COLORED PETRI NET MODELS FOR CLUSTERED AND TREE-BASED DATA AGGREGATION IN WIRELESS SENSOR NETWORKS

Alaa E. S. Ahmed[1] and Mostafa E. A. Ibrahim[2]

[1,2]College of Computer and Information Sciences, Al Imam Mohammad Ibn Saud Islamic University (IMSIU)
[1]Elec. Engineering Dept., Faculty of Engineering (Shoubra), Benha University;
[2]Comm. and Computer Dept., Benha Faculty of Engineering - Benha University;
e-mails: [1]asmohamed@imamu.edu.sa, [2]meibrahim@imamu.edu.sa
[1,2]Kingdom of Saudi Arabia, [1,2]Egypt

Abstract: Colored Petri Net (CPN) is an influential formalism for describing asynchronous distributed systems. They are straightforwardly articulate the behavior of systems particularly those that are structured of replicated components that independently act in a similar manner. Wireless sensor network (WSN) is a typical paradigm of those systems. In this paper, two CPN models for two frequently used data aggregation approaches in WSNs: cluster and tree-based are modeled. The developed models are evaluated using state space analysis and performance evaluation techniques. Performances evaluation is applied in terms of end to end delay and power consumption metrics.

Key words: Wireless Sensor networks; Petri Nets; Data Aggregation; Cluster and tree structures;

1. INTRODUCTION

Wireless sensor networks (WSNs) are widely elaborated research topic due to their prospective in variety of applications such as environmental monitoring, healthcare, and surveillance [1, 2, 3]. Typically, WSNs are structured from large number of sensor nodes that communicate together and send their sensed data to the sink nodes or base stations. The size of the WSN and the frequency of sending data to the sink nodes depend on the application. Sensors nodes are both power and bandwidth constrained so, it is not practical to send their data directly to the base station. The wireless sensor networks uphold incessant data gathering from sensor nodes which are deployed in the service fields. Neighbor nodes constantly produce redundant and highly correlated data. Thus, multi level aggregation process is needed to suppress this redundancy. The challenge in the hierarchy of aggregating data is to formulate various techniques in a handy and approximate model to design, assess, and evaluate WSN applications. Such formulation is achieved using modeling languages such as Petri net. Petri net is a mathematical modeling language for describing distributed systems. It supports graphical notation for presenting a series of distinct steps such as iteration, selection and most importantly events concurrent execution. They are constructed based on a well structured mathematical model for process analysis.

This paper presents CPN models for two data aggregation methods, tree and cluster-based approaches. In the tree-based data aggregation approach, data flow is represented in the form of an overturned multicast tree where leaf sensor nodes are the sources while the sink node is the destination. In this approach not all data received by source nodes or intermediate nodes are forwarded to the sink node, but redundant data are suppressed and the efficiency of data collection increases. Lack of applying data aggregation leads to problem with the scheduling at the link layer and many repeated collisions occurs [4]. In the cluster-based data aggregation approach, sensor nodes are evenly scattered around the WSN field areas. Clustering techniques are applied to logically divide these nodes into clusters and each cluster has a cluster head (CH) node. In literature, many protocols are existed and employed in selecting the CH per cluster. In each cluster every sensor node disseminates its data to its cluster head node. The cluster heads are the only nodes responsible of applying data aggregation process then send aggregated data frames to the base station.

The principal contributions of this paper are summarized as follows:

- Event-driven CPN models to simulate the behavior of sensor nodes when using tree and cluster-based data aggregation approaches.
- Evaluate and validate the model using state space analysis and performance evaluation of the two approaches in terms of time delay and power consumption.

The rest of the paper is organized as follows: in section 2 related works is presented, the proposed model structure and assumptions are defined in section 3. The CPN of the proposed model is shown in section 4, Section 5 presents the model evaluation and results. Finally, the paper conclusion is presented in section 6.

2. RELATED WORK

This section, presents the recent advances in modeling data aggregation used in WSNs. Recently, Petri-Net has been involved in many WSN applications; such as modeling power consumption [5-8], modeling and detecting congestion [9-10].

