption by using a scheme of periodic listening and sleeping which reduces energy consumption. In addition, it uses synchronization to form virtual clusters of nodes on the same sleep schedule. These schedules coordinate nodes to minimize additional latency. The protocol also uses the same mechanism to avoid the overhearing problem and hidden channel problem that is used in IEEE 802.11. But the S-MAC has a problem of latency because of periodic listen and sleep scheme which is dependent on the duty cycle.

WSNs applications have some unique operation characteristics, for example, low message rate, insensitivity to latency. These characteristics can be exploited to reduce energy consumption by introducing an active/sleep duty cycle. To handle load variations in time and location, Tijs van dam et al [14] proposed the Timeout MAC T-MAC protocol. T-MAC can handle an adaptive duty cycle in a novel way: by dynamically ending the active part of it. This reduces the amount of energy wasted on idle listening, in which nodes wait for potentially incoming messages, while still maintaining a reasonable throughput. T-MAC uses *TA* (time out) packet to end the active part when there is no data to send/receive on the node. The protocol balances between energy efficient consumption and latency efficient throughput due to the scheme of burst data sending more effective in terms of energy consumption.

The concept of periodic listen and sleep approach was explored by Changsu suh et al [8]. They proposed a novel MAC scheme named as TEEM (Traffic aware, Energy Efficient MAC) protocol. The proposed TEEM is based on the often cited contention-based MAC protocol S-MAC [10]. The protocol achieves energy efficient consumption by utilizing ‘traffic information’ of each sensor node.

Thus, Changsu suh et al show that the listen time of nodes can be reduced by putting them into sleep state earlier when they expect no data traffic to occur. In this method, Changsu suh et al made two important modifications to the S-MAC protocol: the first modification was to make all nodes turn off the radio interface much earlier when no data packet transfer is expected to occur in the networks, and secondly eliminating communication of a separate RTS control packet even when data traffic is likely to occur. However, it lacks on latency efficiency to conserve energy.

In another approach, Tao Zheng et al [18], proposed a MAC protocol, called Pattern-MAC, PMAC that handles the sleep-wakeup times of the sensor nodes in an adaptive manner. The schedules are decided based on a sensor node's own traffic and that of its neighbours. Experimental results show that in comparison to SMAC, PMAC achieves more power savings under light loads, and higher throughput under heavier traffic loads. The improved performance of PMAC suggests that 'pattern exchange' is a promising framework for improving the energy efficiency of the MAC protocols used in sensor networks. However, PMAC has a computation overhead by using Markov chain approach as a probability check.

The cross-layer approach protocol was investigated by Sangheon Pack et al [19]. They proposed a task aware MAC protocol for WSNs. The TA-MAC protocol determines the channel access probability depending on a node's and its neighbor nodes' traffic loads through the interaction with the data dissemination protocol. In this approach the TA-MAC protocol can reduce energy consumption and improve the throughput by eliminating unnecessary collisions. The TA-MAC protocol is feasible because it can be integrated with other energy efficient MAC protocol example, SMAC. The TA-MAC protocol focuses on the determination of channel access probability that is orthogonal to the previous MAC protocols for WSNs.

Another work that explores the cross-layer approach was presented by Shu Du et al [15]. The proposed scheme called Routing-enhanced MAC protocol (RMAC), exploits cross-layer routing information in order provide delay guarantee without sacrificing energy efficiency. Most importantly, RMAC can deliver a data packet *multiple* hops in a single operational cycle. During the SLEEP period in RMAC, a relaying node for a data packet goes to sleep and then wake up when its upstream node has the data packet ready to transmit to it. After the data packet is received by this relaying node, it can also immediately forward the packet to its next downstream node, as that node has just woken up and is ready to receive the data packet. The mechanism is implemented using a packet called Pioneer. This packet travels to all sensors in down-stream to synchronize the duty-cycles of the nodes to guarantee a multi-hop packet delivery. In this way the protocol achieved latency efficient operation.

The Probability Sensor-MAC (PS-MAC), proposed by Sung-Chan Choi et al [20] is a time slotted MAC protocol like the S-MAC. With the S-MAC all nodes have the same synchronized and periodic listen and sleep cycle. With PS-MAC protocol, different transmitter and receiver node pairs have asynchronous and non-periodic listen and sleep schedules. Each sensor node uses a pseudo-number generator and determines it's listened and sleep schedule randomly based on its pre-wakeup probability and seed. However, this approach produces an over-emitting problem. The source node is sending data while the destination is in sleep mode because of the asynchronous probability. To avoid this problem the neighboring nodes exchange their pre-wakeup probabilities and seed numbers. The protocol provided an energy efficient operation with a good throughput because of asynchronous scheduling which out-performs S-MAC on heavy load situation.

Miguel A. Erazo et al, [11] developed the S-MAC to SEA-MAC, a protocol which aims for energy efficient operation for WSNs for environment monitoring. The protocol assumes only the base station node has the time synchronization schedule. Sensor nodes are active only when there is a sample to be taken from the environment which decreases the duty-cycle of the node and preserves energy. The packet which is responsible for initiating important data delivery in SEA-MAC is called TONE packet which is shorter in period than SYNC packet in S-MAC.

Another approach called O-MAC (Organized-energy MAC) protocol is proposed by [21] Farid Nait-Abdesselam et al. The O-MAC protocol aims to decrease energy consuming and provide high throughput in WSNs. Its design is mainly based on two major ideas, that is, first a locally scheduled algorithm based on a CSMA protocol prevents possible collisions among the neighboring contending nodes. Secondly, it allows the nodes in the vicinity of a transmission that is not concerned with the data being sent the possibility to sleep during the duration of one transmission. It also informs their neighbors of their ultimate entry into sleep mode to prevent them from sending data wastefully during the sleep period. This protocol has packet overhead because it has to utilize another to control packets OTS (Order To Sleep) and NTS (Node To Sleep).

The Demand-Wakeup (DW-MAC) [22], is a synchronized duty cycle MAC protocol, where each cycle is divided into three periods: Sync, Data, and Sleep. DW-MAC assumes that a separate protocol is used to synchronize the clocks in sensor nodes during the Sync period with required precision. The basic concept of DW-MAC is to wake up nodes on demand during the Sleep period of a cycle in order to transmit or receive a packet. This demand wakeup adaptively increases effective channel capacity during a cycle as traffic load increases, allowing DW-MAC to achieve low delivery latency under a wide range of traffic loads including both unicast and broadcast traffic.

In 2007 Qingchun Yu et al, introduced the Low-Latency (LL) MAC protocol, which improved the problem of the conflict between energy efficiency and low-latency. This scheme uses asynchrony (ASYNC) message package to broadcast the schedule information between neighbor nodes instead of SYNC package, and brings in a stagger active schedule which is derived from DMAC [23]. This protocol ensures the sender and the receiver node will be both active for one packet transmitting time, which avoids the data forwarding interruption problem and reduces the transmission latency.

In terms of CSMA-based scheduling there are also works have been done and can be looked for through [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, and 34]. The literature trawl has revealed that few protocols use TDMA-based scheduling because of the overhead of time slot scheduling as sensor network deployment usually includes large number of sensors. A protocol that uses TDMA-based scheduling is the Energy and Rate (ER) proposed by Rajgopal Kannan [35] et al. The ER_MAC protocol has the ability of avoiding extra energy wastage.

The main advantages of ER-MAC are:

- packet loss due to collisions is absent because two nodes do not transmit in the same slot. Although packet loss may occur due to other reasons like interference, loss of signal strength etc.
- no contention mechanism is required for a node to start sensing its packets since the slots are pre-assigned to each node. No extra control overhead packets for contention are required.

ER-MAC uses the concept of periodic listen and sleep. A sensor node switches off its radio and goes into a sleep mode only when it is in its own time slot and does not have anything to transmit. It has to keep the radio awake in the slots assigned to its neighbors in order to receive packets from them even if the node with current slot has nothing to transmit.

Real-Time MAC (RT-MAC) proposed by Anirudha Sahoo [36] et al, is another TDMA-based MAC protocol that can provide delay guarantee. TDMA based MAC protocols suffers from latency caused by the assigning of time slots which takes up a lot of time because of the number of sensor nodes deployed. RT-MAC overcomes this problem by reutilizing the connection channel between two successive channel accesses of a sensor node. RT-MAC also allows sensors to go to sleep which preserves energy. Although it provides delay guarantee, the RT-MAC protocol requires a lot of computation that exhaust the sensor node itself in some cases like clock drifting problem.

There are other works on design of MAC protocol based on TDMA scheme [37, 38]; they all share the same complexity in time slot assigning. But this thesis will concentrate on two of the most used MAC protocols for WSNs which are S-MAC [1], T-MAC [5].

2.3. Sensor MAC (S-MAC)

The S-MAC protocol is a wireless MAC protocol designed specifically for wireless sensor networks, as in Figure 2-5, it employs a periodic cycle, where each node sleeps a while, and then wakes up to listen for an interval. The duty cycle of this listen–sleep schedule, which is assumed to be the same for all nodes, provides for a guaranteed reduction in energy consumption. During initialization, nodes remain awake and wait a random period to listen for a message providing the sleep–listen schedule of one of their neighbors [13].

Figure 2-5: the Listen/Sleep Scheme

Aside from the sleep scheduling, S-MAC is quite similar to the medium-access contention in IEEE 802.11, in that it utilizes RTS/CTS packets. Both physical carrier sense and the virtual carrier sense based on NAV are employed. S-MAC implements overhearing avoidance, whereby interfering nodes are sent to sleep as long as the Network Allocation Vector (NAV) is non-zero (the NAV, as in IEEE 802.11, is set upon reception of RTS/CTS packets corresponding to the ongoing transmission).

S-MAC also provides for fragmentation of larger data packets into several small ones, for all of which only one RTS/CTS exchange is used (Figure 2-6).

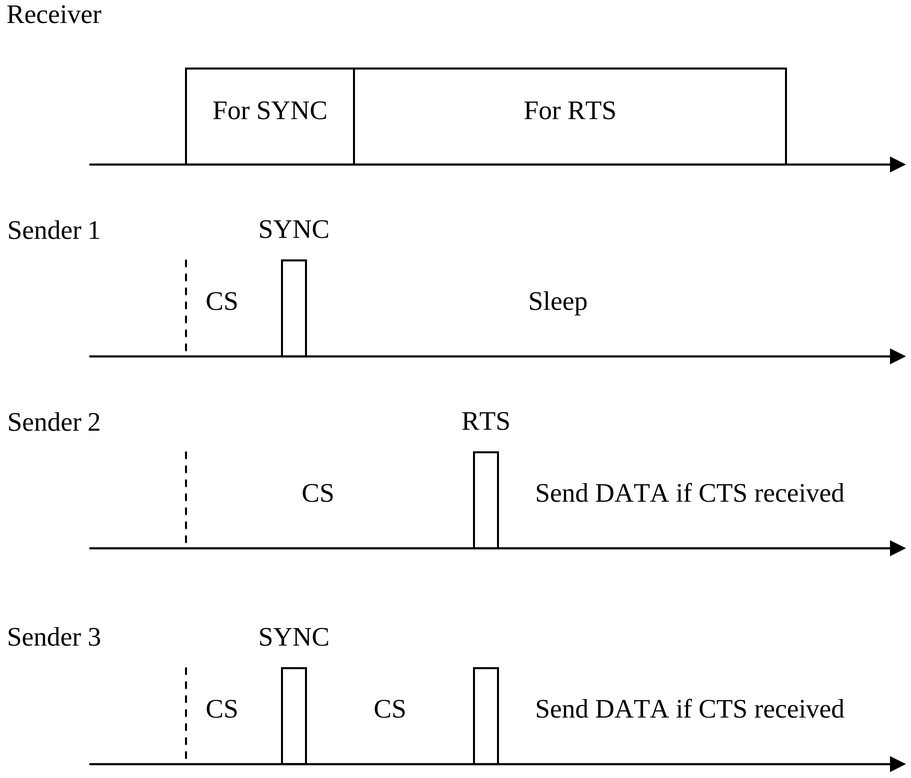

Figure 2-6: The relation between a receiver and different senders in S-MAC [10]

An extension to the basic S-MAC scheme called *adaptive listening* [24] allows the active period to be of variable length, in order to mitigate sleep latency to some extent.

Energy savings in S-MAC come at the cost of potentially significant sleep latency: if a packet is travelling in the network it will have to pause for a period of time because of the sleep period of intermediate nodes.

2.4. Timeout-MAC (T-MAC)

T-MAC [14] is a contention-based MAC-layer protocol designed for applications characterized by low message rate and low sensitivity to latency. To avoid collision and ensure reliable transmission, T-MAC nodes use RTS, CTS, and acknowledgment packets to communicate with each other. Furthermore, the protocol uses an adaptive duty cycle to reduce energy consumption and adapt to traffic load variations. The basic idea of the T-MAC protocol (Figure 2-7) is to reduce idle listening by transmitting all messages in bursts of variable length. Nodes are allowed to sleep between bursts. In addition, the protocol dynamically determines the optimal length of the active time, based on current load. Since messages between active times must be buffered, the buffer capacity determines an upper bound on the maximum frame time [13].

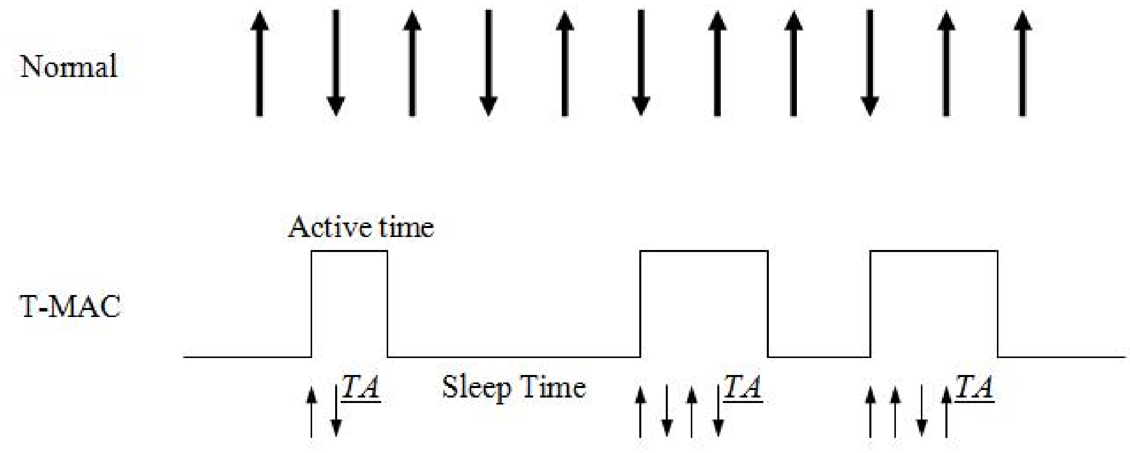

Figure 2-7: The basic T-MAC protocol scheme [14]

With T-MAC protocol the nodes alternate between sleep and wakeup modes. Each node wakes up periodically to communicate with its neighbors. A node keeps listening and potentially transmitting as long as it is in the active period. An active period ends when no active event occurs for predetermined time interval. Active events include the hearing of a periodic frame timer, the reception of data over the radio, the sensing of an activity such as collision on channel, the end of transmission of node's data exchange, determined through overhearing of prior RTS and CTS packets. At the end of the active period, the node goes into sleep mode.

The basic T-MAC scheme suffers from the so-called *early sleep* problem, which can reduce throughput, particularly in the case of unidirectional flows. When a node has to be silent due to contention in a given cycle, it is unable to send any message to its intended receiver to interrupt its timeout. When the sender can send after the end of the contention period, the intended receiver is already in sleep mode. Figure 2-8 shows this issue.

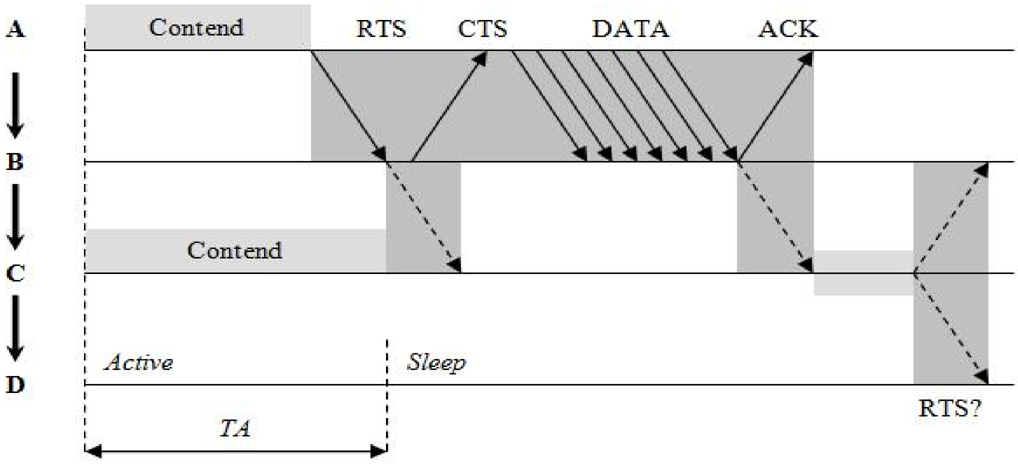

Figure 2-8: Early-Sleeping problem [14]

Two possible solutions to the early sleep problem are proposed and studied in [14]. Figure 2-9 shows a solution which uses an explicit short Future Request To Send (FRTS) control message that can be communicated to the intended recipient asking it to wait for an additional timeout period.

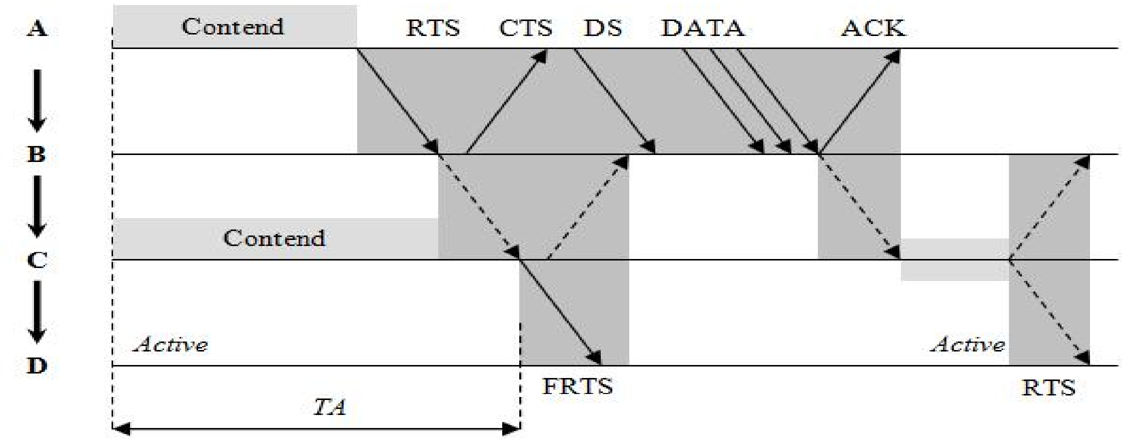

Figure 2-9: FRTS packet exchange [14]

An alternative solution is called "full buffer priority," in which a node prefers sending to receiving when its buffer is almost full. With this scheme, a node has higher priority to send its own packet instead of receiving another packet, and is able to interrupt the timeout of its intended receiver. Figure 2-10 represents this solution.

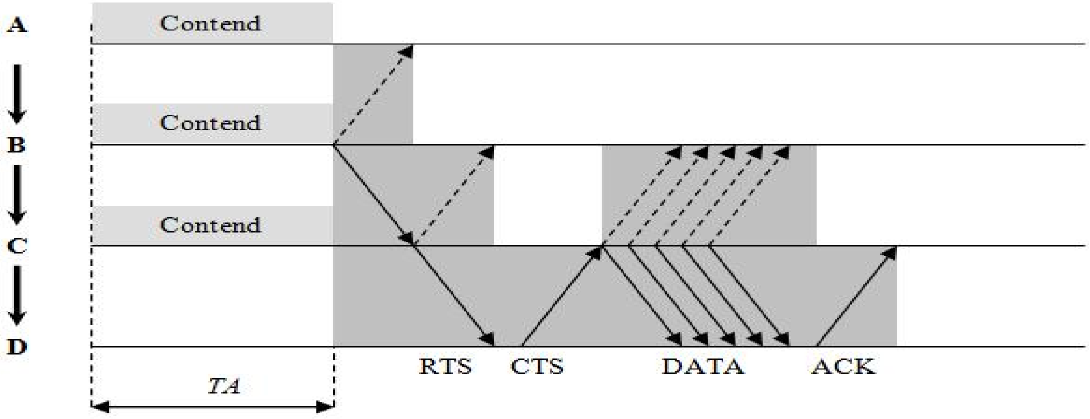

Figure 2-10: "full buffer priority" scheme [14]

2.5. Summary

To summarize the investigated literature, a table that illustrates the categories of MAC protocols proposed for WSNs showing their advantages and disadvantages. Refer to Table 2-2:

Table 2-2: Summary of the related work

MAC Protocol	**Category**	**Main Advantage**	**Main Disadvantage**
IEEE 802.11	CSMA/CA	The Highest system throughput	Inefficient energy consumption
S-MAC	CSMA/CA	Scalable, energy efficient due to the sleep/listen scheme	Suffers from Latency issues
T-MAC	CSMA/CA	Energy efficient, Reasonable throughput	Requires extended control packet to achieve efficient operation
TEEM	CSMA/CA	Energy efficient due to the eliminating the use of RTS packet	Suffers from Latency issues
P-MAC	CSMA/CA	Energy efficient under light load, high throughput under heavy load	Excessive computation overhead because of the use of Markov chain as probability check
TA-MAC	CSMA/CA	Cross-Layer approach	Suffers from latency issues
R-MAC	CSMA/CA	Enhanced throughput	Control Packet Delivery overhead

PS-MAC	CSMA/CA	Energy efficient and decent throughput on heavy load	Requires excessive control attributes to avoid Over-emitting problem
SEA-MAC	CSMA/CA	Energy efficient operation	Suffers from Latency issues
O-MAC	CSMA/CA	Energy efficient and higher throughput than S-MAC	Control Packets Overhead
DW-MAC	CSMA/CA	Increases effective traffic channel capacity	Energy issues
LL-MAC	CSMA/CA	Low Latency	Fair Energy consumption issues
ER-MAC	TDMA	Collision free environment	Scalability and latency issues
RT-MAC	TDMA	Increased the system throughput	Excessive calculation and clock drifting problems

CHAPTER THREE

METHODOLOGY

This chapter will discuss the proposed scheme and describe the operation on the protocol. It also discusses how it manages control packets and data packets exchanges between the network nodes. Energy consumption and packet exchange delay analysis are also discussed. To prove the method proposed we devised simulation experiments using the most common tool to simulate networking systems the Network Simulator 2 (NS2) [39]. The analysis equations were based on the theory of S-MAC [10].

3.1. The Network Simulator 2 (NS2):

NS2 is the most widely used tool in researches involved in general networking systems analysis and wireless networking systems includes Mobile networking, Satellite networking, Wireless Sensor Networks, LAN networks and other network technologies. NS2 is built using C++ language and uses OTcl (Object Oriented Tcl) language as an interface with the simulator. The network topology is built using OTcl and the packet operation protocol is written in C++ [39, 40].

3.1.2. Mobile Networking in NS2:

The wireless model essentially consists of the MobileNode at the core, with additional supporting features that allows simulations of multi-hop ad-hoc networks, wireless LANs etc. A MobileNode thus is the basic Node object with added functionalities of a wireless and mobile node like ability to move within a given topology, ability to receive and transmit signals to and from a wireless channel. Figure (3-1) shows a schematic of the wireless node in NS2 [39].

3.1.3. Routing and MAC Protocols provided in NS2:

Two MAC layer protocols are implemented for mobile networks, which are IEEE 802.11 and TDMA, while S-MAC was added to NS2 as a Patch by Wei [10]. The four different ad-hoc routing protocols currently implemented for mobile networking in NS2 are dsdv, dsr, aodv and tora [39].

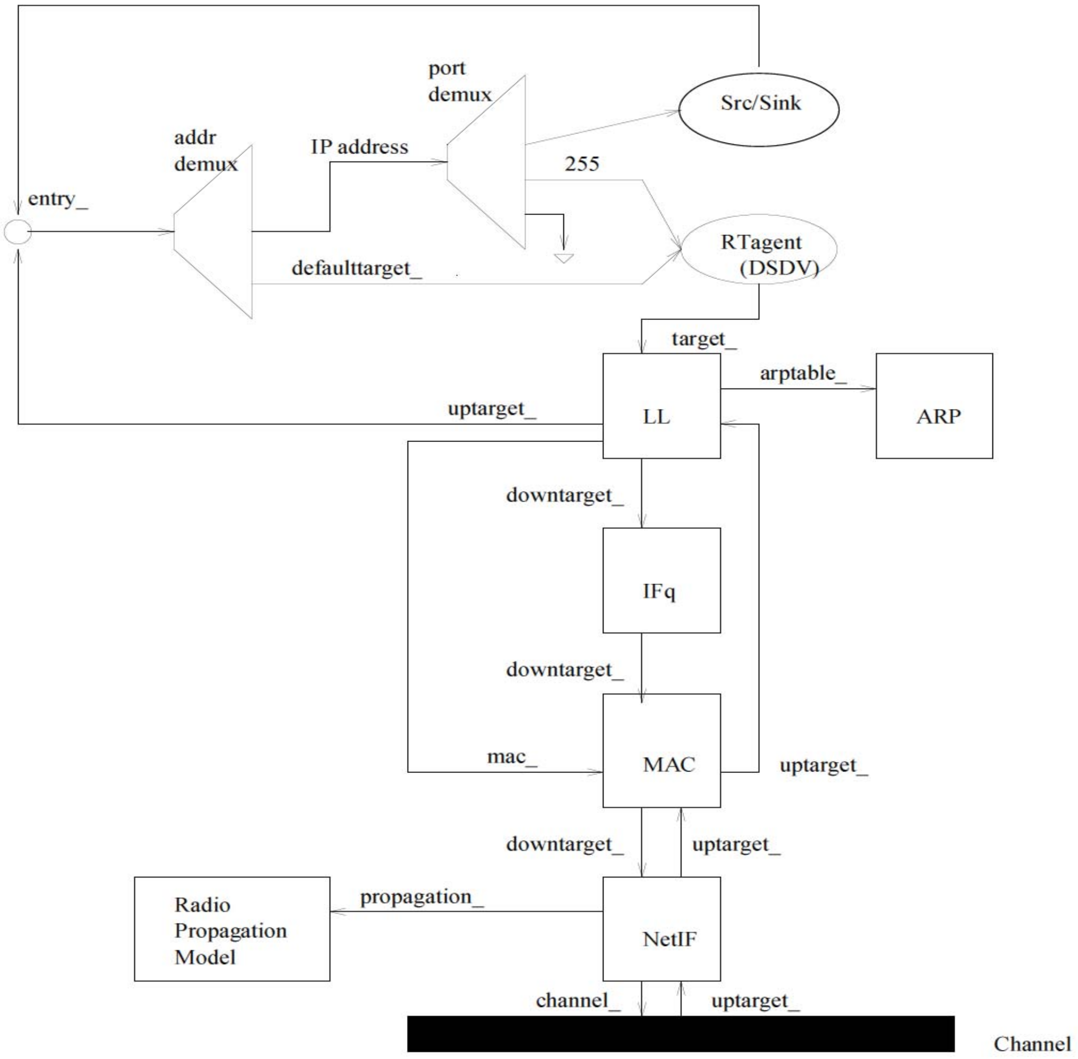

Figure 3-1: schematic graph of mobile node in NS2 by CMU Monarch [39]

3.2. Proposed Scheme:

The proposed scheme considers the following:

1. Combining the functionality of SYNC packet with RTS packet will provide both energy and latency efficient operation which will eliminate the need of sending two packets and decrease control packet overhead. This packet from now on would be referred to as SEEK.
2. To increase the throughput of the system (SEEK) packet will be sent all the way to the down stream nodes before sending CTS packet to the upper stream node. This will open the way to DATA packet to move through the stream of nodes until DATA packet reaches the base station node.

Figure 3-2 describes the approach mentioned above:

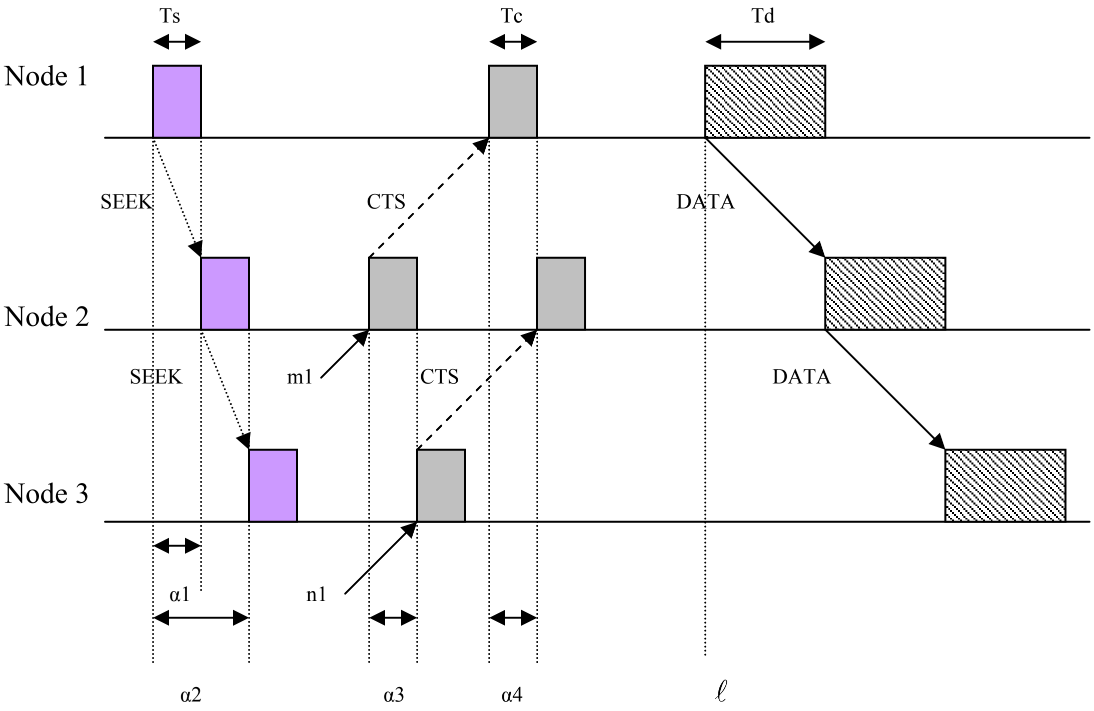

Figure 3-2: Proposed Scheme operation for Synchronization in MAC layer Protocol

3.2.1. Energy consumption analysis:

The first step is to analyze the proposed approach energy consumption for three nodes operation. The following assumptions are made for the analysis (using the scenario shown in Figure 3-3 below:

1. All nodes in the way are by all means available for any packet transmission.
2. The packet delivery direction is from node 1 to node 3.
3. No collision happens between nodes (assuming that Carrier Sense is successful in each transmission start).
4. SEEK packet follow this rule (SYNC<SEEK<SYNC+RTS).
5. DATA packet could be transmitted in one hop.
6. All control packets are fixed in size.
7. In a more realistic scenario upper-layer routing information provides the shortest route to the destination.
8. DATA packet can be transferred in one hop.
9. If the next node in the way is in sleep mode (SEEK) works as the signal that wakes up the node.

The analysis scenario is described in Figure 3-3:

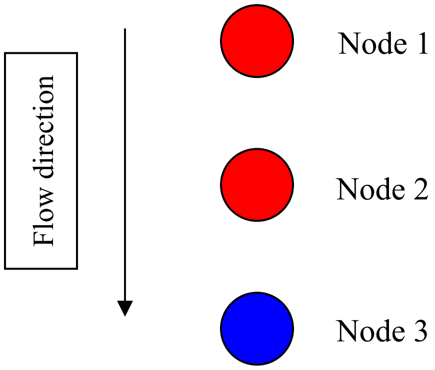

Figure 3-3: Analysis Scenario

Node (1) operation:

$$S_1(t) = X(t) + Y(t - \alpha_3) + X_d(t) \text{..} (1)$$

$$S_1(t) = P_t \times rect\left(\frac{t}{T_s}\right) + P \times rect\left(\frac{(t - \alpha_3 - m_1)}{T_c}\right) + P \times rect\left(\frac{(t - \ell)}{T_d}\right)$$

The Parameters used in the equation above are:

T_s : SEEK packet time length.

T_c : CTS packet time length.

T_d : DATA packet time length.

α : the delay in each state of transmitting SEEK packet and receiving CTS packet.

P_t : Transmission Power.

P : Reception Power.

X(t): rectangular function of delay for SEEK packet.

Y(t): rectangular function of delay for CTS packet out from the exact node.

Z(t): rectangular function of delay for CTS packet received from the down stream node.

X_d(t): rectangular function of delay for DATA packet.

Node (2) operation:

$$S_2(t) = X(t-\alpha_1) + Y(t) + Z(t-\alpha_4) + Xd(t-\alpha_4) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$S_2(t) = \begin{matrix} \left[P_t \times rect\left(\dfrac{(t-\alpha_1)}{T_s}\right) + P_t \times rect\left(\dfrac{(t-m_1)}{T_c}\right) + P \times rect\left(\dfrac{(t-\alpha_4)}{T_c}\right) \right] + \\ \left[P \times rect\left(\dfrac{(t-\alpha_4)}{T_c}\right) + P \times rect\left(\dfrac{(t-\ell-\alpha_4)}{T_d}\right) \right] \end{matrix}$$

Node (3) operation:

$$S_3(t) = X(t-\alpha_2) + Y(t) + Z(t) + X_d(t-\alpha_4) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$S_3(t) = P_t \times rect\left(\frac{(t-\alpha_2)}{T_s}\right) + P_t \times rect\left(\frac{(t-n_1)}{T_c}\right) + P \times \left(\frac{(t-\ell-\alpha_4)}{T_d}\right)$$

From equations (1, 2 and 3) the amount of energy consumed can be computed using:

$$E_s(t) = S_1(t) + S_2(t) + S_3(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where (E_s) represents the energy consumed by the proposed analysis system in Figure (3-3). Substitute equations (1, 2 & 3) into (4) results in:

$$\begin{aligned}E_s(t) \quad = \quad & \left[P_t * rect\left(\frac{t}{T_s}\right) + P * rect\left(\frac{t-\alpha_3 - m_1}{T_c}\right) + P * rect\left(\frac{t-l}{T_d}\right)\right] + \\ & \left[P_t * rect\left(\frac{t-\alpha_1}{T_s}\right) + P_t * rect\left(\frac{t-m_1}{T_c}\right) + P * rect\left(\frac{t-\alpha_4}{T_c}\right) + P * rect\left(\frac{t-l-\alpha_4}{T_d}\right)\right] + \\ & \left[P \times rect\left(\frac{(t-\alpha_4)}{T_c}\right) + P \times rect\left(\frac{(t-\ell-\alpha_4)}{T_d}\right)\right] + \\ & \left[P_t \times rect\left(\frac{(t-\alpha_2)}{T_s}\right) + P_t \times rect\left(\frac{(t-n_1)}{T_c}\right) + P \times \left(\frac{(t-\ell-\alpha_4)}{T_d}\right)\right] \qquad \text{…….(5)}\end{aligned}$$

3.2.2. System Delay analysis:

The proposed scheme deals with more that one node in a duty-cycle because of the concurrent (SEEK) packet transmission so the packet delay will only be counted as (extra SEEK packet) and (extra CTS packet) in the middle nodes, instead of going through the whole operation (SYNC+RTS+CTS+DATA) as described in chapter 2. Below is the mathematical delay approach of the proposed scheme:

Using the same parameters and the same assumptions made for energy consumption:

Node 1 delay:

D_1 (t) = $T_s + T_c + T_d$ ……………..……………………………………………..(6)

Node 2 delay:

D_2 (t) = $\alpha + T_s + 2 * T_c + T_d$ ………………………………………….……. (7)

Node 3 delay:

D_3 (t) = $T_s + T_c + T_d$ ……………………………………………………….. (8)

From (5, 6 and 7) above a system delay equation can be derived:

D_s (t) = $\sum_{1}^{N-2} \alpha * T_s + T_c$ ……………………………………………………….(9)

N: the number of nodes in the system.

While for S-MAC [10] because each node have to go through the same operation to send the data packet it is possible to describe S-MAC delay operation for the same system as:

$SYNC_t$: time length for SYNC packet.
RTS_t: time length for RTS packet.
CTS_t: time length for CTS packet.
$DATA_t$: time length for DATA packet.

