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# A Framework for Energy based Performability models for Wireless Sensor Networks

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***Abstract*—A novel idea of alternating node operations between Active and Sleep modes in Wireless Sensor Network (WSN) has successfully been used to save node power consumption. The idea which started off as a simple implementation of a timer in most protocols has been improved over the years to dynamically change with traffic conditions and the nature of application area. Recently, use of a second low power radio transceiver to triggered Active/Sleep modes has also been made. The idea of Active/Sleep operation modes has also been used to separately model and evaluate performance and availability of WSNs. The advancement in technology and continuous improvements of the existing protocols and application implementation demands continue to pose great challenges to the existing performance and availability models. In this study the need for integrating performance and availability studies of WSNs in the presence of both channel and node failures and repairs is investigated. A framework that outlines and characterizes key models required for integration of performance and availability of WSN is in turn outlined. Possible solution techniques for such models are also highlighted. Finally it is shown that the resulting models may be used to comparatively evaluate energy consumption of the existing motes and WSNs as well as deriving required performance measures.**

## I. INTRODUCTION

In Wireless Sensor Networks a large number of low cost sensing nodes interconnected via wireless radio channels are sparsely deployed in the habitat of interest to form an ad hoc wireless network. In most cases sensors self configure to align themselves with the topology of interest once deployed. As low-end devices sensors monitor their habitat and forward observed measurements to the fusion centres (Sink) either directly or by hopping through neighbouring nodes towards the Sink. Wireless Sensor Networks have continued to find use in diverse application areas including; habitat sensing, infrastructure monitoring, target tracking, smart factories, battlefield surveillance, environmental monitoring, smart agriculture and many other areas. This diversity in application areas has brought with it numerous performance and availability/reliability challenges as well.

The main concern has been limited energy normally supplied through use of batteries attached to the sensors. A number of schemes have been proposed to save energy in WSNs. These include implementation of sleep schedules within MAC [1] and [2] and routing [3] protocols and also in other layers. Hardware developers have also continued to improve devices with the aim of achieving low levels of energy consumption and efficiency [4].

The reliability and availability of WSNs have been considered in studies such as [5], [7]. In addition, schemes have also been proposed for repair and replacement of failed nodes [8] as well as repair of network holes [9]. Various energy harvesting mechanisms such as the use of solar systems has also been proposed [6] and [7].

In order to address issues of performance and availability/reliability, independent studies continue to be carried out in the various areas of concern [10], [11] and many others. Since these studies are carried out assuming other factors do not affect the system, a number of performance and reliability related concerns remain unresolved. The novelty of this study is therefore to identify relevant performance and availability concerns which require integration into the models of study if meaningful results are to be obtained for better WSN quality of service in the presence of mote failures. To this end an integrated study of performance and availability is highly recommended. To the best of our knowledge, this is the first framework presenting the need for performability studies for WSN in order to address modelling issues resulting from independent availability and performance studies while at the same time reflect the gains in energy saving. The rest of the paper is organised as follows; section II reviews past and related studies, Section III presents system description and assumptions, section IV presents system model while energy computation is presented in section V. Finally the work is concluded in section VI with highlights of possible extensions.

## II. PAST AND RELATED WORK

### *A. Sleep Wakeup schemes in wireless Sensor Networks*

The main challenges that should be considered in design and operation of WSNs include network wide longevity and maintenance after deployment [13]. In both cases energy conservation is paramount considering the fact that sensor nodes are equipped with limited battery power. In order to address these concerns, several power saving schemes have been proposed. One scheme widely used in several energy saving protocols is to alternate operations of sensor nodes between Active and Sleep modes. This may be implemented by either integrating duty cycling within MAC protocols [12], [14] or by use of independent Active/Sleep protocols on top of MAC layer, for example at the application or network layers. Independent Active/Sleep protocols may further be divided into on demand, scheduled and asynchronous wakeup mechanisms. On demand schemes make use of a second low power radio transceiver to monitor channel for arriving data packets and wakeup the receiving node before data is received [4]. This mechanism is known to be very efficient though not commonly used because many sensor platforms only have one radio transceiver. In scheduled wakeup mechanism the low power sleeping nodes are required to be in synchronism hence they wake up at the same time periodically to communicate between themselves [14], [16], [17]. Finally in asynchronous wakeup mechanism clock synchronization is not required and the nodes follow their own wakeup schedule while in the idle state as long as the wake up intervals among neighbours overlap [19], [20]. Whilst the choice of a particular power saving scheme may depend on application areas, the underlying trade-offs need to be considered for optimal performance.