Many approaches have been presented for modeling data aggregation in literature. In [11], authors handled the modeling data aggregation in WSN as a scheduling problem. They modeled the main sensor node activities, reading, processing and transmitting as a task-flow graph. They grouped all the sensor nodes task-flow graphs in the form of super task-flow-graph then applied different scheduling algorithms to order tasks within that graph. They target to minimize the number of nodes that apply data aggregation.

In [12], authors presented a formal model of data aggregation within WSN using the Unified Modeling Language (UML). The objective is to enhance the development of WSN applications using an efficient object oriented programming tool such as UML. UML features as use case diagrams, sequence diagrams, collaboration diagrams and activity diagram are employed to analyze data aggregation protocols. The results in this work show that more rapid and efficient WSN applications could be achieved with the help of the object oriented programming tools. Aggregating redundant data process could be achieved by having either spatial or temporal correlation. In spatial correlation, data fusion is applied on neighboring nodes where node location is a major factor that affects the process. While in temporal aggregation is based on applying temporal correlation on data received by the same sensor node in a certain period of time.

In [13], a temporal data aggregation model is provided to predict the successful transmission that reduces redundant transmission and consequently minimize the overall energy consumed by the network. The presented work is based on constructing cluster of nodes and each cluster elects one node to act as a cluster head. A rotation algorithm is used to balance the load among clusters. The value of the prediction error in this algorithm overcomes other similar prediction techniques.

Another prediction model is presented in [14], they developed a data aggregation model based on applying time series prediction model to reduce the number of transmitted information between sensor nodes and aggregator nodes. The model leads to lower battery energy consumption while keeping the aggregated data within a pre-defined threshold error. However, the model performance needs to be evaluated using need one of the famous existing wire sensor network test beds. Cluster and tree- based approaches have been used by researchers when handling data aggregation.

In [15], authors provide a model for efficient data aggregation within wireless sensor network. They adopted the cluster-based approaches where each cluster head decides whether to send or drop the received packet based on a local forwarding history. When data packets arrive at the cluster head, a threshold value is computed based on the local forwarding history then used an indicator of dropping or forwards the packets. The model in this work evaluated using both simulation and analytical modeling. The advantage of using analytical models is to give the WSN designer useful information about the network before starting out the actual real development process.

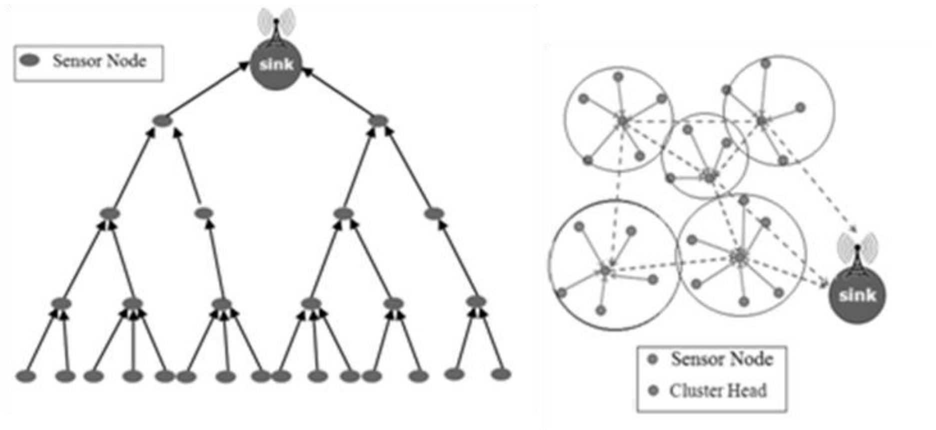
Authors in [16], their work adopted the use of tree-based approach. They focus on maximizing the network life time by constructing a virtual data aggregation trees and applying a scheduling strategy called local-tree-reconstruction-based scheduling algorithm.

