

# Performance investigation of low power radio duty cycling MAC for resource constrained WSN

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## Abstract

Wireless Sensor Networks (WSN) are the corner stone of next generation communication networks. The OSI Layer 2 and Layer 3 communication technologies of the WSN are the important aspects in communication and networking research. The protocols and standards of WSN in different layers are already well defined. In this article, we evaluate the Layer 2 mechanisms which meet the special demands of WSNs for resource constrained applications. Large number of WSN devices need to be deployed in a typical environmental monitoring use cases. In this work we consider a use case of sensors and actuators in a small geographical region. For this a short range communication technology such as IEEE 802.15.4 is considered. Various type of sensors are deployed in the same region, in this cases effective MAC mechanism is required to effectively allocate the channel resource among these devices. The main concentration of this article is about the energy consumption of WSN devices. As the devices and network is resource constrained, energy efficient hardware's, communication networking protocols and suitable software implementations are required. As far as the energy efficient protocols are considered MAC mechanisms is one of the very important processes, where suitable energy efficient mechanisms need to be selected. In the recent literatures showed that Contiki MAC is one of the suitable MAC layer implementation with dedicated Radio Duty Cycling Layer (RDC) which conserves the WSN nodes battery power. In this article we analyze the state of the art Layer 2 mechanisms for WSN in environmental monitoring use case, by a theoretical analysis and simulation based experiments.

**Keywords:** WSN; Energy Efficiency; MAC; RDC.

## 1. Introduction

The technologies such as wireless sensor networks, machine to machine communication, pervasive computing, embedded communication technologies and mini- hardware manufacturing is the major enablers of next generation smart communication solutions. Next generation smart technologies such as Internet of Thing (IoT) allow little objects or devices to work immediately and intelligently by integrated with electronics, software and network connectivity to connect and exchange data for certain applications such as home appliances, vehicles, medical applications etc. The recent research around smart technologies showed that all the underlying technologies introduced specialized standards and challenging protocols to contribute its significance. Among them WSN is the most important element. Wireless sensor network consists of several tiny sensor nodes, often referred as motes, connected to each other in ad hoc environment and coordinate with each other to form a network. Wireless sensor networks have a wide variety of use cases in the emerging smart city/ smart world revolutions such as home and building automation, intruder alert and tracking, environmental monitoring, industrial process monitoring, and tactical systems. In wireless sensor network deployments, reliably reporting data while consuming the least amount of power is the ultimate goal [1].

An environmental monitoring WSN use case is considered in this work. In this use case the sensor nodes are typically battery powered as it operates in a region where we cannot attach a constant

power supply. In these use cases, WSN devices such as, sensors and attenuators, are extremely resource constrained in memory, processing power and energy. If more number of sensor devices are used then the utilization of shared wireless channel of WSN becomes extremely crucial. MAC layer protocols are responsible for efficient allocation of the channels [2], [3]. As the devices operate in the same frequency band and they are within the communication range it leads to many issues such as interferences, collision, packet drop and retransmissions. Due to all these process the node's energy consumption will increase. Maximizing Energy and improving efficiency is more important in WSNs. Such networks have the ability to be self-organized and failure-adaptive to provide an efficient and stable network.

Most of the researchers concentrate on developing energy efficient routing algorithms for maximizing the lifetime of the networks. An intelligent routing algorithm to adaptively adjust the transmission power with location and energy as heuristic parameters was developed in concern with even load distribution [4]. However, this algorithm is suitable for indoor applications as it doesn't consider GPS. Results in[5] demonstrate that the clustering method has a significant influence on the performance of multi hop networks.

The main concentration of this article is about the energy consumption of WSN devices. As the devices and network is resource constrained, energy efficient hardware's and communication networking protocols and suitable software implementations are required. As far as the energy efficient protocols are considered MAC layer is one of the very important layer where suitable ener-

gy efficient mechanisms need to be selected. The selection of efficient MAC mechanism in [6] is important in this kind of applications. In this context we concentrate on the MAC protocols in WSN which plays a major role in the IoT landscape. To attain low-power operation of the radio, a default radio mechanism is used called as Contiki MAC. In Contiki MAC mechanism the node can be able to receive and deliver messages in low-power mode.

