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Tunable Parameters for Energy Efficient Communication in Industrial Stack Monitoring WSN

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Abstract: The design of Wireless Sensor Networks (WSN) significantly on the application. In sensor network design, physical and logical topology plays major role. One of the key challenges in physical topology of WSN design is to provide energy efficient communication. The goal of this paper is to study the impact of parameters like Tx power (Transmission power), duty cycle and their correspondence in order to reduce idle listening and unnecessary high transmitting power for energy saving that can be considered more in case of industrial stack monitoring scenario. The tuning of these parameters is tested using value reporting application module of a Castalia simulator.

Keywords: wireless sensor networks; physical topology; tunable MAC; Tx power; duty cycle; listen interval; Castalia simulator.

I. INTRODUCTION

Wireless Sensor Networks (WSN) has the potential to enhance and change the way people interact with technology and the world. The design of WSN depends significantly on the application. Industrial air pollution monitoring at point source stack is one of the applications for green growth analysis. To construct an efficient WSN monitoring, application domain space and network domain space are the two avenues to be considered [1, 2]. Without through knowledge of the application domain, one cannot design an effective sensor network.

In sensor network design, physical and logical topology plays major role. The physical topology refers to the configuration of connection between peripherals involved in the network like sensor, computer and transmission media. The logical topology is a method used to pass information between them. The general physical and logical topology considerations for industrial stack monitoring are discussed and reported in our previous papers [3, 4].

One of the key challenges in physical topology of WSN design is to provide energy efficient communication. There are several levels of power consumption that can be minimized in sensor networks are Idle Listening, Retransmissions resulting from collisions, Control packet overhead, Unnecessary high transmitting power and Sub-optimal utilization of the available resources. Medium Access Control (MAC) protocols provide the greatest influence over communication mechanisms and provide the most direct influence over the utilization of the transceiver, the largest energy consumer in most sensor nodes [5, 6].

In this paper an attempt is made to study the impact of parameters like Tx power (Transmission power), duty cycle and their correspondence, in order to reduce idle listening and unnecessary high transmitting power for energy saving that can be considered more in case of industrial stack monitoring scenario. To the best of our knowledge, the impact of single parameter is considered and analyzed in many papers. This study is made by tuning the combination of Tx power, duty cycle and listen interval, to save energy. The tuning of these parameters is tested via value reporting application module in Castalia simulator based on OMNeT++ (Object Modular NeTwork based on C++).

The rest of the paper is organized as follows. Section 2 describes the features of Castalia simulator used in this study, Section 3 reported a survey of related study, and Section 4 discusses the simulation steps carried out using Castalia simulator to test the impact of Tx power, duty cycle and listening interval for energy efficient communication. The physical topology design factors obtained from the results are also listed. Section 5 concludes the paper.

II. FEATURES OF CASTALIA

There is a variety of simulators that WSN researchers are using to cover their needs. The choices are NS2, Glomosim, Opnet, Jsim etc. All the available WSN simulators are falling short of the current state of the art modeling done in sensor networks. Due to its accurate modeling and relative ease of use, Castalia has gained wide acceptance in the WSN research community with a number of citations in the literature [7].

Recently Castalia based on OMNeT++ platform is attracted by developers for networks of low power embedded devices such as wireless sensor nodes. The main declared advantages are advanced channel model based on empirically measured data and radio model based on real radios for low-power communication and monitoring [8]. A highly tunable MAC protocol with several parameters is available to adjust the communication component. The parameters that can be tuned in MAC are Duty cycle, Listening interval, Number of beacons sent before data transmission (Tx), Packet retransmissions, Probability of Tx, Tx power level, Random Tx offset and Retransmission intervals [9].

Flexible application module templates are available for the user, which will most commonly change, usually by creating a new module to implement new algorithm. The standard templates in Castalia are Value reporting, Value propagation, Simple aggregation, Connectivity map, Throughput test and Bridge test. To carry out the energy efficient physical topology design for the application, Value reporting application module is used in this study.

III. RELATED STUDY

MAC protocols attempt to provide reliable communication and achieve high throughput with bounded latency, while at the same time minimizing collisions and energy dissipation [10]. There are many sleep/wake MAC protocols proposed in the literature trying to save energy of nodes in WSNs by avoiding idle listening, collision and/ or overhearing**.** They can be classified into three categories: Preamble-based, Slot-based and duty-cycle synchronization based as shown in Fig.1.

Among these, duty cycle synchronization protocols are energy efficient however; schedule synchronization causes large overheads and leads to high contention, which degrades performance significantly. Asynchronous duty cycle adjustment allows nodes to set their own sleep/wake schedules independently, to avoid schedule synchronization overhead [11].