Node 1 delay (S-MAC):

$$D_1 (t) = SYNC_t + RTS_t + CTS_t + DATA_t. \quad \ldots\ldots (10)$$

Node 2 delay (S-MAC):

$$D_2 (t) = D_1 (t) + SYNC_t + RTS_t + CTS_t + DATA_t. \quad \ldots\ldots (11)$$

Node 3 delay (S-MAC):

$$D_3 (t) = D_2 (t) + SYNC_t + RTS_t + CTS_t + DATA_t. \quad \ldots\ldots (12)$$

From (10, 11 and 12) we can reach to a system delay equation using S-MAC:

$$D_{S\text{-}MAC} (t) = \sum_{1}^{N} D(N-1)(t) + SYNC_t + RTS_t + CTS_t + DATA_t \quad \ldots\ldots (13)$$

3.3. Research Procedure:

The next chapter will show that the proposed scheme satisfies the fact of efficient energy consumption and delay guarantee. Two simulation scenarios are devised and simulation parameters with a range of duty-cycles from (5% - 25%) for the first scenario and from (5%-40%) for the second scenario in three steps to cover most of operation environment that can a WSN suffer.

Adding the proposed approach to SEA-MAC [11] to see the effect on other MAC protocols based on S-MAC (as SEA-MAC is an improvement on S-MAC) and the same simulation range of duty-cycles.

A comparison has been made between S-MAC and SEA-MAC before adding the proposed approach to their core and to check where their strength and week spots. Figure 3-4 is flow-chart describes our proposed scheme.

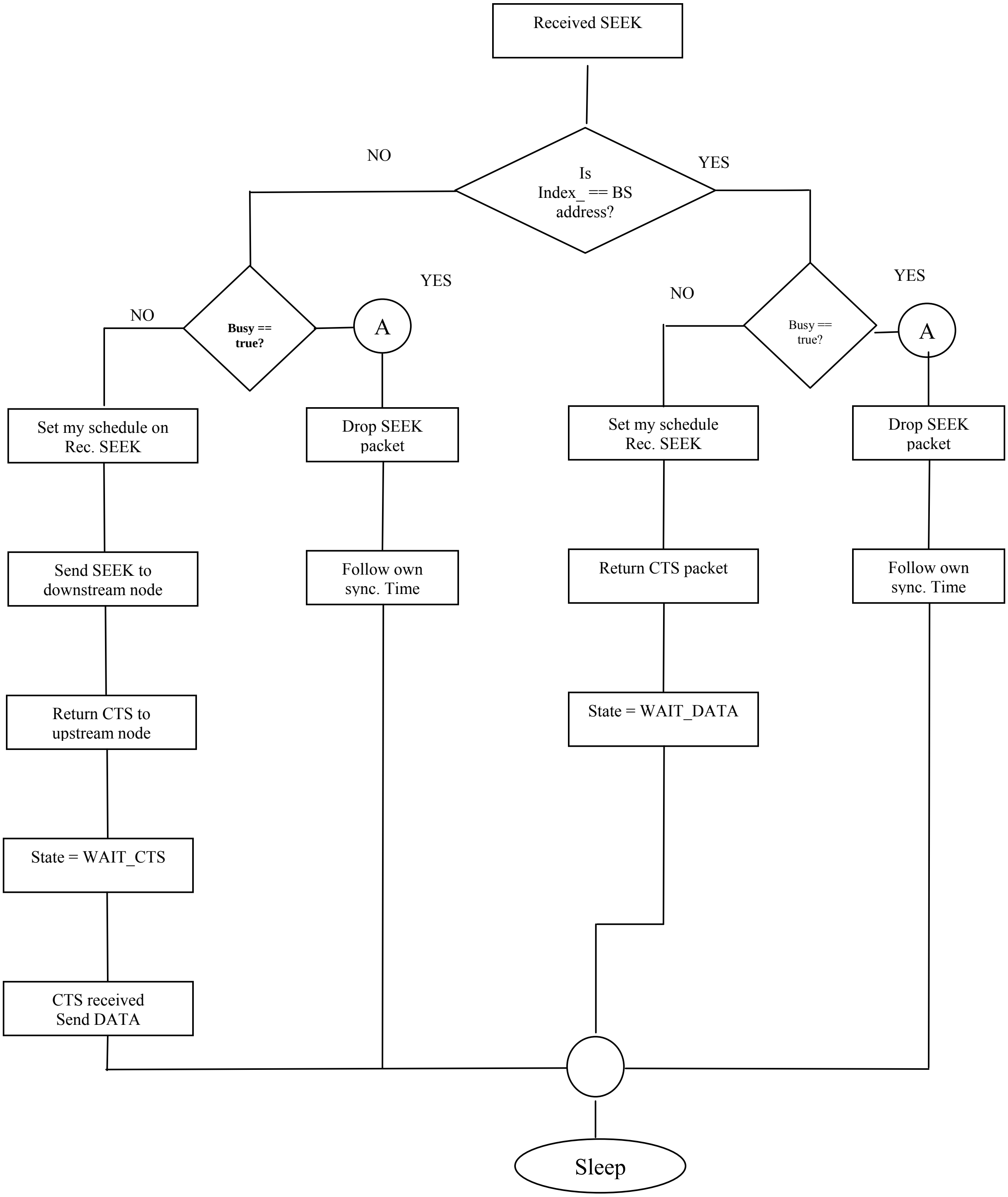

Figure 3-4: Proposed Scheme flow-chart

3.4. Summary

This chapter has illustrated the proposed scheme of improvement to MAC protocols that share the same theory of S-MAC protocols. An energy analysis has been conducted with the assumptions that have been proposed for the analysis. Delay analysis has been conducted too to provide a better anticipation about the proposed approach operation fidelity. The next chapter will discuss the implementation of the proposed scheme in a single line of nodes deployment environment. Chapter 5 will discuss the implementation of the scheme in uniformed nodes deployment. The chosen criterion of discussion and comparison between the basic and the improved scheme through this thesis are energy consumption and system throughput. It has been an obligation to note that another criterion has been chosen for comparison and benchmarking. Those criterions are message delay and collisions.

CHAPTER FOUR

THE PROPOSED SCHEME IMPLEMENTATION IN A SINGLE LINE SENSOR NODES ENVIRONMENT

This chapter will discuss the results of the simulations that have been conducted using the proposed scheme discussed in chapter 3.

The next section will discuss the simulation scenario and parameters. This thesis proposes an improvement scheme to be used on MAC protocols. For this purpose this chapter will discuss a comparison between S-MAC [10] and SEA-MAC [11] before applying the proposed scheme to reveal both protocols pros and cons. The next, is an illustration of the implementation of the proposed approach results ending this chapter with a summary of the achievements that has been established during the implementation of the proposed approach.

4.1. Simulation Parameters and Scenario

The simulation environment was built and made using NS2 version 2.33 [39], the scenario consists of five nodes in one row Starts from node 0 to node 4 considering node 4 as the destination node in the simulation. The simulations are conducted on a wide range of duty cycles from 5% - 25% in three steps (5, 10 and 25). The simulations include a comparison between the MAC protocols and the proposed approach. The proposed approach will be referred as Proposed Protocol (PP-) before or after any protocol name. Refer to Figure 4-1 for simulation scenario topology diagram.

Simulation parameters are the following (Table 4-1):

Table 4-1: Simulation Prameters

Parameter	**Amplitude**
Simulation time	700 second
Duty-Cycle	5%, 10%, 25%
Routing Protocol	None
Node Idle power	100 mW
Node Rx Power	100 mW
Node Tx Power	100 mW
Node Sleep Power	1 mW
Transition Power	20 mW
Transition time	5 ms
Energy model	NS2 Energy model
Propogation model	TwoRayGround
Initial Energy for each node	1000 mJ

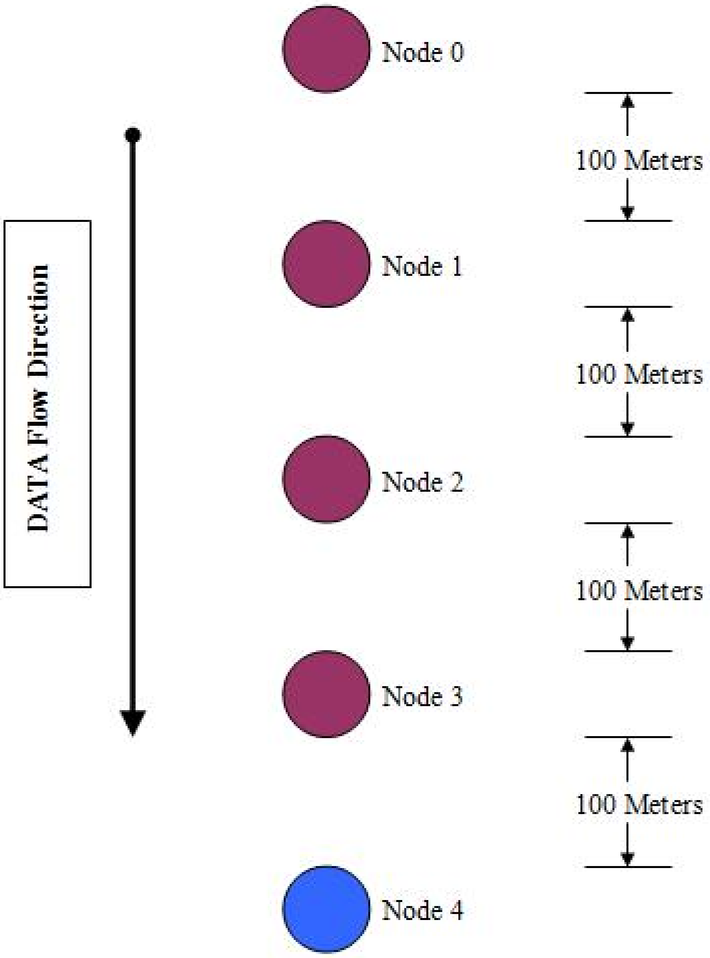

Figure 4-1: Simulation Topology

4.2. Performance evaluation: S-MAC vs. SEA-MAC

Initially, it is needed to prove that the proposed approach is effective. In order to do this it is necessary to show the performance operation of each tested MAC protocols in terms of latency efficiency and energy consumption. The weak points in both protocols during simulations are also shown which were: S-MAC has better operation in low operation Duty-Cycles will SEA-MAC provides better operation at higher Duty-Cycles.

4.2.1. Simulation for 5% Duty-cycle operation

S-MAC operation is more prone to lose energy than SEA-MAC as it uses much more for (SYNC) packet than in SEA-MAC (TONE) packet. Refer to Figure 4-2 with reference to Appendix A Table A-7 it can be seen that the SEA-MAC has a harsh operation and prone to lose energy in one node than S-MAC which has more even consumption at the end of simulation. This because that the (TONE) packet in low operation Duty-Cycle does not have much time to make the sensor finish data transmission and it will be forced to sleep before it finishes data transmission.

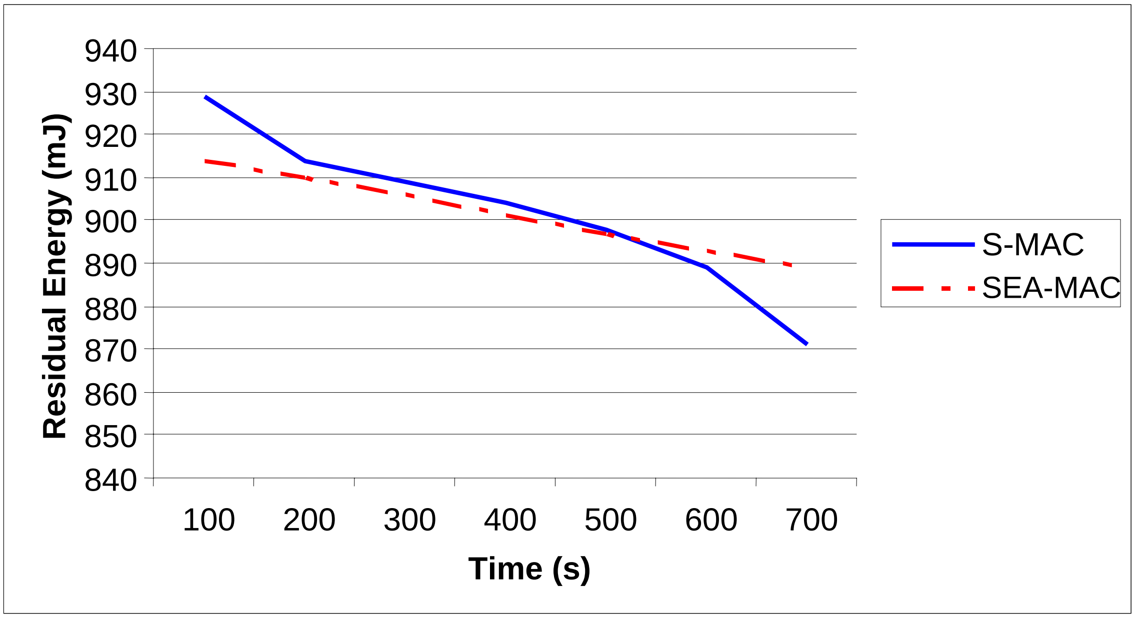

Figure 4-2: Energy consumption for 5% Duty-Cycle

In terms of throughput SEA-MAC has approximately the same throughput that S-MAC produces. When a (TONE) packet is triggered SEA-MAC will follow (SYNC+RTS+CTS) operation as S-MAC does which produce this throughput operation Figure 4-3.

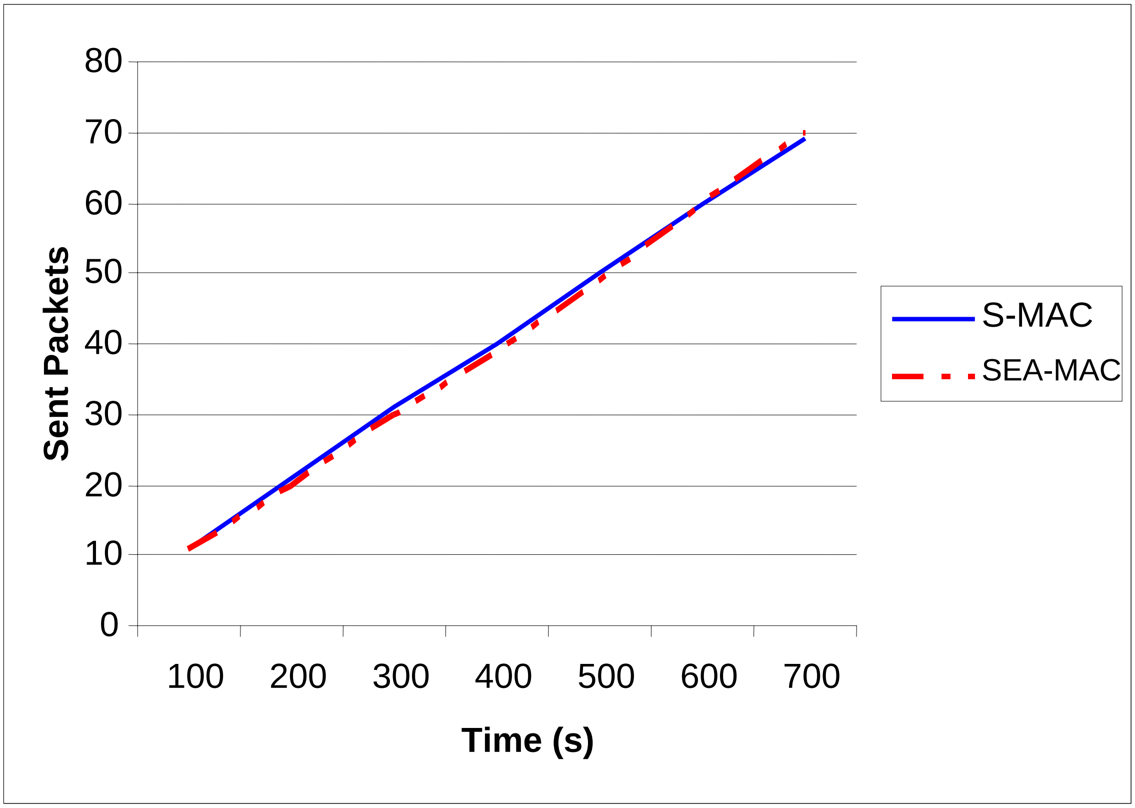

Figure 4-3: Throughput Production for 5% Duty-Cycle

4.2.2. Simulation for 10% Duty-Cycle operation

From Figure 4-4 below, SEA-MAC has better energy consumption than S-MAC. Most of the MAC protocols produced for WSNs are configure to work ideally in 10% Duty-Cycle. The consumption is more even for SEA-MAC in this Duty-Cycle.

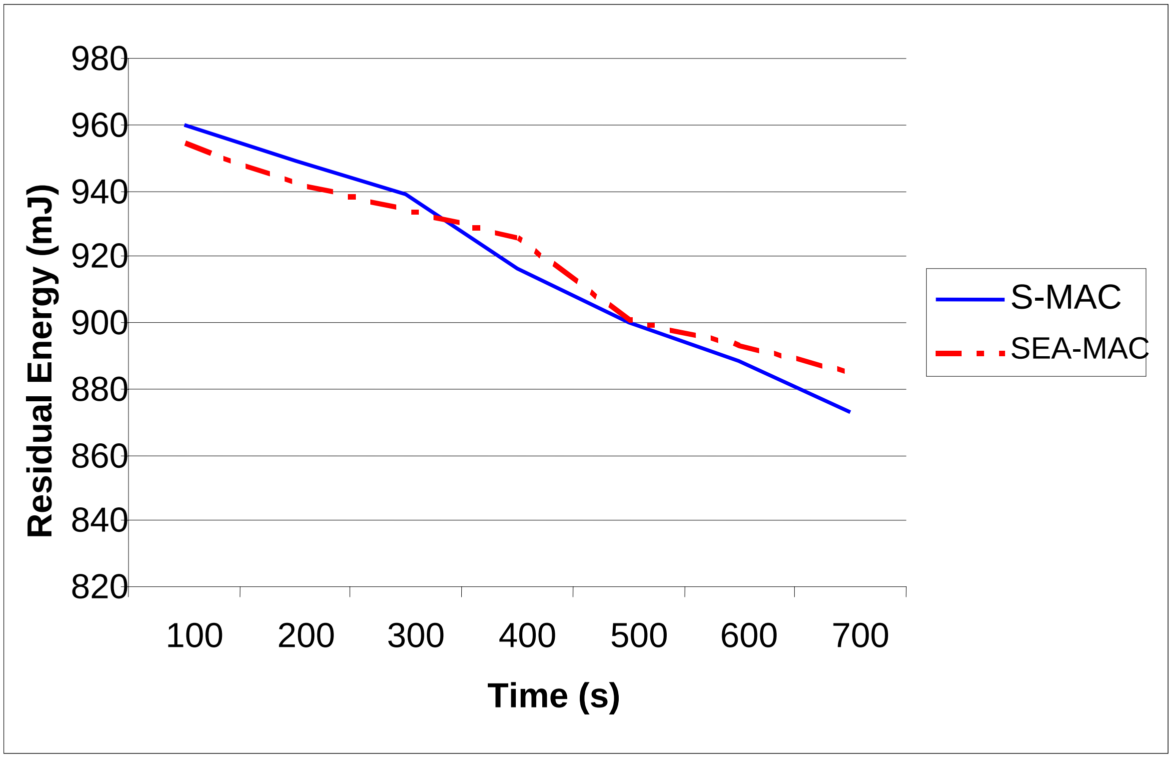

Figure 4-4: Energy consumption for 10% Duty-Cycle

While for throughput both protocols have almost the same productivity. SEA-MAC is considered better than S-MAC because it will produce more data in time than S-MAC because SEA-MAC consumes less energy than S-MAC Figure 4-5.

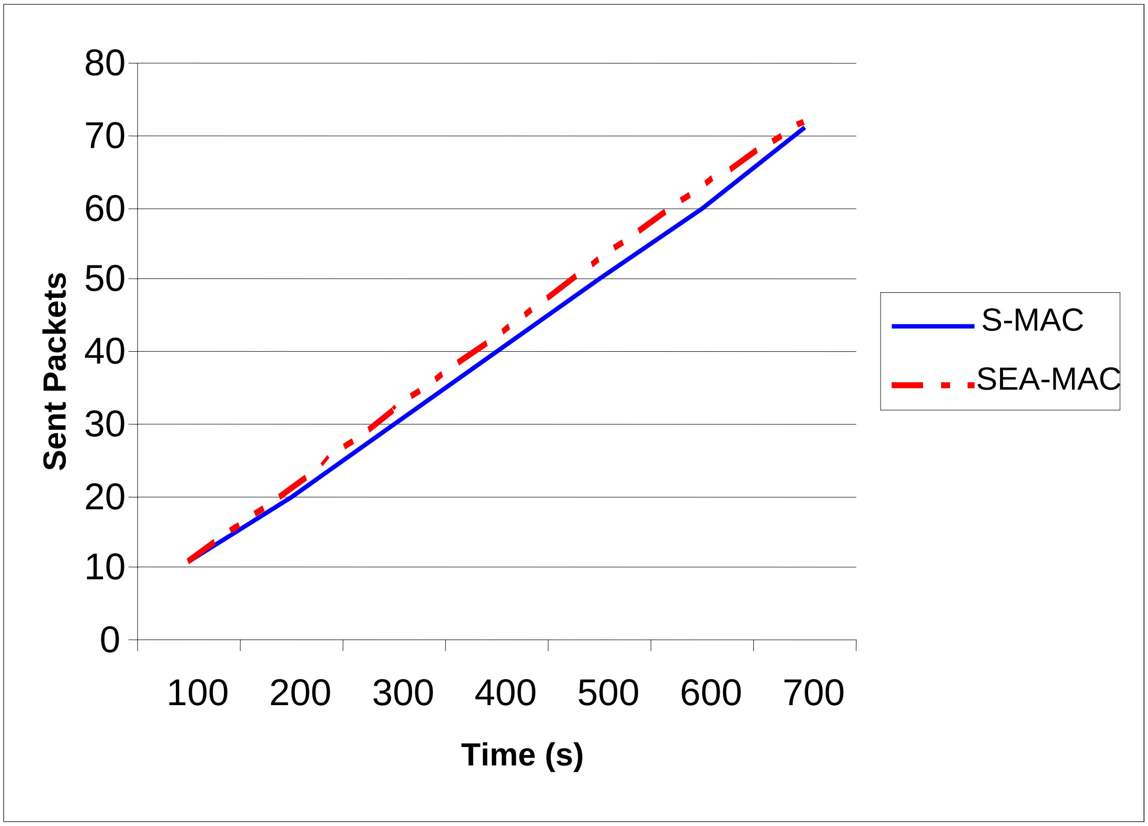

Figure 4-5: throughput productivity for 10% Duty-Cycle operation

4.2.3. Simulation for 25% Duty-Cycle operation

SEA-MAC has the advantage in energy consumption than S-MAC Figure 4-6. SEA-MAC is more efficient in high Duty-Cycles operation than in the lower one and it is more even in consumption (refer to Appendix A Table (A-3 and A-9)) for more detailed results). The reason for this effect is because that (TONE) packet has the advantage to control when to finish transmitting data and to accurately send the node to sleep mode. While S-MAC work in more periodic and more time consuming operation (SYNC packet > TONE packet).

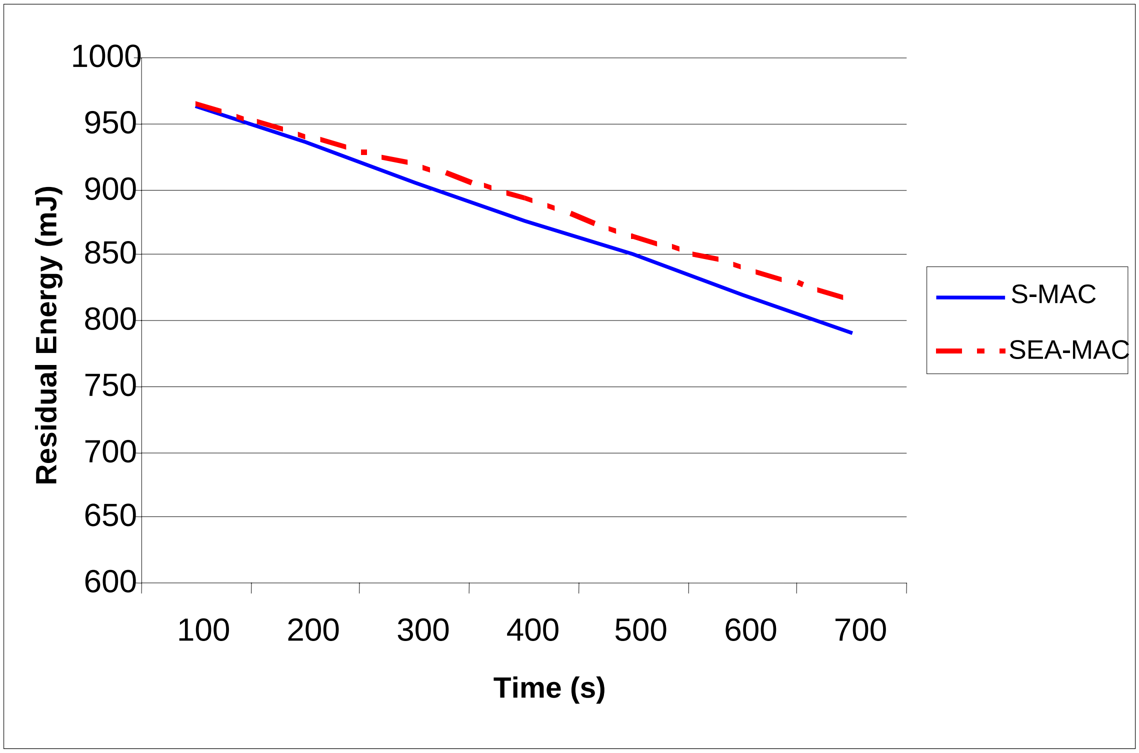

Figure 4-6: Energy consumption for 25% Duty-Cycle

SEA-MAC has more throughput productivity than S-MAC. It means that the more increment in Duty-Cycle the more data produced from SEA-MAC as the higher the Duty-Cycle the larger the amount of data processed; refer to Figure 4-7.

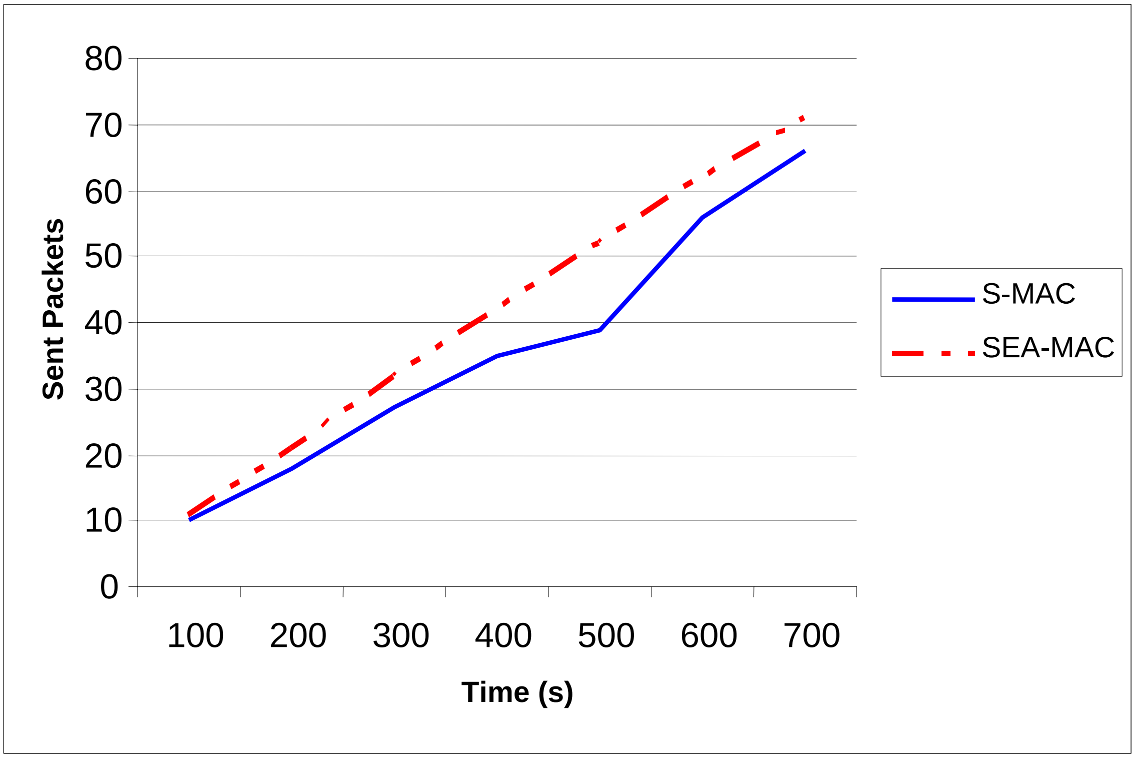

Figure 4-7: Throughput productivity for 25% Duty-Cycle

4.3. Case study conclusions

After applying simulation for both SEA-MAC and S-MAC it is possible to list their advantages and disadvantages in terms of energy consumption and throughput productivity:

S-MAC Advantages:

> S-MAC has stable energy consumption through all the duty-Cycles applied through the simulations.

S-MAC Disadvantages:

> The periodic operation makes the system consumes more energy than it needs to achieve a better throughput. This behavior can be controlled by adding a period control packet like SEA-MAC approach however it suffers from delay in throughput productivity.

SEA-MAC Advantages:

> SEA-MAC has better energy consumption than S-MAC and more even when the operation Duty-Cycle is high. Has better throughput than S-MAC on higher Duty-Cycles.

SEA-MAC Disadvantages:

> SEA-MAC suffers from uneven energy consumption when it is applied in low operation Duty-Cycle. It has almost the same throughput productivity as S-MAC on lower operation Duty-Cycles.

4.4. The proposed approach implementation and discussion:

This section will present and describe the results of implementing the proposed approach by mixing it with S-MAC and SEA-MAC and provides a performance evaluation and benchmarking against the enhanced version of both MAC protocol with their basic model schemes. The simulations will follow the same procedure that has been carried out to the performance evaluation between S-MAC and SEA-MAC. This section will end with a summary of the achievements that has been established when implementing the proposed approach.

4.5. PP-S-MAC vs. S-MAC Simulations Results:

This section presents the enhanced S-MAC operation against the basic version S-MAC when implementing the chain scenario following the parameters described in simulation parameters section 4.1.

4.5.1. Simulation for (5%) Duty-Cycle:

From the results in Figure 4-8 it can be seen that the proposed approach has effect on energy consumption that is because of the elimination of the two steps (SYNC+RTS) and put them in one packet. The approach is more stable in energy consumption than S-MAC. Following the considerations in chapter 3 the equation in Figure 4-8 is the same equation (4) in chapter 3 with adding the effect of node 3 and node 4 for the simulation scenario.

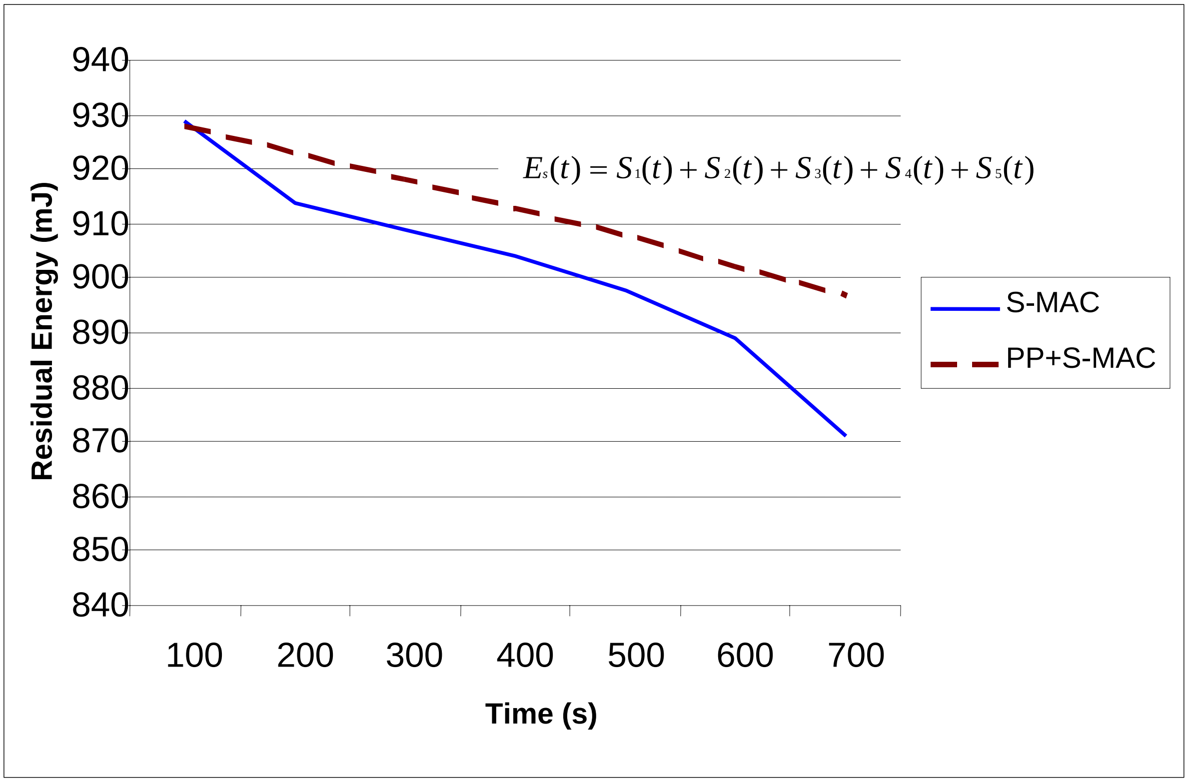

Figure 4-8: Energy consumption for 5% Duty-Cycle

The approach provided also an improved throughput against S-MAC as shown in Figure 4-9 below. This is due to the rapid operation of SEEK packet provided by the approach.

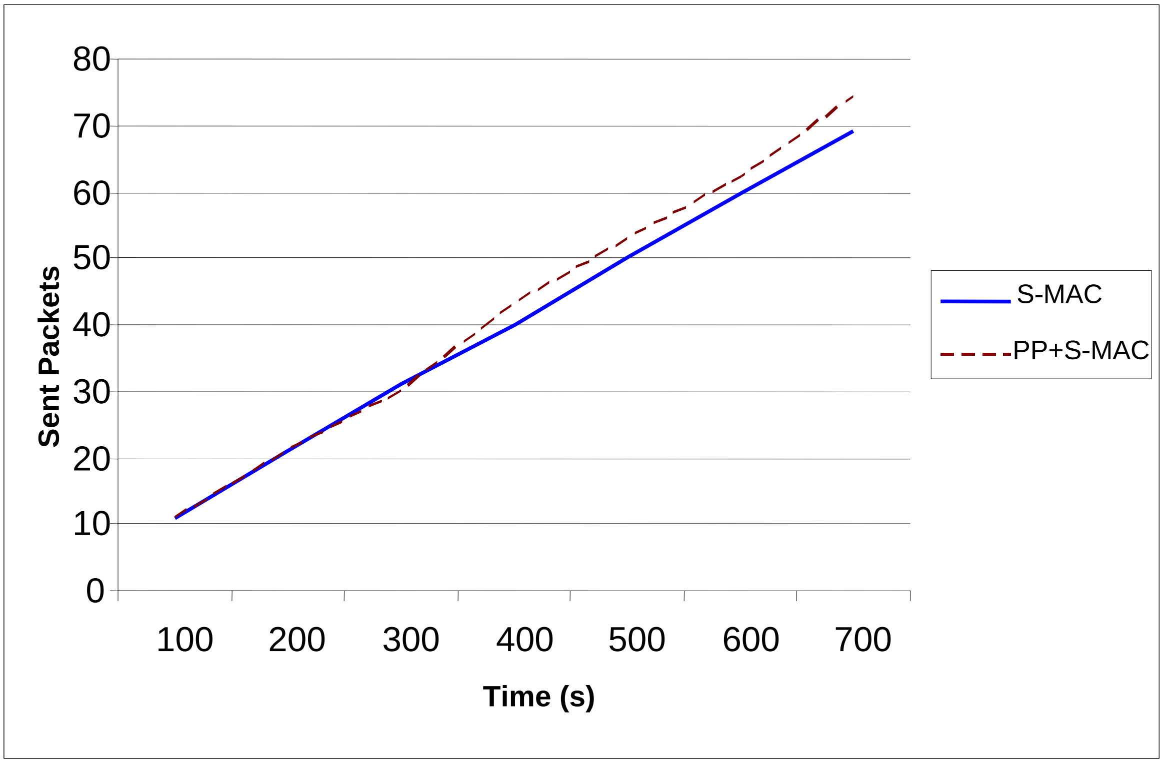

Figure 4-9: Throughput productivity for 5% Duty-Cycle

4.5.2. Simulation for (10%) Duty-Cycle:

In 10% operation the proposed approach yields better energy consumption than S-MAC and better throughput. Figure 4-10 shows that both protocols almost have the same energy consumption at the start of simulation. However, towards to the end of the simulation the proposed approach shows that the energy consumption is more consistent. This is because the proposed approach can consume an amount of energy in the first step of operation as explained in chapter 3 extra SEEK packet in the first step of establishing data delivery.