However, Petri net is a powerful tool for developing formal models for discrete event systems [17]; the authors have not found Petri net data aggregation models in literature. In this paper, two Petri net models for data aggregation based on cluster and tree approaches are introduced. The proposed two models are evaluated with the aid of two metrics namely End to End delay and power consumption.

3. PROPOSED MODEL STRUCTURE AND ASSUMPTIONS

3.1. Model structure

In this section, the structure of the proposed models is presented to illustrate the behavior of WSNs in case of applying the tree and cluster based data aggregation approaches. The two models utilize the following two structures as shown in Fig. 1.



(a) (b)

Figure 1. (a) Tree based structure (b) Cluster-based structure

In the tree structure as in Fig. 1(a), the direction of data flow starts from any of the source nodes and passes through different intermediate nodes (i.e. communication channel nodes and source nodes) until reaching the sink node. The data aggregation is performed on the sensed data when received by the intermediate nodes. While in the Clustered based approaches, nodes are arranged in two-level hierarchy where the cluster-head nodes form the higher level and the cluster-member nodes form the lower level. Sensor nodes forward sensed data to the corresponding cluster-head nodes. The cluster-head nodes aggregate the data and send them to the sink node (i.e. base station). The topology shown in Fig. 1(b) consists of four clusters; each cluster has a cluster-head node that is chosen based on several parameters such as the residual energy and the distance to the sink node. Cluster-members nodes are either intermediate or source nodes. The direction of data flow starts with the source node and passes through cluster head nodes to forward data to the sink node through communication channels. The data aggregation is performed on the sensed data when received by the cluster heads.

3.2. Model Assumptions

In this paper, M/M/1 queue is considered for the arrived packets with Poisson arrivals where those packets are originated from large population of independent source nodes. The packets arrival rate equals λ. The rate of service time for all nodes is the same. The processing rate for data aggregation equals μ. It is also assumed that there is no mobility attached to either the source nodes or the sink node [18].

Data packets are generated at the source nodes following an exponential distribution with a rate λ. While packets are processed by the node according to an exponential distribution with rate μ. The processing unit of a sensor node serves only one task at any time. The time spent in processing includes two portions, time consumed in the aggregation process and time for the node duty cycle. The time consumed in doing aggregation depends on the number of processed data packets. The time consumed by the duty cycle is computed based on exponential distribution with rate μ. After packets aggregation has been done whether by the intermediate nodes in the tree structure or by the CH nodes in the clustered structure, they are sent to other nodes through the communication channels. Data transmission between neighbors is performed in one hop and it is successfully received if the distance between nodes is within the sender radiation range. Packets loss that is not due to noise or bad connection is not considered in the proposed models.

4. COLORED PETRI NET MODELS

The proposed CPN models for both the tree and cluster based data aggregation structures employed in a WSN nodes are composed of three components, source node, and communication channel and sink node. However, in case of the clustered based approach, the source node may act as cluster head or a cluster member node. Thus, the cluster based structure model is composed of four components.

4.1. Tree based structure model

Hereafter, we describe the CPN model for a WSN source node that employs a tree based data aggregation technique. Figure 2 shows the structure of the WSN source node in case of tree based approach. It consists of six transitions and eight places. Table 1 presents each place and the functions attached to it.

Table 1. CPNs places in source node

Place	Function
"int" & "next"	Generating the input tokens according to exponential distribution with rate λ
"Tvalue_Place" & "Queue_Place"	Representing a FIFO buffer to store the generated tokens (packets)
"PUT"	Routing tokens or packets between "Tvalue_Place" and the "Queue_Place"
"Busy & "idle"	Emulating the processing time which includes the time spent for aggregating the data and performing the node duty cycle.
"After_Agg"	Forwarding aggregated packets to the next module "communication channel"