WSN application classifications with examples and their main features are discussed in various papers [12-15]. Some paper proposes solution to specific problem like algorithm to reduce the retransmission traffic to improve throughput and reduces the error rate, using NS2 [16] , new analytical model to accurately evaluate the throughput, service delay and energy consumption of S-MAC protocol verified using NS2 [17], traffic aware MAC protocol which dynamically adjusts the duty cycle adaptive to the traffic load [18], high level communication functionalities for WSN [19], and experimental study of long-range WSN to monitor large geographical area [20]. The modeling of carrier sensing & state transition delays and how these aspects of low power radios are captured in the Castalia simulator is also described [21].

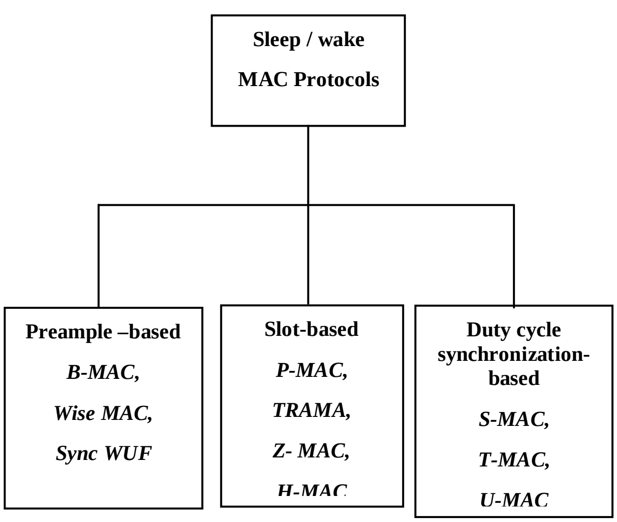

Figure 1. Classification of sleep/wake MAC protocols for WSNs

Duty-cycling (percentage of active period) has been proposed as an effective mechanism for reducing idle listening. The idea is to periodically cycle between a sleep and a listen state. Sleep time and listen time are to be chosen so that energy is minimized while satisfying all the communication constraints [22]. Duty-cycling MAC protocols are of two types: scheduled/synchronous and asynchronous, based on their wake-up schedule. Scheduled protocols [23-25] maintains synchronized wake-up schedule among neighbors. Asynchronous protocols [26-28] allow nodes to wake up independently of its neighbors, employing a preamble-based transmission approach.

IV. SIMULATION STEPS

In this paper, an attempt is made to study the impact of parameters like Tx power, duty cycle and listen interval together for energy saving mechanism. The simulation steps done are

- By tuning transmission power level,
  - For one-to-one network (Base work)
  - For many- to- one network (To test scalability)
- By tuning duty cycle and listen interval
  - For many-to-one network.

A. *Wireless Transmission Power:*

Any wireless equipment (sensor) can achieve certain transmission distance. There are too many factors that affect the transmission distance, particularly the combination of transmission power and antenna gain. The theoretical transmission distance between wireless devices can be calculated from the key specifications like, Tx power (Transmission power of device, measured in dBm), Data rate (The number of bits that are conveyed or processed per unit of time), Rx sensitivity (Receiver sensitivity of device, measured in dBm), Antenna gain (How much signal is boosted by the antenna, measured in dBi), Frequency (To indicate which electromagnetic band is used for wireless communication. The frequency is determined by the IEEE 802.11 standard and is measured in MHz or GHz).

In addition to that, determining sensor coverage for a designated area is important when evaluating the WSNs effectiveness. The quality of monitoring in WSN depends on the application [29].

Transmission Power Control (TPC) techniques to dynamically adjust the transmission power is a significant way to reduce energy consumption. Optimal transmit power is the minimum power required to sustain the network connectivity while maintaining a predefined maximum tolerable bit error rate. Optimization helps to increase battery life by reducing inter node interference significantly. One of the design considerations of WSN is to have each node transmit at the lowest possible power while preserving network connectivity [30].

In industrial stack monitoring WSN scenario, each sensor (sources) is fixed near to every stack and a sink to receive information from all sources (Many-to-one Network). Since this application is based on fixed infrastructure, selection of opt Tx power is one of the energy saving mechanism.