## 2. Motivation

The major objective of this research is to analyze how the traditional WSN MAC protocols can be applied to the next generation smart environment use cases and to summarize the suitable WSN MAC mechanisms.

The major challenges during the selection of WSN MAC mechanism are,

- 1) Due to the distributed nature the WSNs usually require a decentralized monitoring and management.
- 2) The communication links of WSN is error prone and highly volatile.
- 3) The network should support scalable topology to support large no of nodes.
- 4) Energy efficiency and reliability are the major concerns other than high packet delivery ratio.

The energy efficiency of wireless nodes is the prime concern in this work. We concentrate on the Layer 2 mechanisms. In our previous works we concentrated on MAC mechanisms, but Radio Duty Cycling is also an important mechanism which can significantly reduce energy consumption. The WSN motes are in environmental monitoring use case cannot be attached with constant power supply, so the selection of suitable hardware and software elements of WSN mote is really important. First, as we concentrate on Layer 2, we analyze ways to effectively utilize the radio transceiver of WSN mote. The proper selection of transceiver hardware and a suitable energy efficient radio driver is important.

The contribution of this work is as follows;

- 1) Analyzing and summarizing the reasons and need of MAC layer energy consumption optimization techniques by a comprehensive state of the art.
- 2) Theoretical comparison of energy consumptions of popular WSN motes and discussion based on this.
- 3) Performance analysis using Cooja and network simulator (ns-2) based simulations and summarizing the investigations.

## 3. State of the art

This section is divided into three subsections, we explain

- 1) The state of the art elements of WSN in environmental monitoring use case.
- 2) The MAC layer mechanism suitable for this use case
- 3) The Radio Duty Cycling mechanisms suitable for this use case

a) WSN in environmental monitoring use cases

A typical architecture of WSN in environmental monitoring use case is shown in Fig. 1. The WSN nodes such as sensor and actuator deployed in a remote geographical location. And the sensed results will periodically communicate with corresponding sink nodes for further processing. These WSN motes can be based on various Physical and MAC layer protocols.

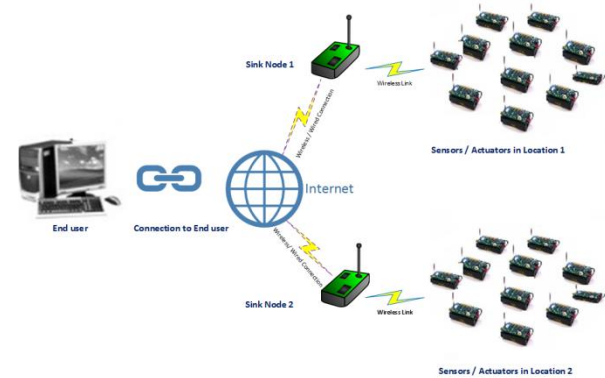


Fig. 1: Typical WSN Architecture.

In this article we consider WSN motes which are arranged on IEEE 802.15.4 standard. We select this because it is one of the widely accepted WSN standard and which is suitable in the above mentioned use case with necessary mechanisms to reduce energy consumption. It has a frame format consists of header, payload and a footer. The MAC header defines the communication of the node with the details of the source and destination. In case of overhead these frame formats are not suitable for low power multi-hop networking in this use case. In 2008, IEEE802.15.4e [2] was created to extend IEEE802.15.4 and support low power communication. In environmental monitoring use case to reach the communication requirements it follows the time synchronization and channel hopping technique.

The IEEE 802.15.4 based WSN are composed of the various device types. The sink device is referred as Coordinator and the sensor and actuator devices are usually referred as the router device, and the end device.