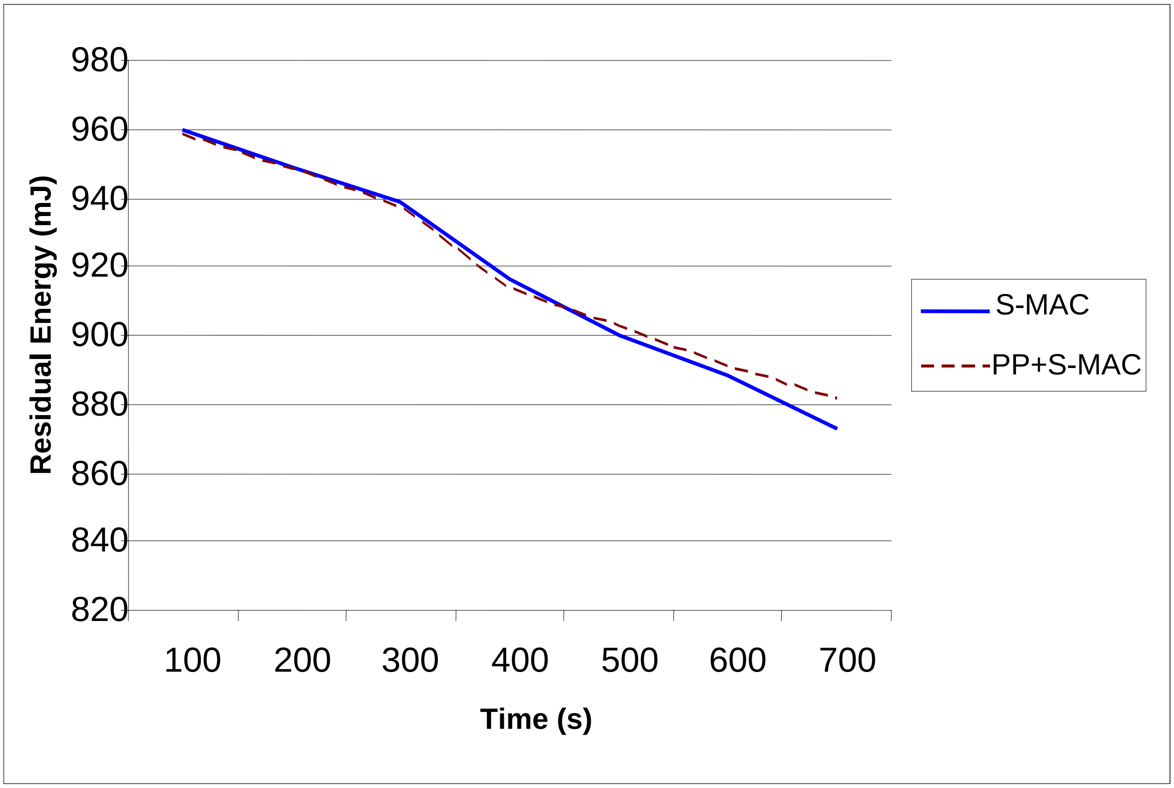

Figure 4-10: Energy consumption for 10% Duty-Cycle

Still adding the proposed scheme to S-MAC gives an effect on throughput which is higher than basic S-MAC because of the rapid operation. Figure 4-11 shows this result.

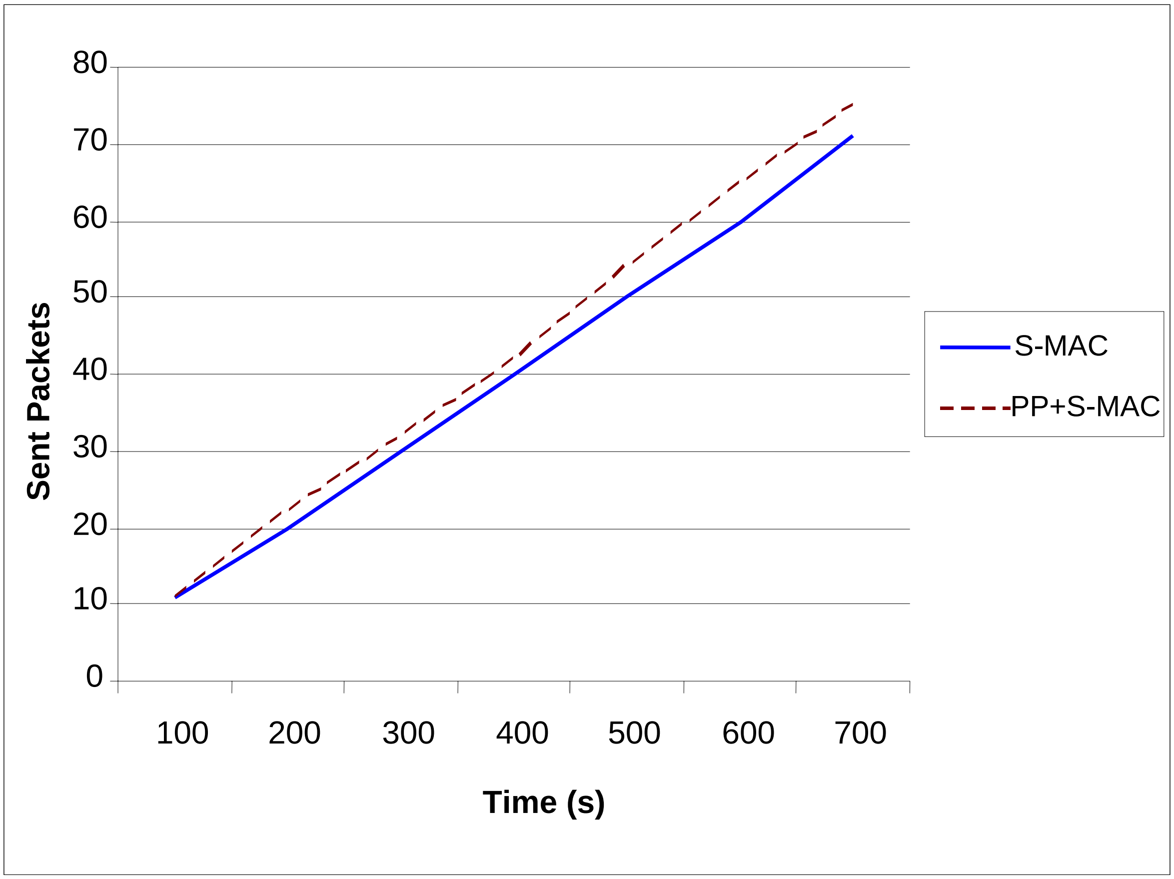

Figure 4-11: Throughput productivity for 10% Duty-Cycle

4.5.3. Simulation for 25% Duty-Cycle:

In higher Duty-Cycles power consumption increases. Adding the proposed approach to S-MAC did affect on energy consumption but the effect is not obvious, refer to Figure 4-12. It is suggested to refer to Appendix A Tables (A-3 and A-6) to see the effect of the approach on S-MAC. This is because of the periodic SYNC packets instantiated in S-MAC producing an effect on energy consumption.

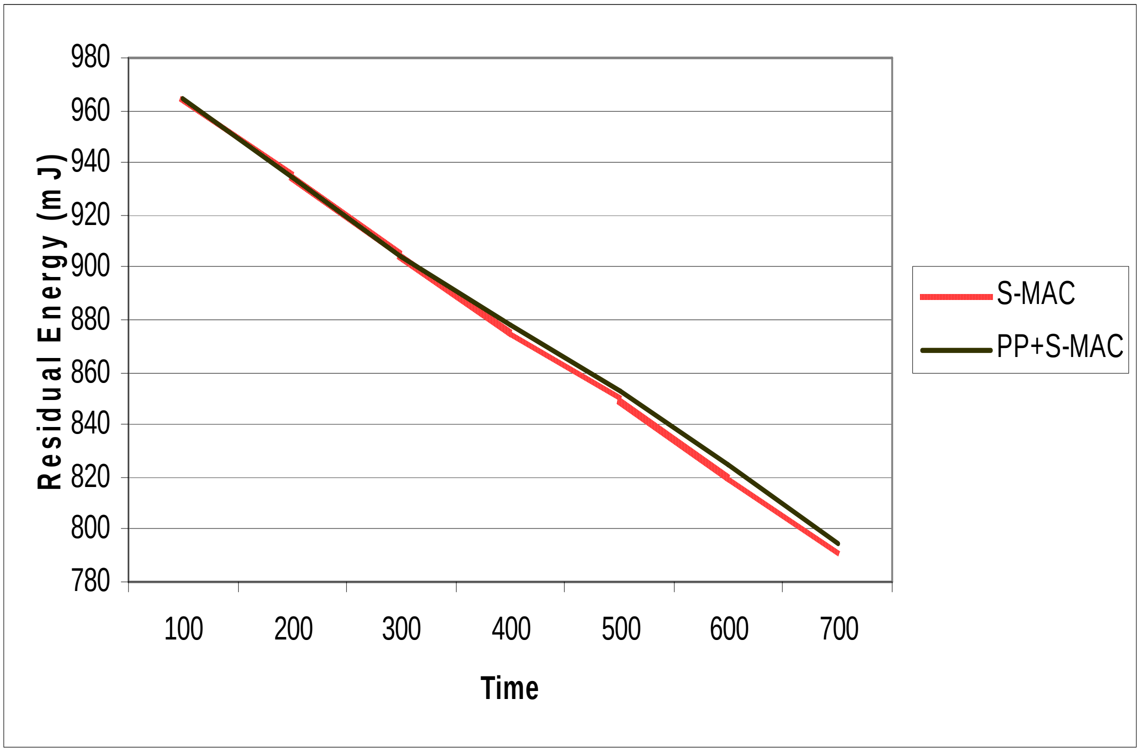

Figure 4-12: Energy consumption for 25% Duty-Cycle

But in terms of throughput adding the approach to S-MAC still gives a higher throughput than S-MAC with out the approach. Figure 4-13 shows the effect.

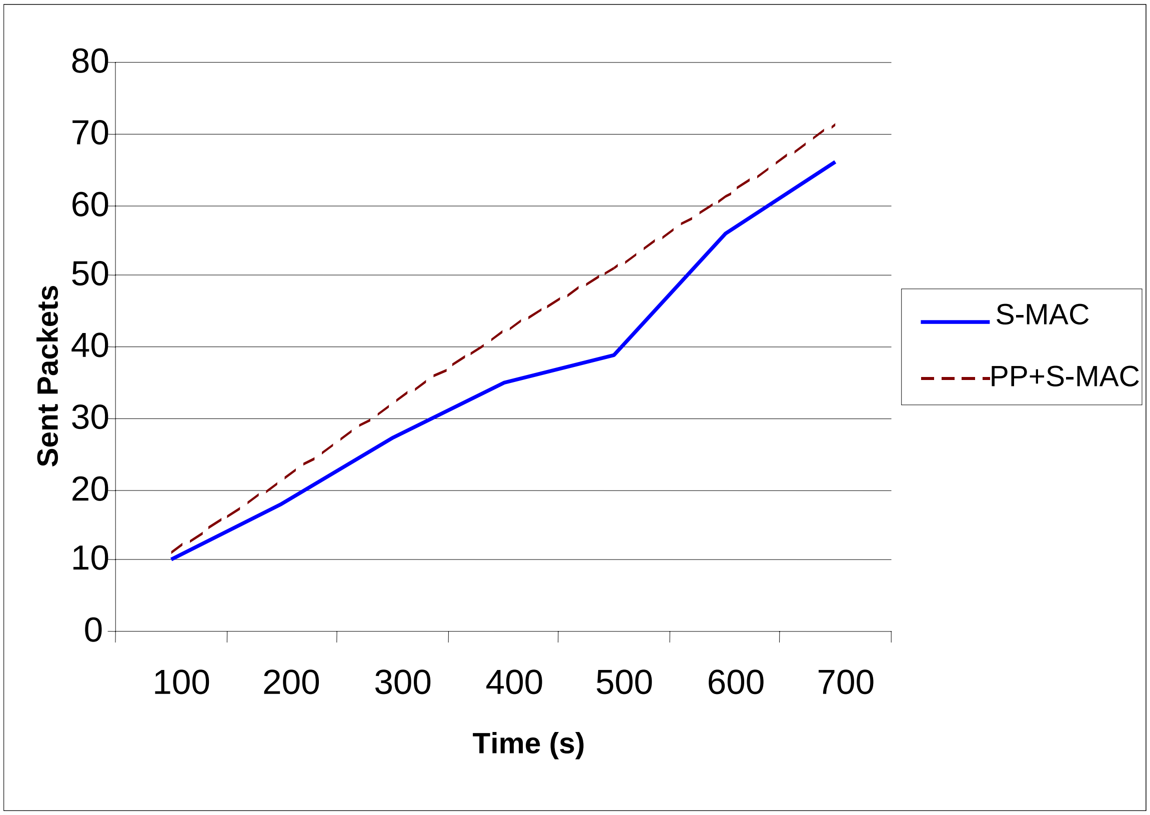

Figure 4-13: Throughput productivity for 25% Duty-Cycle

From the results above it is established that our approach decreases energy consumption in low duty cycles after adding it to S-MAC and increases the throughput in all the scenarios. S-MAC is designed for low duty cycle operation that is why the approach did affect the performance on higher duty cycles in terms of energy consumption.

4.6. PP-SEA-MAC vs. SEA-MAC Simulation Results:

In this section performance evaluation has been carried out through simulations.

4.6.1. Simulation for 5% Duty-Cycle:

Adding the approach to SEA-MAC protocol, for energy consumption does not provide the expected results like basic SEA-MAC Figure 4-14. However, from Table A-7, it is observed that SEA-MAC energy consumption is not even for all the nodes. With the proposed approach from (Appendix A Tables (A-7 and A-10)) it can be seen that the consumption fairly distributed between the nodes. This is considered an advantage for the proposed approach as fair energy consumption between nodes is an important feature when designing MAC Protocols for WSNs.

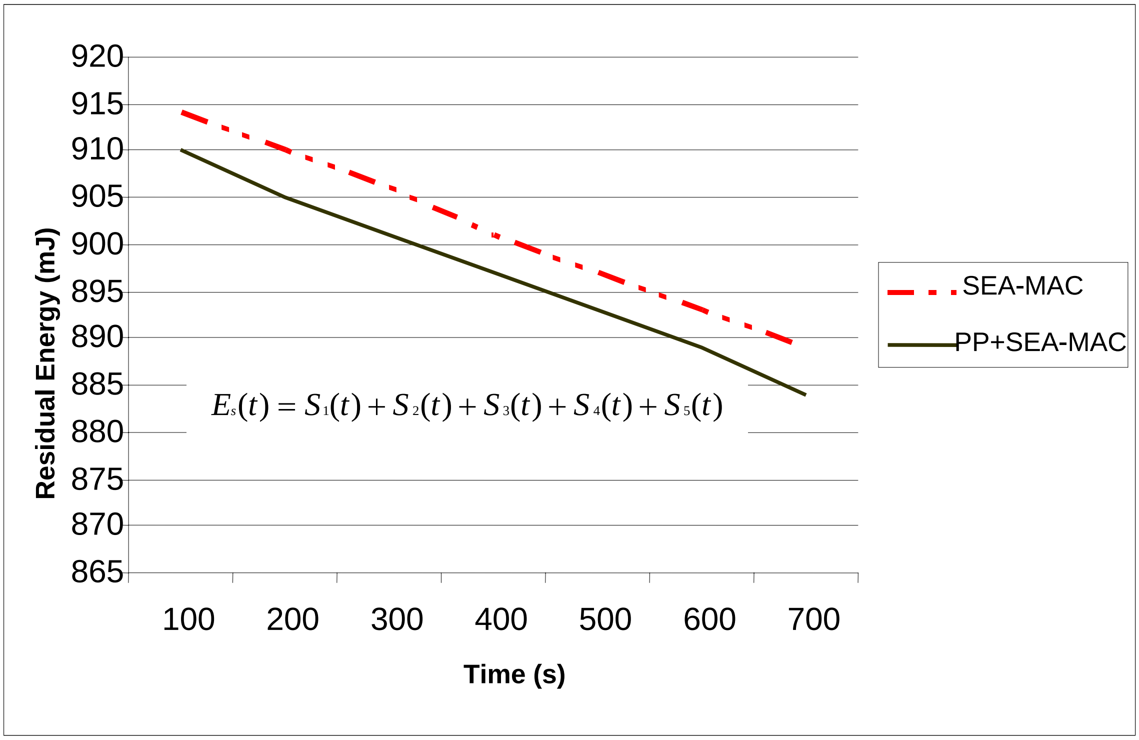

Figure 4-14: Energy consumption for 5% Duty-Cycle

But in terms of throughput it is obvious that the proposed approach added to SEA-MAC is higher than SEA-MAC alone (Figure 4-15). This means that the consumed energy is not wasted for nothing.

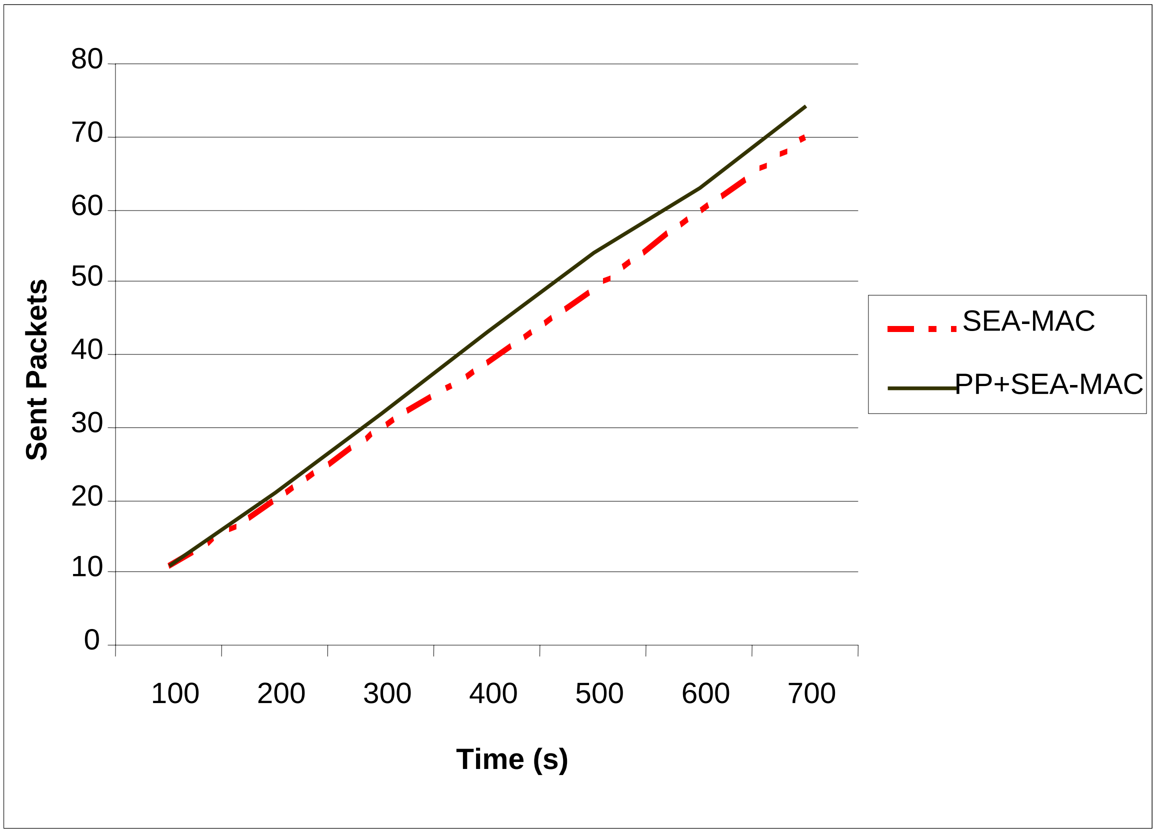

Figure 4-15: Throughput productivity for 5% Duty-Cycle

4.6.2. Simulation for (10%) Duty-Cycle:

For (10%) Duty-Cycle SEA-MAC with the proposed approach and basic SEA-MAC almost have the same energy consumption Figure 4-16. SEEK packet follows the rule of (SEEK < SYNC+RTS). Yet because of the rapid production of this packet in the proposed scheme it adds an extra SEEK for middle operation nodes this affect the energy consumption of the proposed scheme on low duty-cycle.

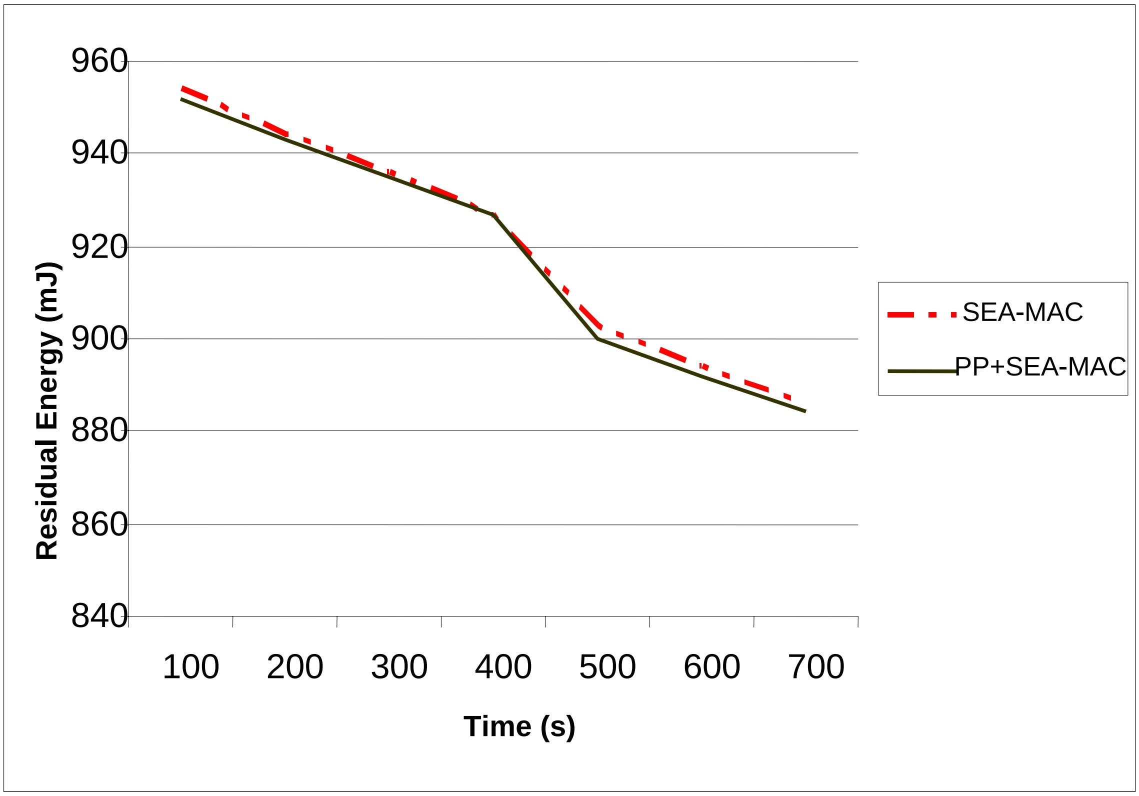

Figure 4-16: Energy consumption for 10% duty-cycle

In terms of throughput it is observed that SEA-MAC with the proposed approach has higher throughput than basic SEA-MAC Figure 4-17 because of the concurrent delivery of SEEK packet which opens the way for data packets to be delivered in a multi-hop fashion in one cycle.

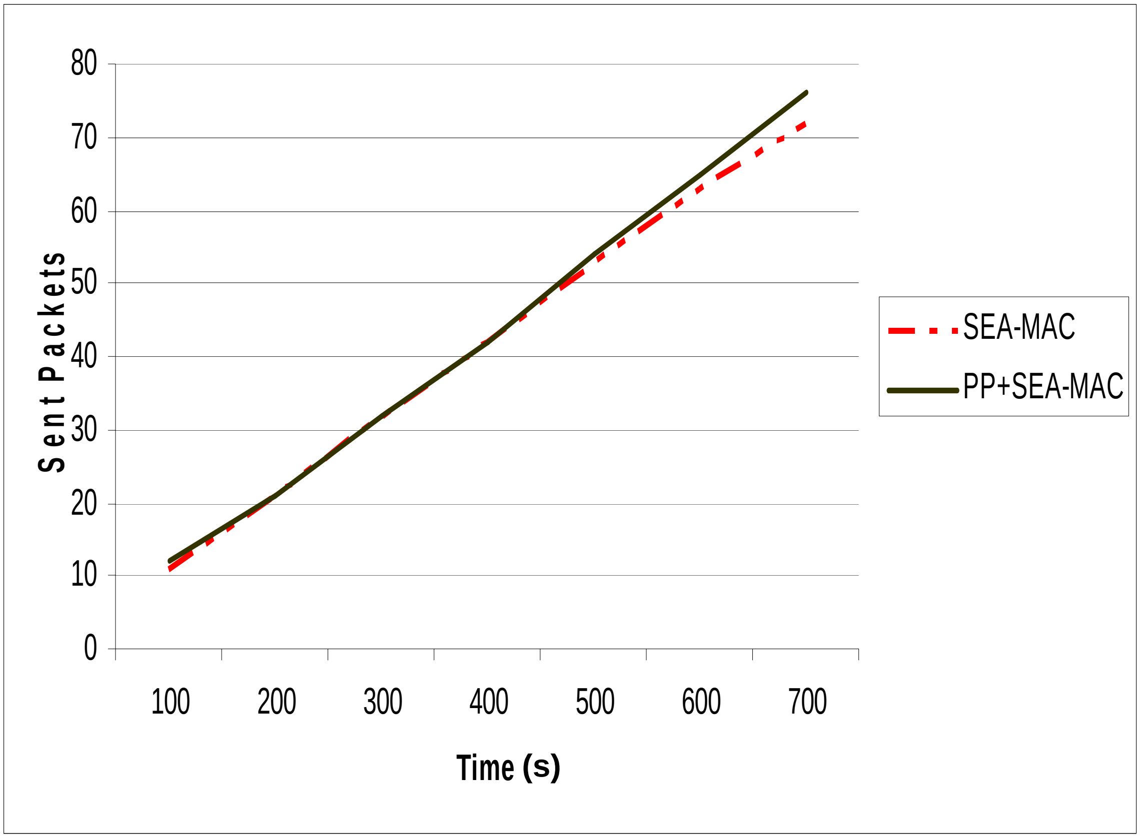

Figure 4-17: Throughput productivity for 10% Duty-Cycle

4.6.3. Simulation for 25% Duty-Cycle:

SEA-MAC is basically designed for high duty cycle operations. That is why when SEA-MAC added to the proposed approach gives better energy consumption than basic SEA-MAC Figure 4-18.

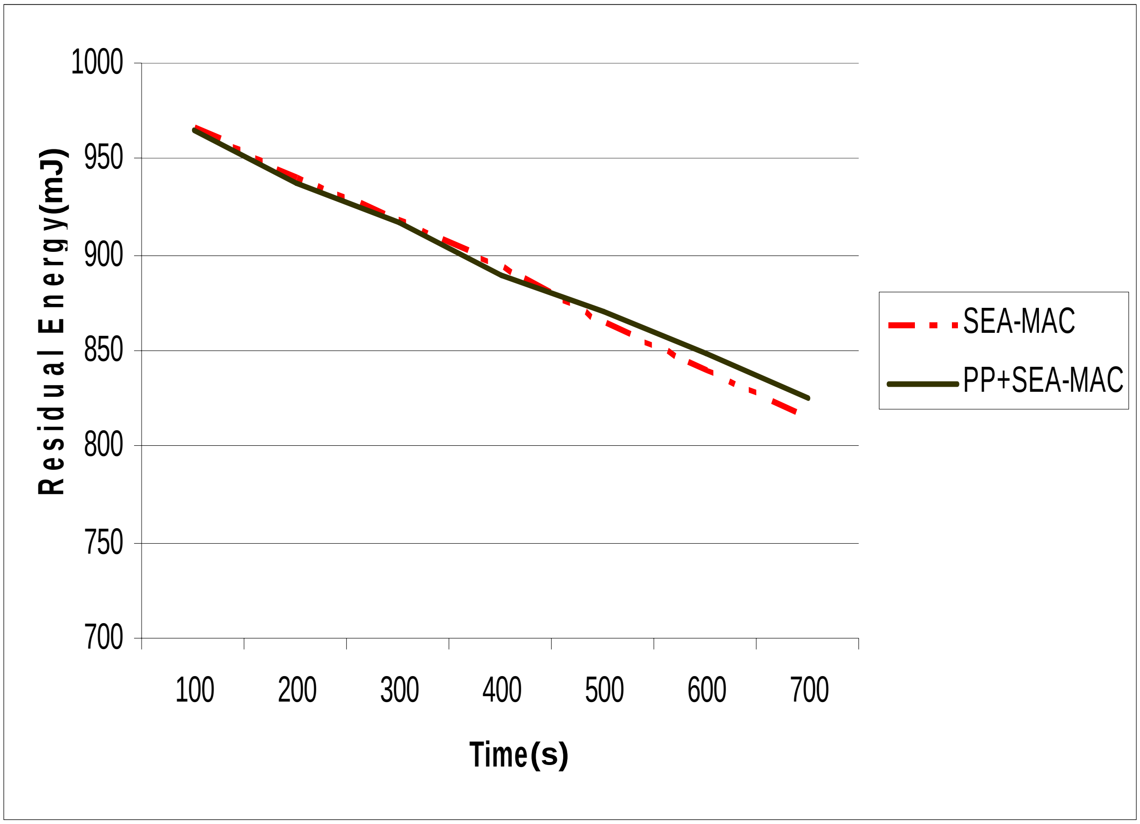

Figure 4-18: Energy consumption for 25% Duty-Cycle

The proposed approach gives better operation in terms of throughput too when it is added to SEA-MAC Figure 4-19.

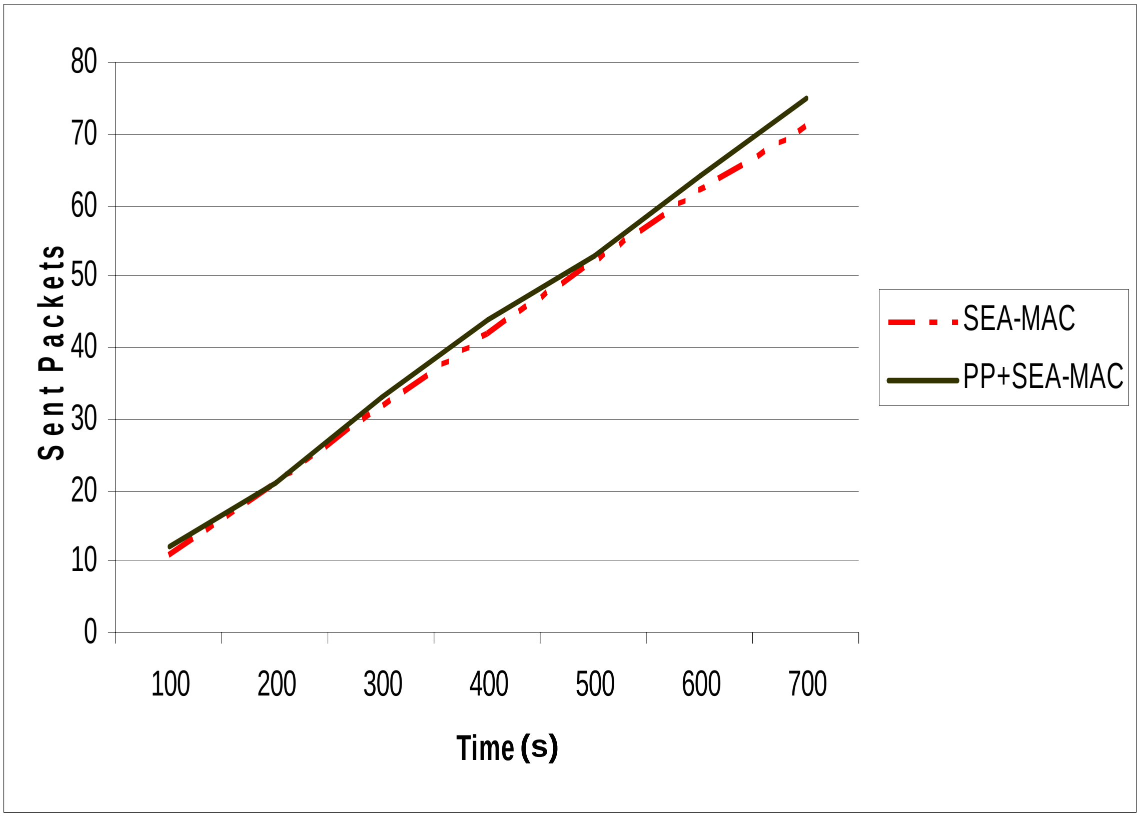

Figure 4-19: Throughput productivity for 25% duty-cycle

From the above simulations (PP-SEA-MAC vs. SEA-MAC) the proposed approach did increased the throughput of the network. On high duty-cycle the energy consumption is affected while on low duty cycle the proposed approach did not affect energy consumption. The proposed approach has an advantage over the basic protocol by making the energy consumption between the nodes even on low duty-cycle operation.

4.7. PP-S-MAC vs. PP-SEA-MAC Simulation Results:

Having completed the comparisons above between the old state of the MAC protocol and after adding the proposed approach on them, now there is a need to establish a comparison for both the new states of the protocols.

4.7.1. Simulation for 5% Duty-Cycle:

From Figure 4-20 it is observed that the approach added to S-MAC produce a high effect on energy consumption than on SEA-MAC. This is because S-MAC is designed for low duty cycle operation networks but that does not mean that SEA-MAC is not better than S-MAC as it is noted from the comparison between them. But adding the proposed approach to S-MAC increased the advantage side of S-MAC. It did affect on SEA-MAC because of the (Tone Packet) that comes with SEA-MAC providing another source of energy consumption.

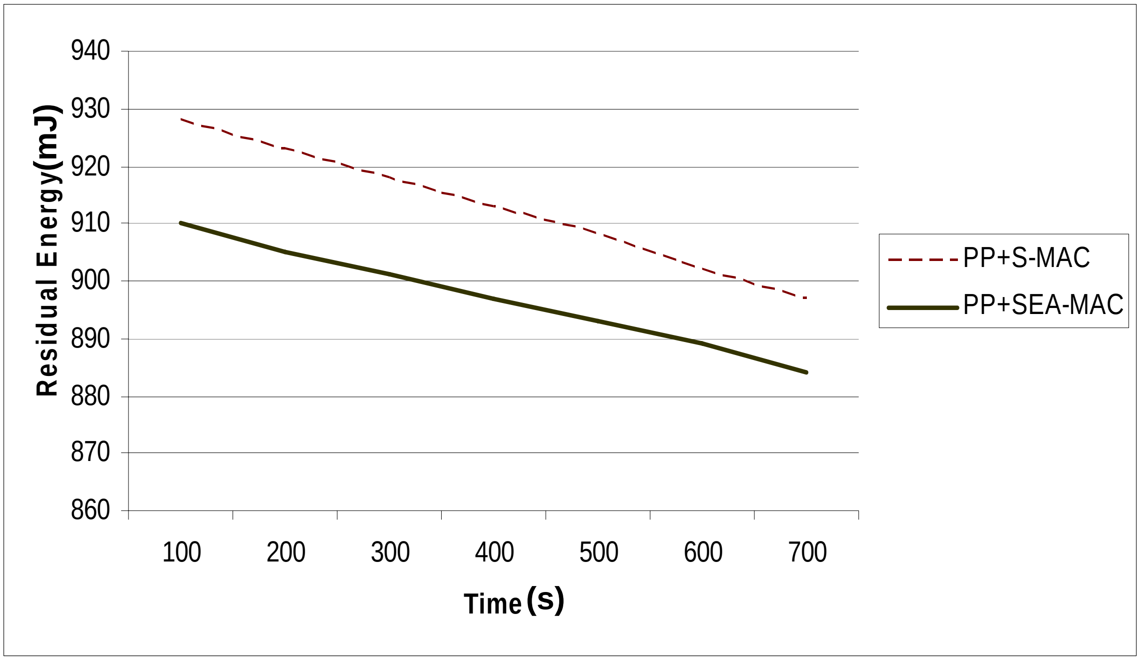

Figure 4-20: Energy consumption for 5% Duty-Cycle

While in terms of network throughput, both PP-S-MAC and PP-SEA-MAC have almost the same results due to the rapid effect sending the mixed (SYNC + RTS) packet to downstream nodes till the destination Figure 4-21.

