The Role of Queueing Theory in the Design and Analysis of Wireless Sensor Networks: An Insight

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I. Abstract

Most research on the mathematical modelling of wireless sensor networks (WSNs) have focussed mainly on the optimization aspects, such as those relating to sensor placements, data routing, reliability, etc. Surprisingly the issue relating to performance analysis of data processing and transmission at the nodes, have not received as much attention. A considerable amount of delay to data actually happens at the nodes as a result of queue build up. Hence, understanding the role of queueing in WSN modelling is very important. In this paper we study the literature of queueing as applied to WSNs and provide insight to the current state of the art and directions for the future. The utilization of queueing theory in WSNs is broadly classified into four categories, namely, congestion control methods, power allocation schemes, network performance evaluation techniques and scheduling schemes.

***Index Terms*—congestion control, power allocation, network performance, scheduling, queueing, wireless sensor networks**

II. Introduction

A wireless sensor network (WSN) is a self-organization network that consists of a number of sensor nodes deployed in a certain area. The sensor nodes are light weighted, compact and battery powered devices which consist of three basic components: a sensing subsystem for acquiring data from the environment, a processing subsystem for data processing and storage, as well as a communication subsystem for data transmission. There are a number of different applications of sensor networks in areas such as environmental monitoring, industrial control, disaster recovery, and battlefield surveillance [1]. The major constraint in large scale deployment of WSNs is the limited capacity of processing, storage and energy of the wireless sensor nodes. It is important that the buffer capacity is sufficient to avoid data loss, that the processing capacity is high enough to obtain very good latency, especially for time sensitive data for the Internet of Things, and most important is that processing is limited to times when the system can be utilized efficiently, i.e. energy is conserved through the sleep/awake management of the sensors. In order to effectively carry out the design of many aspects of sensor networks, a very good queueing analysis is important. Queueing theory plays a major role than has been emphasized in the literature.

This paper highlights the value of queueing theory in the design and analysis of WSNs. It reports on the current literature available regarding the application of queueing theory in WSNs and provides an insight on important issues. The literature study classifies the work found into four categories, namely, congestion control methods, power allocation schemes, network performance evaluation techniques and scheduling schemes. Suggestions are then made for future research in this area.

III. Congestion Control Methods

As a result of the limited resources associated with the sensor nodes in WSNs, the quality of service (QoS) parameters are negatively affected. The resource constraints along with the many-to-one communications and event-driven nature of WSNs containing large numbers of high traffic sensor nodes, can cause network congestion. Network congestion takes place when the offered traffic load exceeds the available capacity at any point in the WSN for a period of time. Congestion is one of the highly critical challenges in WSNs and has a profound adverse effect on the QoS parameters and the energy efficiency of the node [1]. The use of queues in alleviating issues related to congestion, mainly occur in the form of queue-assisted protocols, which focus on the queue length of the nodes and use a simple rate adjustment technique to keep the queue length of the nodes as low as possible. A typical congestion control protocol includes three phases: congestion detection, congestion notification and rate-adjustment. Queueing models are primarily used for congestion detection.

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Ding *et al.* [1] proposed an efficient solution for addressing problems related to energy consumption and congestion simultaneously. An important part of the proposed solution is to effectively detect the network congestion. This is achieved by modelling the physical network into an equivalent queuing network model. Another queue-assisted congestion control protocol was proposed by Aghdam *et al.* [2]. The queuing model is used to detect congestion in intermediate nodes and notifies the source congestion avoidance protocol for WSNs. Each node's queue is modelled using the $\sum$MMPP/D/1/S queueing system. This model is used to find the blocking probability and the load of each node. Similar work that utilizes queuing theory to detect congestion for application in proposed congestion control algorithms, include the predictive congestion control protocol developed by Zawodniok and Jagannathan [3]. The proposed protocol predicts and mitigates the onset of congestion by gradually reducing the traffic flow defined by using the queue availability and channel state.

Ren *et al.* [4] utilized queue length and occupancy parameters at sensor nodes in order to develop a traffic-aware dynamic routing protocol to alleviate congestion in WSNs. Similarly, Park [5] used a M/M/1 queue to model network traffic for the proposed congestion aware protocol. A cross-layer active predictive congestion control protocol for WSNs was proposed by Wan *et al.* [6]. Queueing theory is applied to the proposed protocol in order to analyze data flows of a single-node according to its memory status. Wan *et al.* [6] also established the notion that queue length alone is not a sufficient factor to accurately reflect the congestion level at the sensor node. Liang *et al.* [7] proposed a method for congestion detection in which queue length fluctuations are also taken into account when determining the congestion state of a sensor node. A priority queue model is used in modelling the network traffic which is scheduled according to a weighted round-robin scheduler. The $\sum$MMPP/D/1/S by Aghdam *et al.* [2] is more realistic than those by Zawodniok and Jagannathan [3], Park [5], Wan *et al.* [6], and Liang *et al.* [7].

