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Modelling the Energy Efficient Sensor Nodes for Wireless Sensor Networks

R. Dahiya · A. K. Arora · V. R. Singh

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Abstract Energy is an important requirement of wireless sensor networks for better performance. A widely employed energy-saving technique is to place nodes in sleep mode, corresponding to low-power consumption as well as to reduce operational capabilities. In this paper, Markov model of a sensor network is developed. The node is considered to enter a sleep mode. This model is used to investigate the system performance in terms of energy consumption, network capacity and data delivery delay.

Keywords WSN · Markov model · Sensor model

Introduction

Sensor networks have a large number of sensing devices, which are equipped with limited computing and radio communication capabilities [1]. Although sensors may be mobile, they can be considered to be stationary after deployment. A typical network configuration consists of sensors working unattended and transmitting their observation values to some processing or control center, the so-called sink node, which serves as a user interface. Due to the limited transmission range, sensors that are far away from the sink deliver their data through multihop communications, i.e., using intermediate nodes as relays. In this case, a sensor may be both a data source and a data router. Most application scenarios for sensor networks involve battery-powered nodes with limited energy resources. Recharging or replacing of the sensors battery is inconvenient, or even impossible in harsh working environments. Thus, when a node exhausts its energy, it cannot help but ceases sensing and routing data, possibly degrading the coverage and connectivity level of the entire network. This implies that making good use of energy resources is a must in sensor networks. Various solutions have been proposed to reduce the sensors energy expenditure with the energy saving viewpoint. A widely employed technique is to place nodes in a low-power operational mode, the so-called sleep mode, during idle periods. In idle state, sensors do not actually receive or transmit, nevertheless they consume a significant amount of power. In sleep mode, some parts of the sensor circuitry [e.g., microprocessor, memory, radio frequency (RF) components] are turned off. As more circuitry components are switched off, the power consumption as well as the operational capabilities of the sensor decreases. A sensor network with stationary nodes convey the gathered information to the sink node through multihop communications. Each sensor is characterized by two operational states: active and sleep. In active state, the node is fully working and is able to transmit/receive data, while in sleep state, it cannot take part in the network activity; thus, the network topology changes as nodes enter/exit the sleep state [1–20].

Markov model of a sensor network is developed here. The nodes are considered to enter a sleep mode. This model is used to investigate the system performance in terms of energy consumption, network capacity and data delivery delay.

R. Dahiya (✉) · V. R. Singh
Prabhu Dayal Memorial College of Engineering, Bahadurgarh, Haryana, India
e-mail: dahiya_rajiv@yahoo.com

A. K. Arora
Manav Rachna International University, Faridabad, Haryana, India

System Considerations

In this paper, the following assumptions are made for the development of the energy efficient wireless sensor network (WSN) system.

Sensor Node Distribution

A network composed of N stationary identical sensor nodes and sensors are uniformly distributed [1] over a disk as shown in Fig. 1.

Network Topology

Network topology of the reference scenario of unit radius is in the plane. The sink node collecting all information gathered by the sensors is located at the center of the disk. An example of network topology is shown in Fig. 1 for $N = 200$. All nodes are assumed to have a common maximum radio range r which is equipped with omni directional antennas. Nodes can choose an arbitrary transmit power level for each data transmission, provided that their transmission range does not exceed r. The information sensed by a network node is organized into data units of fixed size that can be stored at the sensor in a buffer of infinite capacity; the buffer is modelled as a centralized FIFO queue. Sensors cannot simultaneously transmit and receive; the time is divided into time slots of unit duration and the transmission/reception of each data unit takes one time slot. The wireless channel is assumed to be error-free, although our model could be easily extended to represent a channel error process [17].

Sensing and Communication

The main functions (and hence causes of energy consumption) in a sensor node are sensing, communication and data processing. Correspondingly, different operational states for a sensor can be identified. Two major operational states are considered: active and sleep. The sleep state corresponds to the lowest value of the node power consumption; while being asleep, a node cannot interact with the external world. The active state includes three operational modes: transmit, receive, and idle. In the transmitting mode, energy is spent in the front-end amplifier that supplies the power for the actual RF transmission. In the receiving mode, energy is consumed entirely in general, several sleep states could be defined considering that each sensor component may have different power states. In the idle state, a node typically listens to the wireless channel without actively receiving. In idle mode, energy expenditure is mainly due to processing activity, since the voltage controlled oscillator is functioning and all circuits are maintained ready to operate. An energy cost Et is associated with each transition from sleep to active mode, while the cost of passing from active to sleep mode can be neglected [10]. Et is assumed as twice the energy consumption per time slot in idle mode (Fig. 2).