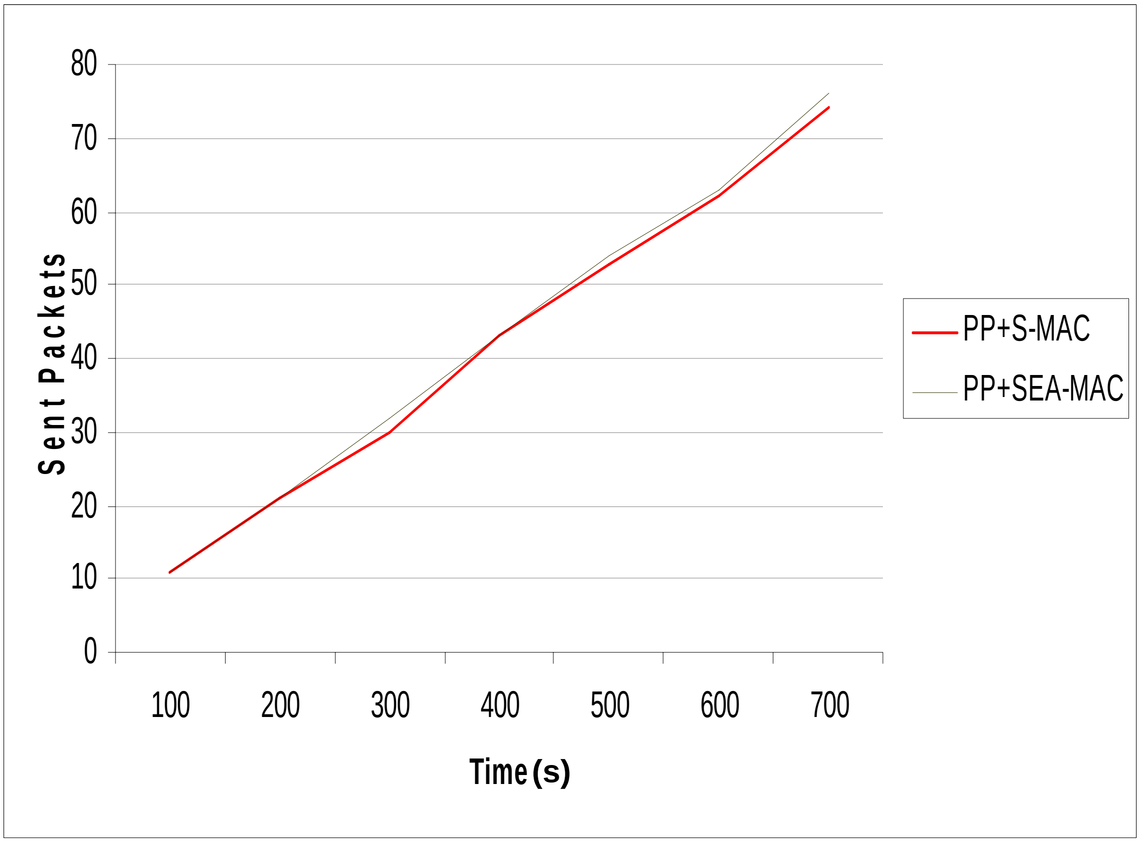

Figure 4-21: Throughput productivity for 5% Duty-Cycle

4.7.2. Simulation for (10%) Duty-Cycle:

For (10%) duty cycle the proposed approach did yield an improvement when it was added to S-MAC and in addition an improvement in performance is also observed when it was added to SEA-MAC. Figure 4-22 below illustrates the difference between the both protocols when adding the proposed approach to them. This is because most of MAC protocol for wireless sensor networks designed to work on (10% Duty-Cycle). This indicates that they do work on higher or lower duty cycle but the ideal state is 10% Duty- Cycle. (Refer to Appendix A to check the data tables).

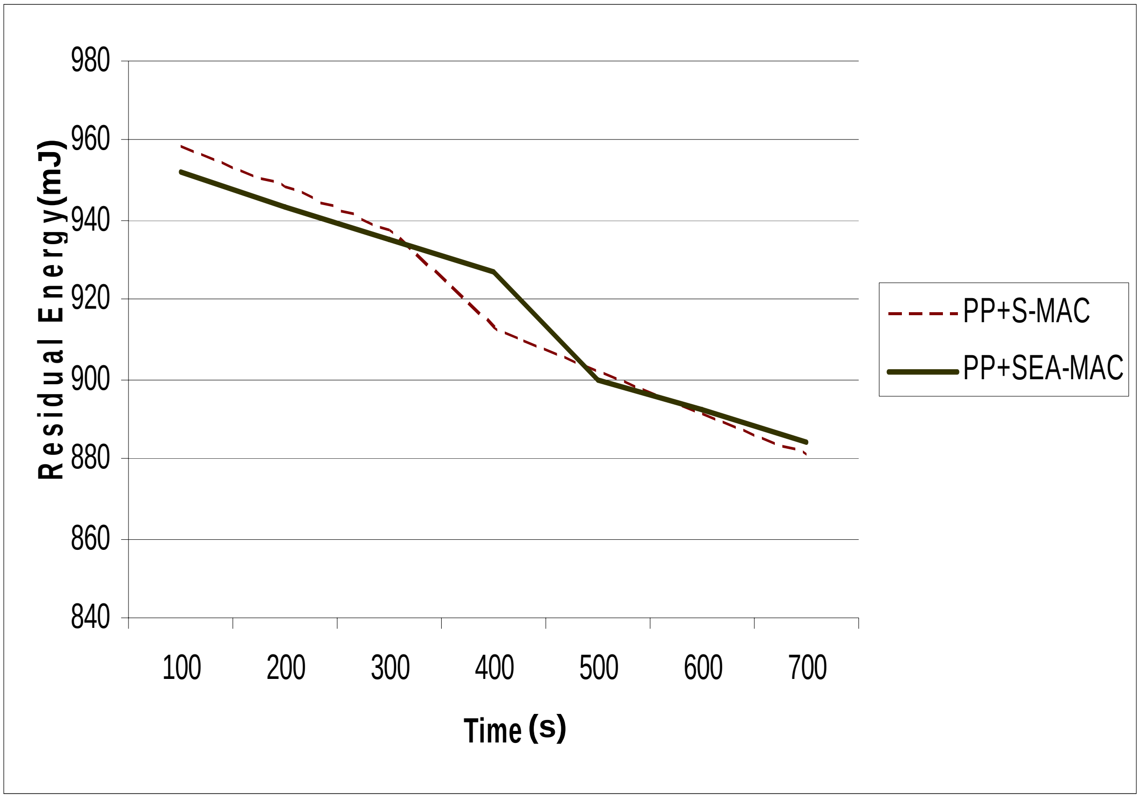

Figure 4-22: Energy consumption for 10% Duty-Cycle

For network throughput after adding our approach Figure 4-23, the both protocols yield similar performance as both has the ability to deliver packets in multi-hop fashion (refer to Appendix A table A-35 for more clear results).

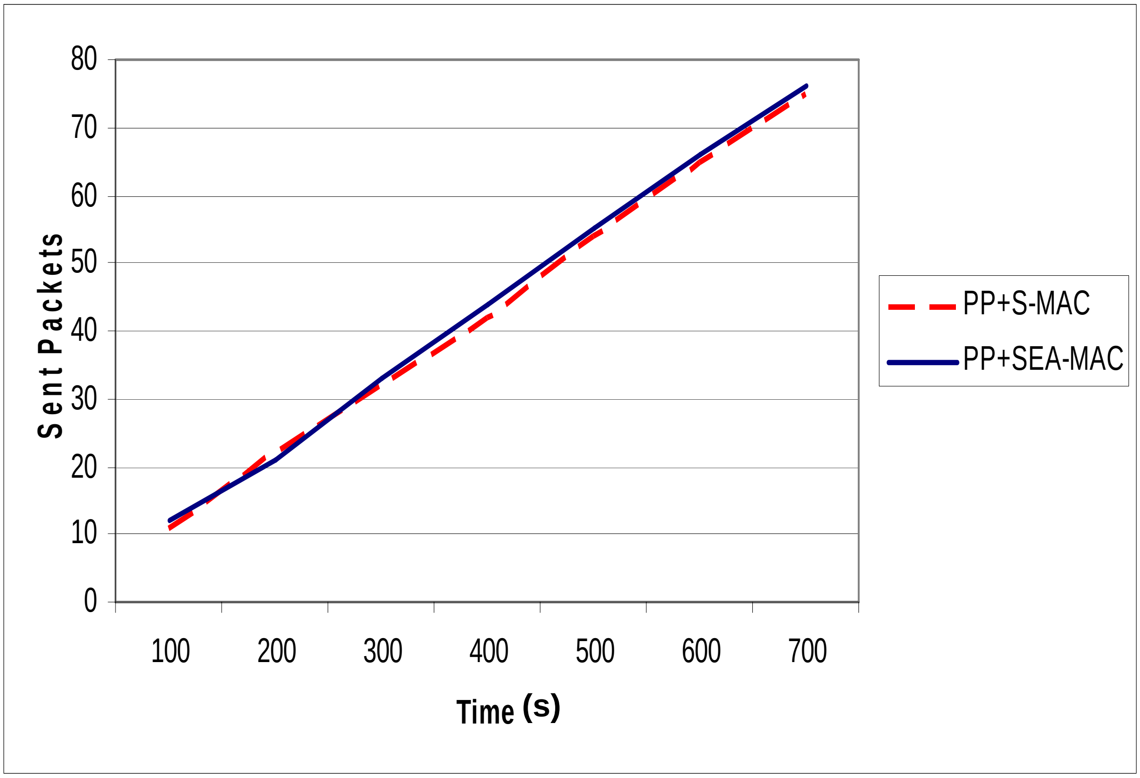

Figure 4-23: Throughput productivity for 10% Duty-Cycle

4.7.3. Simulation for 25% Duty-Cycle:

The proposed approach produce the effect on SEA-MAC better than on S-MAC because SEA-MAC is well designed for higher duty cycles because the (Tone) packet now can control when to make the node sleep and make it active. S-MAC suffers from periodic (SYNC) packet emitting whether there is need to send them or not (Figure 4-24). (Refer to Appendix A Tables (A-6 and A-12) for more clear results).

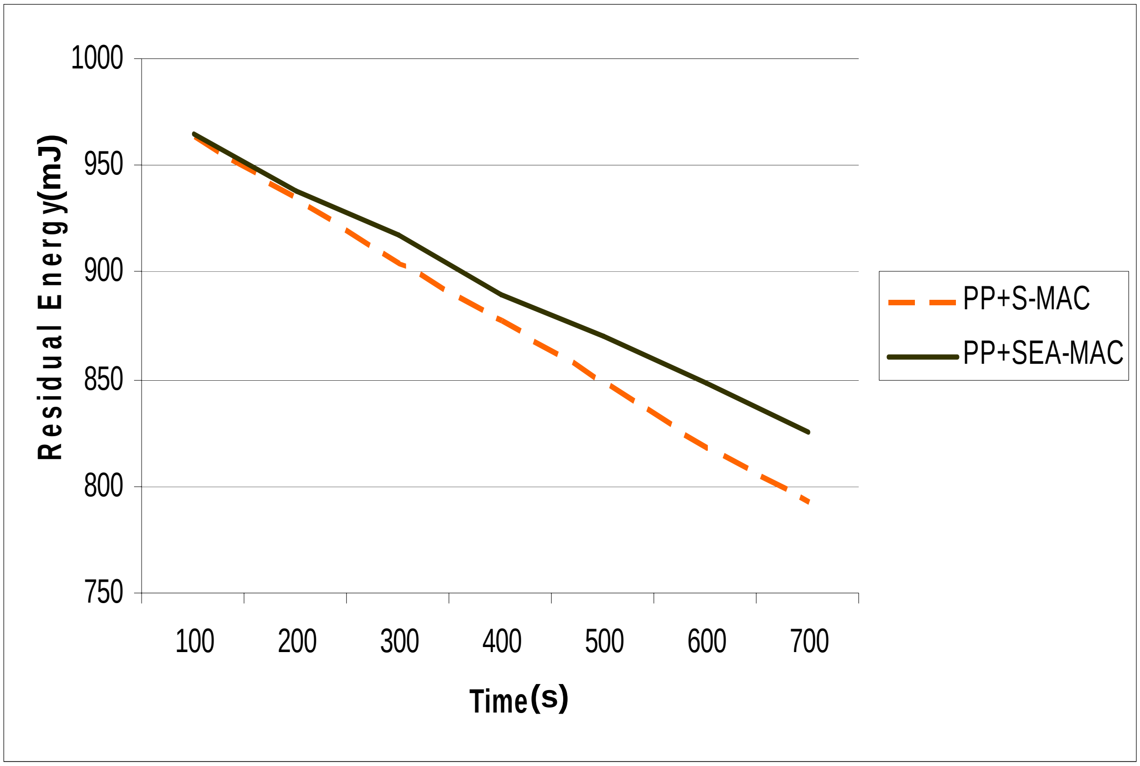

Figure 4-24: Energy consumption for 25% Duty-Cycle

Concerning latency issue, SEA-MAC with the proposed approach has more throughput than S-MAC with the proposed approach for the same reason established above (Figure 4-25 throughput analysis).

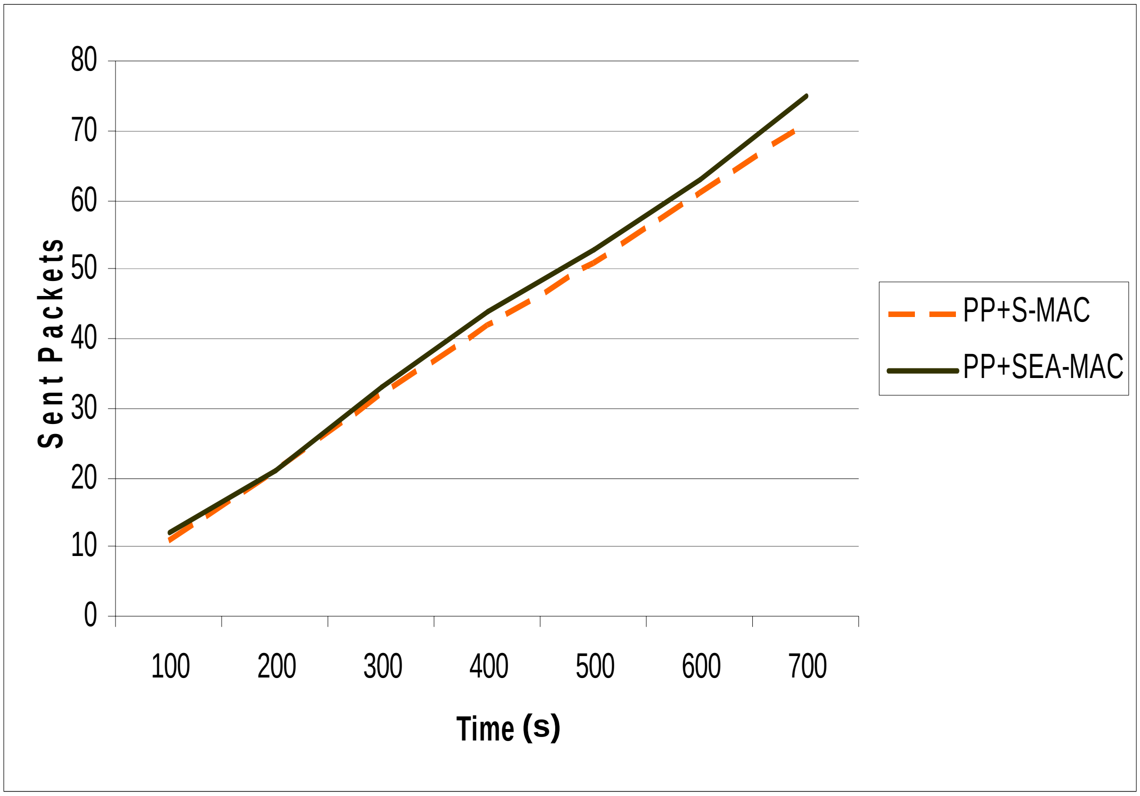

Figure 4-25: Throughput productivity for 25% Duty-Cycle

4.8. Summary

This summary describes the achievements that were obtained and performed through the implementation of the proposed scheme:

The proposed scheme gave the effect on S-MAC and made the consumption in terms of energy at low Duty-Cycle operation better than the original scheme of S-MAC.
The proposed approach provided better operation in terms of energy consumption at high Duty-Cycle operation than the original SEA-MAC scheme.
Both protocols provided better throughput for most of the scenarios after adding the proposed scheme to the original scheme of the protocols.

The next chapter will discuss the implementation of the proposed scheme and the effects that comes with the implementation when increasing the number of deployed nodes in the simulation scenario.

CHAPTER FIVE

THE PROPOSED SCHEME IMPLEMENTATION IN A UNIFORMED SENSOR NODES ENVIRONMENT

Following the procedure applied in chapter four, this chapter will discuss the results of the simulations that have been conducted using the proposed scheme in a uniformed sensor node deployment.

The simulation parameters and the scenario are discussed in the next section. Almost the same parameters that have been used in the single line sensor environment the difference is the simulation time, routing protocol & the node initial energy. As in chapter four a comparison between S-MAC [10] and SEA-MAC [11] will be discussed. The achievements that have been established of this proposed approach are discussed.

5.1. Simulation Parameters and Scenario

The simulation environment was built and made using NS2 version 2.33 [39], the scenario consist of ten nodes nine nodes 0-8 formed a square deployment and one node 9 was separated from the other as a base node. The simulations are conducted on a wide range of duty cycles from 5% - 40% in three steps (5, 25 and 40). The simulations include a comparison between the MAC protocols and the proposed approach. The proposed approach will be referred as Proposed Protocol (pp-) before or after any protocol name. Refer to Figure 5-1 for simulation topology applied.

Simulation parameters are the following Table 5-1:

Table 5-1: Simulation Parameters

Parameter	**Amplitude**
Simulation time	7000 seconds
Duty-Cycle	5%, 25%, 40%
Routing Protocol	DSR
Node Idle power	100 mW
Node Rx Power	100 mW
Node Tx Power	100 mW
Node Sleep Power	1 mW
Transition Power	20 mW
Transition time	5 ms
Energy model	NS2 Energy model
Propogation model	TwoRayGround
Initial Energy for each node	mJ

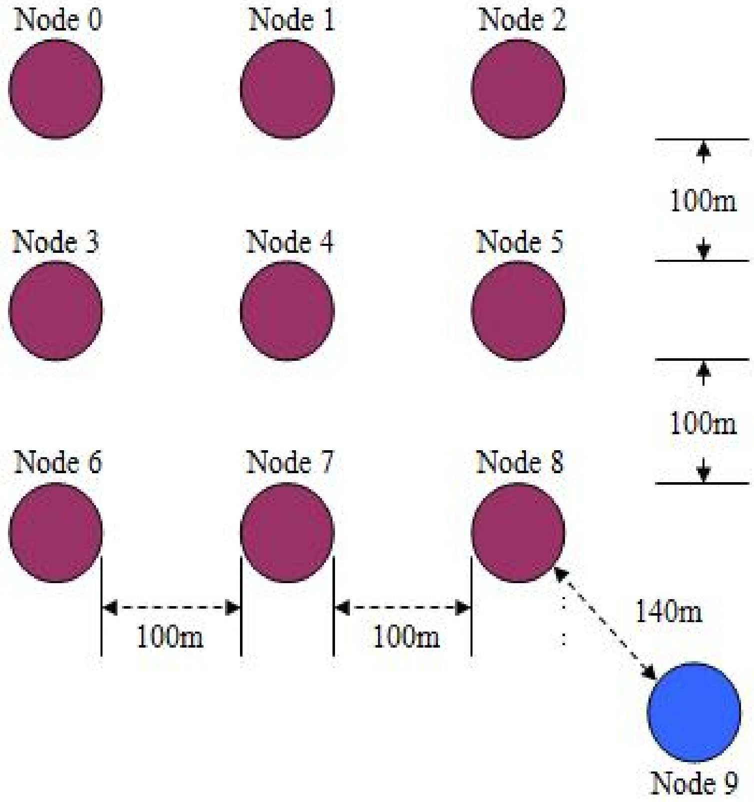

Figure 5-1: Simulation Topology

5.2. Performance evaluation: S-MAC vs. SEA-MAC

Initially, it is needed to prove that the proposed approach is effective. In order to do this it is necessary to show the performance operation of each tested MAC protocols in terms of latency efficiency and energy consumption. The weak points in both protocols Simulations are also shown. Increasing the number of nodes should give more accurate results for the operation of both protocols. Thus, performances evaluation for both protocols has been conduct including the second simulation scenario proposed parameters.

5.2.1 Simulation for (5%) Duty-Cycle

For (5%) operation duty-cycle, it is observed that SEA-MAC performs better than S-MAC in terms of energy consumption Figure 5-2. This operation is based on the uneven distributed energy consumption between nodes as SEA-MAC tends to load on single node in operation (stated in chapter four).

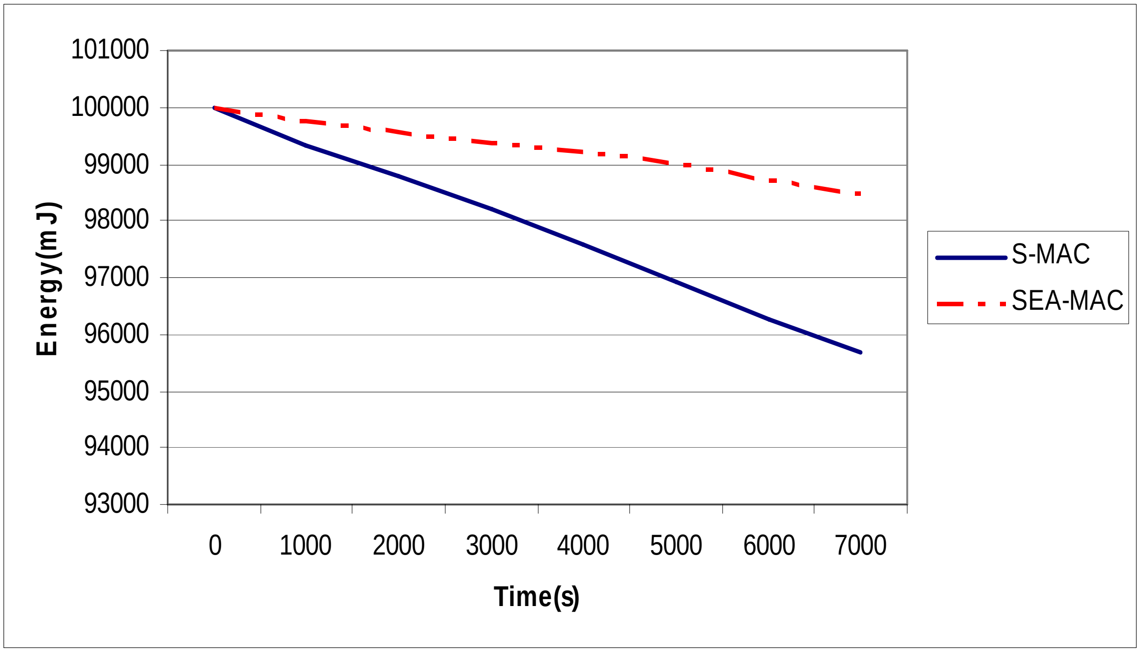

Figure 5-2: Energy consumption for 5% Duty-Cycle

Both SEA-MAC and S-MAC follows the same (SYNC+RTS+CTS) operation when ever there is a triggered event with the urgent need to send data to the next node. This will result in similar throughput operation for both protocols Figure 5-3.

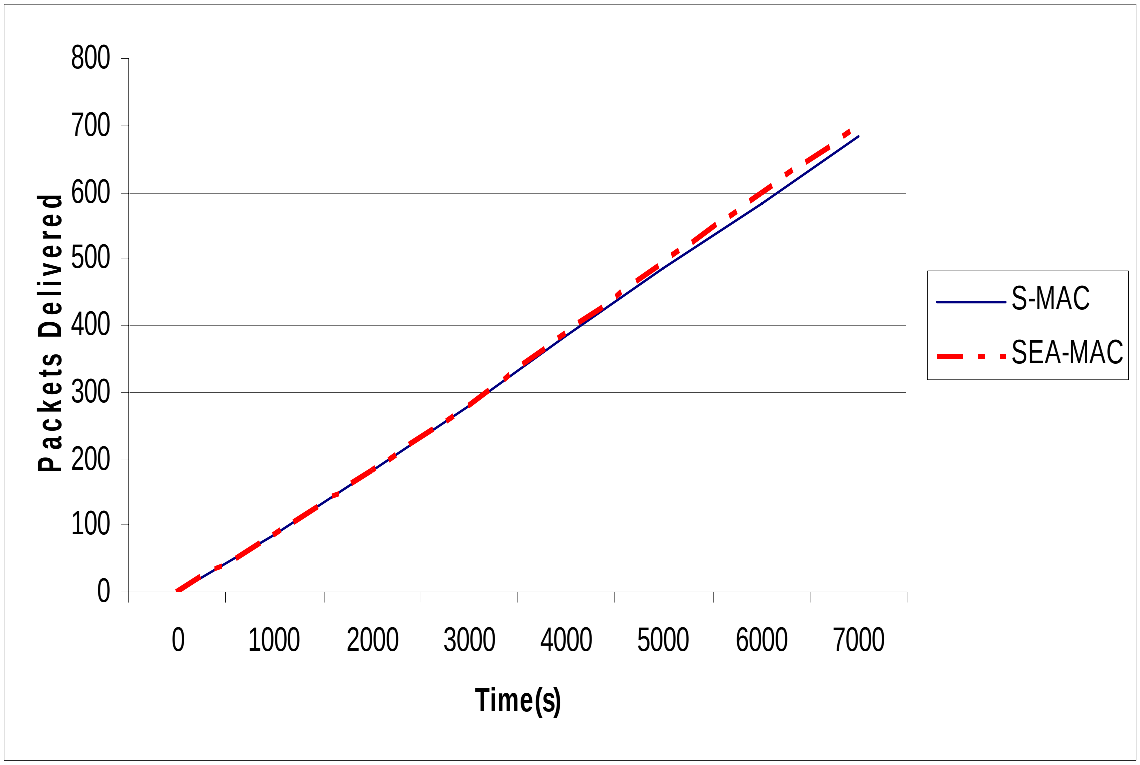

Figure 5-3: Throughput productivity for 5% Duty-Cycle

5.2.2 Simulation for (25%) Duty-Cycle

As the duty-cycle increased to (25%), SEA-MAC has a slight improvement over S-MAC. SEA-MAC is more stable in terms of energy consumption on high duty-cycles than in low duty-cycles. Figure 5-4 illustrates the relationship of the consumed nodes energy over time.

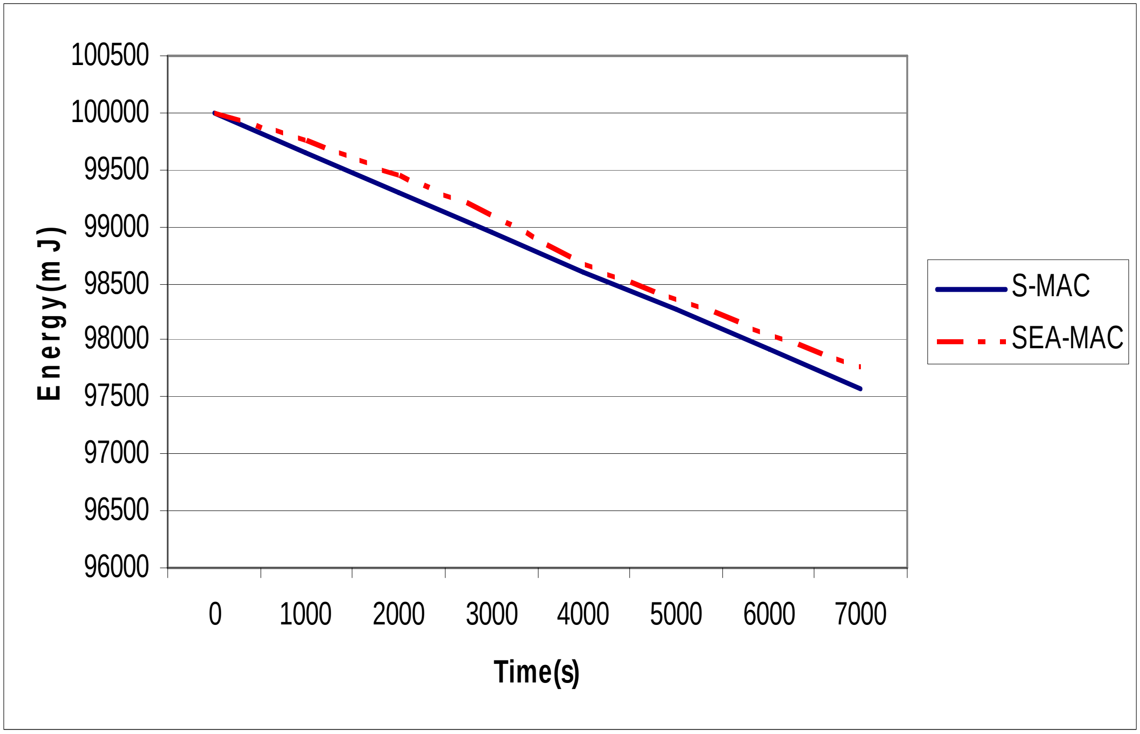

Figure 5-4: Energy consumption for 25% Duty-Cycle

As mentioned in section 5.2.2, both protocols operate the same way in terms of exchanging control packets and data packets between the nodes. This will also result in a slightly similar system throughput; refer to Figure 5-5.

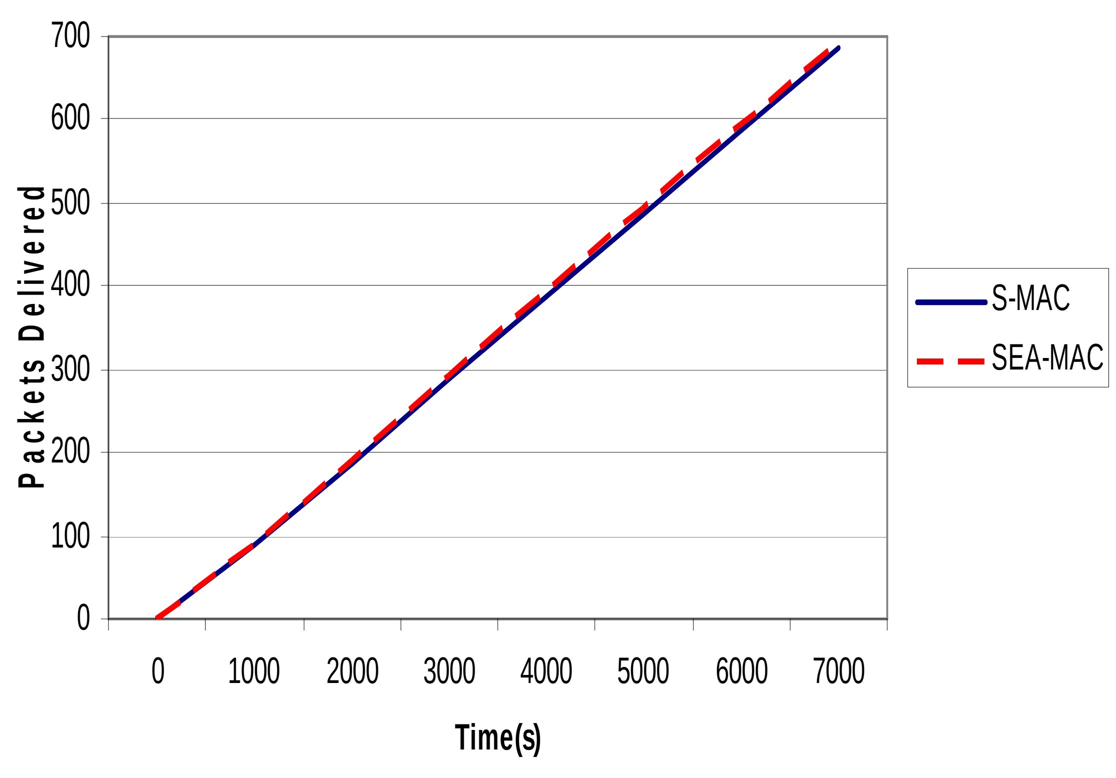

Figure 5-5: Throughput productivity for 25% Duty-Cycle

5.2.3 Simulation for (40%) Duty-Cycle

While increasing the simulation duty-cycle to (40%), it is observed that SEA-MAC has the lead in terms of energy consumption Figure 5-6. SEA-MAC operation is stable at high duty-cycles unlike S-MAC which suffers from periodic (SYNC) packet emitting yields into more consumed energy refer to Appendix A Table (A-15 and A-21) for more detailed results.

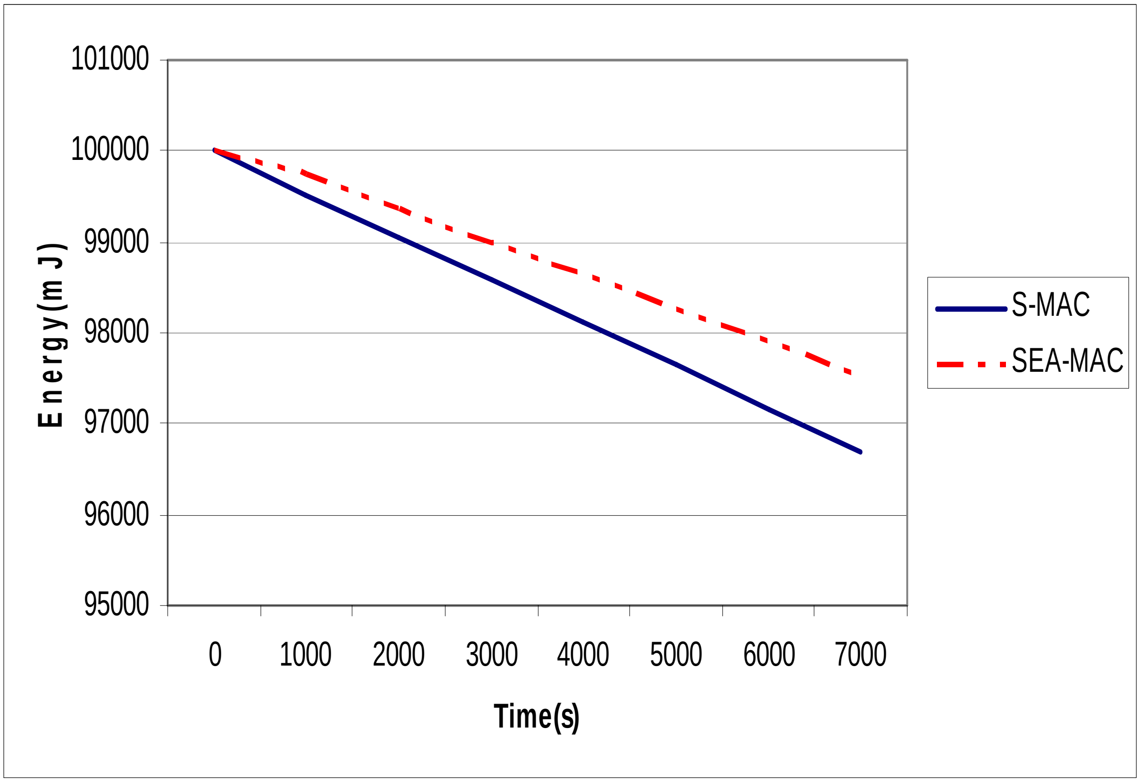

Figure 5-6: Energy consumption for 40% Duty-Cycle

In terms of throughput, both protocols end the simulation with slightly similar amount of delivered DATA packets (refer to Appendix A Table A-39 for more details). For the time slice (0-3500) seconds, it is observed that SEA-MAC falls back in throughput production rather than S-MAC. This is because of the additional TONE packet that SEA-MAC produces to maintain the protocol operation Figure 5-7.