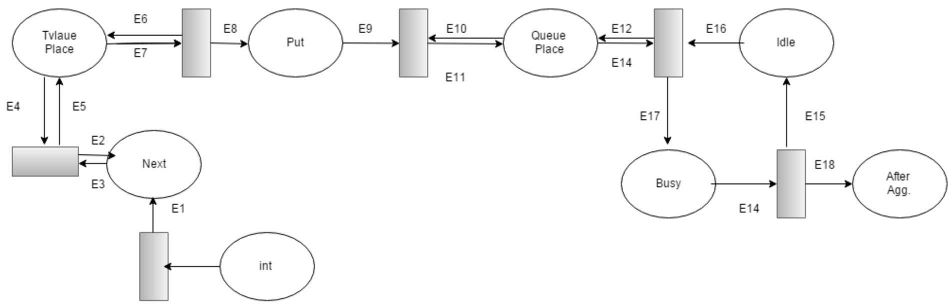


Figure 2. CPN model of the source node

The "int", "next" and "Tvalue_Place" places are employed to generate the packets using exponential distribution. After tokens generation, they move from place "int" to place "next". The value of the sensed physical condition is determined using the place "Tvalue_Place". This value is stored in a FIFO queue represented by "Queue Place". Data aggregation process and the node duty cycle behavior is modeled using the loop formed by the two places "Busy" and "Idel". The time spent within the loop represents the node service time which is exponentially distributed according to the model assumptions.

The CPN model of the communication channel is shown in Fig. 3 in which it consists of three places and two transitions. Table 2 lists the function of each place.

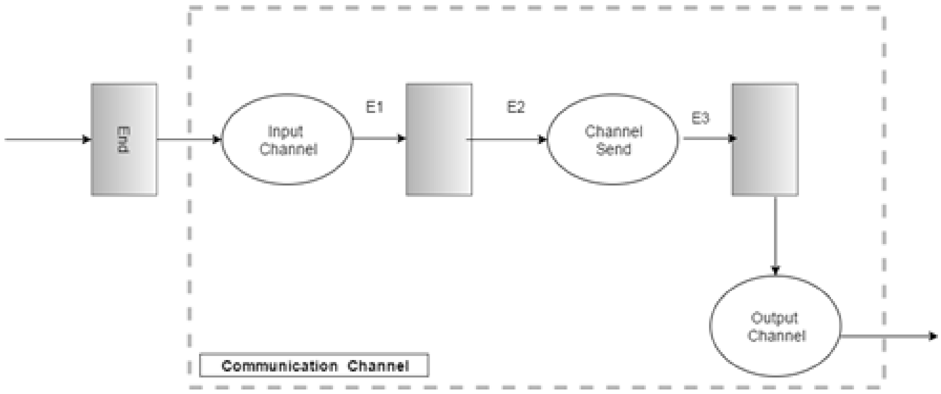


Figure 3. CPN model of the communication channel

Table 2. Places functions in communication channel

Place	Function
Input-Channel	Receive tokens sent by the node
Channel-Send	Receive the packet after applying exponential time delay attached to arc E2.
Output-Channel	Forward the tokens to the next Node

Figure 4 shows the CPN model of the sink node, which contains only one transition and two places. Transition T-Put-sink is fired to allow packet to go through the output sink place.

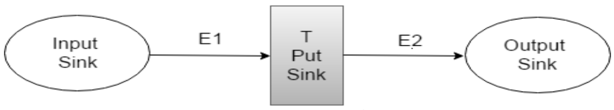


Figure 4. CPN model of the sink node

4.2. Cluster based structure model

Clustering based data aggregation approaches are mostly useful for applications that demand energy efficiency, better network communication and efficient network resources utilization. Currently, in most researches, clustering is a key technique that is used with WSN. Grouping sensor nodes into clusters have been adopted by the research community to achieve highly efficient power consumption and increase the network lifetime [19]. As illustrated in Fig. 1, it is assumed that the nodes are arranged in the network into two-level hierarchy where the cluster-head nodes form the higher level and the cluster-member nodes form the lower level. Sensor or source nodes forward sensed data to the corresponding cluster-head nodes. The cluster-head nodes aggregate the data and send them to the sink node (i.e. base station). Unlike the CPN model of the tree based structure, the CPN model of the clustered based structure consists of four components; cluster-head node, cluster member node, communication channel and sink node. The cluster member node, communication channel and sink node models are similar to the former presented tree structure model. However, the cluster member node is not responsible for aggregating the data. Data aggregation task responsibility is moved to the cluster head node. As illustrated in Fig. 5, the cluster head node model performs two extra tasks than the cluster member node model. First, it receives data either from the environment according to exponential distribution or from the neighboring nodes at the "input" place. Second, it performs data aggregation and communication to sink nodes.