- Coordinator: Coordinators are Full Function Devices (FFD). It accomplishes the routing mechanism, coordination and sensing function. In each network one node is named as a coordinator. Its responsibility is to begin the network and function as the root of the network
- Router: Routers work as an intermediary. The function of this router is to transmit data from one node to another. These routers are also considered full function devices (FFD)
- End Device: It is a low-power device. Some times which could be work either as a full function device (FFD) or reduced function device (RFD). It can communicate with the origin node. The origin node may be a coordinator or a router. It cannot broadcast any data. So it admit the node to sleep. Due to this battery life should be improved.

In order to conserve the energy consumption of WSN it is important to select the proper hardware elements and layer 2 mechanisms such as MAC and RDC.

b) Energy efficient WSN motes

The power consumption of WSN motes are mainly due to the processor and transceiver. For example in the Telos B Sky Mote, the power consumption of the processor is 1.8 milliamps and power consumption of the transceiver is 23 milliamps. Depending up on the complexity of applications more power is consumed by the processor, but with the help of proper Layer 2 mechanisms the energy consumption of transceiver can be reduced. In this article we discuss how the MAC and RDC mechanisms help to reduce the energy consumption of WSN motes.

c) MAC mechanisms

In this work we concentrate on IEEE 802.15.4 based MAC mechanisms. The specific 802.15.4 MAC features are Slot frame Structure, Scheduling, Synchronization, Channel Hopping and Network formation [7], [8]. Nowadays to improve the energy efficiency in various layers of the protocol stack endless research has been undertaken. Among that layers MAC layer was of high interest. In general energy has been wasted by means of over-hearing, over-head, collision, idle listening and over emitting. To reduce the

wastages MAC layer is considered as a base. Till now so many protocols have been developed to improve the energy.

The MAC protocol in WSN is basically classified into Reservation based and Contention based [19]. The reservation based protocols such as TDMA allows the channels to access based on a predefined schedule so that it can avoid collisions, over hearing and idle listening. In order to deploy these protocols the nodes should be time synchronous and should have the knowledge of network topologies. These protocols need a dedicated access point to manage the changes in the network. Because of this these protocols more complex over WSNs where the nodes have very limited resources. So such protocols are not suitable if the network consists of large no of mobile nodes and never the less network reestablishment in terms of failure are really difficult. Whereas the contention based are often unscheduled and asynchronous like CSMA, ALOHA etc. It has to compete with other the channels to get access. The upper hand of this mechanism is that it is robust and reliable with the volatility and mobility of the network. The down side is that it has higher amount of overhearing overheads and idle listening. If a node is located in the radio range of at least two nodes it cannot receiving any data successfully due to collision. Because these nodes are simultaneously transmitting data packets to it. In order to reduce the collisions the control messages RTS/CTS/ACK and/or the wake-up /sleep mechanism are used to design energy efficient MAC protocols for WSN as those described in T-MAC, Z-MAC, X-MAC and B-MAC. A very detailed state of the art of MAC protocols for WSN is done by the authors in [2].

A comparative analysis of suitable WSN MAC protocol is performed in Table I.

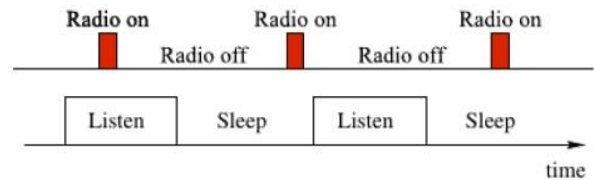
**Table 1:** Analysis of Mac Protocols

MAC Protocols	Advantage	Disadvantage
CSMA	Reduce Collisions	Higher energy consumption
CSMA/ARC	Reduce Overheads	Higher energy consumption
PAMAS	Reduce Overhearing	Time synchronization issues
PSM	Reduce Idle Listening	Higher energy consumption
Sensor MAC	Reduce energy consumption	Over hearing, idle listening

There are many mechanisms in MAC layers, which are addressed in previous works [2], [6], [10]. But in this work we mainly concentrate on energy efficient mechanisms by Radio Duty Cycling (RDC) of mote radio.