IV. Power Allocation Schemes

WSNs consist of a number of power-constrained devices that are used for sensing and communicating. Power efficiency and operational lifetime of sensor nodes are critical aspects related to the design of WSNs. The sensor nodes that are close to sink nodes have a large forwarding traffic burden and thus consume more energy than sensors that are further away. This creates uneven node power consumption patterns and the energy hole problem arises. This problem is an embedded risk and adversely affects the lifetime security of WSNs [8]. The two prominent techniques used to alleviate this problem and to increase the lifetime of the nodes are through effective sleep/wake-up schemes, and energy efficient routing protocols. Queuing theory can prove to be an effective tool to analyse and design efficient power allocation schemes to increase the power efficiency of WSNs [9]. Sleep/awake models are based on special kinds of vacation models. When the sensor goes to the sleep mode, that means it is switched off and cannot process data. This is essentially a vacation mode. Data arrivals accumulate at the buffer. The node wakes up depending on, the time which is based on a policy of how many packets are waiting (N), how long they have been waiting (T) and the total amount of Kilo-bytes of data (D). These models are classified as N-policy, T-policy or D-policy models. Recently there have been combined versions of these models, such as the NT-policy, and there are research activities going on regarding developing ND, and NDT-policies.

Sleep/wake-up schemes essentially makes use of duty cycle schemes which are used to wake a node up from an idle state to the busy state by turning on the radio server. This plays an important role in the level of power savings in the context of MAC protocols. Kabiri *et al.* [9] derived an analytical model utilizing a M/G/1 queue to model the sensor node; and by altering the queue parameters, different sleep/wake-up strategies were analysed. Some IEEE 802.11 MAC protocols like the sensor MAC, sparse topology and energy management, or the Berkeley MAC utilize a queued wake-up where a threshold value is used to control the average time of switching on a node and the latency for buffered data packets. Determining the optimal value of the packet queue length of a node after which the node is switched on for transmission, is referred to as the N-policy.

A continuous M/M/1 queue using the N-policy method is proposed by Jiang *et al.* [10] as a power-saving scheme to alleviate the energy hole problem. Lee and Yang [11] extended the work presented by Jiang *et al.* [10] to consider discrete-time Geo/G/1 queues under disaster prone environments. The concept of disasters in WSNs relates to unreliable network connections where data packets in sensor nodes are lost by external attacks or shocks. In such scenarios, the N-policy scheme for reducing the power consumption may not be as effective because this policy causes the number of lost packets to increase as a result of increasing queue lengths to reduce the switching between busy and idle modes. This implies that more power is needed for retransmitting these lost packets. Further work based on determining the optimal N-policy scheme was performed by Lee and Yang [11], and Huang *et al.* [12]. A power-saving scheme is proposed by Byun and Yu [13] which involves controlling the duty cycle through queue management in order to achieve high-performance under variable traffic rates in WSNs. Similar queue management policies were utilized by Aby *et al.* [14] and Seo [15].

A different approach for reducing power consumption utilizing queueing theory in WSNs, was performed by Mann *et al.* [16]. The authors characterized the performance of random-walk WSN search algorithms when both agents and queries are assigned expiration times in effort of minimizing the total energy expended by the network. A M/M/∞ queue was used to model the behaviour of the node's event table and transmission queue.

V. Network Performance Evaluation Techniques

Queuing networks are particularly useful for evaluating the performance of networks and serve as an effective way of maintaining the QoS in WSNs. One of the major challenges of sensor networks is the estimation of end-to-end delay which has a significant impact on the performance of real-time applications. Zhang *et al.* [17] modelled a many-to-one WSN as a queueing network, in which each wireless sensor is treated as an independent queue so that all sensors can be analysed separately. A G/G/1/K queueing model is proposed and its closed-form expressions under the protocol interference model when the CSMA/CA MAC protocol is adopted, was derived. For distributed and receiver-oriented sensor networks (DRMA-CSN), Nagendrappa and Takawira [18] studied discrete-time Geom/G/1 and M/G/1 multiple vacation queueing models. Lenin and Ramaswamy [19] proposed a mathematical model to capture an entire given WSN with intermittency introduced between the communication links due to mobility. The model involves open GI/G/1/N queuing networks. Such a model based on queueing networks was also used by Kamarei *et al.* [20].