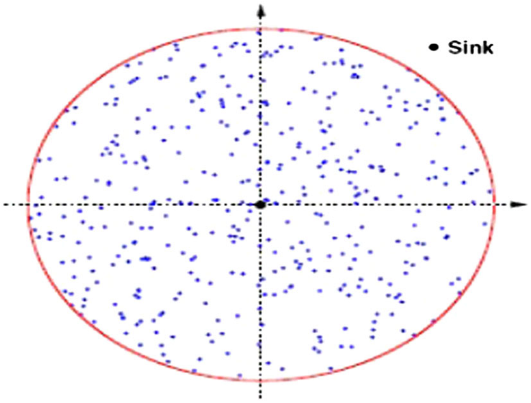

Fig. 1 Network topology of the reference scenario

Routing Topology

Sensor networks are those whose nodes have already performed the initialization procedures necessary to self configure the system. Therefore, sensors have knowledge of their neighbouring nodes, as well as of the possible routes to the sink. Since a network of performing stationary nodes is considered, for instance, environmental monitoring and surveillance, the routes and their conditions can be assumed to be either static or slowly changing. The sensors can communicate with the sink using multiple routes. Each sensor constructs its own routing table where it maintains up to M routes, each of which corresponds to a different next-hop node (hereinafter just called next-hop) and is associated with a certain energy cost. The routing table might contain a smaller number of entries if the sensor has less neighbours. When a sensor wants to transmit a data unit, it adopts the routing strategy (although other strategies could be considered as well). The node polls its next-hops giving priority to the routes associated with the lowest energy cost, until it finds a next-hop that is ready to receive.

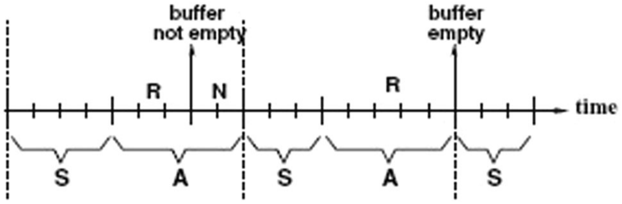

Fig. 2 Temporal evolution of the sensor state

Thus, a sensor always dispatches its data units to the best next-hop among the available ones [11].

Transmission

For a transmission over one hop, let nodes i and j ($1 \leq i \leq N$, and $0 \leq j \leq N$ with 0 indicating the sink) has the transmitter with the receiver. The transmission is successful [13] if

(a) The distance between i and j is not greater than r, $di, j \leq r$
(b) For every other node, k, simultaneously receiving, $di, k > r$
(c) For every other node, l, simultaneously transmitting, $dl, j > r$.

To avoid unsuccessful transmissions, sensors employ a CSMA/CA mechanism with handshaking, as in the MACA and MACAW schemes although other MAC protocols could be considered as well), and that the radio range of handshaking messages transmission is equal to r. If i wants to transmit to j and senses the channel as idle, i sends a transmission request to j and waits till either it receives a message indicating that j is ready to receive (i.e., it is active and there are not other simultaneous transmissions that could interfere), or a timeout expires. In the former case, i sends the data to j; in the latter case, i will poll the following next-hop3. While i is looking for a next-hop that is ready to receive, data are buffered at the node waiting for transmission. This accounts for channel contention, however data transmissions are collision-free. Moreover, since buffers are assumed to be of infinite capacity, data units are never lost while traveling through the network.

Network System Model

The modelling approach to analyze the behaviour of the system network consists of three building blocks as shown in Fig. 3. They are (1) the sensor model A, (2) the network model B (3) the interference model C. The overall solution is obtained by means of a fixed point approximation procedure in which the three blocks interact by exchanging various parameters along a closed loop till a final equilibrium is reached. The response delays should be set according to the order of the associated routes in i's routing table. In this case, i will just wait to receive a response from one of its next-hop until a timeout expires [8].