### B. *Routing protocols and related models*

In studies such as [23], [25], energy conservation routing protocols have been developed to improve WSN performance. In [23] PEGASIS was developed as an improvement of LEACH. A comparison of LEACH, PEGASIS and VGA was carried out in [26] where it was noted that PEGASIS outperforms the other two while LEACH performs better than VGA. However VGA turned to be best in power saving when sensing range is wider. Further comparative studies about routing protocols have been carried out in [27], [15]. In [15] it is noted that since sensor networks are application specific and may require use of a particular protocol, no protocol is listed as better than the others. A systematic review on clustering and routing techniques based upon LEACH protocols for WSNs is presented in [25]. In this study a comprehensive discussion is provided in the text highlighting the relative advantages of many of the prominent proposals in this category in order to enable designers make informed choices based on merits. Further analysis of LEACH energy parameters is also presented in [30] while a new clustering approach in Wireless Sensor Networks based on LEACH is presented in [31]. In order to conserve node power and prolong network lifetime, routing protocols that switch off nodes along inactive links have been proposed in [3]. From the preceding discussions, the need for further improvement of existing routing protocols as WSN application demands widen remains a big challenge if energy is to be conserved and a better quality of service is to be maintained.

### C. *Availability/Reliability Modelling*

Various approaches have been proposed in the literature in order to maintain good quality of service after deployment. Authors in [32] proposed use of mobile sinks for collecting data packets from the fixed monitoring nodes. In another study robots have been proposed for repairing failing nodes and broken network connections (holes) [8], [9]. Other studies have also recommended use of redundant nodes deployed at inception to be used to replace failed nodes [33]. The redundant nodes are to be kept inactive until until need arises. In addition, on board solar panels have been used to re-charge the sensor batteries thereby prolonging sensor life time for a longer span [6]. Fault tolerant systems have also been developed to make WSN systems more resilient to operational effects [10], [5]. Noting that distributed detection applications for WSNs have limited time to collect and process local decisions to produce a global decision, In [35] a high reliability scheme for collecting and processing location information which would otherwise not be possible if left to WSN is proposed. The idea is accomplished by incorporating a reliability based splitting algorithm into the random access protocol of WSNs. A study carried out in [36] considers the problem of infrastructure communication reliability (ICR) of wireless sensor networks (WSN) on sink-manycast and sink-anycast model. Authors formulate ICR metrics for WSN with hierarchical clustered and tree topology base on a reduced ordered binary decision diagrams (ROBDD) approach. Their results depict WSN with anycast as the most reliable compared to broadcast which is the least reliable.

### D. *Performance Modelling*

Performance modelling and analysis continue to play a very important part in supporting research as well as design, development and optimization of computer and communication systems and applications. The use of WSNs in various application areas also calls for performance and availability modelling for optimization purposes. In [11] authors present a Markov model for WSNs whose nodes may enter sleep mode and use it to investigate system performance in terms of energy consumption, network capacity, data delivery and delay. This model presented a trade-off which exists between performance metrics and sensor dynamics in sleep/active modes. In [40], a new evaluation method for optimising packet buffer capacity of nodes using queuing network model was presented to improve the transmission QoS. However, the effects of node failures on network performance were not considered. Using M/M/1 queue in tandem, a model for convergence of WSNs and Passive Optical Network (PON) is proposed in [41]. The results indicate the effects of the PON and WSN dimensions on average queue length hence recommended as a guideline for resource allocation. In an earlier study [42], the need for integrated performance and availability studies is highlighted and a single queuing model is used to evaluate performance of a cluster head in the presence of failures and repairs. The study is further improved in [43] where the limiting capacity of various sensor nodes is analysed for use in different application environments.