#### d) Radio duty cycling mechanisms

In order to reduce the energy consumption of WSN motes so far we discussed in detail the need of proper hardware and the need of MAC layer protocol for efficient utilization of channel without consuming much energy. Another important functionality as part of MAC layer is how to effectively use wireless transceiver. The mote's transceiver need to be powered on for transmission and reception. Managing a WSN mote's transceiver in an energy efficient manner is inherently challenging in a use case like environmental monitoring. The sensors are usually deployed to sense some unknown event which may occur unexpectedly. In those cases it is essential that the mote's transceiver is in active state to make the communication among them on time and take necessary action. But, if we keep the mote's transceiver on for long time to passively listening for messages over the air, during this time also the motes consume same power as when actively sending data. So in such cases the battery will drain in short time. But it also is clear that depending on the use case, the mote may utilize its transceiver in an unpredictable fashion. For increased life time, the radio transceiver of the mote should be switched off as much as possible. During this period the But when the radio is switched off, the node is not able to send or receive any messages.



**Fig. 2:** Radio Duty Cycling.

So in order to reduce the energy consumption an intelligent way to handle this transceiver during its operation is essential. Thus the mote's transceiver must managed in a way that allows nodes to receive messages but keep the radio turned off in between the reception and transmission of messages. This can be done in synchronous and asynchronous way. The strategies for minimizing the duty cycle of a radio are also part of the MAC layer of the networking stack in an operating system. In most of the networking stacks RDC is part of MAC layer. In contiki OS there is a separate layer called RDC layer for this activity. Currently, Contiki provides two RDC protocols that follow the asynchronous paradigm, which relies heavily on low-power probing and low-power listening (LPL). Conversely, synchronous protocols rely on tightly synchronized clocks and predictably repeating events to minimize wireless transmission collisions [11], [12], [13], [14].

#### e) Different RDC drivers

There are various RDC drivers like ContikiMAC, X-MAC, CX-MAC, LPP, and NullRDC. Among these ContikiMAC is one of the need mechanism that contributes a very good power efficiency but is somewhat comfortable for the 802.15.4 radio and the CC2420 radio transceiver. The next is X-MAC. It is a former mechanism and also it does not provide the same power-efficiency as ContikiMAC. It has inflexible timing requirements. The CX-MAC (Compatibility X-MAC) is an exertion of X-MAC that has more flexible timing than the default X-MAC and therefore works on a broader set of radios. LPP (Low-Power Probing) as a receiver-initiated RDC protocol. NullRDC is a "null" RDC layer that never switches the radio off and that therefore can be used for testing or for comparison with the other RDC drivers [11, 12]. Table 3 provides the summary of RDC mechanisms.

## 4. Performance Measurements RDC and MAC

#### a) Description of Simulation use case

The use case considered in a WSN application for environmental monitoring where the sensor and actuator devices need to be alert all the time and the properties of environment is changing or challenging all the time. Sink node is acting as the Co-coordinator and the end devices with reduced functionalities simulate as sensor/actuator.

The MAC layer lies on head of the RDC layer. Because of retransmitting packets at the radio medium collisions were occur. MAC layer has the major role to avoid the collisions. As our analysis concentrate of the performance of Radio Duty Cycling of the motes we perform simulations using the available MAC and RDC libraries of Contiki in Cooja Simulator.

#### b) Simulation Environment

For performing the analysis of the WSN use cases mentioned in our work, we have performed extensive experiment using the open source Cooja simulator as part of the Contiki development release. Cooja is an extensible Java-based simulator capable of emulating Tmote Sky (and other) node. Cooja allows us to run the codes (c codes) which we run on same WSN hardwares to run on a software platform. Cooja allows flexibility in terms of multi node execution and configuring various node characteristics. We have used the open Contiki MAC implementation available with the cooja simulator and performed the experiments using various mote types available in Cooja. Cooja has two Open network stack such as uIP and Rime. For the experiment campaign we have used Rime

c) Simulation Experiments

By simulation analysis in this work we evaluate how the MAC mechanisms in the use case considered in this article. In order to reduce the energy consumption of WSN mote radios you have to also consider Radio Duty Cycling Layer techniques. The current WSN systems use a new MAC known as Contiki MAC (it is basically CSMA and Radio Duty Cycling Techniques).