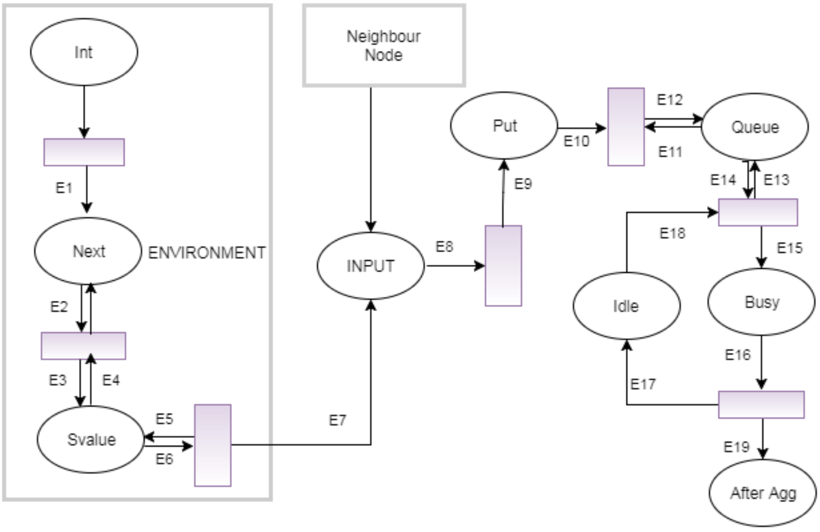


Figure 5. CPN model of the cluster head node

5. EVALUATION OF THE PROPOSED MODEL

To evaluate the proposed models, state-space analysis and performance analysis are adopted. State-Space analysis is used to assess the liveness and fairness properties of the presented models. While, performance metrics such as End-to-end delay and power consumption indicators are used to evaluate the CPN models of both the tree and the cluster based data aggregation structures. Table 3 list the parameters considered in the evaluation process.

Table 3. Simulation parameters considered in the evaluation process

Parameter	Value
Total Simulation steps	5000
Inter-Arrival time (L)	100 sec
Service time (M)	50 to 90 sec
Traffic intensity	0.5 to 0.9

5.1. State space analysis

State-Space analysis is a frequently utilized approach for Petri Nets and consequently for CPN. The ordinary state-space analysis performs an exhaustive search through all possible states. Since the number of states in the proposed models is large, it is more appropriate to apply the state-space analysis in a modular base [21]. The tree structure is composed of three sub models namely; sensor node, communication channel, and sink node. While the cluster-based structure model has four sub models; cluster-member node, cluster-head node, communication channel and sinks node. The resulted reports of the state-space analysis for both the tree-based and the cluster-based data aggregation models are illustrated in Table 4a and Table 4b respectively. The report is constituted of three parts, home properties, liveness properties and fairness properties.