In this study we investigate the optimal transmit power, used by nodes based on the distance between source and sink to guarantee network connectivity. Castalia is a "tunable" simulator where many parameters may be adjusted using input files to simulate real environment. One among them is Tx power level, the level of transmission and their power consumptions. The tuning of different Tx power with different transmission distance is analyzed using

Table 1. Tx power levels and their corresponding power consumption

Tx Power level	Output Power (dBm)	Energy (mW)
0	0	57.42
1	-1	55.18
2	-3	50.69
3	-5	46.20
4	-7	42.24
5	-10	36.30
6	-15	32.67
7	-25	29.04

Value reporting application module of Castalia simulator. For this study the value of Network Interface.Radio.TxPowerLevels and their corresponding Tx Power Consumption PerLevel for Radio/TelosB_cc2420/ radio_CC2420 (single chip 2.4GHz IEEE 802.15.4 complaint RF transceiver) model is used and the values are shown in Table I.

a. *One to one Network:*

To test the influence of Tx power, sink is fixed randomly at location (25m, 25m, 2m) and source locations are changed from near to far to receive all sensed data (maximum packet reception rate). The variation of Tx power (mW) and their corresponding transmission area (m2) obtained is shown in Fig.2. From Fig.2, it is observed that nodes within the communication range receive all sensed data and with greater Tx power, greater transmission distances can be achieved. So, select opt Tx power level based on the distance between source and sink.

As per pollution control board norms, sampling point at stack must be located at least 8*stack diameter height from downstream of a bend and 2*stack diameter height from upstream from stack exit. So it is decided to fix various source locations with fixed height of 80mts near the stack. The other standard parameters used are Simulation time: 60s, Application sample interval: 10s, Listen interval: 355ms. The energy obtained for all Source locations with maximum Tx=0 is 2.28761. Table II shows the opt Tx power selection for various source locations, obtained energy and energy save.

From Table II, it is observed that, when Tx power level increases, the consumed energy decreases, this leads to energy save. This result is taken as a base work, to test the scalability in terms of many-to-one network.

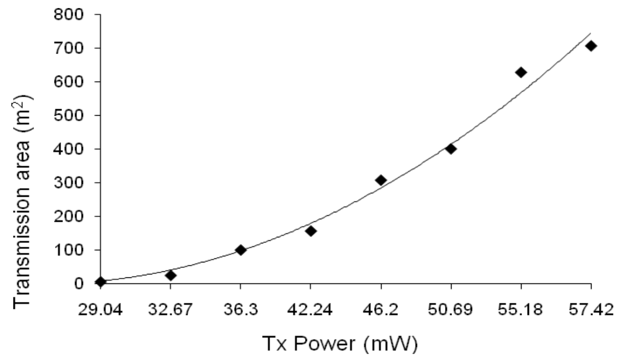

Figure 2. Tx power and their corresponding transmission area

Table 2. Variation of Tx and and their energy save (Single source and a sink)

Source Location	Opt Tx Power level	Energy (mW)	Energy save 10^{-3}(mW)
(26,26,80)	7	2.28727	0.34
(27,27,80)	6	2.28731	0.30
(29,29,80)	5	2.28736	0.25
(30,30,80)	4	2.28743	0.18
(32,32,80)	3	2.28747	0.14
(33,33,80)	2	2.28753	0.08
(35,35,80)	1	2.28758	0.03

b. *Many-to-one Network:*

In many-to-one network scenario the distance between different sources and sink may vary. So based on the distance between source and sink, different Tx power levels can be assigned for different source nodes in order to save energy. Tx power level can be adjusted by using the following assignment in Omnetpp.ini file.

SN.node[x].networkInterface.Radio.
Tx PowerLevelUsed = ……

The simulated value of a simple network with two sources in meters, Node(1): (26,26,40), Node(2): (18,18,80) and a sink in meters, Node(0): (25,25,2) are considered and represented in Case 1 & Case 2 of Table III. Case 1: Fixed (maximum) Tx power level assigned for all nodes in a network, Case 2: Variable (opt) Tx power level assigned for different nodes in a network, based on the distance between source and sink. Common parameters used in both case are Simulation Time: 60s, Application Sample Interval: 10s, Duty cycle: 0.1, Listen Interval: 400 ms. Tunable parameter is Tx power level used for a node.

From Table III, it is noted that the energy consumed in case 2 for two sources Node (1) & Node (2) is reduced as expected. Thus opt Tx power selection based on distance between source and sink is one of the design factors for energy efficient WSN design. And for more than one source, it is not necessary to assign same Tx power level for all sources in a network.

To reduce energy consumption further next parameter to be considered are duty cycle and listen interval.

Table 3. Effect of Tx power in energy variation for a simple Network

Case	Node	Tx Power level	Consumed Energy
1	0	0	2.30347
	1	0	2.32875
	2	0	2.30223
2	0	0	2.30347
	1	7	2.32842
	2	3	2.2858

B. Duty Cycle and Listen Interval:

The energy consumed for transmission is regulated by the radio model. The radio transceiver is the most power consuming component in a sensor node. A typical radio transceiver consists of four possible modes with different power consumption: transmitting, receiving, listening and sleeping.

The first three modes are also called active or wake modes, in which more energy is consumed. Observing idle listening, the status that a sensor node turns on the radio to monitor wireless medium but do not receive any packets, wastes lot of energy .