d) Contiki MAC & RDC based Simulations

Cooja allows large and small networks of motes to be simulated. We have performed many simulations to analyze the working of MAC and RDC functionalities. For example, we tried to simulate our use case of 30 sensor/actuator nodes and 1 sink nodes as shown in Fig.3. We have analyzed the features using various tools available in Cooja such as Timeline, mote Radio Duty Cycle and Collect View. Most of the results are explained in many other research works and matches with our experiments.

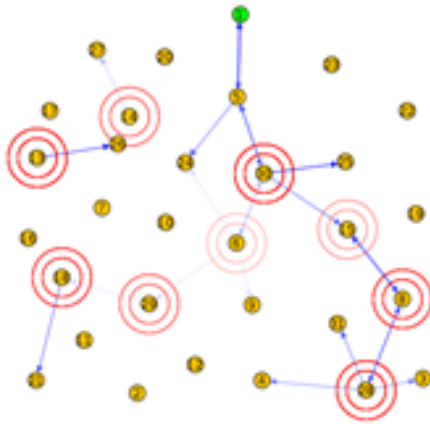


Fig. 3: Typical WSN Environmental Monitoring Usecase Simulation.

e) Contiki MAC in Various Topologies

First we perform a simulation using RDC protocol in a two different network topologies such as star and mesh topology. These are the two different suitable topological set up in case of environmental monitoring use cases.

1) Ring topology

The sink and sensor/actor devices are connected in a star topology, so routing layer and router devices are no needed for this. We limit our simulation to 10 sensor/actor devices and 1 sink device as in Fig.4. The sensors are communication to sink node directly in single hop fashion.

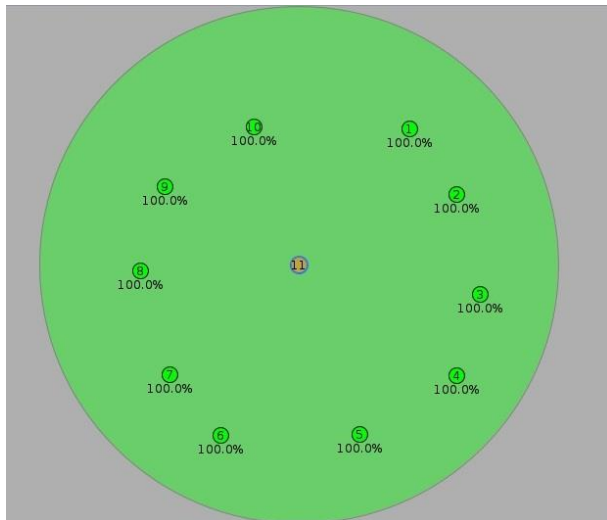


Fig. 4: Ring topological set up.

f) Mesh topology

Mesh topological set up is another widely used topological set up in this use case. In which the sensor communicate via multiple

hops. We have also performed above simulation scenario using mesh as well as shown in Fig.5.

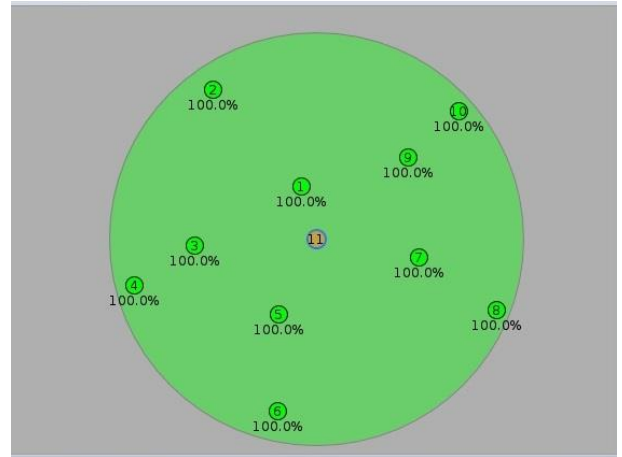


Fig. 5: Mesh Topological Set Up.