The evaluation of the reliability of WSNs is also performed using queuing theory. Mizanian *et al.* [21] used a M/M/1/k queue to model the sensor nodes in order to evaluate the reliable real-time degree of WSNs. Similarly, for evaluating the coverage-oriented reliability of WSNs, the same M/M/1/k queue structure was used in [22]. Wang *et al.* [23] proposed a queuing performance evaluation approach based on regular expression match. A M/G/1/K queueing model was also used by Misic *et al.* [24] to model the behaviour of nodes in a beacon-enabled sensor cluster.

A M/G/1 queue-based analytical model was utilized by He *et al.* [25] to evaluate the performance of an on-demand collection scheme. The first-come-first-serve (FCFS) service discipline was utilized in the modelling of the queue; however, due to the randomness of service requests in both the time and space domains, the mobile elements may have to unnecessarily travel back-and-forth thereby increasing data latency. He *et al.* [26] extended their own work by modelling the data collection process as a M/G/1 queue but with a nearest-job-next (NJN) based service discipline. This model is shown to outperform FCFS. A closed queueing network was employed by Al-masaeid and Kamal [27] to evaluate the data latency of mobile agents aiding in data collection for WSNs. Jie *et al.* [28] proposed a communication task scheduling evaluation model in which pre-emptive priority queues are used for simulating and analyzing typical WSNs. Another similar application of queueing theory is employed by Wang *et al.* [29].

VI. Scheduling Schemes

Scheduling in WSNs refers to the process of deciding where to place resources between a selection of possible tasks. The need for a scheduling algorithm arises from the requirement of most modern systems to perform multitasking and multiplexing. The main criteria for a good scheduling algorithm depends on factors such as fairness, efficiency, response time, turn around-time and throughput. Most existing WSNs use first-come-first-serve schedulers, which process data packets in the order of their arrival time [30].

In fair scheduling, data packets are classified into flows by the system and then assigned to the queue. The queues are then serviced one packet at a time in a round robin fashion and empty queues are rejected. Jagabathula and Shah [31] proposed a new algorithm for fair scheduling in which packets are scheduled based on a maximum weight schedule with the urgencies of the queues modelled as the weights. Another queueing based scheduling mechanism utilizing priority queues is proposed for application to cluster-based hierarchical-routing in WSNs [32].

In order to alleviate the high processing overhead and long end-to-end delays that are incurred in WSNs with the use of most existing first-come-first-served, nonpreemptive and preemptive priority scheduling algorithms, Nasser *et al.* [33] proposed a dynamic multilevel priority packet scheduling scheme. A similar three-class priority packet scheduling algorithm for large scale wireless sensor networks is proposed by Karim *et al.* [34]. The algorithm was shown to outperform FCFS and multi-level queue schedulers in terms of end-to-end delay. A different scheduling scheme that is based on different *grades* of channel side information is proposed by Srivastava and Koksal [35]. A transmission controller is designed that utilizes these different *grades* to schedule packet transmissions in an optimal way, while meeting a deadline constraint for all packets waiting in the transmission queue. Jiao *et al.* [36] designed a virtual queue-based back-pressure scheduling algorithm for achieving delay reduction in WSNs.

VII. Conclusion

In conclusion, literature pertaining to the application of queueing theory in WSNs has been investigated and reviewed. Table I summarises the literature associated with each of the four sections. It was found that several congestion control protocols utilize queuing models to detect congestion in networks which often constitutes the first phase of congestion control protocols. Queueing theory was also found to be an effective tool to analyze and design efficient power allocation schemes to increase the power efficiency of WSNs. Queuing networks are also particularly useful for evaluating the performance of networks and serve as effective way of maintaining the QoS in WSNs. Several scheduling schemes for WSNs utilize queueing based structures for the development of scheduling algorithms.

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TABLE I
SUMMARY OF LITERATURE STUDIED

Section	Related papers
Congestion control methods	[1], [2], [3], [4], [5], [6] and [7]
Power allocation schemes	[9], [10], [11], [12], [13], [14], [15] and [16]
Network performance evaluation techniques	[17], [18], [19], [20], [21], [22], [23], [24], [25], [27], [28] and [29]
Scheduling schemes	[30], [31], [32], [33], [34], [35] and [36]

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