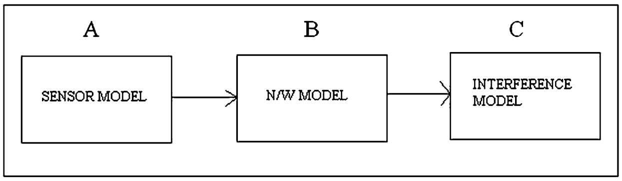

Fig. 3 System network model

Sensor Model [A]

The behavior of a single sensor is developed using a discrete-time Markov chain (DTMC) model, in which the time is slotted according to the data unit transmission time, i.e., time interval necessary to transmit a data unit including the overhead is required by the MAC layer. Although the DTMCs describing the individual node behaviour are solved independently of each other, the sensor model incorporates the dynamics resulting from the interactions between the sensor and its neighbors. As a first step, the DTMC of a sensor neglects the operational state of its neighbours. The state of this simplified DTMC is defined by: (1) the cycle phase in which the sensor is in the current time slot (namely, S, R, or N), and (2) the number of data units stored in the sensor buffer, which can be any integer value ranging from 0 to ∞. The resulting Markov chain is shown in Fig. 4, where the different phases are indexed with the number of data units stored in the sensor buffer [3]. The sensor's sleep-active dynamics is determined by the input parameters p and q.

Network Model [B]

The sensor network can be regarded as an open queuing network in which each queue corresponds to the buffer of a sensor, and the external arrival rate to each queue corresponds to the data unit generation rate at the sensor. First of all, data units are never lost while traversing the network. The transition probabilities between the queues of the network, element $R(i, j)$ represents the fraction of outgoing traffic of sensor i that is sent to its next-hop j. In order to compute R, one has to account for the routing policy chosen by the sensor, as well as the effect of the sleep/active dynamics of the next-hops and the contention on the

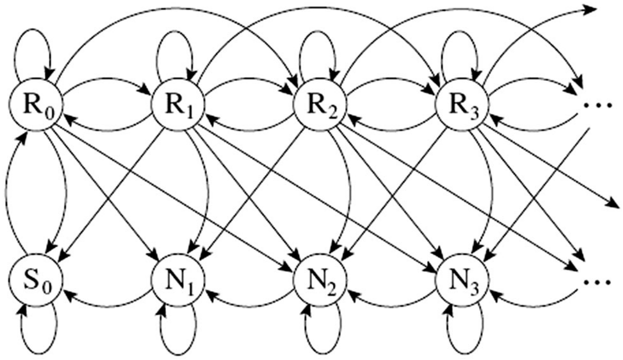

Fig. 4 Markov chain describing the sensor behavior [11]

wireless channel. Here the routing policy is a strict priority for the best available next-hop. The simplest approach is to consider only the stationary probabilities of the next-hops state, and to assume that the next-hops states are independent [13].

Model of Interference Parameters [C]

The purpose of the interference model is to compute, for each node, the parameter β to be used into the sensor model. The method used to estimate the parameters α, *f*, and *w* needed to solve the sensor model will be described. β is defined as the probability to transmit a data unit in a time slot given that the buffer is not empty and at least one next-hop is in phase *R* at the beginning of the slot. If there were no contention on the wireless channel, β would be equal to 1. A node transmission attempt is successful if the conditions expressed are satisfied. The computation of β thus requires a careful investigation of the interference produced by other sensors trying to transmit in proximity of the node for which β is to be estimated. In order to explain our approach, the set of nodes considered is shown in Fig. 5.

The transmission range of three nodes {*A*,*F*,*H*}, is represented by a circle. Let us assume that the estimate of parameter β of node *A*, which has two next-hops, *B* and *C*. Now find all transmissions that could potentially interfere with the transmission of *A* to its next-hops. Let (*X*, *Y*) denote the transmission from the generic node *X* to the generic node *Y*. It is noticed that transmissions like (*D*, *E*) and (*H*, *C*) violate condition (4) since the receivers are within the radio range of *A*. A special case is given by the transmissions whose receiver is *A* itself (e.g., (*E*, *A*)). Instead, transmissions like (*F*, *G*) and (*H*, *I*) meet condition (4) and violate condition (5) since the transmitters interfere with A's next-hops. In addition, the transmissions as (*D*, *E*), (*E*, *A*), (*H*, *C*) and (*F*, *G*) totally inhibit A's transmission, thus they are called total interferers. Instead, transmissions like (*H*, *I*) do not necessarily prevent *A* from sending data (e.g., (*A*, *B*) could take place), thus they are called partial interferers. Transmissions violating are being highlighted. Here *A*, being the receiver are always total interferers [8].