Table 4. State-Space Analysis Reports of data aggregation models

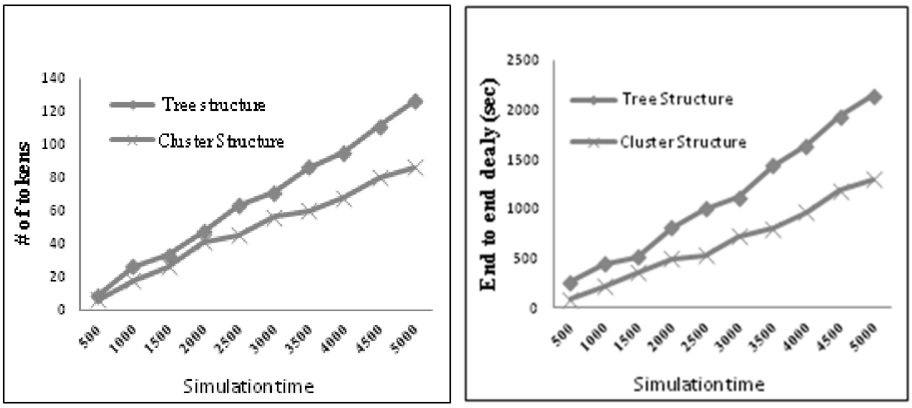
(a) Tree structure	*(b) Cluster Structure*
Home Properties ------------------------------------- Home Markings Initial Marking is not a home marking Liveness Properties -- Dead Markings77422 [9999,9998,9997,9996,9995,...] Liveness Properties -- Dead Transition Instances None Live Transition Instance None Fairness Properties -- No infinite occurrence sequences.	Home Properties ---------------------------------- Home Markings Initial Marking is not a home marking Liveness Properties --- Dead Markings 71263 [9999,9998,9997,9996,9995,...] Liveness Properties -------------------------------------- Dead Transition Instances None Live Transition Instances None Fairness Properties -- No infinite occurrence sequences.

Home markings are those that are always reachable from all other markings. In both models, the initial marking is not a home marking. This is because once the token is received and gets in processing; it is not possible to return back. As such, the two implemented models are concluded to be not cyclic. In other words, the initial marking is used for starting the model execution by generating packets according to their inter-arrival rate through the transition “Int”. The subsequent markings are not permitted to loop back to that initial marking. The second part of the report is related to the liveness properties. The first property is the number of dead markings; A dead marking refers to a token that is able to reach an end state which in turn demonstrates that there is no more enabled transitions to fire. Hence, the presence of dead markings indicates that there are many terminal markings at which all packets have successfully transmitted. The model reports show that the reachability graph of the tree based and cluster based models result in 77,422 and 71,263 dead markings respectively. The remaining properties are the number of dead transitions and live transitions. The state-space analysis reports show that the proposed models have neither dead nor live transition instances. This indicates that every transition in the models is enabled at least once. Also, there is not any transition instance that can be enabled once reaching its final state. Moreover, the reports illustrate that there is not any live transition and thus the models are deadlocks free. The last part of the report represents the fairness property. This property shows that the proposed models have no infinite occurrence sequences.

5.2. Performance analysis

End to end delay and power consumption indicators are two performance metrics used through the simulation of the CPN models to evaluate the validity of the proposed models. In this section, several experiments were conducted to assess the impacts of varying service time parameter on both the end to end delay and power consumption.

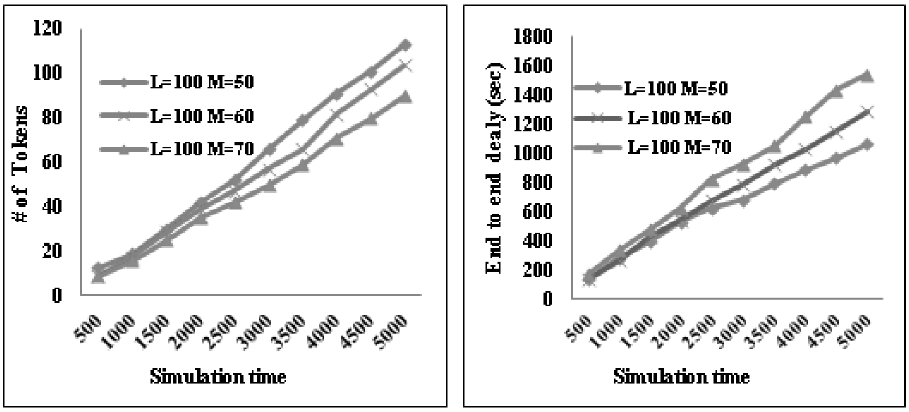
Results in Fig. 6a, and 6b compares the performance of the tree and the cluster structure models in terms of the end to end delay and power consumption. Figure 6a indicates that the time delay achieved in case of the cluster based structure is lower than the case of tree based structure. Figure 6b presents the number of tokens consumed by the models which is adopted as a power consumption indicator. As the number of consumed tokens increases the power consumption level increases. As such, the cluster based structure achieves lower power consumption compared to the tree structure. The reason behind the aforementioned result is that in cluster structure both data aggregation and communication with the sink node are delegated to only the cluster head nodes. Which in turn reduces the tasks performed by cluster member sensor nodes and consequently reduces the power consumed by the WSN.