In order to further conserve and evaluate energy, authors in [46] have proposed WSN models and used them to analyse network performance and to evaluate residual node power. Energy evaluation for WSNs with mobile sinks is presented in [32]. Other models for WSN were proposed in [47] where a novel performance evaluation method employed examines all probability mass function (pmf) trajectories in a dense Euclidean space by exploring only finite relevant portions of the space. In [10] a fault tolerant sensor node model for applications with high reliability requirements is proposed. In this study Markov models characterising WSN reliability and Mean Time To Failure (MTTF) are presented for facilitation of WSN application specific design. Impact of finite buffers on Cluster tree based WSNs are considered and a comprehensive analysis of the end to end delay, reliability and power consumption are presented in [49] using various traffic and network conditions. Delay distribution in IEEE 804.15.4 is shown to depend mainly on the MAC parameters [50]. In the preceding research work, it is clear that performance and availability studies have continued to be studied independently. The need to integrate performance and availability of WSN system as proposed in our earlier studies [42] and [43] is therefore very important if an optimised system operation is to be achieved.

### *E. Wireless Sensor Network Performability Modelling*

Performability modelling has widely been used in literature to study systems which exhibit failures during operations and are repairable [52]. For such systems it is preferable to model their behaviour in a manner that accounts for performance degradation and availability together. In wireless Sensor Networks minimal work has been reported in this area [54]. Majority of studies consider availability and performance independently. Pure availability systems tend to be conservative while on the other hand pure performance models tend to over estimate systems ability to perform since they assume the systems never fail. In order to establish more realistic results integrated studies of performance and availability are highly recommended [55].

Wireless Sensor Networks like others continue to face numerous challenges in addition to the well known energy limitation. Though this makes performability studies more complicated, it remains a novel idea that would eliminate and improve WSN quality of service in many application area. Our earlier studies in [42]and [43] clearly show that WSN performability related issue like, throughput, delay, and queue length capacity can be considered in the presence of failures and repairs.

## III. SYSTEM DESCRIPTION AND ASSUMPTIONS

As a case study, a Wireless Sensor Network of $Y$ stationery, identical nodes is considered.The nodes are organised into a group of $K$ Clusters, each with one CH coordinating cluster operations. In order to enhance reliability and availability of the network, the cluster head operations is rotated among strategically deployed full function nodes. The choice of the CH is based on node energy levels and other metrics deemed appropriate [11]. To conserve energy, CHs rotationally go to sleep after transferring operations to the next CH. For this purpose, use of the best energy saving protocols like UHEED [57] is assumed. The system is also assumed to have redundant sensor nodes deployed at inception but kept inactive until the need to replace a failing node arises [10]. It is further assumed that all nodes are equipped with omnidirectional antennas with same radius ($d$) and can communicate directly with the CH based on the Zigbee 802.15.4 standards. To reduce the energy consumption further, nodes are capable of choosing an arbitrary transmission power level as long as the radius $d$ is not exceeded.

Information sensed and aggregated at the nodes are forwarded to the CH which finalises cluster data aggregation. The CHs may also generate data packets based on their observations. The total information is then transmitted by the CH to the sink directly or through other intermediary CHs. It is assumed that at least one path exists towards the sink [11]. Like other communication networks, this system is subject to failures which may result from hardware, software and channel link errors. Figure 1 shows the system scenario in consideration.