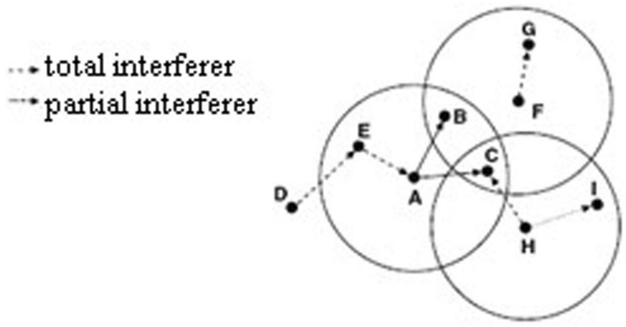

Fig. 5 Example of channel contention transmissions

Simulation Results

In this work, all sensors generating data are assumed to have a set of the number of nodes as $N = 200$. The network capacity and mean data delivery delay, averaging the result of topology, are shown in Table 1. As is known, a node never enters phase *N*, having $p = q$ that corresponds to the case where a sensor spends an equal amount of time in sleep and in active state. Several simulation results are derived under different traffic load conditions.

The important phenomenon is observed when the network load *G* is close to 1. Multipoint to-point communications suffer from the well known problem of data implosion at the destination. An architectural solution is adopted that allows nodes to adapt to traffic conditions avoiding network instability for any value of *G*.

The WSN nodes are powered by a 9 V battery. A sensor node is made to transmit continuously and was able to deplete the fully charged battery in approximately 3 h. Continuous voltage readings of 10 samples per second were taken using a data acquisition device together in order to monitor the state of charge (SOC) of the battery as, shown in Fig. 6.

The average delay significantly increases as the distance from the sink grows, and as the network load increases. However, once *G* is fixed, there may be some nodes experiencing a smaller delivery delay than other nodes that are closer to the sink. This is due to the specific considered network topology. Also, in this case, the main contribution to the delivery delay is given by the time spent by the data units in the sensor buffers. Moreover, the impact of p on the delivery delay is very much mitigated by the fact that several routes are now available. In fact, a sensor can poll more next-hops, thus increasing its probabilities to forward a data unit through the network, even when the system dynamics are slow.

Table 1 Network capacity and mean data delivery delay (averaging the result of topology)

	N = 200	
	50 % S–50 % A	80 % S–20 % A
Network capacity (*C*)	0867 (0873)	0720 (0811)
Average delay ($\bar{D}$)	1,443 (1,680)	3,939 (2,365)

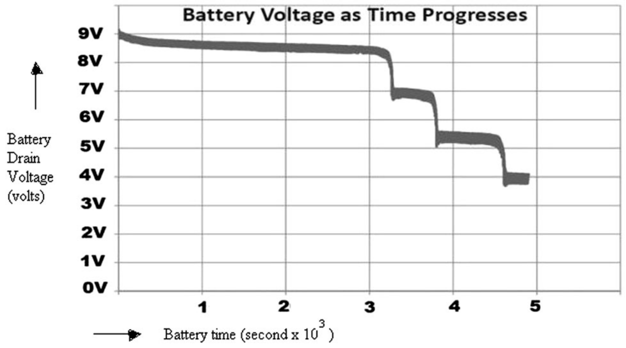

Fig. 6 Graph between battery voltage and battery drain time

Conclusions

A sensor network has been studied where nodes send their data to a sink node by using multihop transmissions. To save energy, sensors operate alternately between two operational modes, sleep and active mode. While in sleep mode, sensors consume lower power, their functional capabilities are also reduced. This enables to investigate the trade-offs existing between energy saving and system performance, as the sensors dynamics in sleep/active mode may vary. By comparing analytical and simulation results, it was validated for the present model showing the good accuracy of the present approach. The model specifically represents the sensor dynamics in sleep/active mode, while taking into account channel contention and routing issues. The model could be easily modified to take into account some aspects that have not been addressed in this work and that can be interesting subject of future research. For instance, a model of the error process over the wireless channel can be included and some of the assumptions that are considered here enable development of the analytical model, such as those on infinite buffer capacity or on the data generation process at the network nodes, assisting in the further modification.

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