(a) *(b)*

Figure 6. Comparison between tree and cluster structure models from perspectives of (a) end to end delay (b) power consumption indicator

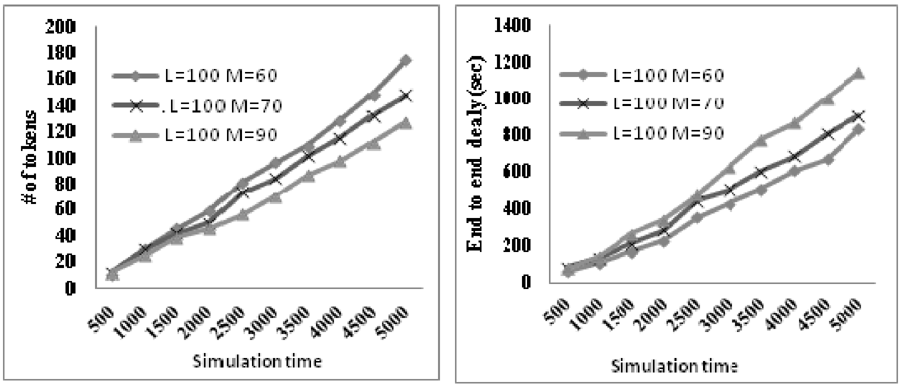
The second experiment studied the effects of varying the service time on both end to end delay and power consumption for the tree and cluster based aggregation structure models. Figure 7a shows the time delay behavior while fixing the packets inter-arrival time and varying the service time. As the service time increases and gets closer to the inter-arrival time the time delay increases. While Fig. 7b shows power consumption in terms of the number of consumed tokens while fixing the packets inter-arrival time and varying the service time. As the service time increases the number of tokens in the system decreases and consequently the power consumed in processing data decreases.



(a) *(b)*

Figure 7. Effect of varying service time for Tree Structure on (a) end to end delay (b) power consumption indicator

Similarly, Fig. 8a and 8b show the effect of changing service time with fixed inter arrival times on the time delay and the power consumption respectively.



(a) *(b)*

Figure 8. Effect of varying service time for cluster based Structure on (a) end to end delay (b) power consumption indicator

5. CONCLUSIONS

In this paper, CPN models for the tree and cluster-based data aggregation structures are presented. The proposed models are evaluated using two methods, by state-space analysis and by performance metrics evaluation. In the first method liveness and fairness properties are investigated while in the second method the end to end delay and power consumption performance metrics are evaluated for the two CPN models. The presented models allow the WSN designer to evaluate the network parameters consistency before constructing and deploying the real system. The state-space analysis illustrates that the proposed models are dead lock free and that all the nodes are reachable. In addition, the performance evaluation demonstrates that the cluster-based data aggregation approach outperforms the tree-based aggregation method in terms of end to end delay and power consumption. As a future work, other data aggregation approaches need to be implemented to form a complete abstract platform that could be used as pre-deployment tool.

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Information about the authors:

Alaa E. S. Ahmed - received his Ph.D degree in computer Science in 2005 from University of Connecticut, USA. His Ph.D was in fault tolerant Real time scheduling. He works as Assistant Professor in the college of Engineering, Computer Engineering Dept., Benha University. His research interests include Distributed systems, cloud computing environment, and wireless sensor network performance evaluation.

Mostafa Ibrahim - received his his PhD in electronics and comm. Eng. from Cairo University, Egypt in conjunction with Vienna University of Technology, Vienna, Austria under a channel supervision grant. He is now an assistant professor at Faculty of Engineering - Benha University, Egypt. His research interests include embedded code optimization from energy consumption perspective, image processing, and WSNs.

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