In case of periodic sampling of air pollution in stack monitoring application, samples may be transferred to the sink in the period mentioned in the parameter application sample interval (Value reporting application module.cc). The increase of application sample interval will lead to idle listening wastage. Many techniques exist to reduce idle listening energy wastage, such as S-MAC/T-MAC implementation which provides duty cycled sleep scheduling.

The well structured MAC-Tunable.ini file in Castalia simulator is used to analyze the possibilities of energy minimization. The parameters namely, Duty cycle (0.1 to 1.0), Listen interval (>0.5ms), are tuned for the same two sources and one sink network used in previous section.

Duty cycle is fixed based on the following suggestion in the literature. When the minimum duty cycle is set, the power consumption of the WSN can be reduced [11]. Variation in duty cycle consequently affects the system characteristics including the interference and collision of signals. Setting the duty cycle at predetermined value would help minimize the packet drop ratio of the network [31]. The interference model used in this study is include../Parameter_Include_Files/Wchannel/Additive_Interference_Model/Wchannel_Realistic.ini and the minimum duty cycle 0.1 is fixed. Sleep interval is calculated by using the formula available in MacTunable.cc.

Sleep interval

= Listen interval * ((1-dutycycle)/dutycycle)

Table 4. Variation of listen interval for sink with number Of received values

Listening interval for sink-Node(0)	Number of received values from	
	Node(1)	Node(2)
395	3	1
400 (2.3035)	5	2
405	6	0
410	6	0
415	6	0
420	1	1
425	2	1
430	3	1
435 (2.3231)	5	2

The two steps carried out to minimize energy are,

Step 1: Fix suitable listen interval for sink to receive maximum number of sensed data. Number of values obtained from Node (1) & Node (2) for various listen intervals is shown in Table IV. It is found that the maximum number of sensed values are received (maximum Packet Reception Rate) from both nodes at listen interval 400ms and 435ms. But listen interval 400ms is selected because of minimum energy consumed.

Step 2: To reduce energy further for sources Node (1) and Node (2) an attempt is made to fix different listen interval for different nodes. Fig.3 shows various listen intervals and their corresponding consumed energy. Listen interval that receives maximum number of sensed values is only considered. The minimum energy consumed for Node (1) and Node (2) is shown in Table V.

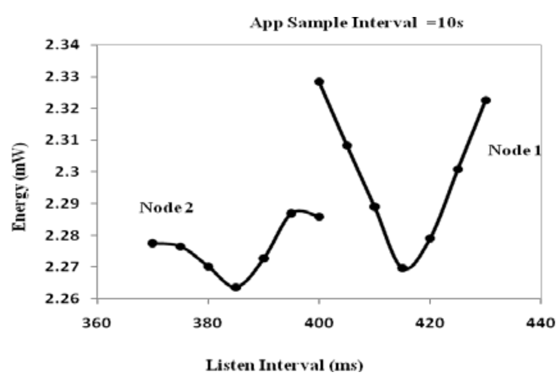

Figure 3. Energy variations with Listen interval

Proper tuning of parameters namely Tx power, Duty cycle, Listen interval makes improvement in energy saving of 2.542% and 1.68% in Node(1) and Node(2) respectively for just 60s of Simulation time.

Table 5. Effect of duty cycle and listen interval in energy variation

Node No. & Location (m)	Tx	Listen interval	Energy at Duty cycle	
			Max 1.0	Min 0.1
0: (25,25,2)	0	400	4.07405	2.30347
1: 26,26,40)	7	400 415	4.07373	2.32842 2.26956
2: 18,18,80)	3	400 385	4.07397	2.28580 2.26355

From the above result it is concluded that, Fix minimum duty cycle since maximum duty cycle will leads to maximum energy, select opt listen interval for both source and sink and it is not necessary to fix the same listen interval for all sources and sink in many-to-one network.

V. CONCLUSIONS

One of the key challenges in physical topology of WSN design is to provide energy efficient communication. For that, study is made by tuning the parameters like Tx power, duty cycle and their correspondence in order to reduce idle listening and unnecessary high transmitting power that can be considered more in case of industrial stack monitoring scenario. From the result obtained, it is concluded that proper tuning of parameters makes improvement in energy saving. The conclusions derived from this study for energy efficient communication in WSN are Fix maximum Tx power for sink, Select opt Tx power and listen interval based on distance between source and sink, no need to fix same Tx power and listen interval for all sources in many-to-one network and Fix minimum duty cycle based on interference.

The simulation time and application sample interval considered in this study is 60s and 10s. Proper tuning of parameters namely Tx power, Duty cycle, Listen interval makes improvement in energy saving of 2.542% and 1.68% in Node(1) and Node(2) respectively for just 60s of Simulation time. To generalize the result, the same study may be extended by tuning both simulation time and application sample interval. These results may be taken as a design guideline for energy efficient physical topology design of WSN.

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