In both these cases the Contiki MAC RDC performs well than other RDC methods and this clearly saving the energy of WSN radios. This again proves the feasibility of these MAC mechanisms in real use cases.

g) Comparison of RDC

Contiki aids two MAC layers mechanism such as CSMA (Carrier Sense Multiple Access) mechanism and NullMAC mechanism. But the above two mechanisms don't do any MAC-level processing. Similarly it has many RDC drivers. The most frequently used are Contiki MAC, CX-MAC and Null RDC.

In order to analyze the effectiveness of Contiki MAC we perform a comparative analysis of using different combination of MAC and RDC protocols available in Cooja simulator. We have followed the steps given in Contiki WiKi pages to change the MAC layer functionalities and compiled the Cooja motes using the available rpl-udp-powertrace.csc file for simulation. The various combinations of MAC Parameters for simulation are given in Table. II.

Table 2: Comparison Parameters of MAC and RDC

Combinations (No)	Channel Check Rate	MAC Layer	RDC Layer
1	8 Hz	NullMAC	NullRDC
2	8 Hz	CSMA	CX-MAC
3	8 Hz	CSMA	ContikiMAC

The use case for this experiment is a simulation of 30 sensor/actuator nodes and 1 sink nodes. The SINK node remains ON for almost close to 100 percent since it keeps receiving packets from Clients. The RDC results of three combinations are given in Table. III.

Table 3: Comparison Results of MAC and RDC Combination

MAC, RAC (Combina-tion)	Average Radio ON	Average TX (%)	Average RX (%)
Null MAC, Null RDC	96.06%	0.06%	0.34%
CSMA MAC, CX-MAC	10.28%	0.65%	0.30%
CSMA MAC, Conti-kiMAC RDC	5.93%	1.32%	0.34%

Above results in Table. IV shows by comparing the Average values from the Radio Duty Cycle window, that Contiki MAC RDC has clear upper hand in this use case by turning OFF the radio effectively during its operation. ContikiMAC is has better performance than others in terms of PRR and is more energy efficient for nodes (9 percent v/s 20 percent respectively).

## 5. Performance measurement of IEEE 802.15.4 over CSMA-CA

We conduct this experiment using network simulator (ns-2). The total nodes are assumed not to be beyond the carrier sensing range of one another. This will remove the probability of hidden nodes and reduce the collisions. MAC level acknowledgements are not considered here. The MAC layer does not have an interface queue. It allows new packets from the upper layer only when it is not trying to transmit a formerly received packet. Since we are analyzing the star topology, there is no need for a routing layer. We have used the ns-2 module for IEEE 802.15.4 available in [15], [16], [17], [18] by integrating the CSMA-CA mechanisms into it.

A huge series of simulation was driven out using the IEEE 802.15.4 CSMA-CA Beacon-enabled mode. After analyzing the trace file, we concentrate the following metrics which are used to study the performance of the recommended model of the IEEE 802.15.4. In this a scenario of IEEE 802.15.4 MAC showing end-to-end data transfer is simulated with the characteristics.

### a) Data rate vs Beacon Order

The data rate of the transmission is analyzed in various beacon orders. As the beacon order increases shows increases data rate. The result is shown in Fig.6

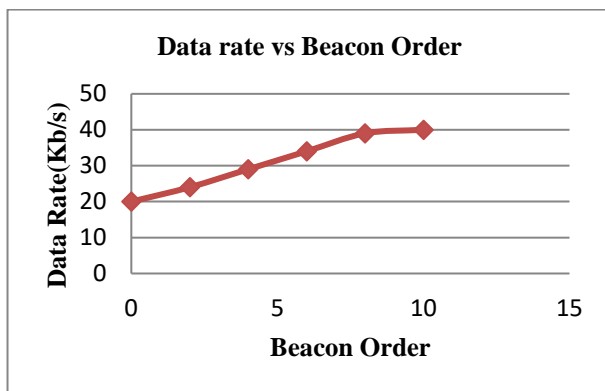


Fig. 6: Data Rate with Beacon Order Analysis.