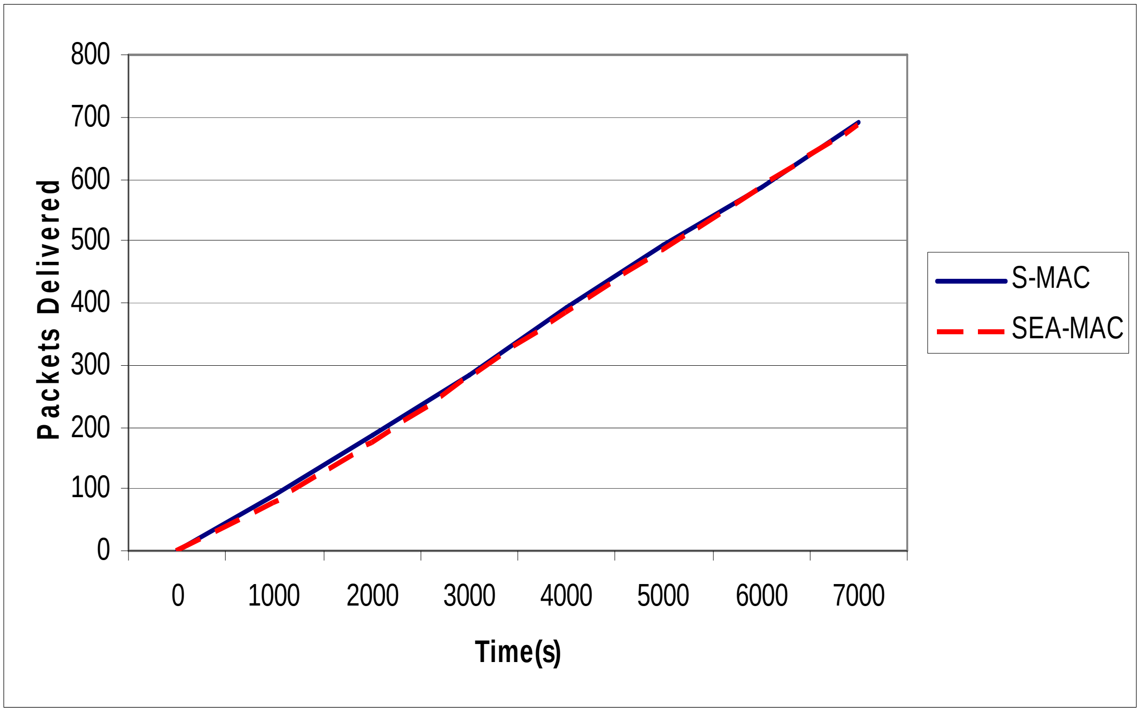

Figure 5-7: Throughput productivity for 40% Duty-Cycle

5.3. The proposed Approach implementation and discussion

This section will present and describe the results of implementing the proposed approach by mixing it with S-MAC and SEA-MAC and provides a performance evaluation and benchmarking against the enhanced version of both MAC protocol with their basic model schemes. The simulations will follow the same procedure that has been carried out to the performance evaluation between S-MAC and SEA-MAC. This section will end with a summary of the achievements that has been established when implementing the proposed approach. This section will demonstrate the performance of the improved MAC protocols against their basic architecture to prove the feasibility of the proposed approach using the square uniform scenario following the parameters presented.

5.4. S-MAC vs. S-MAC-PP Simulations Results:

This section will present the performance of S-MAC against the improved version of S-MAC.

5.4.1. Simulation for (5%) Duty-Cycle

It is observed that when S-MAC-PP applied on a larger network deployment the energy consumption was better than S-MAC alone. This indicates that increasing the density of node deployment can achieve better energy consumption as the nodes will co-operate in processing the information Figure 5-8.

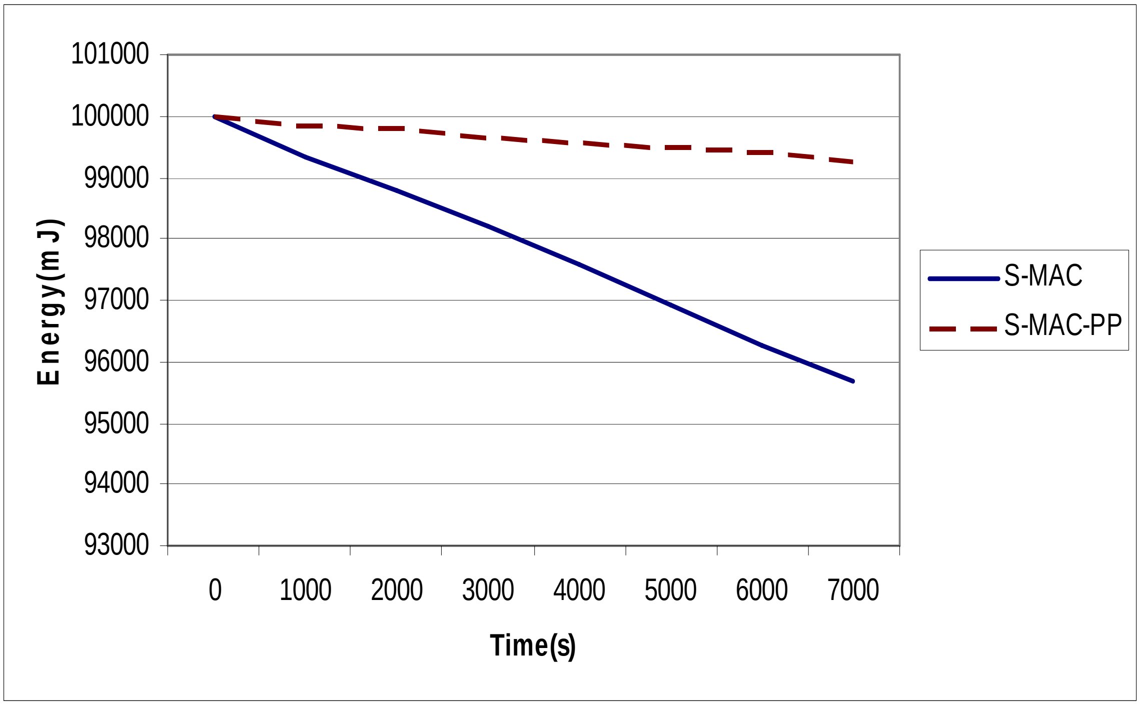

Figure 5-8: Energy consumption for 5% Duty-Cycle

Throughput on the other hand look’s the same in Figure 5-9 it is observed from the simulations that the wireless channel seized from accepting more data packets delivered. It is recommended to refer to Appendix A Table A-40 for more detailed results concerning network throughput through the simulation.

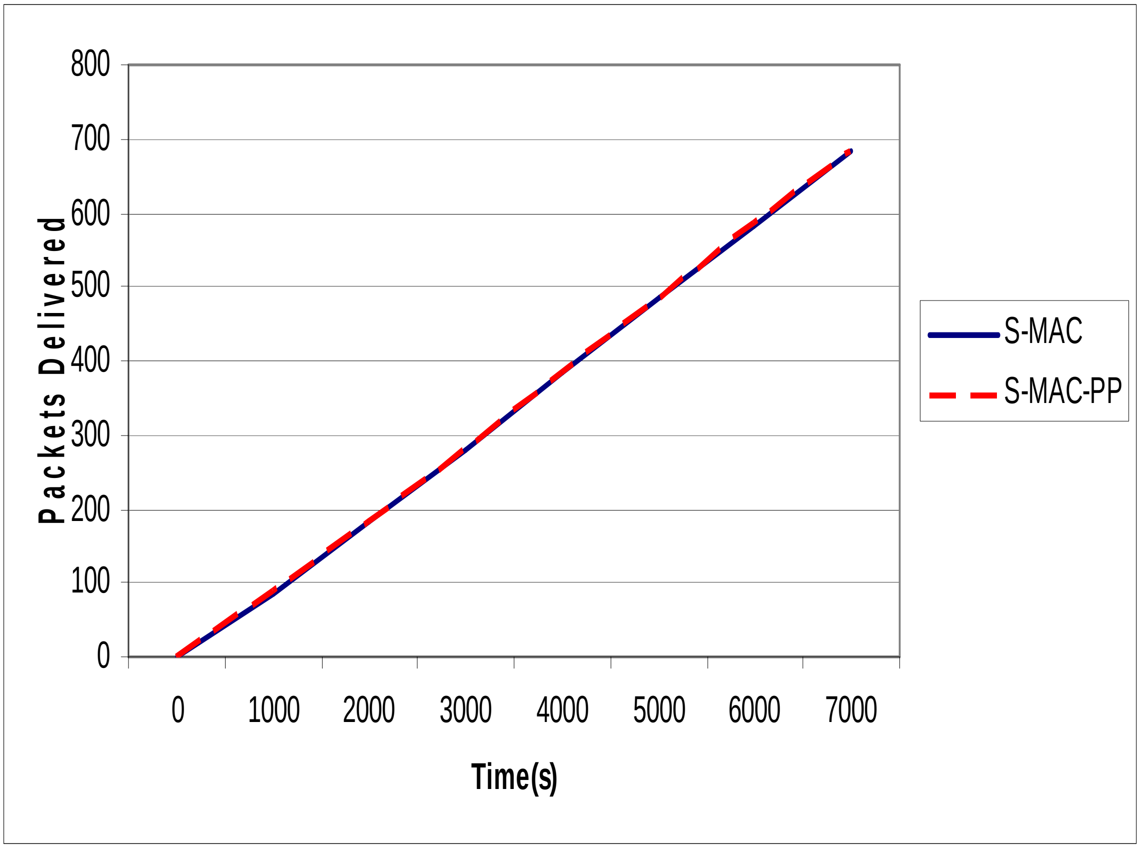

Figure 5-9: Throughput productivity for 5% Duty-Cycle

5.4.2. Simulation for (25%) Duty-Cycle

When increasing the nodes operation duty cycle to (25%), it is well observed the effect of the proposed approach on S-MAC Figure 5-10. Energy consumption is improved. Two catalysts helped in this improvement the first one is the mixed functionality of SEEK packet and the second is the increment in the number of deployed nodes. The more the number of nodes deployed the more efficient the network operation because it will divide the load on the network between the nodes.

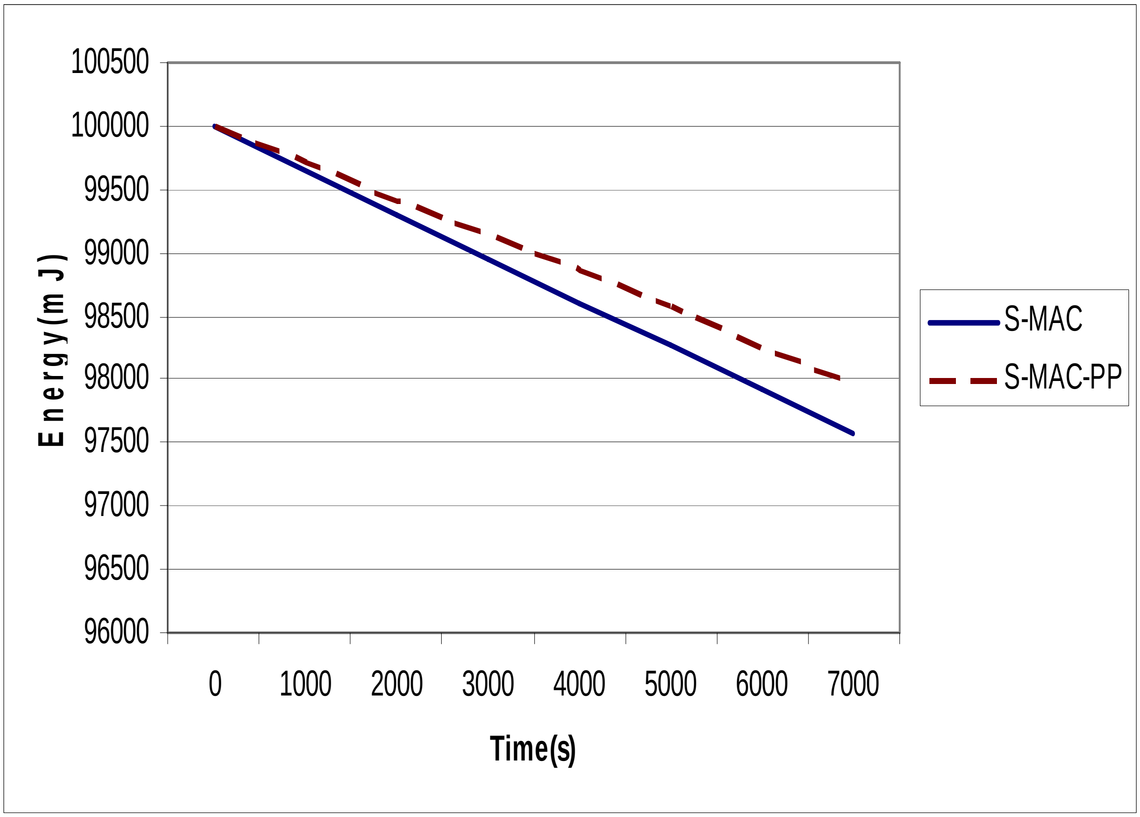

Figure 5-10: Energy consumption for 25% Duty-Cycle

There is slight deference in throughput in Figure 5-11 but to be more accurate it is preferred to check Appendix A Table A-41 for more detailed results.

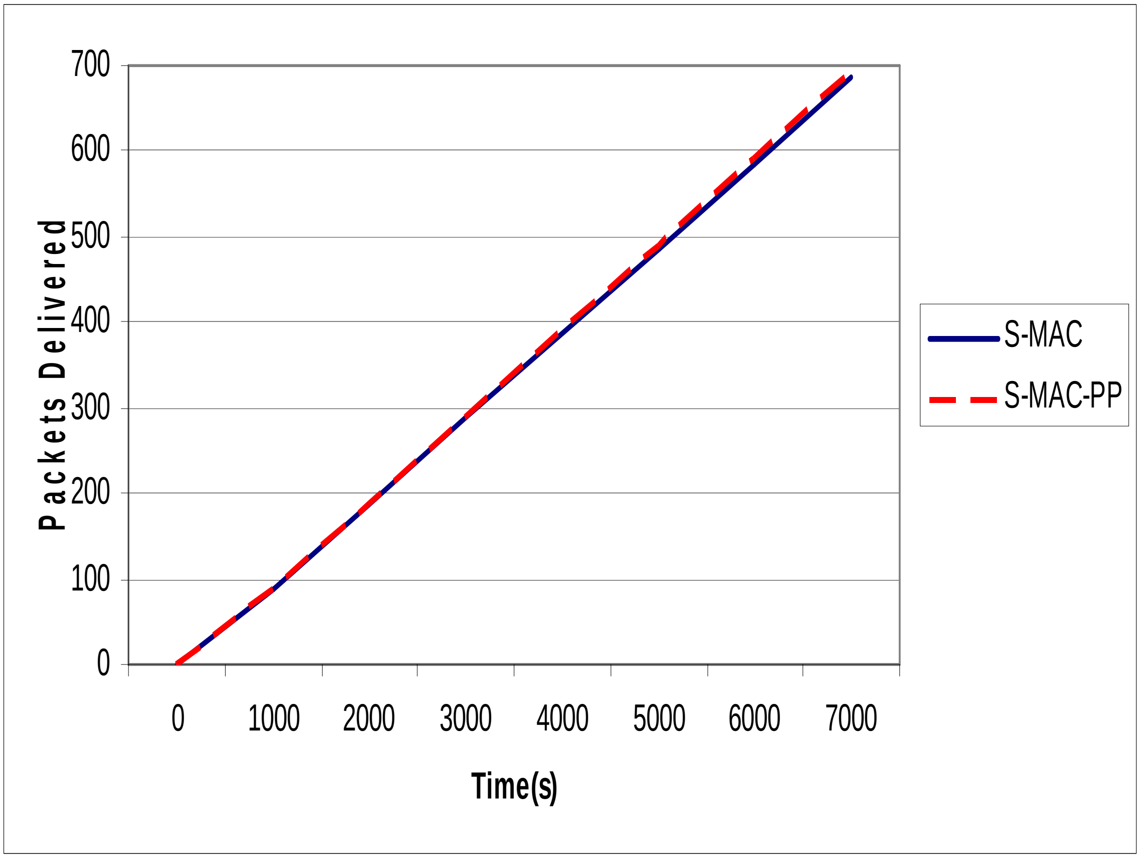

Figure 5-11: Throughput productivity for 25% Duty-Cycle

5.4.3. Simulation for (40%) Duty-Cycle

For (40%) operation duty-cycle, the proposed approach yields more improved energy consumption than S-MAC Figure 5-12. Here the consumption is even better when the number of deployed nodes was five. This improved operation follows the same considerations stated above in other sections that is the more nodes deployed, the better the network operation.

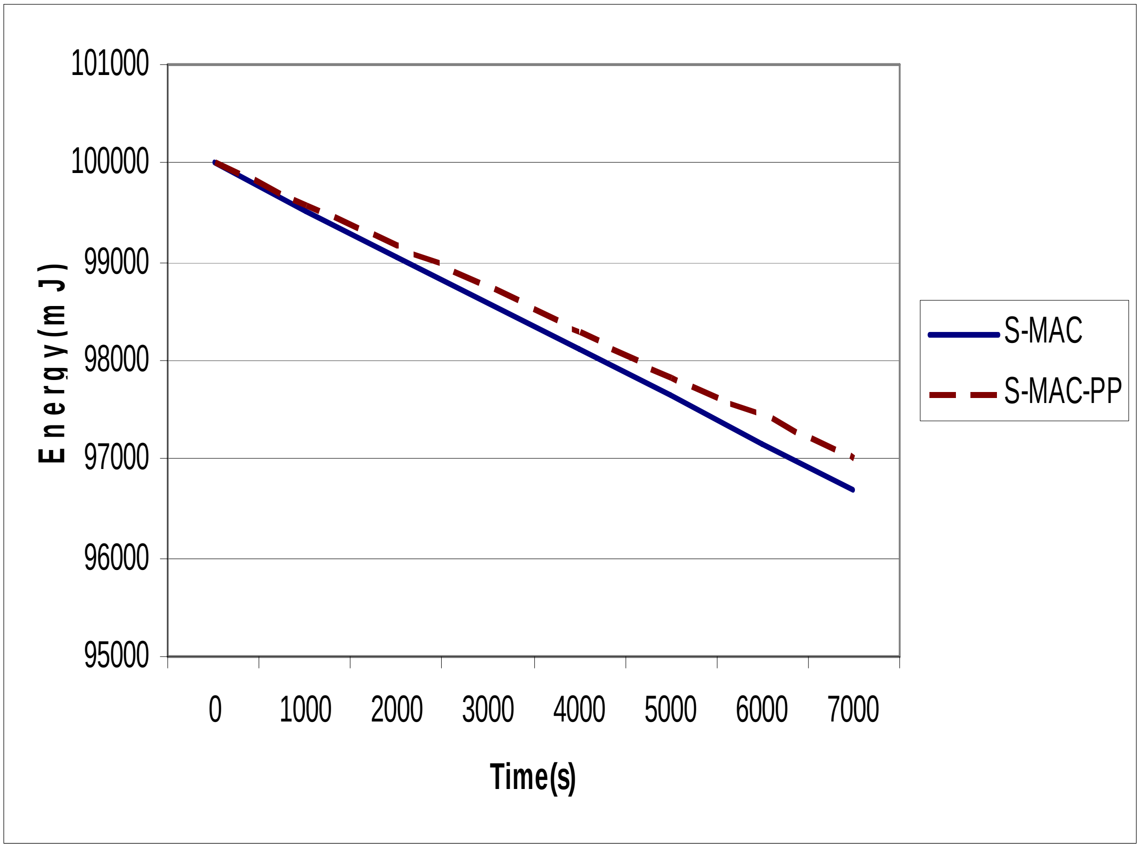

Figure 5-12: Energy consumption for 40% Duty-Cycle

With high operation Duty-Cycle the proposed approach improved the throughput of the network Figure 5-13. This will help in applications that have to maintain both efficient energy consumption and low message exchange delay (Real-Time systems).

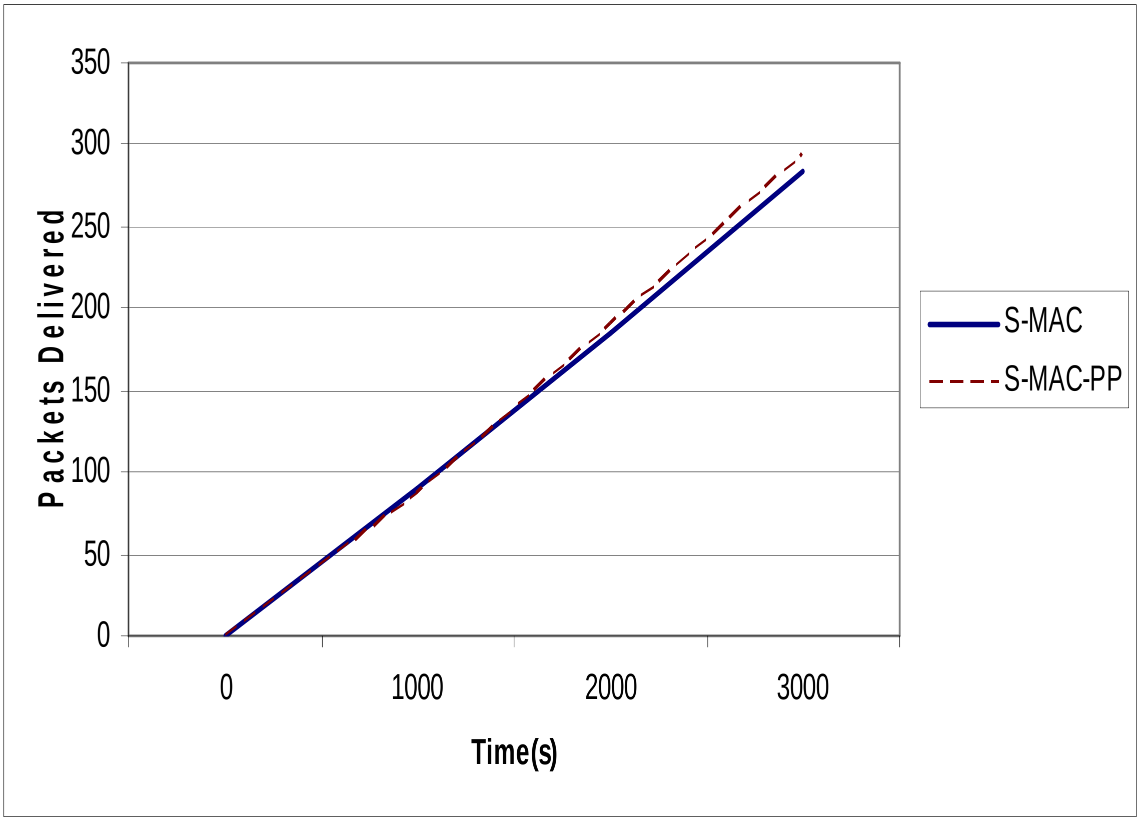

Figure 5-13: Throughput productivity for 40% Duty-Cycle

5.5. SEA-MAC vs. SEA-MAC-PP Simulations Results:

This section shows performance comparison and evaluation between SEA-MAC and the improved version of SEA-MAC protocol.

5.5.1. Simulation for (5%) Duty-Cycle

For low operation Duty-Cycle (5%), it has been demonstrated earlier that SEA-MAC-PP lacks the efficient energy consumption than SEA-MAC Figure 5-14. Increasing the number of deployed nodes, SEA-MAC-PP has better energy consumption than SEA-MAC because of the aggressive and uneven energy consumption of SEA-MAC especially in low operation Duty-Cycles.

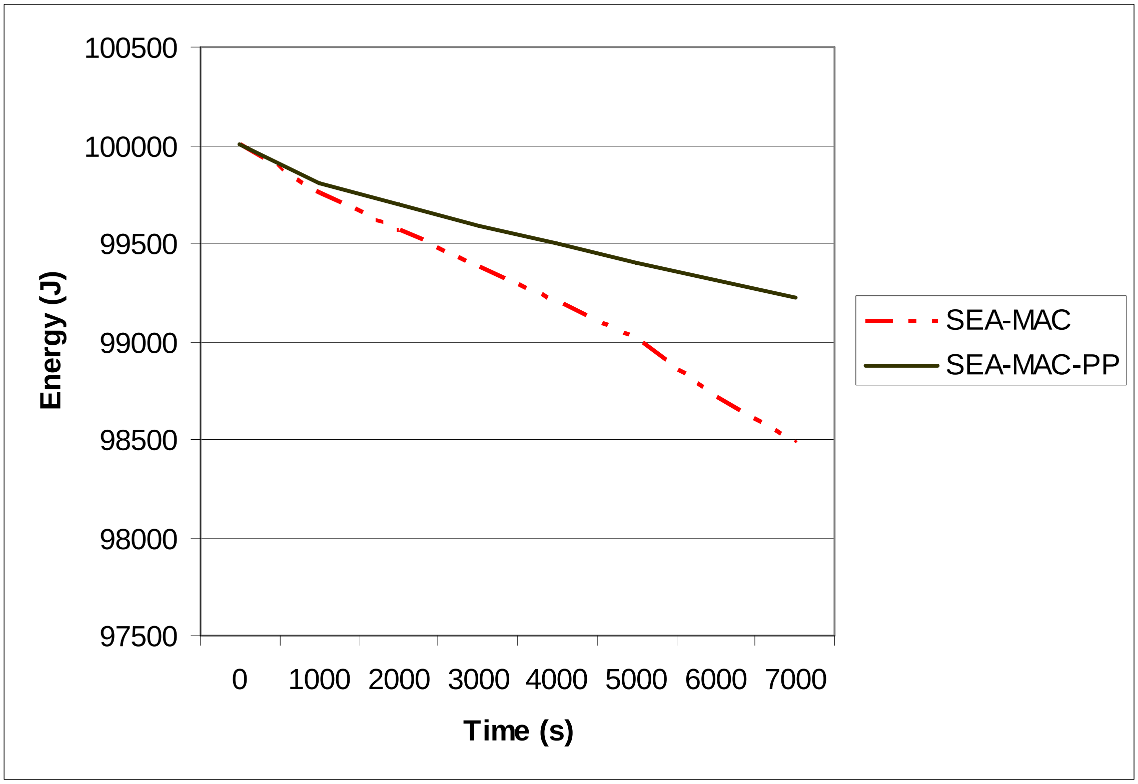

Figure 5-14: Energy consumption for 5% Duty-Cycle

There is marginal improvement in terms of system throughput Figure 5-15. It is recommended to refer to Appendix A Table A-43 for more results.

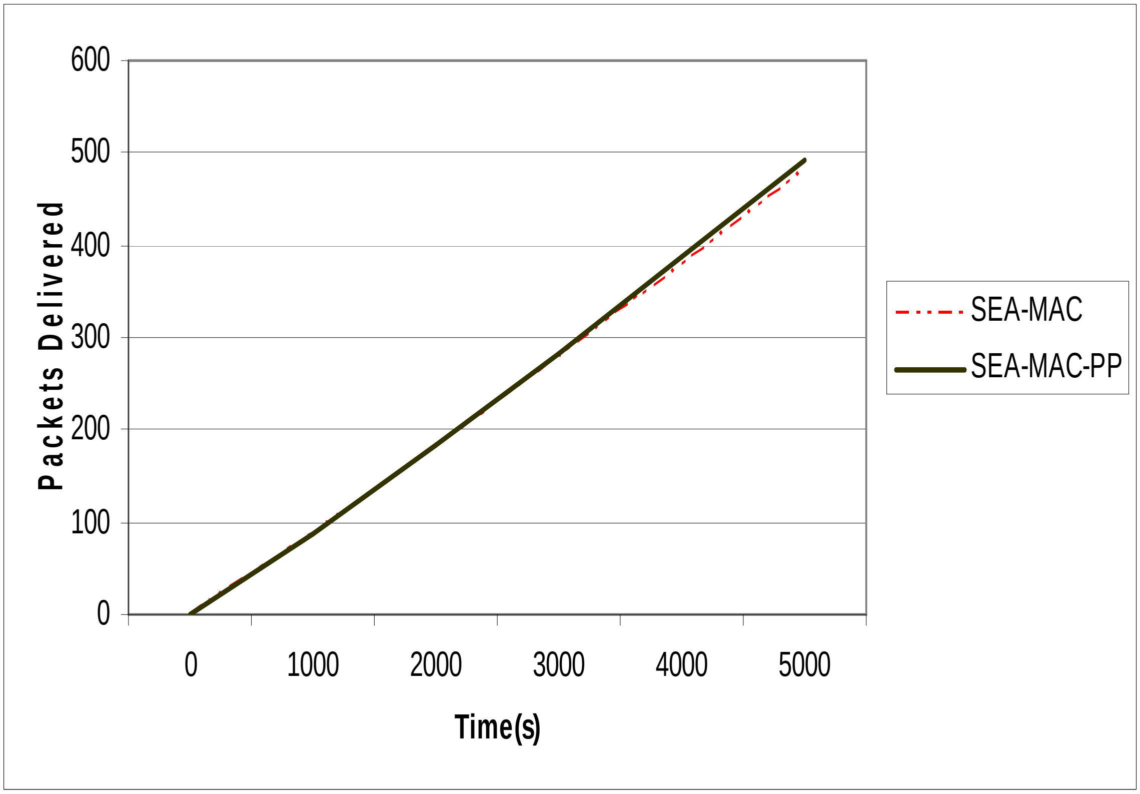

Figure 5-15: Throughput productivity for 5% Duty-Cycle

5.5.2. Simulation for (25%) Duty-Cycle

With increased Duty-Cycle SEA-MAC-PP has better operation than SEA-MAC Figure 5-16. Basic SEA-MAC performs better than S-MAC on high Duty-Cycle operation. Here it is observed that the proposed approach improved the network operation in terms of energy consumption.

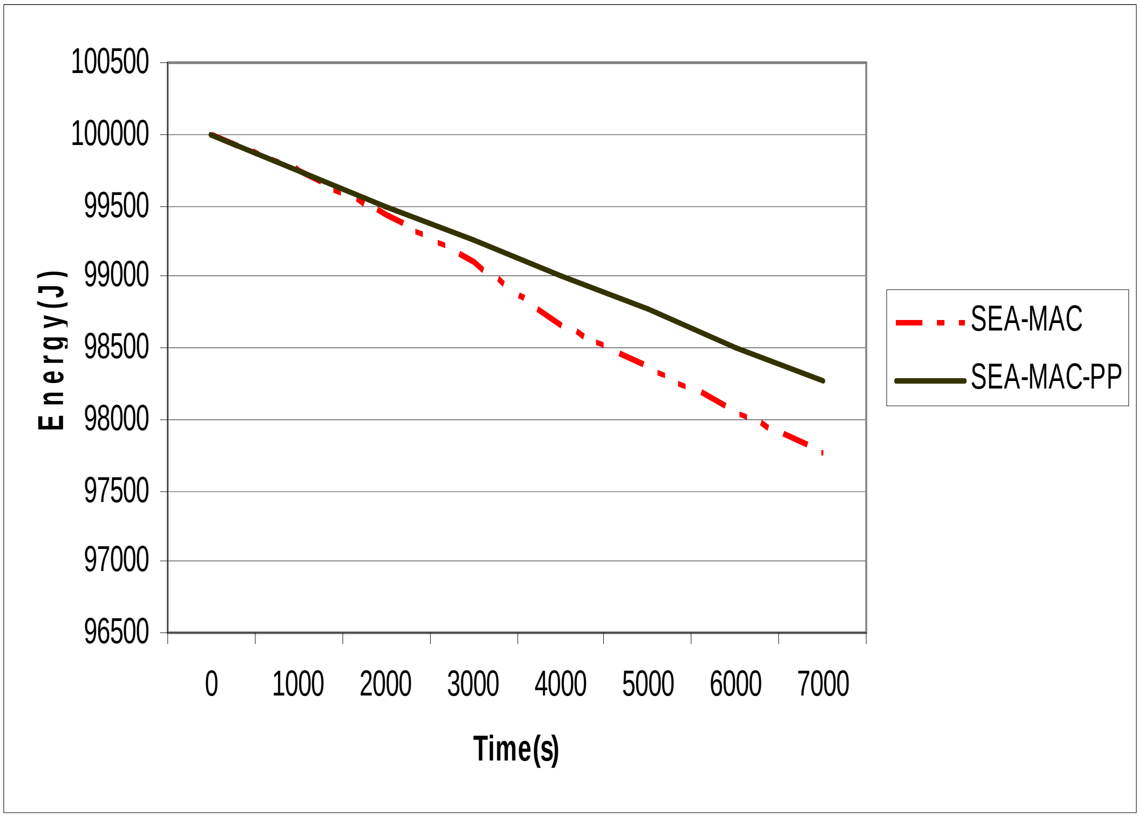

Figure 5-16: Energy consumption for 25% Duty-Cycle

On the other hand, system throughput is similar between SEA-MAC and SEA-MAC-PP Figure 5-17. The proposed approach did not provide the expected results when applied on SEA-MAC rather than S-MAC. SEA-MAC is configured for environment sample operation which means that SEA-MAC only produces data when ever the TONE packet indicates the urgent need to send data. This behavior can affect the system throughput.

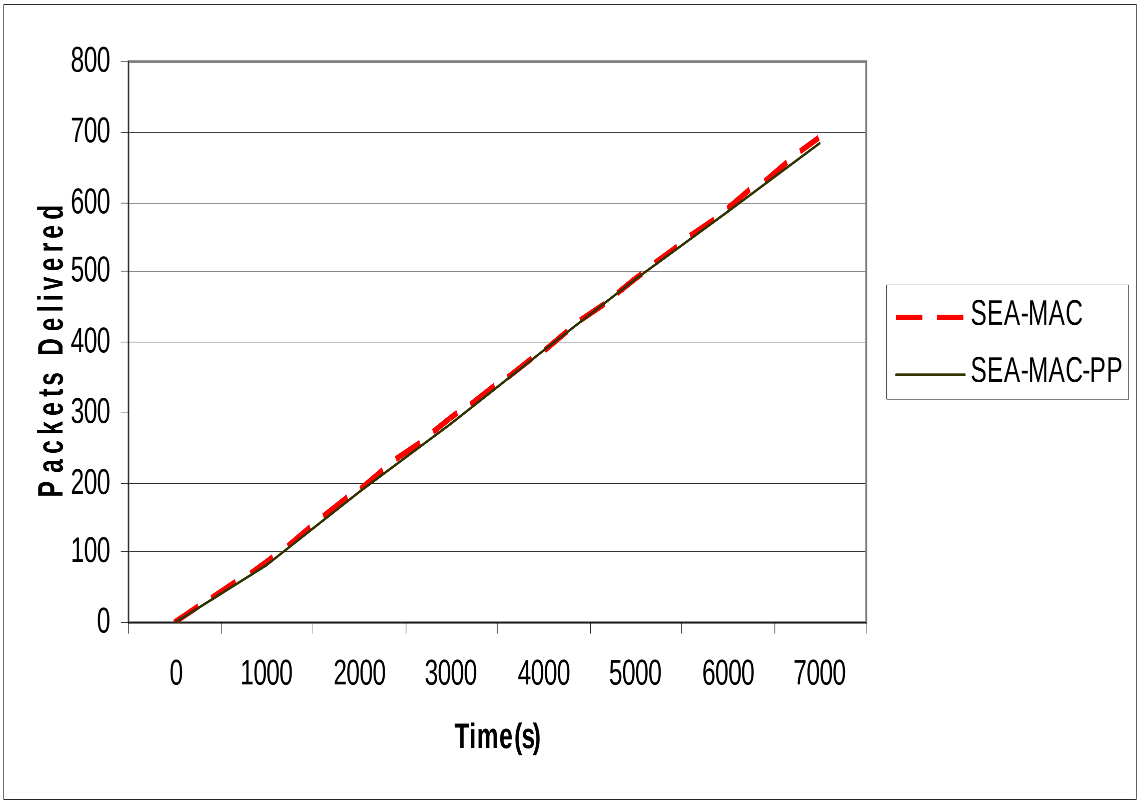

Figure 5-17: Throughput productivity for 25% Duty-Cycle

5.5.3. Simulation for (40%) Duty Cycle

As the simulation moves to (40%) duty-cycle operation, both SEA-MAC and SEA-MAC-PP have similar energy consumption operation Figure 5-18. This is not what was expected from the proposed approach as mentioned before that SEA-MAC performs well on high duty-cycle operation.