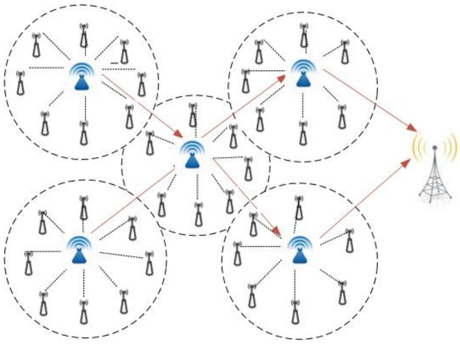

Fig. 1. Network topology of the reference scenario

A closer look at the operations of the CH indicate several possible operative states including active and sleep modes implemented in several protocols in order to conserve the limited power available for node operations.

### *A. Cluster Head Node Behaviour*

In this section two scenarios are considered. In the first case, asynchronous dynamic MAC protocols (Adaptive Duty-Cycling) used for implementing Sleep schedule in sensor nodes are considered [1], [48]. However in the second case on demand sleep scheduling protocols are considered. The main goal for using active and sleep modes in both cases is to save on sensor power as illustrated in previous researches [46] [44] [11]. In both cases the CH or the channel may fail while operating in any state. In the event of such failures, the CH or Channel is taken into repair and system operations restored only once repairs are completed.

*1) Adaptive Duty-Cycling Scheme:* Adaptive duty cycling schemes are known for adjusting sleep wakeup periods depending on the observed operating conditions. Several implementation approaches have been proposed in literature [48], [14], [3].

In figure 2, a block diagram is presented to illustrate the possible states of the CH operation. The operative states are broadly represented in three categories as; Active mode, Sleep mode and Node Failure mode. The active mode is further divided into Full operation (Denoted by phase R) and Reduced operation (Denoted by phase N) phases. During normal operations the CH switches back and forth between Active and Sleep modes. The two modes operate for a time period modelled as random variables exponentially distributed with parameters $\alpha$ and $\beta$ respectively. While in the active mode, the CH may either be in phase (R) or in phase (N). In phase (R), the CH may receive and transmit data packets or idle if there are no data packets to be processed. Depending on the prevailing conditions the CH may;

a.) The CH goes to sleep mode (phase S) if active mode period expires and there are no jobs remaining in the system to be processed.

b.) If there are jobs remaining in the system at the expiry of active period, the CH continues to process and transmit the jobs in the system (reduced operation state) and enters sleep mode at the transmission of the last data packet.

c.) While operating in any of the Active phases, the CH may fail as a result of corrupt software configuration, battery power depletion, and hardware malfunctions. In case of a failure, the CH is restored back to the active state once the repair is complete.

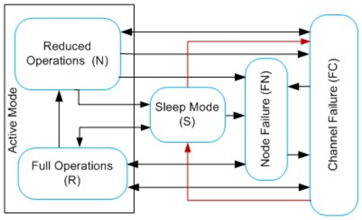

Fig. 2. Phase transition diagram of Cluster Head using dynamic MAC protocol sleep schedule scheme

During Sleep mode, the CH is completely cut off from network activities. It does not receive or transmit data packets. It is assumed to be in its lowest power consumption state. The CH only switches back to full active phase at the expiry of sleep period. In order to explicitly explain the models proposed, the following assumptions and notations are introduced for the sensor node under investigation.

a.) The duration a CH takes operating in full-active phase (R) is a random time distributed exponentially with a mean of $1/\alpha$ . During this period, the CH may:
    i.) generate packets following Poisson distribution with rate $\lambda$.
    ii.) receive data packets originating internally from cluster nodes and externally from other CHs. Packet arrival distribution at the CH is assumed to follow Poisson process with rate $\lambda_k$ .
    iii.) process and transmit or relay data packets with random exponential time with a mean of $1/\mu$ .
    iv.) be in idle state while listening to the wireless channel in readiness to receive arriving data packets. In this state all the internal circuitry is kept ready to operate.

b.) At the elapse of full-active phase R, the CH may transition to sleep or Reduced-active phases. In order to enter reduced-active phase, there must be at least one data packet in the system waiting to be processed. In reduced active phase $(N)$ the CH may only process and transmit the remaining data packets in the system following an exponentially distributed service time with a mean of $1/\mu$. It is not possible to generate or receive any relayed external data packet. After the transfer of all data packets in reduced-active phase, the CH automatically enters sleep mode. Phase N therefore allows the sensor to adapt to traffic conditions and prevent network instability due to overloading [11].