### b) Data rate vs No. of devices

In the next experiment we evaluate the performance of the protocol by varying the no of sensor devices connected with the coordinator and find out the data rate during each execution of experiment. The result is given in Fig.7.

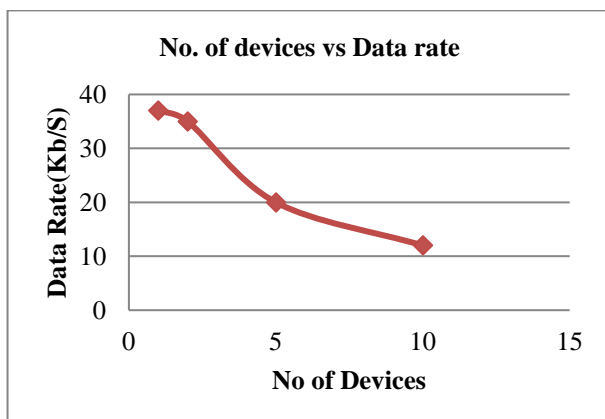


Fig. 7: Data Rate with No. of Devices Analysis.

### c) No. of devices vs Packet Delivery Ratio

In this experiment we evaluate the packet delivery ratio of each transmission in terms of number of devices connected to the coordinator. The result is given in the Fig.8.

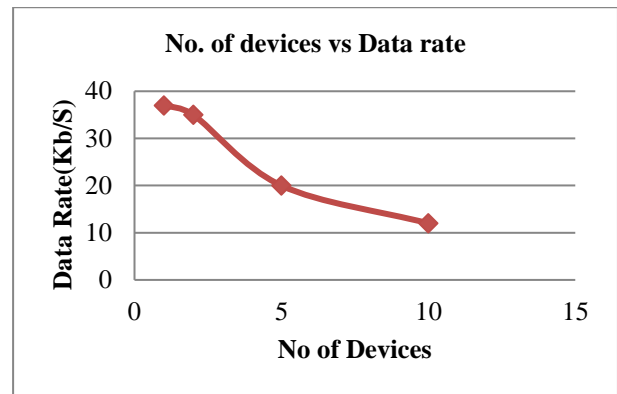


Fig. 8: PDR with No of Devices Analysis.

### d) Duty Cycle vs Throughput

The Fig.9 shows the result of duty cycle vs throughput. As the duty cycle increases throughput also increases.

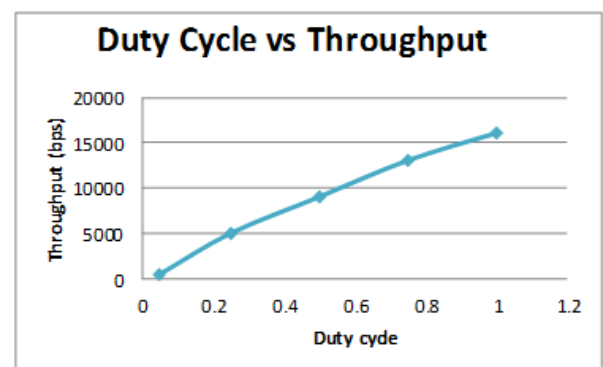


Fig. 9: Duty Cycle with Throughput.

## 6. Conclusion

This paper presents the detailed analysis of energy efficient MAC and RDC mechanisms in an environmental monitoring use case. This also provides performance analysis using open source Cooja & ns-2 simulations. We can conclude that proper radio duty cycling mechanism with periodic sleep features can be a better solution for reducing the energy consumption of WSN nodes. The Contiki MAC mechanisms meet the low power requirements along with Radio Duty Cycling features and it is a promising candidate for next generation WSN applications including the use case considered in this article.

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