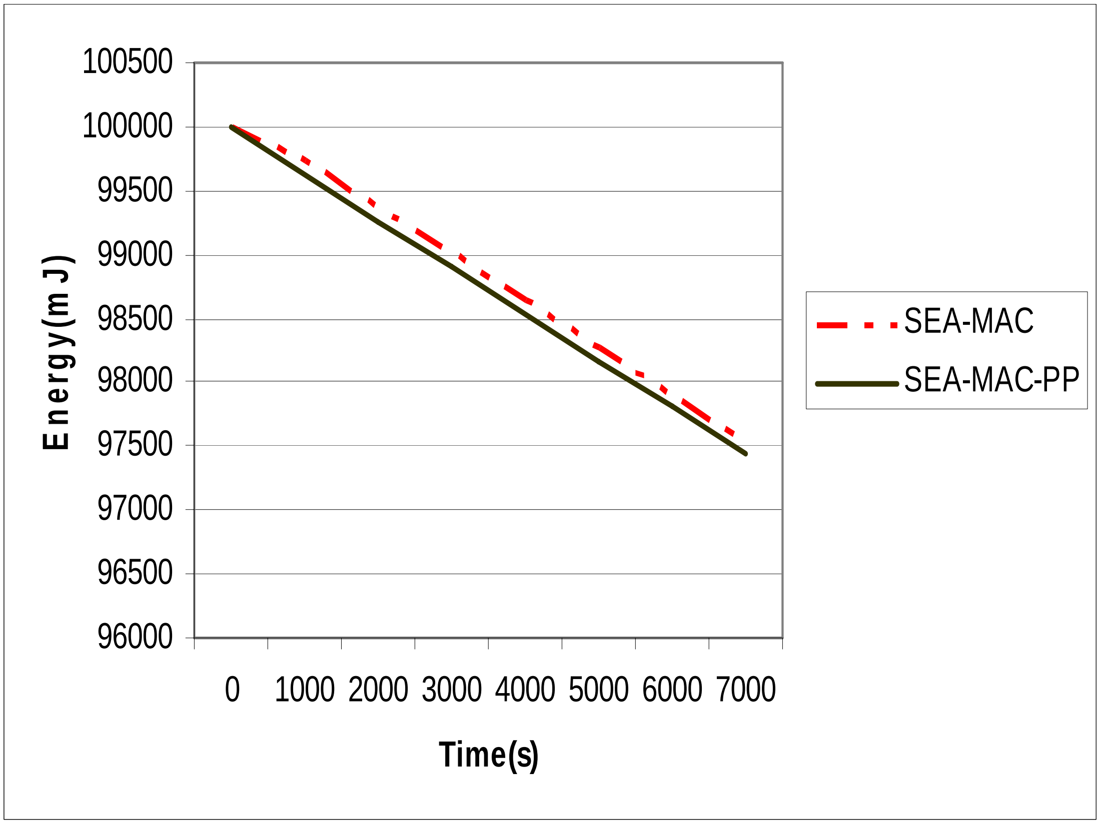

Figure 5-18: Energy consumption for 40% Duty-Cycle

As for throughput, it is observed that SEA-MAC-PP has better throughput than SEA-MAC this is due to the rapid exchanging of SEEK packet through the nodes rather than proceeding through the whole (SYCN+RTS+CTS) control packet exchanging Figure 5-19.

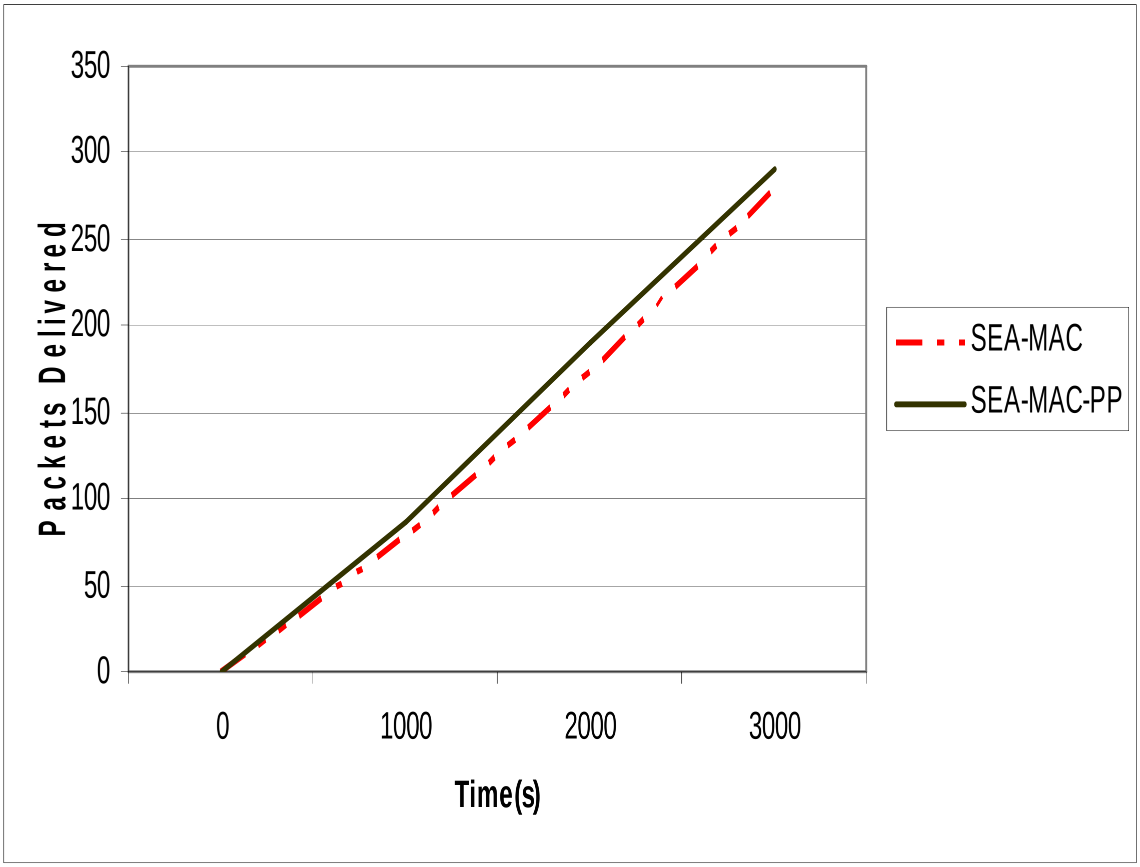

Figure 5-19: Throughput productivity for 40% Duty-Cycle

5.6. S-MAC-PP vs. SEA-MAC-PP Simulation Results:

A comparison evaluation has been conducted in this section between SEA-MAC-PP and S-MAC-PP protocols.

5.6.1. Simulation for (5%) Duty-Cycle

As mentioned before, basic S-MAC has better operation and more fair energy consumption between nodes than SEA-MAC. Mixing the proposed approach with S-MAC proved this lemma (SEA-MAC enhanced with the proposed approach) from the Figure 5-20:

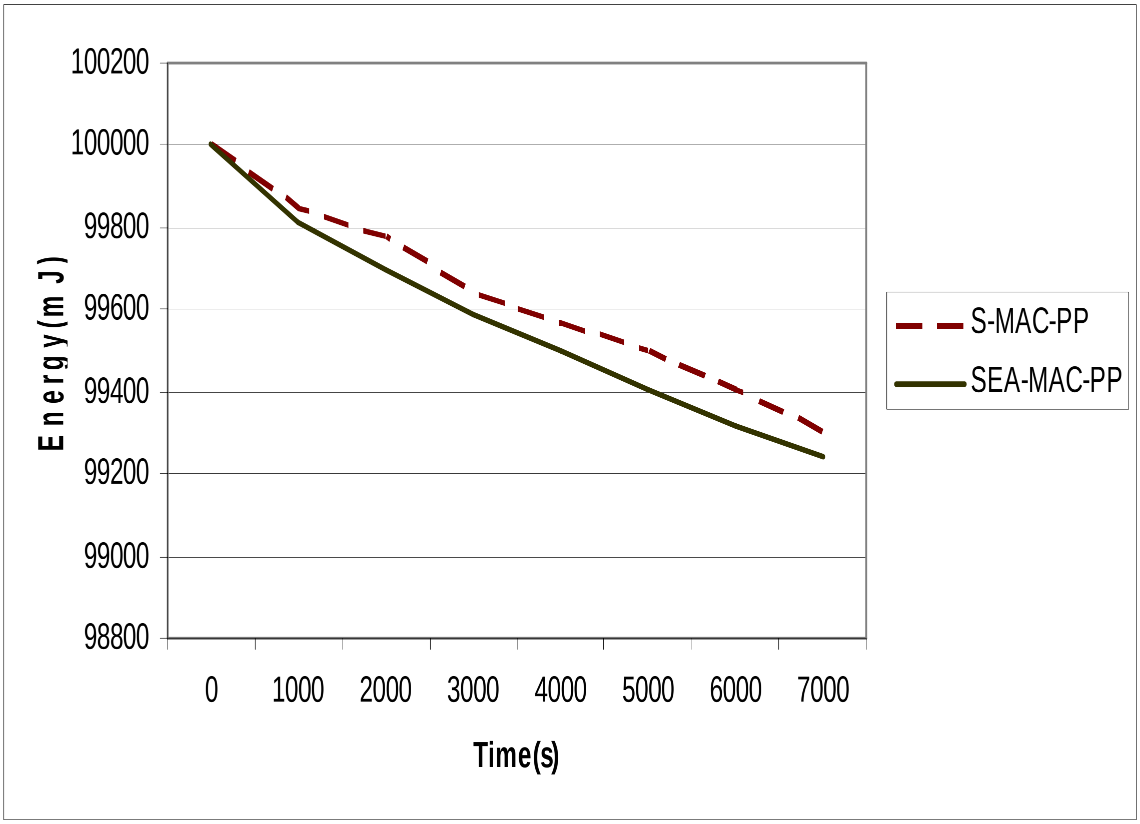

Figure 5-20: Energy consumption for 5% Duty-Cycle

Both protocols have the same system throughput because of the concurrent packet delivery in the proposed approach. Figure 5-21 illustrates system throughput. It is recommended to refer to Appendix A Table A-46 for more detailed results.

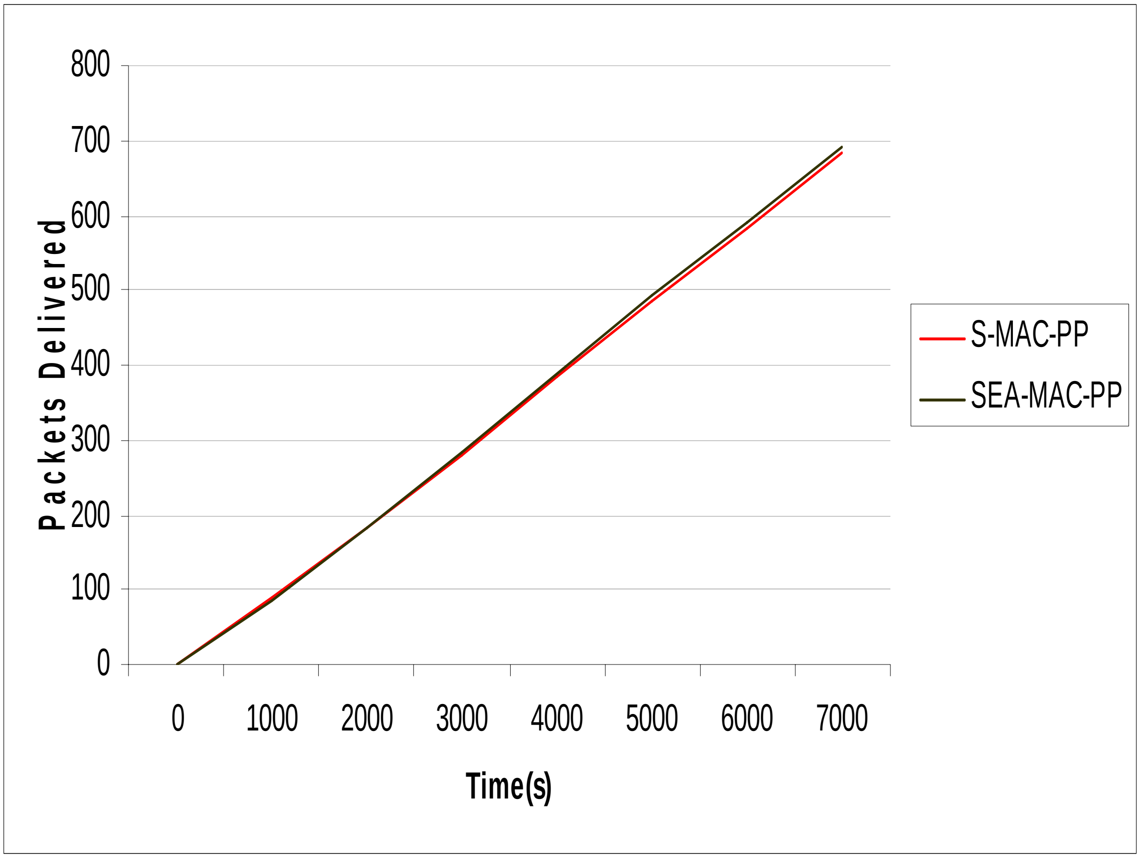

Figure 5-21: Throughput productivity for 5% Duty-Cycle

5.6.2. Simulation for (25%) Duty-Cycle

One of the advantages of SEA-MAC is that it performs better than S-MAC in terms of energy consumption at high duty-cycle operation. Adding the proposed approach improved the energy consumption for SEA-MAC over S-MAC-PP. Figure 5-22 illustrates this fact.

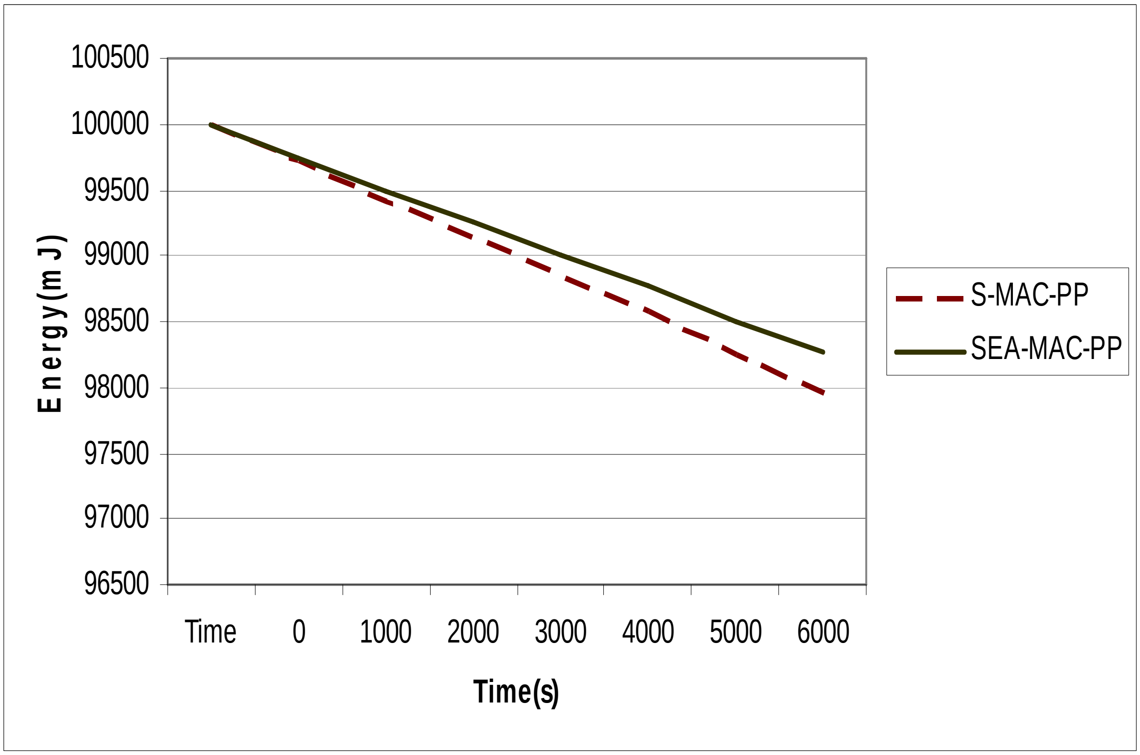

Figure 5-22: Energy consumption for 25% Duty-Cycle

Both protocols have similar throughput as they are improved with the proposed approach so basically they should have maintain similar throughput. Refer to Appendix A Table A-47 for more detailed results. Figure 5-23 shows system throughput for both protocols.

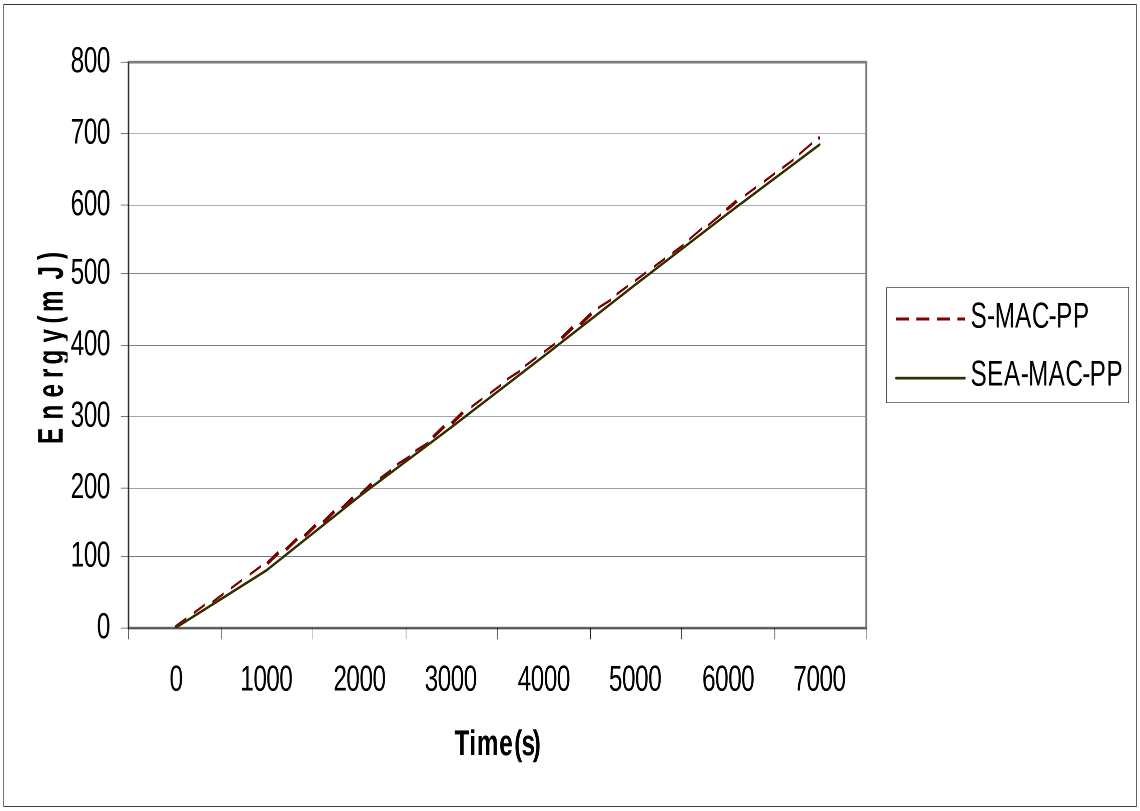

Figure 5-23: Throughput productivity for 25% Duty-Cycle

5.6.3. Simulation for (40%) Duty-Cycle

The same conclusion in the last section can be considered for higher Duty-Cycle operation. SEA-MAC-PP still leads S-MAC-PP in terms of energy consumption Figure 5-24. (Refer to section 5.3.2 for detailed explanation about this state).

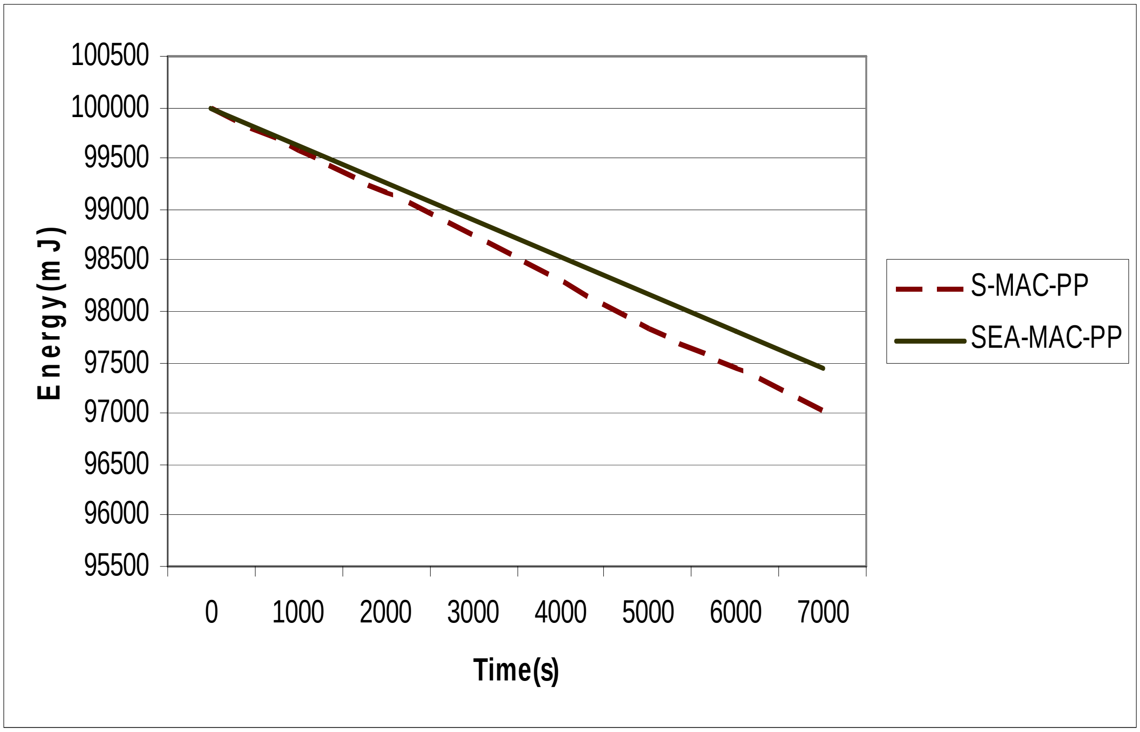

Figure 5-24: Energy consumption for 40% Duty-Cycle

Both Protocols provides the same throughput production after the augmentation of the proposed scheme with a marginal lead to S-MAC Figure 5-25. Both of the Protocols have the concurrent approach which led to this result. Refer to Appendix A Table A-48 for more detailed throughput results.

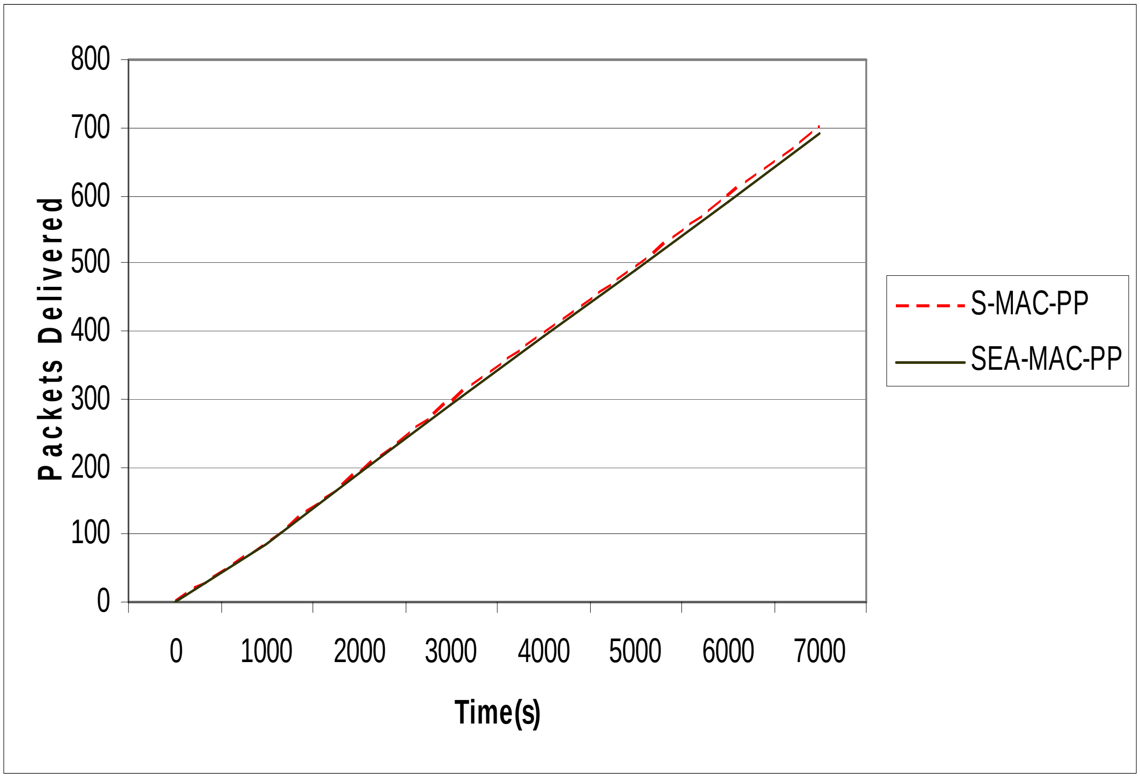

Figure 5-25: Throughput productivity for 40% Duty-Cycle

5.7. Summary

This summary is a general summary for both chapter four and five describes the achievements that have been conducted through the implementation process. The purpose of these simulations is to demonstrate that the proposed scheme has achieved the objectives mentioned in this thesis which are:

1. Providing an energy consumption and latency efficient MAC approach that can be mixed with basic MAC protocols that follows S-MAC basic operation.
2. Improving the operation of S-MAC protocol in terms of energy and latency considerations.
3. Improving the operation of SEA-MAC protocol to prove that the approach is feasible for implementing in MAC systems follows S-MAC approach (SEA-MAC is an improvement over S-MAC Protocol).

From the simulation results above it can be established of that the approach increases throughput in all the cases above and provides better energy consumption for the network. It is observed that the approach provided an efficient energy consumption and delay guarantee where these work better. For example the situation of (5%) duty cycle operation when comparing between both (PP-S-MAC vs. PP-SEA-MAC) it has been described that S-MAC was better in energy consumption than SEA-MAC. And another example the situation of (25%) duty cycle comparing between (PP-S-MAC) and (PP-SEA-MAC) SEA-MAC energy consumption was better than S-MAC.

This section shows that it is possible to establish that the approach have satisfied the above mentioned objectives of this thesis. Chapter 6 will discuss the message delay and collisions criterion. Chapter 7 will discuss the conclusion and important consideration for the proposed approach to enhance its operation including cross-layer approach and some other considerations.

CHAPTER SIX

MESSAGE DELAY AND COLLISIONS EVALUATION

This Chapter will discuss the Delay and collisions criterions for the proposed scheme as it considered an important factor to this thesis. The structure of this chapter will include the comparison study between S-MAC [10] and SEA-MAC [11] protocols for both implementation scenarios with the figures that describe the simulations results of both protocols with respect to message delay efficiency and the number of collisions occurred through the simulations. The next step will include the enhanced protocols and the benchmarking between the basic state and the enhanced state for both of the simulation environments.

6.1. Delay and collision evaluation in a Single Line of sensor nodes deployment

6.1.1. S-MAC vs. SEA-MAC

During the simulations, S-MAC provided a better delay both for the (5%) Duty-Cycle and (25%) Duty-Cycle. While SEA-MAC performed better in terms of delay at 10% Duty-Cycle. At 10% duty cycle S-MAC suffered from aggressive collisions while SEA-MAC provided better collisions at 10% duty-cycle which led to a better delay Figure (6-1, 2, 3, 4, 5 and 6).

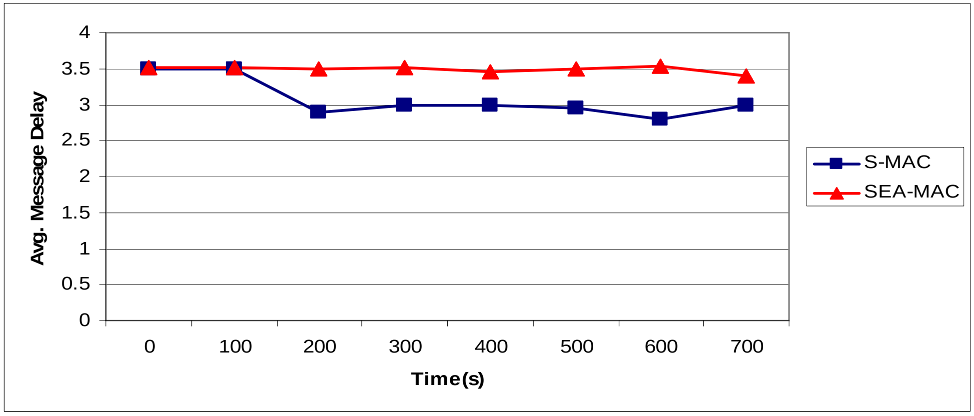

Figure 6-1: Delay evaluation S-MAC vs. SEA-MAC 5% Duty-Cycle

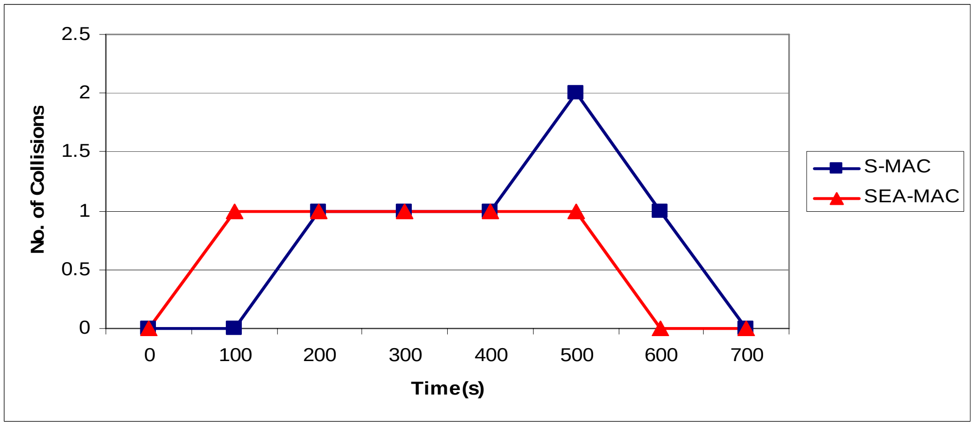

Figure 6-2: Collisions evaluation S-MAC vs. SEA-MAC 5% Duty-Cycle

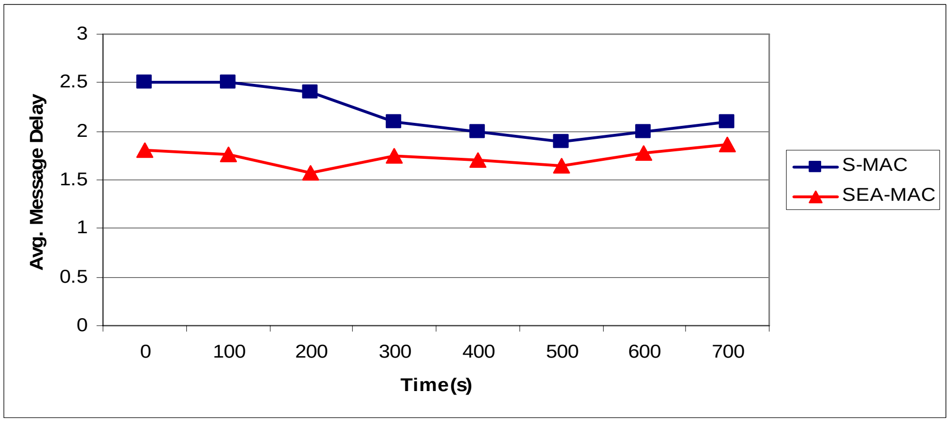

Figure 6-3: Delay evaluation S-MAC vs. SEA-MAC 10% Duty-Cycle

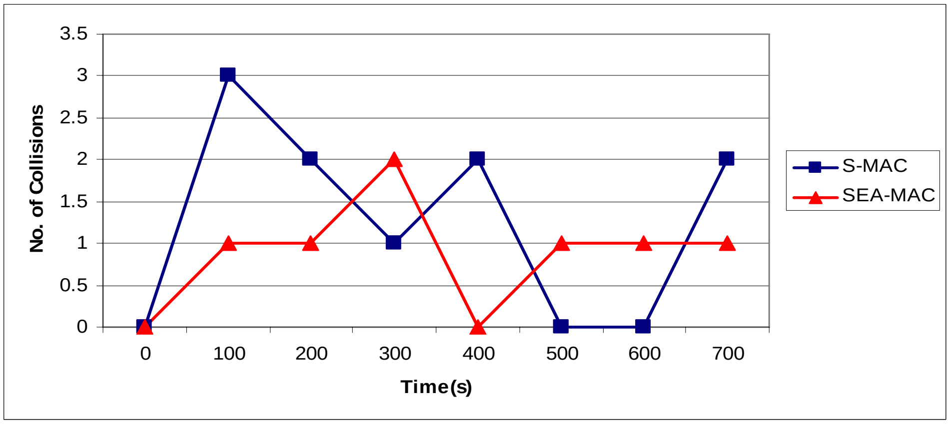

Figure 6-4: Collisions evaluation S-MAC vs. SEA-MAC 10% Duty-Cycle

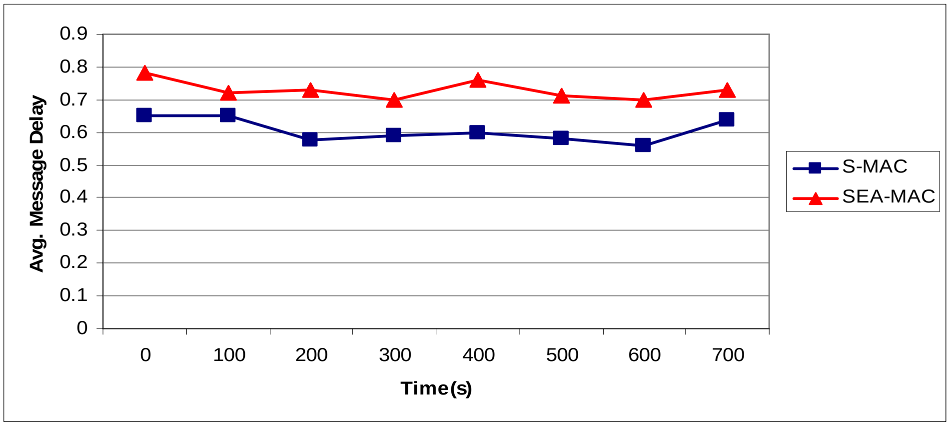

Figure 6-5: Delay evaluation S-MAC vs. SEA-MAC 25% Duty-Cycle

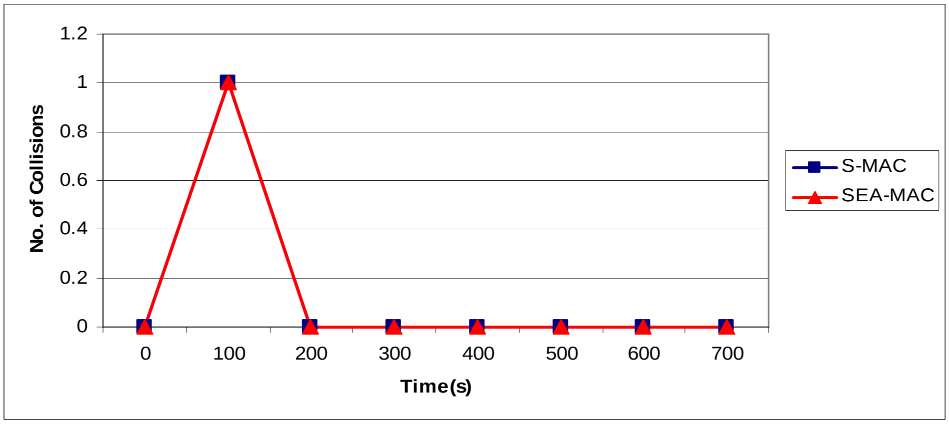

Figure 6-6: Collisions evaluation S-MAC vs. SEA-MAC 25% Duty-Cycle

6.1.2. S-MAC vs. S-MAC-PP

The proposed approach improved the delay performance of S-MAC over basic S-MAC approach because of the elimination of RTS packet which decreased the packet overhead for the scheme. The proposed approach did not suffer from any collisions during the simulations on the contradictory of S-MAC which produced collisions during the simulations Figure (6-7, 8, 9, 10, 11 and 12).