c.) The duration the CH takes in sleep mode is distributed exponentially with a mean of $1/\beta$ . While in sleep mode, the sensor is completely cut off from the rest of the network. At the expiry of the sleep mode, the sensor automatically reverts to full-active phase (R).

d.) The CH can deal with one activity at a time and the order of service is based on First Come First Served basis $(FCFS)$.

e.) Considering the memory limitation of the CH, a finite buffer length of L is assumed.

f.) In the event of a failure, the CH is taken into repair immediately. It is assumed that a backup CH installed at inception takes up all the responsibilities of the CH until a new choice of CH is made from the remaining Cluster nodes [34].

*2) On demand Wake-Up Scheme:* In figure 3, on demand wake-up schedule is considered. In this scheme a second low power radio transceiver is used to continuously monitor the channel for any packet arrivals while the main radio transceiver is put to sleep. In this scenario, the cluster head goes to sleep automatically following service end for the last job in the system and wakes up each time a new arrival occurs [4]. Service and arrival distribution times remain exponentially distributed. The main difference in the two cases is the elimination of reduced operation state seen with duty cycled schemes. In this scenario the cluster head stays active for as long as there are jobs to be served. Service priority also remains First in First Served (FCFS) as in the case above. Also in a similar manner the CH may Fail and be taken for repairs immediately and restored back to the system as a full function node only when the repair is complete.

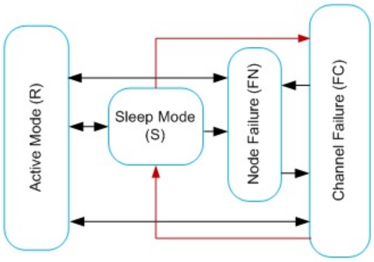

Fig. 3. Phase transition diagram of Cluster Head using on demand Sleep Scheduling schemes

*3) Periodic duty cycling Scheme:* This scheme has widely been used by the MAC protocols to periodically put the sensors to sleep and wake them up in order to reduce energy wastage during idle listening. In this scheme time synchronization is required to enable nodes sleep and wake up at the same time. This scheme has been found appropriate with high data rates though it tends to waste a lot of energy when used with low data rate applications. In this scheme, data generation rate is more of deterministic at the nodes [18]. At the cluster head however depending on the application area, the cluster head may be configured to receive data packets from the nodes based on the deviations from the previous readings. These eventually tend to follow exponential distribution considering that their arrival time at the server can never be determined. In this category however, the nodes require overhead for exchanging sleep/wake-up schedules with neighbouring nodes and can be very significant when the network data packet is light [2].

### B. Packet arrival and service distribution

In this study it is assumed that packet arrival at the cluster head follow Poisson distribution and service times are exponentially distributed. In earlier research studies, these assumptions do not always hold [59], [60]. The distribution of packet arrival is found to be mostly influenced by the nature and area of application due to the varying quality of service and reliability requirements [61]. Classification of arrival distribution models include constant bit rates, Event driven, Query driven and Hybrid-based data delivery models. Though in most studies Poisson distribution is employed, it might not suit all categories depending on application environment. It is therefore important to appropriately map the application environment with the most appropriate distribution model if meaningful results are to be achieved.

## IV. SYSTEM MODELLING

### A. Model Choice

In a cluster based WSN topology, the CH is the central point of communication between the cluster nodes and the sink. All cluster nodes are assumed to be directly connected to the CH. The CH connects either directly or through other CHs to the sink forming an overall cluster tree network. The nodes independently monitor their habitat and contend with others for channel availability to relay their observed data to the cluster head. It is assumed that the CH is not aware of the next arrival source until the arrival actually occurs. Due to limited memory capacity of the CH, it is assumed that any data arriving when the CH buffer is full is not allowed in the system and is automatically dropped.