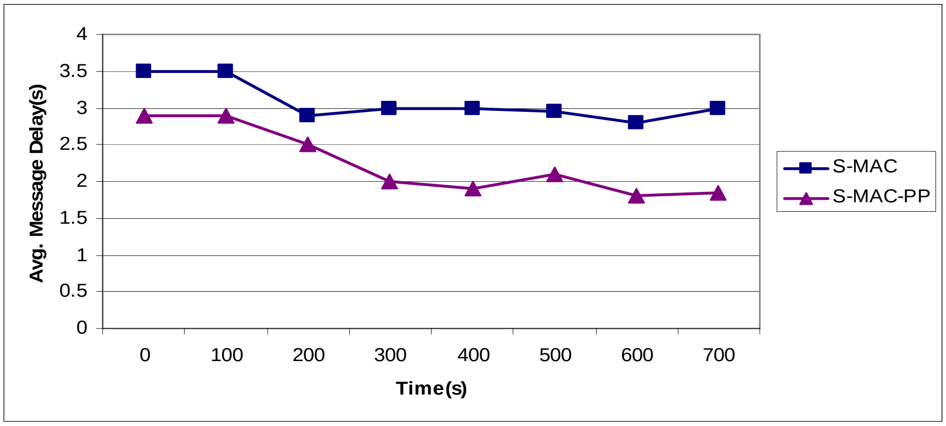

Figure 6-7: Delay evaluation S-MAC vs. S-MAC-PP 5% Duty-Cycle

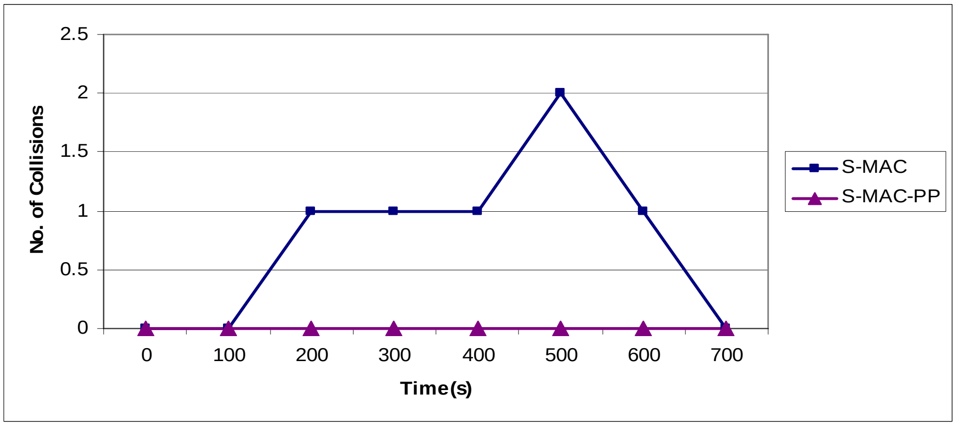

Figure 6-8: Collisions evaluation S-MAC vs. S-MAC-PP 5% Duty-Cycle

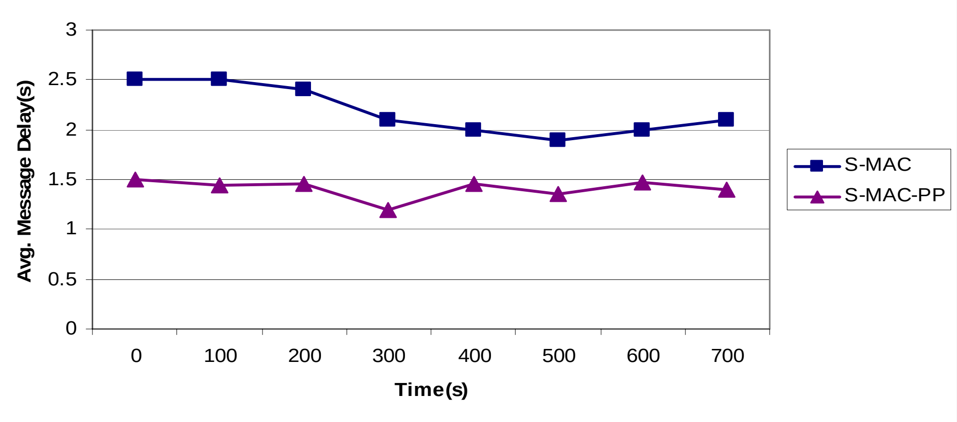

Figure 6-9: Delay evaluation S-MAC vs. S-MAC-PP 10% Duty-Cycle

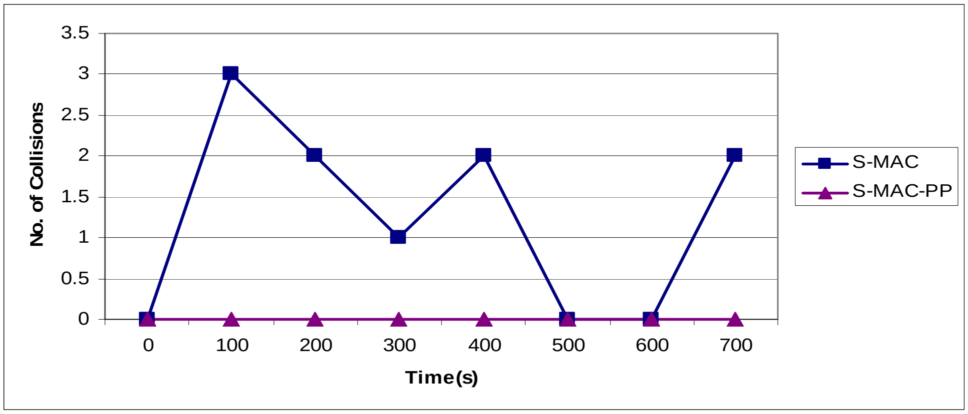

Figure 6-10: Collisions evaluation S-MAC vs. S-MAC-PP 10% Duty-Cycle

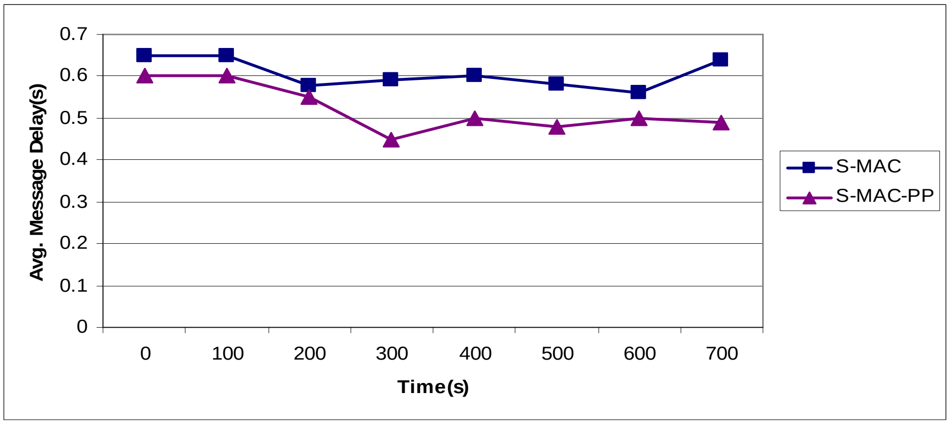

Figure 6-11: Delay evaluation S-MAC vs. S-MAC-PP 25% Duty-Cycle

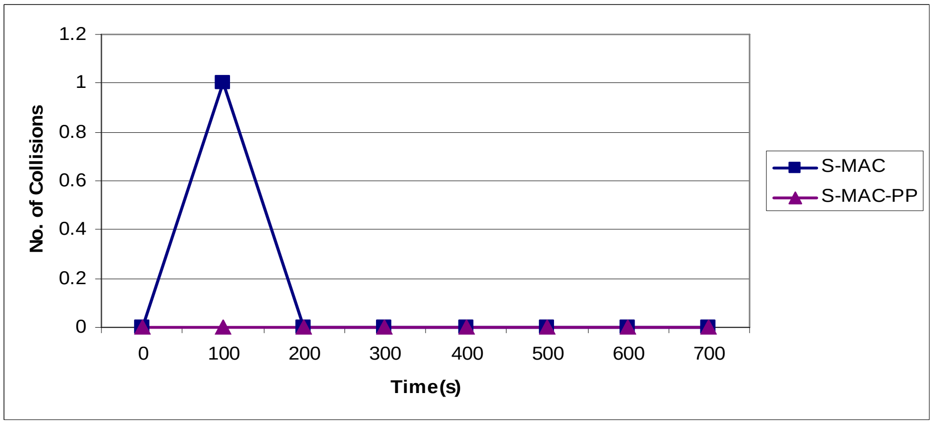

Figure 6-12: Collisions evaluation S-MAC vs. S-MAC 25% Duty-Cycle

6.1.3. SEA-MAC vs. SEA-MAC-PP

The proposed scheme also enhanced the operation of SEA-MAC in terms of message delay because of SEEK packet functionality that has mixed the operation of both SYNC and RTS packets. Like the state with S-MAC-PP, the proposed approach eliminated collisions for SEA-MAC through all the simulations this means that the proposed approach works better in terms of UNICAST message exchanging when there is only one route to the destination Figure (6-13, 14, 15, 16, 17 and 18).

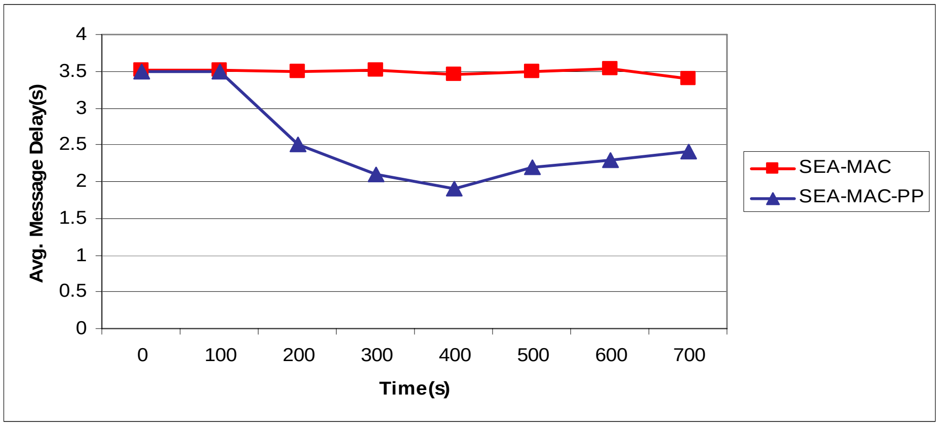

Figure 6-13: Delay evaluation SEA-MAC vs. SEA-MAC-PP 5% Duty-Cycle

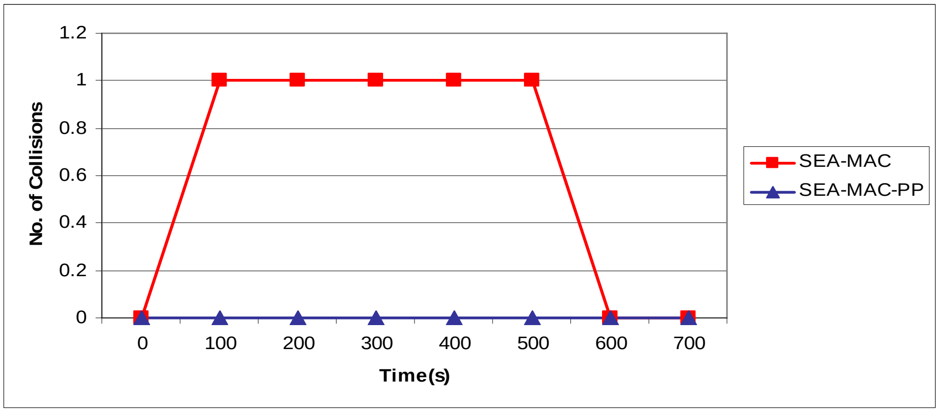

Figure 6-14: Collisions evaluation SEA-MAC vs. SEA-MAC-PP 5% Duty-Cycle

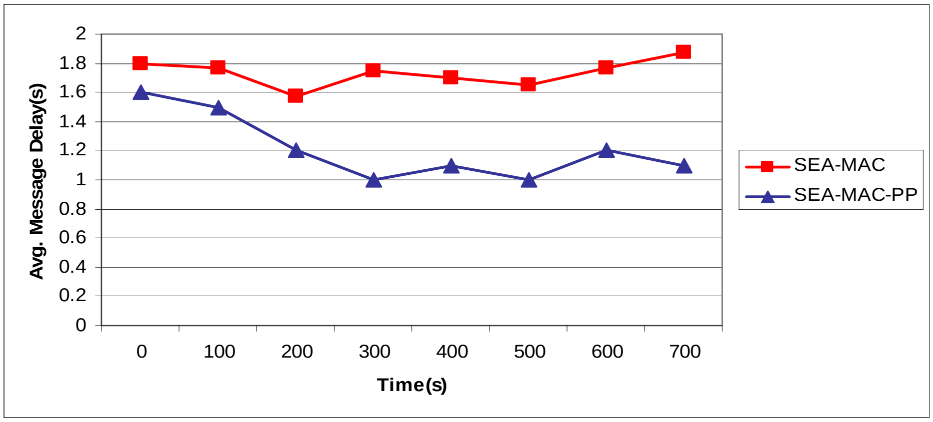

Figure 6-15: Delay evaluation SEA-MAC vs. SEA-MAC-PP 10% Duty-Cycle

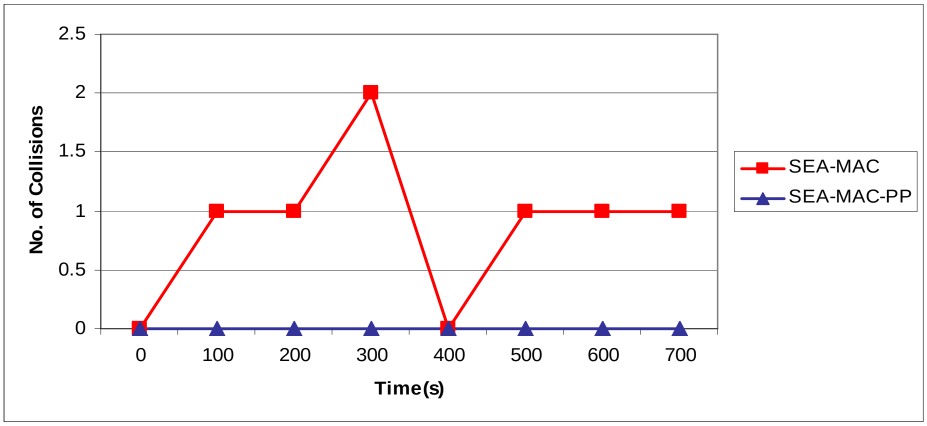

Figure 6-16: Delay evaluation SEA-MAC vs. SEA-MAC-PP 10% Duty-Cycle

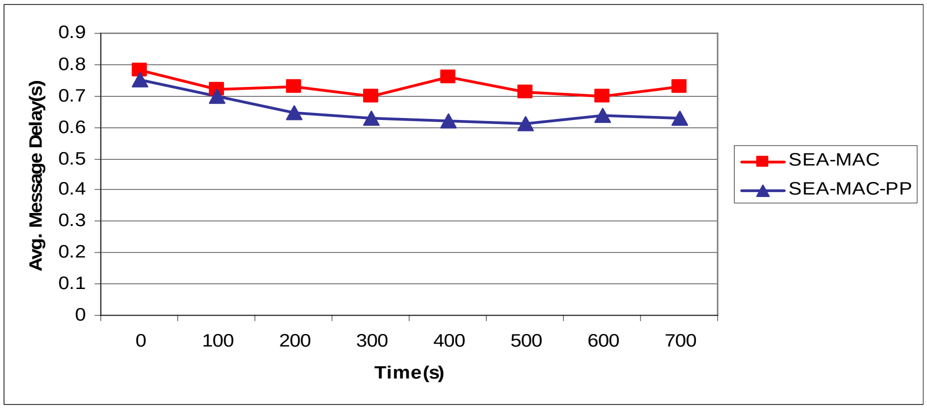

Figure 6-17: Delay evaluation SEA-MAC vs. SEA-MAC-PP 25% Duty-Cycle

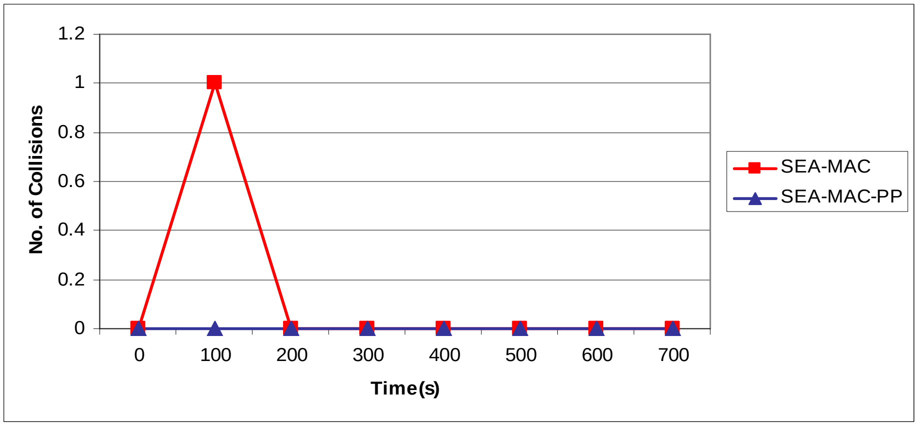

Figure 6-18: Collisions evaluation SEA-MAC vs. SEA-MAC-PP 25% Duty-Cycle

6.1.4. S-MAC-PP vs. SEA-MAC-PP

Overall, the proposed approach improved the operation of S-MAC and SEA-MAC in terms of message delay and the occurrence of collisions when there is a single route to the destination point Figure (6-19, 20 and 21).

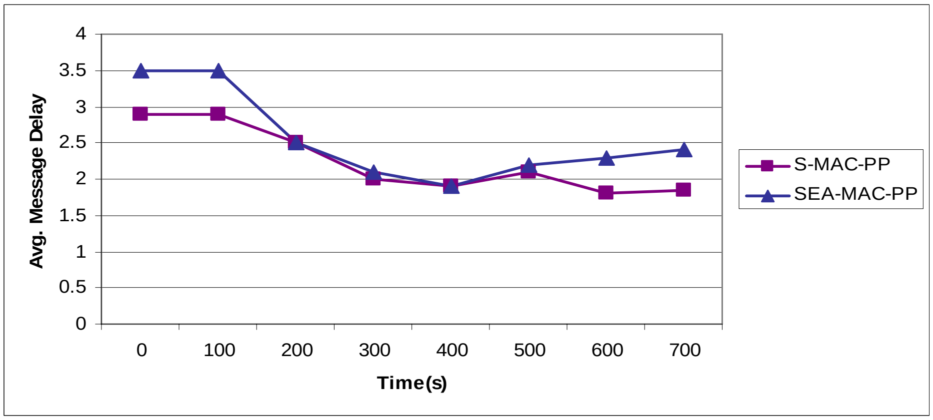

Figure 6-19: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 5% Duty-Cycle

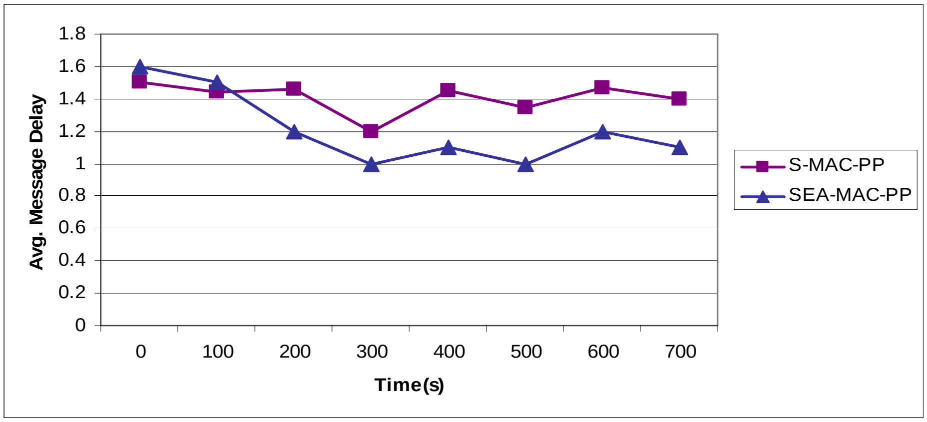

Figure 6-20: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 10% Duty-Cycle

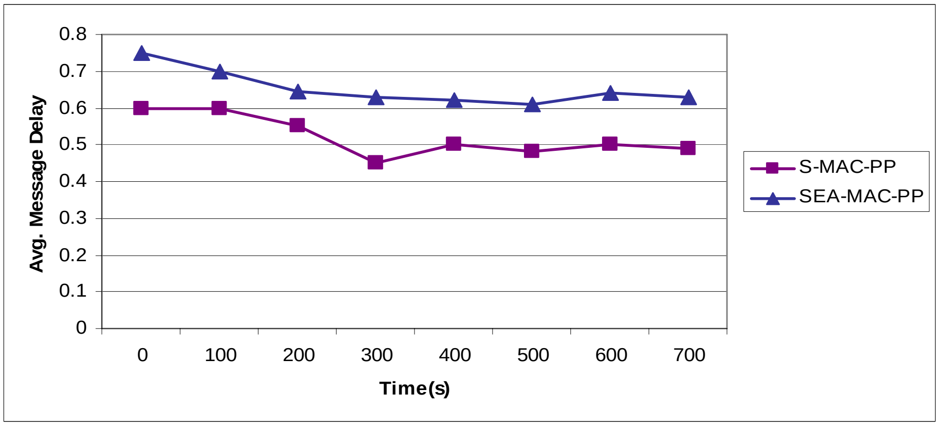

Figure 6-21: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 25% Duty-Cycle

6.2. Delay and Collision in a Uniform distributed sensor nodes deployment

6.2.1. S-MAC vs. SEA-MAC

S-MAC provides better Delay than SEA-MAC at 5% Duty-Cycle and 40% Duty-Cycle, while SEA-MAC performs marginally similar to S-MAC at 25% Duty-Cycle. SEA-MAC provided better collisions occurrence at 5% Duty-Cycle but S-MAC performed better at 25 and 40% Duty-Cycles. SEA-MAC performed this way because of the burden that TONE packet carries which affected delay performance of SEA-MAC. Figure (6-22, 23, 24, 25, 26 and 27).

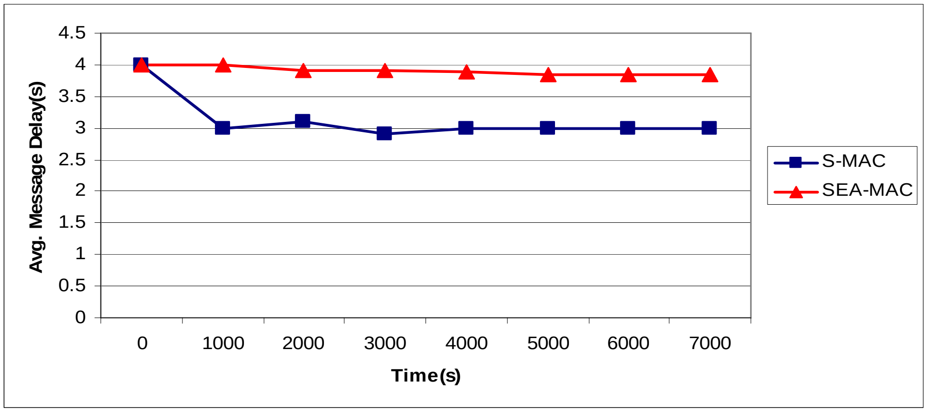

Figure 6-22: Delay evaluation S-MAC vs. SEA-MAC 5% Duty-Cycle

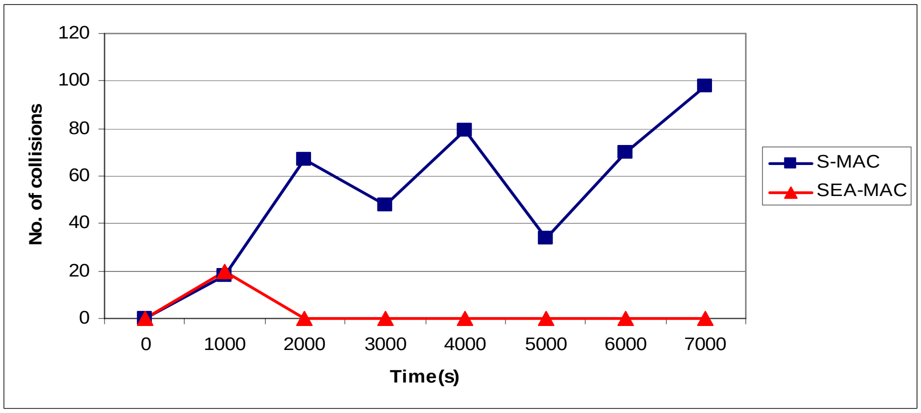

Figure 6-23: Collisions evaluation S-MAC vs. SEA-MAC 5% Duty-Cycle

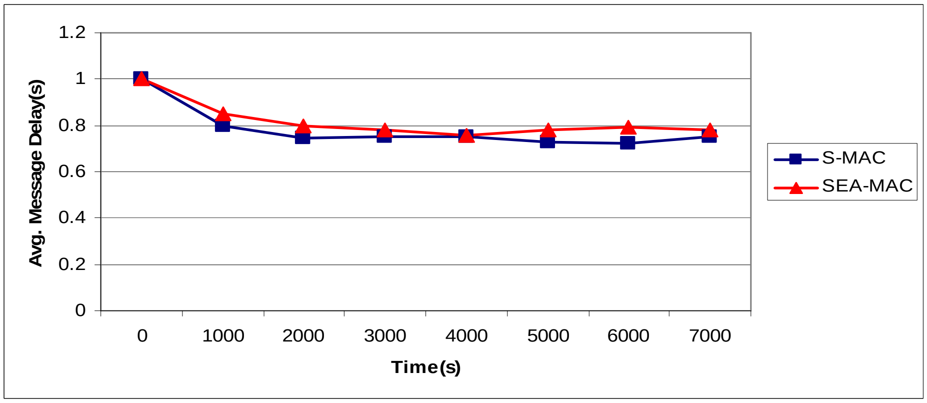

Figure 6-24: Delay evaluation S-MAC vs. SEA-MAC 25% Duty-Cycle

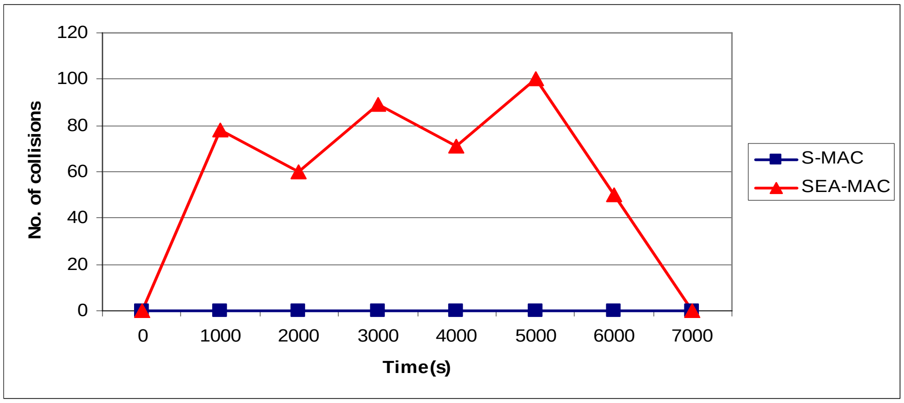

Figure 6-25: Collisions evaluation S-MAC vs. SEA-MAC 25% Duty-Cycle

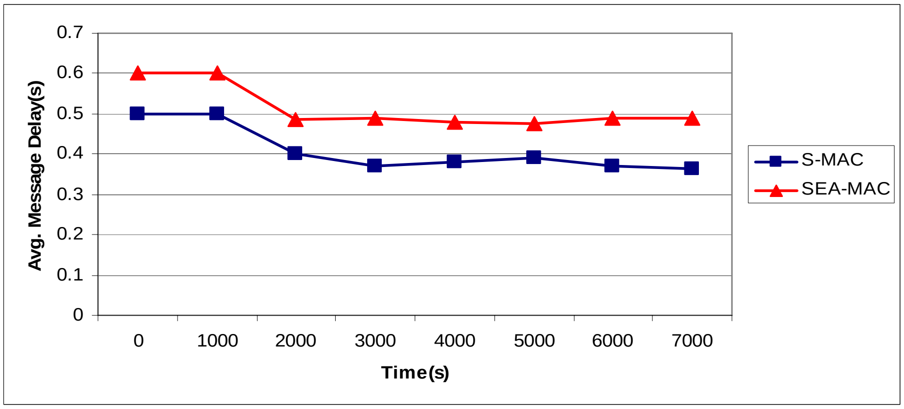

Figure 6-26: Delay evaluation S-MAC vs. SEA-MAC 40% Duty-Cycle

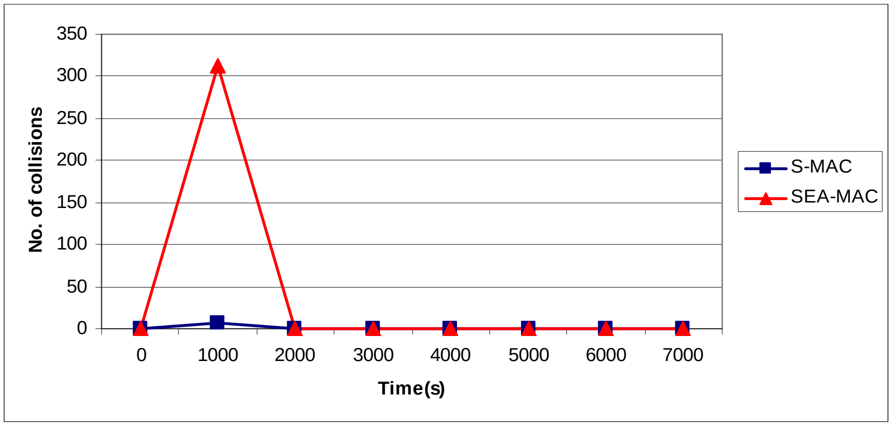

Figure 6-27: Collisions evaluation S-MAC vs. SEA-MAC 40% Duty-Cycle

6.2.2. S-MAC vs S-MAC-PP

The proposed approach provided better message Delay over basic operation of S-MAC because of SEEK packet effect on the scheme. In terms of collisions occurrence the proposed approach provided better collisions at 5% Duty-Cycle while S-MAC led the proposed approach at 25 and 40% Duty-Cycles. This happened because SEEK packet was designed to be a UNICAST packet because of the mixed functionality. When the environment required a broadcast approach, SEEK performed the broadcast by sending it to the neighbor nodes. This phenomenon led to more collisions occurrence. Figure (6-28, 29, 30, 31, 32 and 33)

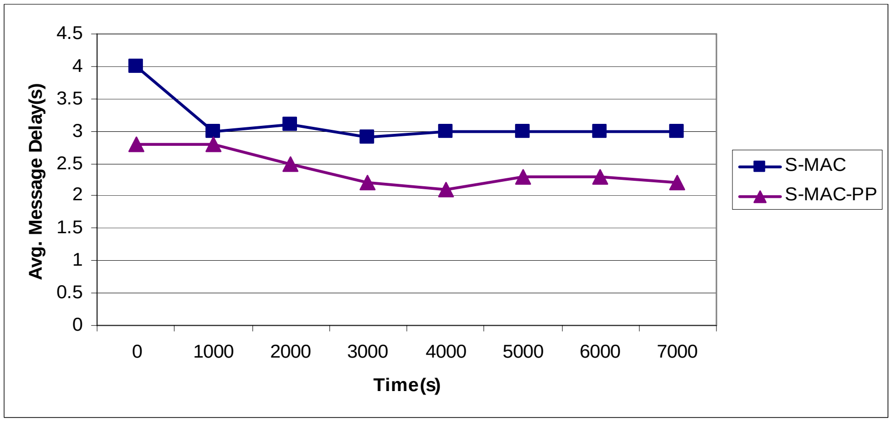

Figure 6-28: Delay evaluation S-MAC vs. S-MAC-PP 5% Duty-Cycle

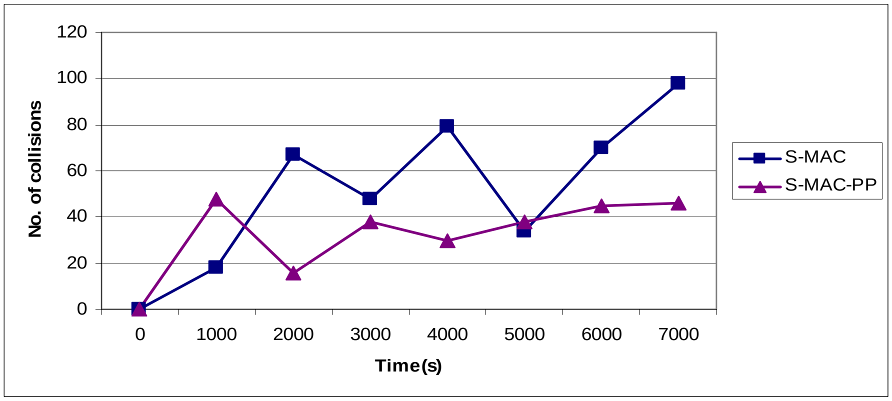

Figure 6-29: Collisions evaluation S-MAC vs. S-MAC-PP 5% Duty-Cycle

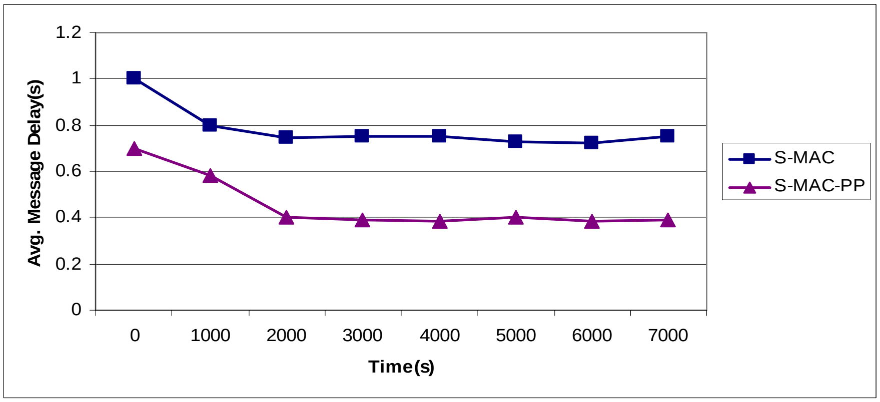

Figure 6-30: Delay evaluation S-MAC vs. S-MAC-PP 25% Duty-Cycle

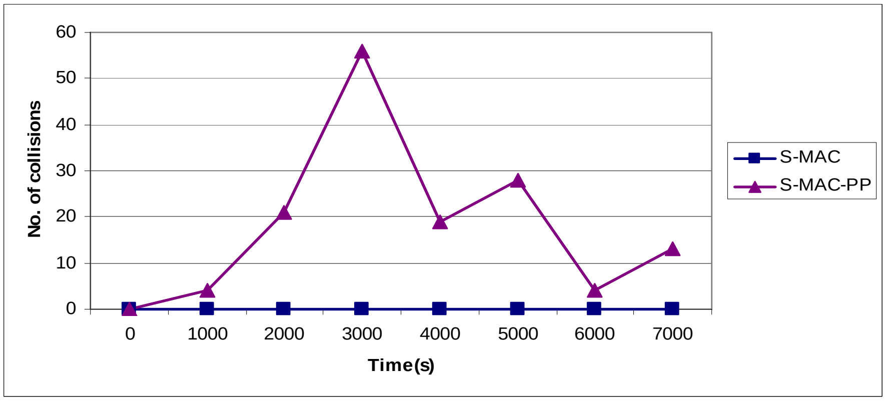

Figure 6-31: Collisions evaluation S-MAC vs. S-MAC 25% Duty-Cycle

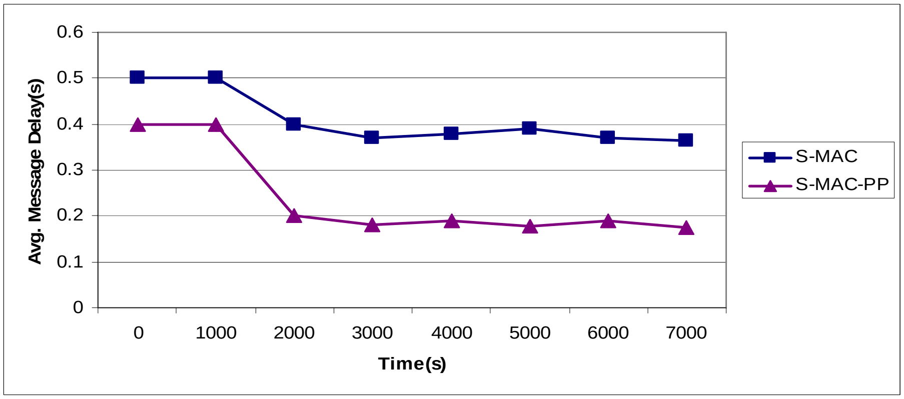

Figure 6-32: Delay evaluation S-MAC vs. S-MAC-PP 40% Duty-Cycle

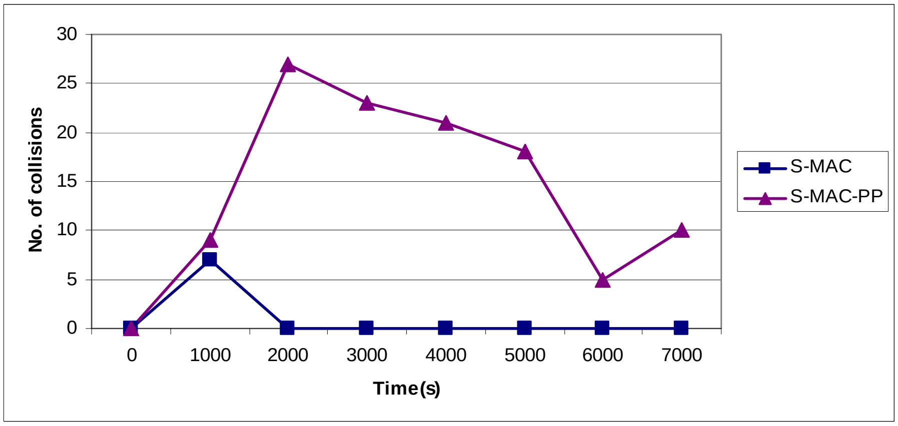

Figure 6-33: Collisions evaluation S-MAC vs. S-MAC-PP 40% Duty-Cycle

6.2.3. SEA-MAC vs. SEA-MAC-PP

Form the Figures (6-34, 35, 36, 37, 38 and 39) below, it is observed that the proposed approach enhanced the operation of SEA-MAC in terms of message delay and provided better collisions occurrence at 25% and 40% Duty-Cycles.

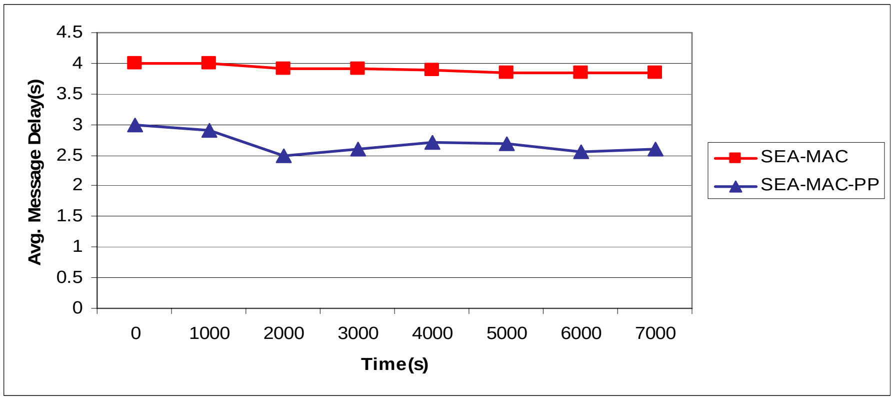

Figure 6-34: Delay evaluation SEA-MAC vs. SEA-MAC-PP 5% Duty-Cycle

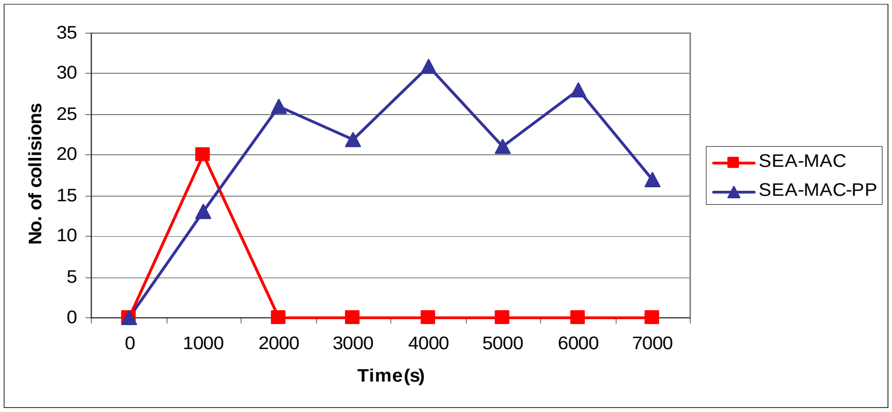

Figure 6-35: Collisions evaluation SEA-MAC vs. SEA-MAC-PP 5% Duty-Cycle

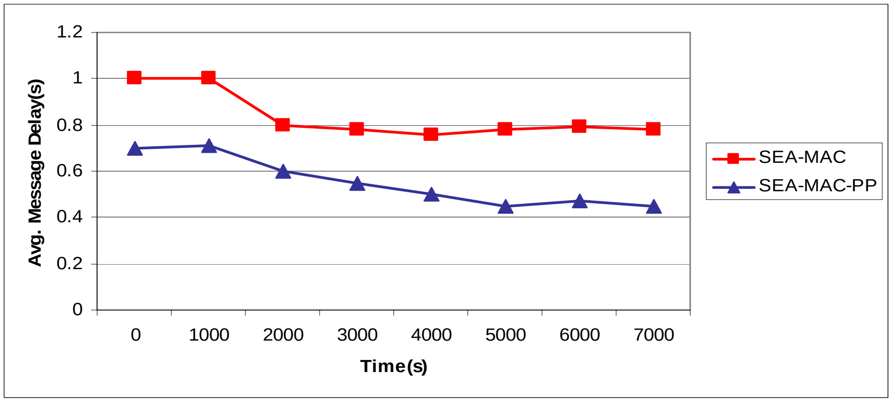

Figure 6-36: Delay evaluation SEA-MAC vs. SEA-MAC-PP 25% Duty-Cycle

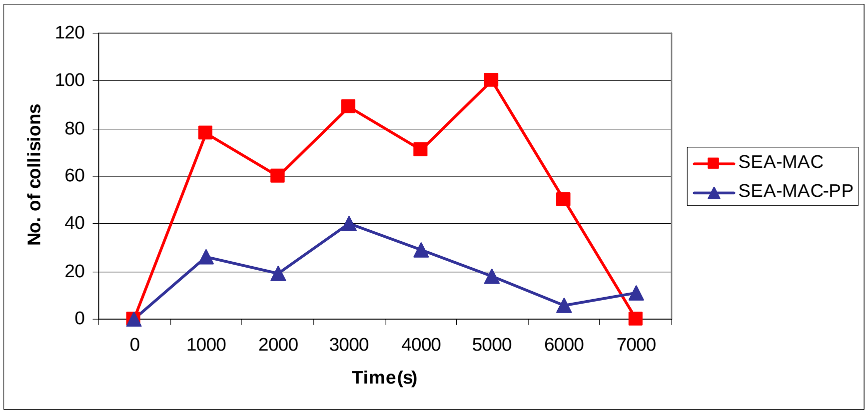

Figure 6-37: Collisions evaluation SEA-MAC vs. SEA-MAC-PP 25% Duty-Cycle

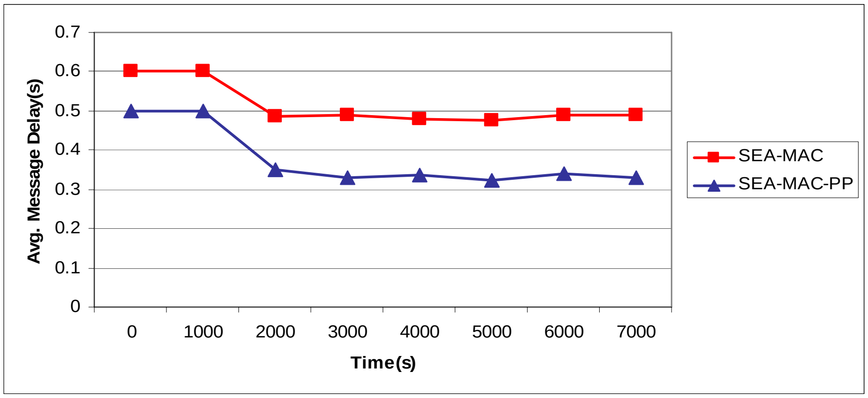

Figure 6-38: Delay evaluation SEA-MAC vs. SEA-MAC-PP 40% Duty-Cycle

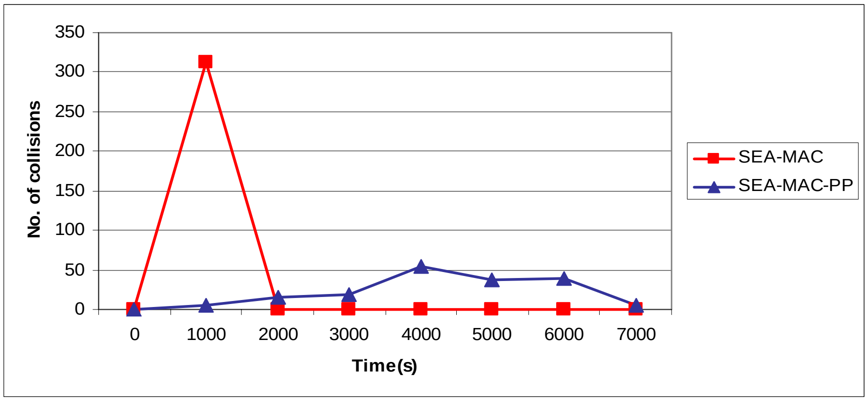

Figure 6-39: Collisions evaluation SEA-MAC vs. SEA-MAC 40% Duty-Cycle

6.2.4. S-MAC-PP vs. SEA-MAC-PP

Form the Figures (6-40, 41, 42, 43, 44 & 45), it shows that the proposed scheme enhanced the message delay efficiency for S-MAC against SEA-MAC-PP. while the approach enhanced the collisions occurrence for SEA-MAC-PP over S-MAC-PP.

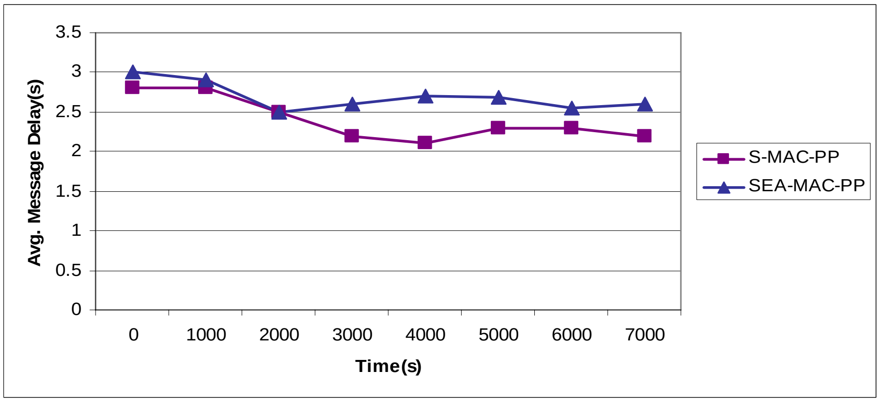

Figure 6-40: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 5% Duty-Cycle

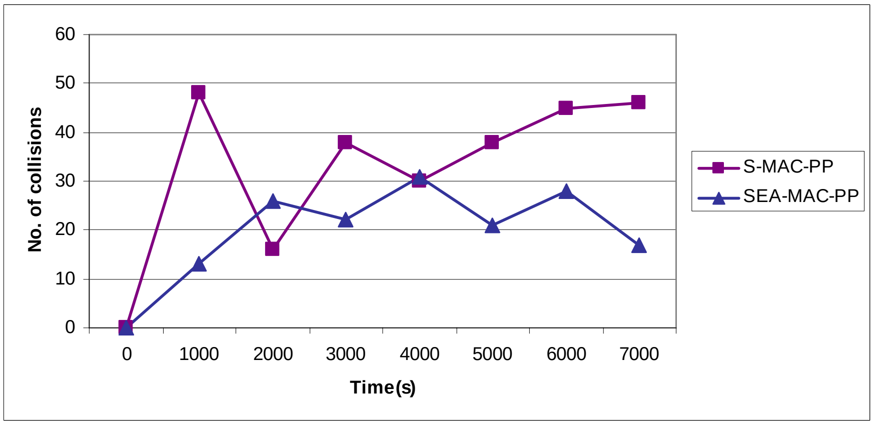

Figure 6-41: Collisions evaluation S-MAC-PP vs. SEA-MAC-PP 5% Duty-Cycle

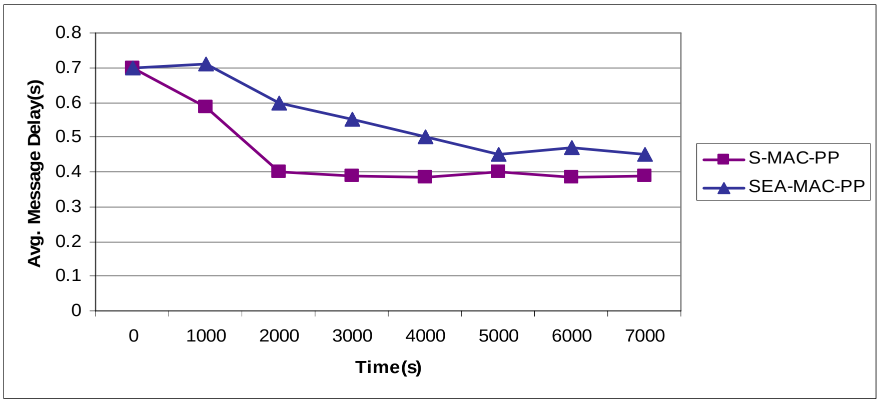

Figure 6-42: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 25% Duty-Cycle

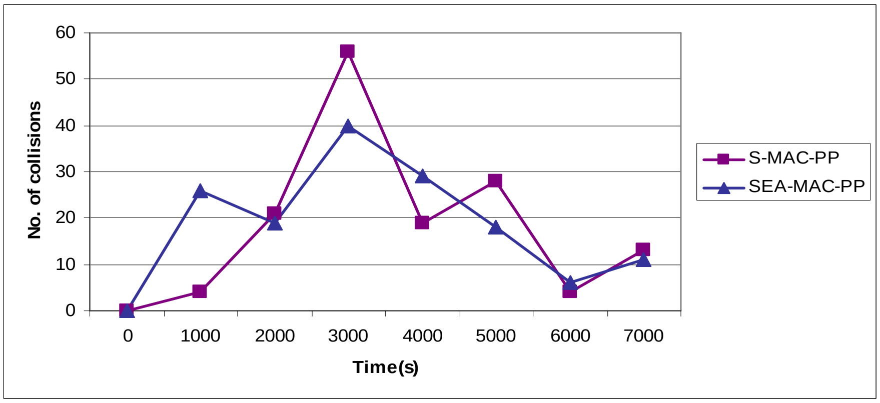

Figure 6-43: Collisions evaluation S-MAC-PP vs. SEA-MAC-PP 25% Duty-Cycle

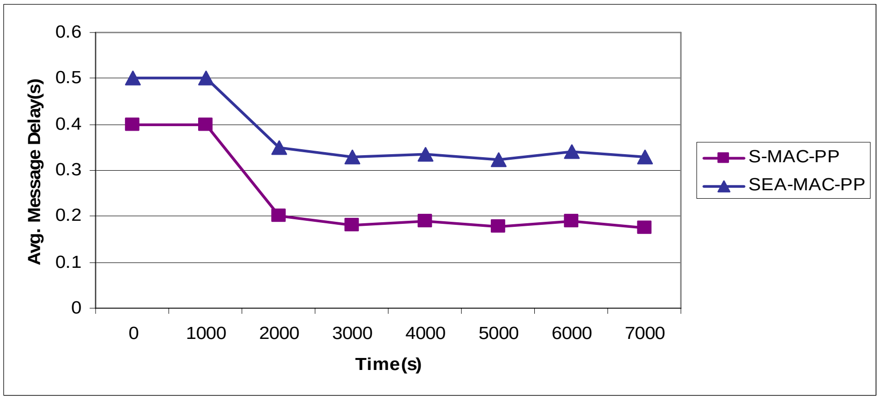

Figure 6-44: Delay evaluation S-MAC-PP vs. SEA-MAC-PP 40% Duty-Cycle

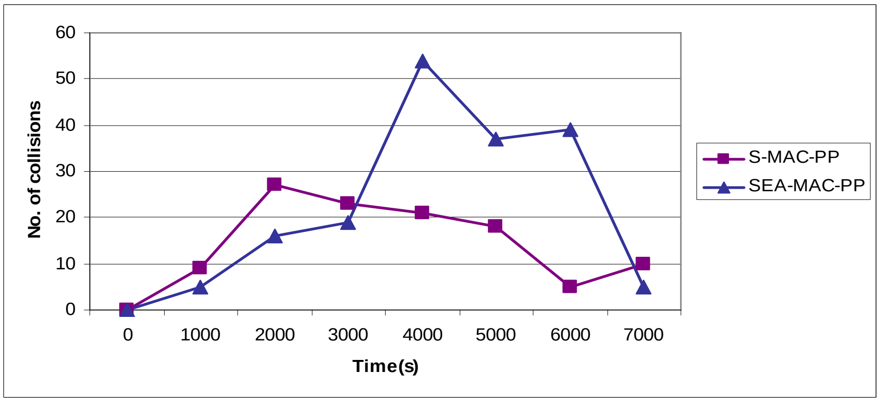

Figure 6-45: Collisions evaluation S-MAC-PP vs. SEA-MAC-PP 40% Duty-Cycle

6.3. Summary

The result that can be established from the evaluation of the message delay and collisions occurrences is that the proposed approach enhanced the message delay for both protocols when it is implemented in both scenarios. The proposed approach provides zero collisions at the single line deployment. While for the distributed scenario the approach suffered from collisions with S-MAC but better performed for SEA-MAC. A cross-layer approach could help in enhancing the collisions occurrences for the proposed scheme.

CHAPTER SEVEN

CONCLUSION AND FUTURE WORK

7.1. Introduction:

In this research efficient energy consumption and latency MAC protocol approach is being proposed. The simulation results in chapter four shows that the proposed approach is broadly successful. Achievements:

1. The proposed approach did decrease the energy consumption especially in the second scenario operation and by that it satisfies the first objective of this thesis which is provide a MAC scheme that can achieve both energy efficient consumption and delay guarantee operation.

2. The proposed MAC Protocols approach increased throughput of the network which means that the latency issue has been minimized for both protocols S-MAC and SEA-MAC. This satisfies the second objective of this thesis which is enhancing the operation of the old MAC protocols by adding the proposed scheme to achieve efficient network operation.

3. Adding the proposed approach to the old versions of the protocols yield better efficient operation of the network in terms of energy consumption and latency issues. This satisfies the third objective of this thesis by providing an approach that can be added to S-MAC or a MAC protocol that is based on S-MAC but suffers from latency issues.

4. The proposed approach enhanced S-MAC when applying it on a low Duty Cycle sensor operation and it enhanced SEA-MAC when it was applied on a high Duty Cycle sensor operation.

5. NS2 is an invaluable and strong tool to measure and test the operation of the proposed approach and the behavior of the network. And because it is free open source project (that’s why most of the researchers use it in doing there research) it is still lacks the issue of user-friendly.

6. There is no MAC protocol proposed for Wireless Sensor Networks is considered as a standard MAC protocol because Wireless Sensor Networks are application dependent. With this research the proposed scheme made this gap closer by providing the solution for energy and latency issues as what most WSNs applications requires.

7.2. Open issues

There are open issues in this thesis that need to be discussed as the solution for these issues can be used as an optimization for this approach:

1. Cross-Layering the approach with upper-layer protocols (Routing protocols) can produce more efficient operation to provide one way through the network from source node to destination node.

2. Different routing protocols are available for wireless sensor networks but the choice of which routing protocol to be used in a cross-layer system is the difficult question because while DSR and AODV are used in most available by the literature. There is an issue of energy consumption and control packet overhead because they use Routing Table technique to establish the route from source to destination. Using LEACH Protocol would be more efficient in terms of energy consumption but would effect on DATA productivity of the network.

This research work did not focus on routing protocols operation because the main concern of the work is about MAC layer, the protocols and their behavior.

7.3. Future Work:

Future work is to implement the approach on a real Mote-sensor based system (example: MICAz motes) taking in consideration the above stated issues (cross-layer approach and efficient routing) to achieve a better network operation and to apply the approach on a mobile node system as mobile sensor networks is a hot research area.

In conclusion, this thesis has shown that it is feasible to manipulate the construction of control packets to achieve better operation for a MAC protocol. The process of providing a standard MAC protocol for wireless sensor network is still on the way because wireless sensor networks are application dependent.

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APPENDIX A: Data Tables

This appendix will illustrate the row data produced from the simulation in NS2 that the thesis implementation discussions were based on. The form of these data is tabular to provide more accurate imagination about the results illustrated in this thesis.

A.1. Results tables for single line of deployment simulation environment

Table A-1: Nodes Energy Consumption (S-MAC) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	921	929	926	918	921
200	916	924	921	913	916
300	911	919	916	908	911
400	905	914	911	903	905
500	900	908	906	898	900
600	895	903	901	892	895
700	871	871	871	871	871

Table A-2: Nodes Energy Consumption (S-MAC) 10%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	956	958	957	960	956
200	945	948	947	949	945
300	935	938	937	939	935
400	912	915	913	916	912
500	902	905	903	906	902
600	892	894	893	896	892
700	869	871	870	873	869

Table A-3: Nodes Energy Consumption (S-MAC) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	963	964	963	961	964
200	934	934	933	932	935
300	904	904	903	902	905
400	874	875	874	873	875
500	849	849	849	847	850
600	819	819	819	818	820
700	790	790	789	788	791

Table A-4: Nodes Energy Consumption (S-MAC-PP) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	926	926	928	923	926
200	920	920	923	915	920
300	915	915	918	910	913
400	910	910	913	905	907
500	905	905	908	899	902
600	900	900	902	894	897
700	895	895	897	889	892

Table A-5: Nodes Energy Consumption (S-MAC-PP) 10%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	957	958	957	955	955
200	945	948	946	945	945
300	935	937	936	935	935
400	910	913	912	910	910
500	900	903	902	900	900
600	890	893	891	890	890
700	880	882	881	880	880

Table A-6: Nodes Energy Consumption (S-MAC-PP) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	963	963	964	962	964
200	933	933	934	932	934
300	902	903	903	902	904
400	877	878	878	877	878
500	847	847	847	848	847
600	817	817	818	816	818
700	791	792	792	791	793

Table A-7: Nodes Energy Consumption (SEA-MAC) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	911	914	907	901	911
200	907	910	903	893	907
300	902	906	899	889	902
400	898	901	895	885	898
500	894	897	891	880	894
600	890	893	886	876	890
700	885	889	882	872	885

Table A-8: Nodes Energy Consumption (SEA-MAC) 10%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	949	952	954	951	949
200	941	944	942	946	941
300	932	936	934	937	932
400	924	927	926	929	924
500	900	903	901	904	900
600	891	894	893	896	891
700	883	886	885	888	883

Table A-9: Nodes Energy Consumption (SEA-MAC) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	965	965	964	962	966
200	938	939	938	936	940
300	918	918	917	916	919
400	892	892	899	889	893
500	865	866	865	863	867
600	845	845	844	842	846
700	817	817	816	814	818

Table A-10: Nodes Energy Consumption (SEA-MAC-PP) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	910	910	906	906	903
200	905	905	902	902	899
300	901	901	898	898	894
400	897	897	890	894	890
500	893	893	886	889	886
600	889	889	882	885	882
700	884	884	880	881	880

Table A-11: Nodes Energy Consumption (SEA-MAC-PP) 10%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	952	950	949	950	949
200	943	942	940	942	940
300	935	934	932	934	932
400	927	925	924	925	924
500	900	899	897	897	897
600	892	891	889	889	889
700	884	882	881	881	881

Table A-12: Nodes Energy Consumption (SEA-MAC-PP) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4
0	1000	1000	1000	1000	1000
100	963	964	964	962	965
200	936	937	937	935	938
300	915	916	917	915	917
400	889	889	890	888	890
500	868	869	869	868	870
600	841	842	842	841	843
700	826	826	828	825	827

A.2. Results tables for uniform deployment simulation environment

Table A-13: Nodes Energy Consumption (S-MAC) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99320	99323	99301	99328	99307	99315	99304	99347	99323	99277
2000	98736	98725	98717	98747	98711	98733	98714	98779	98744	98622
3000	98135	98111	98095	98127	98092	98127	98097	98190	98133	97956
4000	97497	97481	97456	97502	97440	97500	97456	97570	97505	97296
5000	96872	96842	96815	96867	96796	96872	96807	96940	96875	96587
6000	96258	96233	96193	96250	96179	96269	96204	96345	96269	95932
7000	95668	95614	95570	95619	95551	95647	95565	95747	95660	95272

Table A-14: Nodes Energy Consumption (S-MAC) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99643	99642	99641	99643	99644	99644	99640	99642	99643	99641
2000	99301	99296	99294	99298	99299	99300	99293	99296	99298	99297
3000	98952	98946	98944	98948	98948	98952	98942	98946	98948	98950
4000	98603	98594	98593	98596	98597	98604	98590	98594	98596	98598
5000	98261	98250	98249	98251	98255	98263	98247	98251	98252	98255
6000	97914	97900	97899	97901	97904	97916	97897	97900	97900	97904
7000	97566	97547	97547	97547	97554	97570	97548	97552	97552	97557

Table A-15: Nodes Energy Consumption (S-MAC) 40%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99526	99524	99524	99525	99524	99527	99523	99525	99524	99525
2000	99054	99053	99053	99052	99052	99056	99052	99052	99053	99055
3000	98583	98583	98583	98581	98581	98585	98582	98581	98582	98584
4000	98106	98106	98105	98104	98104	98109	98105	98104	98106	98108
5000	97634	97632	97631	97631	97631	97637	97631	97631	97631	97635
6000	97166	97163	97161	97162	97162	97169	97161	97162	97161	97166
7000	96693	96689	96687	96689	96688	96697	96686	96689	96686	96693

Table A-16: Nodes Energy Consumption (S-MAC-PP) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99742	99794	99783	99819	99805	99846	99733	99843	99720	99596
2000	99490	99575	99613	99649	99654	99778	99547	99773	99517	99333
3000	99199	99435	99432	99476	99446	99515	99372	99644	99301	99075
4000	98925	99290	99221	99342	99271	99436	99216	99568	99114	98837
5000	98689	99148	99022	99184	99148	99359	99041	99500	98903	98555
6000	98407	99016	98843	99027	99038	99286	98893	99423	98717	98288
7000	98141	98871	98649	98888	98893	99127	98742	99234	98534	98030

Table A-17: Nodes Energy Consumption (S-MAC-PP) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99693	99696	99695	99699	99697	99723	99696	99640	99660	99686
2000	99394	99407	99400	99402	99403	99402	99402	99379	99343	99390
3000	99096	99116	99110	99114	99112	99141	99112	99118	99048	99099
4000	98798	98826	98817	98824	98824	98801	98821	98851	98773	98805
5000	98505	98535	98528	98534	98536	98539	98527	98585	98504	98514
6000	98213	98247	98237	98246	98246	98239	98238	98210	98229	98223
7000	97917	97958	97946	97956	97957	97977	97946	97948	97959	97935

Table A-18: Nodes Energy Consumption (S-MAC-PP) 40%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99558	99562	99560	99562	99562	99580	99559	99497	99494	99561
2000	99123	99129	99126	99129	99129	99167	99125	99086	99045	99128
3000	98687	98694	98692	98695	98695	98757	98692	98645	98627	98694
4000	98253	98263	98257	98262	98262	98300	98257	98197	98181	98259
5000	97818	97831	97825	97831	97830	97860	97825	97788	97713	97827
6000	97382	97397	97390	97397	97398	97450	97391	97370	97287	97393
7000	97047	97056	97057	97065	97064	97021	97058	97031	97054	97059

Table A-19: Nodes Energy Consumption (SEA-MAC) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99544	99744	99740	99729	99737	99747	99534	99756	99756	99762
2000	99108	99519	99522	99501	99508	99515	99526	99095	99536	99566
3000	98682	99320	99301	99305	99322	99326	99313	98667	99341	99384
4000	98253	99122	99124	99100	99103	99113	99128	98235	99137	99200
5000	97815	98918	98920	98896	98900	98915	98924	97793	98935	99011
6000	97352	98705	98710	98687	98690	98708	98714	97327	98735	98820
7000	98504	98512	98485	98489	98508	98520	98534	98534	98534	98634

Table A-20: Nodes Energy Consumption (SEA-MAC) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99642	99833	99852	99836	99632	99640	99639	99633	99635	99641
2000	99434	99712	99743	99705	99275	99284	99277	99269	99273	99287
3000	99209	99610	99655	99611	98951	98962	98956	98945	98950	98965
4000	99028	99513	99576	99512	98651	98661	98655	98645	98648	98663
5000	98837	99422	99485	99419	98343	98353	98350	98337	98342	98364
6000	98641	99325	99402	99323	98041	98049	98047	98032	98039	98063
7000	98452	99225	99310	99240	97740	97749	97747	97731	97739	97763

Table A-21: Nodes Energy Consumption (SEA-MAC) 40%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99694	99739	99740	99734	99572	99574	99570	99575	99572	99568
2000	99326	99373	99372	99368	99206	99210	99202	99211	99206	99193
3000	98955	99004	99002	98837	98842	98832	98844	98837	98817	98817
4000	98588	98638	98634	98634	98472	98479	98464	98480	98472	98442
5000	98217	98269	98264	98264	98103	98111	98094	98113	98103	98065
6000	97849	97849	97893	97895	97736	97747	97726	97749	97737	97690
7000	97479	97535	97526	97530	97368	97380	97356	97381	97368	97313

Table A-22: Nodes Energy Consumption (SEA-MAC-PP) 5%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99783	99827	99769	99807	99793	99645	99810	99680	99628	99707
2000	99634	99696	99638	99682	99672	99288	99662	99381	99261	99593
3000	99503	99589	99531	99579	99572	98910	99555	99112	98920	99462
4000	99338	99499	99413	99482	98560	99444	99489	98748	98590	99297
5000	99217	99399	99299	99405	99388	98455	99334	98322	98322	99186
6000	99076	99316	99189	99316	99302	98100	99240	98122	98200	99069
7000	98920	99222	99082	99208	99205	98000	99130	98000	98050	98944

Table A-23: Nodes Energy Consumption (SEA-MAC-PP) 25%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99733	99737	99737	99740	99742	99461	99740	99474	99352	99725
2000	99482	99489	99488	99492	99496	99489	98919	98919	98889	99475
3000	99222	99240	99240	99245	99250	98999	99241	98665	98550	99225
4000	98984	99001	99000	99006	99012	98598	99001	98320	98020	98987
5000	98729	98754	98749	98759	98764	98100	98751	98040	97850	98736
6000	98480	98508	98501	98512	98518	97960	98504	97999	97500	98489
7000	98230	98264	98248	98267	98272	97790	98257	97709	97140	98238

Table A-24: Nodes Energy Consumption (SEA-MAC-PP) 40%DC (mJ)

Time	Node 0	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9
0	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
1000	99623	99622	99623	99626	99623	99486	99626	99428	99466	99585
2000	99253	99257	99256	99262	99260	99261	99261	98854	99003	99203
3000	98887	98891	98892	98899	98329	98893	98273	98368	98898	98824
4000	98517	98523	98521	98532	98530	98200	98528	97950	98500	98432
5000	98147	98161	98155	98171	98167	97800	98161	97400	98040	98044
6000	97780	97801	97791	97806	97804	97340	97795	97000	97650	97661
7000	97410	97439	97425	97445	97443	97050	97428	96700	97130	97275

A.3. Throughput results tables

Table A-25: Throughput productivity
S-MAC vs. SEA-MAC 5%DC
5 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
100	11	11
200	21	20
300	31	30
400	40	39
500	50	49
600	60	60
700	69	70

Table A-26: Throughput productivity
S-MAC vs. SEA-MAC 10%DC
5 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
100	11	11
200	20	21
300	30	32
400	40	42
500	50	53
600	60	63
700	71	72

Table A-27: Throughput productivity
S-MAC vs. SEA-MAC 25%DC
5 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
100	10	11
200	18	21
300	27	32
400	35	42
500	39	52
600	56	62
700	66	71

Table A-28: Throughput productivity
S-MAC vs. S-MAC-PP 5%DC
5 Nodes Simulation Scenario

time	S-MAC	S-MAC-PP
100	11	11
200	21	21
300	31	30
400	40	43
500	50	53
600	60	62
700	69	74

Table A-29: Throughput productivity
S-MAC vs. S-MAC-PP 10%DC
5 Nodes Simulation Scenario

time	S-MAC	S-MAC-PP
100	11	11
200	20	22
300	30	32
400	40	42
500	50	54
600	60	65
700	71	75

Table A-30: Throughput productivity
S-MAC vs. S-MAC-PP 25%DC
5 Nodes Simulation Scenario

time	**S-MAC**	**S-MAC-PP**
100	**10**	**11**
200	**18**	**21**
300	**27**	**32**
400	**35**	**42**
500	**39**	**51**
600	**56**	**61**
700	**66**	**71**

Table A-31: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 5%DC
5 Nodes Simulation Scenario

time	**SEA-MAC**	**SEA-MAC-PP**
100	**11**	**11**
200	**20**	**21**
300	**30**	**32**
400	**39**	**43**
500	**49**	**54**
600	**60**	**63**
700	**70**	**74**

Table A-32: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 10%DC
5 Nodes Simulation Scenario

time	**SEA-MAC**	**SEA-MAC-PP**
100	**11**	**12**
200	**21**	**21**
300	**32**	**32**
400	**42**	**42**
500	**53**	**54**
600	**63**	**65**
700	**72**	**76**

Table A-33: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 25%DC
5 Nodes Simulation Scenario

time	**SEA-MAC**	**SEA-MAC-PP**
100	**11**	**12**
200	**21**	**21**
300	**32**	**33**
400	**42**	**44**
500	**52**	**53**
600	**62**	**64**
700	**71**	**75**

Table A-34: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 5%DC
5 Nodes Simulation Scenario

time	**S-MAC-PP**	**SEA-MAC-PP**
100	**11**	**11**
200	**21**	**21**
300	**30**	**32**
400	**43**	**43**
500	**53**	**54**
600	**62**	**63**
700	**74**	**76**

Table A-35: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 10%DC
5 Nodes Simulation Scenario

time	S-MAC-PP	SEA-MAC-PP
100	11	12
200	22	21
300	32	33
400	42	44
500	54	55
600	65	66
700	75	76

Table A-36: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 25%DC
5 Nodes Simulation Scenario

time	S-MAC-PP	SEA-MAC-PP
100	11	12
200	21	21
300	32	33
400	42	44
500	51	53
600	61	63
700	71	75

Table A-37: Throughput productivity
S-MAC vs. SEA-MAC 5%DC
10 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
1000	86	86
2000	182	182
3000	281	280
4000	383	379
5000	486	481
6000	584	588
7000	683	687

Table A-38: Throughput productivity
S-MAC vs. SEA-MAC 25%DC
10 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
1000	87	87
2000	186	189
3000	288	293
4000	388	393
5000	486	493
6000	588	593
7000	688	693

Table A-39: Throughput productivity
S-MAC vs. SEA-MAC 40%DC
10 Nodes Simulation Scenario

time	S-MAC	SEA-MAC
1000	90	79
2000	185	173
3000	283	278
4000	391	384
5000	492	486
6000	587	585
7000	690	686

Table A-40: Throughput productivity
S-MAC vs. S-MAC-PP 5%DC
10 Nodes Simulation Scenario

time	S-MAC	S-MAC-PP
1000	86	88
2000	182	184
3000	281	281
4000	383	383
5000	486	487
6000	584	585
7000	683	685

Table A-41: Throughput productivity
S-MAC vs. S-MAC-PP 25%DC
10 Nodes Simulation Scenario

time	S-MAC	S-MAC-PP
1000	87	88
2000	186	186
3000	288	288
4000	389	390
5000	486	490
6000	586	590
7000	686	692

Table A-42: Throughput productivity
S-MAC vs. S-MAC-PP 40%DC
10 Nodes Simulation Scenario

time	S-MAC	S-MAC-PP
1000	90	86
2000	185	190
3000	283	294
4000	391	396
5000	492	493
6000	587	591
7000	688	691

Table A-43: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 5%DC
10 Nodes Simulation Scenario

time	SEA-MAC	SEA-MAC-PP
1000	86	86
2000	182	183
3000	280	282
4000	379	390
5000	481	495
6000	588	593
7000	687	695

Table A-44: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 25%DC
10 Nodes Simulation Scenario

time	SEA-MAC	SEA-MAC-PP
1000	87	82
2000	189	185
3000	293	285
4000	390	388
5000	488	488
6000	590	586
7000	691	688

Table A-45: Throughput productivity
SEA-MAC vs. SEA-MAC-PP 40%DC
10 Nodes Simulation Scenario

time	SEA-MAC	SEA-MAC-PP
1000	79	86
2000	173	190
3000	278	291
4000	384	391
5000	486	491
6000	585	591
7000	686	692

Table A-46: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 5%DC
10 Nodes Simulation Scenario

time	S-MAC-PP	SEA-MAC-PP
1000	88	86
2000	184	183
3000	281	282
4000	383	390
5000	487	495
6000	585	593
7000	685	695

Table A-47: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 25%DC
10 Nodes Simulation Scenario

time	S-MAC-PP	SEA-MAC-PP
1000	88	82
2000	186	185
3000	288	285
4000	390	388
5000	490	488
6000	590	586
7000	692	688

Table A-48: Throughput productivity
S-MAC-PP vs. SEA-MAC-PP 40%DC
10 Nodes Simulation Scenario

time	S-MAC-PP	SEA-MAC-PP
1000	86	86
2000	190	190
3000	294	291
4000	396	391
5000	493	491
6000	591	591
7000	691	692

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