In this model, the total arriving data at the CH originate from within the cluster (internal sources) and externally from other cluster heads (external sources) forwarding their data to the sink. From IEEE 802.15.4/Zigbee standards, a maximum of 36 nodes is recommended per cluster for better performance. This is confirmed in [42] where performance measures were analysed by varying arrival rates and sensor node density per cluster. In this scenario, more than 30 nodes inclusive of the CH are considered. Since we have relatively large number of independent Poisson streams, the resulting superposition of all the arriving jobs at the CH from both internal and external sources follow Poisson distribution [53] with rate $\lambda_k$ where $k$ stands for the CH (node $k$ ). The total arrival may be represented using equation 1 below.

$$\lambda_k = \sigma_k + \sum_{r=1}^{K} \lambda_r q_{r,k}; \qquad k = 1, 2, \dots, K \tag{1}$$

Here $\sigma_k$ is the sum of all internal arrivals and may be expressed as:

$$\sigma_k = \sum_{n=1}^{N} \lambda_n q_{n,k} \qquad n = 1, 2, \dots, N$$

The term $\sum_{r=1}^{K} \lambda_r q_{r,k}$ represents the externally arriving jobs from other CHs. From equation 1, a set of linear equations for the unknown quantities of $\lambda_k$ may be acquired. Once the system model is developed an appropriate queueing system may then be employed to analyse steady state operation conditions.

### B. Solution Approaches

Several solution approaches exist that may be used to solve the linear equations resulting from the models explained in sections above. Examples for the solution approaches that can be employed include Seleens method which gives an approximate solution for the QBD and QBD-M systems, Block Gauss-Seidel iterative method, Matrix geometric solution method and Spectral expansion exact solution technique.

Spectral solution technique has successfully been used [55], [52] to solve and analyse certain two-dimensional Markov processes in semi-infinite or finite lattice strips. Researchers therefore have a wide range of solution techniques from where appropriate choices can be made. From the sate probabilities, a number of steady state availability, reliability and performance measures can easily be computed.

## V. ENERGY COMPUTATION

Energy consumption remains as one of the main focus areas in WSNs considering their limitations and area of application. In order to conserve the available energy, a number of energy saving schemes have been employed starting from sleep schedules implemented within MAC protocols [12]routing protocols [63], [64] and hardware's used. Existing controllers and radio systems used have varied consumptions and sensitivity gains which may be of great interest when implementing WSNs in given application areas. In this study we consider a generic approach that may be used to evaluate all clustered systems.

Appropriate performability models and relevant solution approaches for steady state probabilities, can be of great help in order to compare the energy consumption of WSN configurations. Similar studies in this area have been reported in [45], [46] and [62]. In this work mean energies consumed to transmit and receive data packets from a single state is considered. With this information, mean energy consumed in a given mode during the period of operation can easily be computed. Residual energy of the CH can also therefore be computed at any given time during operation.

Using this information, energy models can be developed based on inputs derived from the performability model. The analytical models in turn may be used to evaluate and optimize performance as well as energy consumption levels. The need for such an integrated system is very important if appropriate performance levels are to be achieved in various application environment. Finally there is need to evaluate the trade off's between availability, performance and energy consumption in various application environments.

The models developed can be used to comparatively analyse performance and evaluate energy consumption of various existing controllers and transceivers hence enabling the choice of mote models for various application environments.

## VI. CONCLUSION

In this paper, the development of techniques for saving WSN energy are highlighted. The influence these have on performance and availability models are also highlighted hence the proposal for integrated studies of availability and performance. A framework covering all modelling components necessary for a comprehensive performability study is then presented with details of the various components.Taking a case of cluster head behaviour, a model is presented and proposals are provided to identify how performance and availability measures may be computed and models used to evaluate network and Cluster head energy. In this paper however no solution has been provided and those interested are encouraged to make their own choice of working out either simulation studies, analytical studies or integrating the two. The framework presented is useful for extending existing analytical as well as simulation studies.

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