WIRELESS SENSOR NETWORKS: A CASE STUDY FOR ENERGY EFFICIENT ENVIRONMENTAL MONITORING

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Abstract: Energy efficiency is a key issue for wireless sensor networks, since sensors nodes can often be powered by non-renewable batteries. In this paper, we examine four MAC protocols in terms of energy consumption, throughput and energy efficiency. A forest fire detection application has been simulated using the well-known ns-2 in order to fully evaluate these protocols.
Keywords: MAC protocols, energy consumption, wireless sensor network

INTRODUCTION

Advancements in wireless communications and MicroElectro-Mechanical Systems (MEMSs) have enabled the development of low-cost, low-power, multifunctional, tiny sensor nodes that can sense the environment and communicate with each other over short-distances (typically <100m). Wireless Sensor Networks (WSNs) are an emerging area with wide range of potential applications such as environmental monitoring. Such networks normally consist of a large number of distributed nodes that organise themselves into a multi-hop wireless network. Each node is comprised of four main components; the sensing unit, the processing unit, the power unit and the radio transceiver unit. [1] Any of these devices, however, will be typically powered by batteries and hence will have limited energy resources. Therefore, a carefully designed Medium Access Control (MAC) protocol to focus on eliminating the parameters associated with energy inefficiency is required. The main factors for consideration in energy efficient MAC are collisions, control packet overhead, idle-listening, overhearing and frequent switching modes. [6] The objectives of this work are to discuss and evaluate the four main MAC protocols used in sensor networks, which are IEEE 802.11, Time Division Multiple Access (TDMA), Sensor-MAC (SMAC) and IEEE 802.15.4 for energy efficiency. The above protocols are investigated in terms of performance metrics which in our case are energy consumption, throughput and energy efficiency. A case study for environmental monitoring and more precisely, a forest fire detection application, using the software tool Network Simulator 2 (ns-2) [3] is investigated. The aim of this scenario will be the real-time detection of fires and the key goal is to evaluate the existing protocols in this application.

The rest of the paper is structured as follows. In the following section the environmental monitoring application is introduced and the problem statement of our work is defined. Finally, the evaluation of results is presented in the last section.

ENVIRONMENTAL MONITORING

Environmental monitoring in remote forest regions is vital and one way to measure the spread of fires is by using WSNs. Forest fires are increasingly expensive disasters in terms of both property damage and life safety. A forest fire detection application in such areas must be environmentally appropriate, which requires easily installation, removal and replacement at any location, low maintenance and preferably inexpensive instrumentation. In our proposed scenario, sensor devices gather data, for example temperature, humidity, CO_x and NO_x gases and use these measurements for determining the risk of fire at a given moment. The nodes are deployed randomly, and a sink node concentrates sensed data and forwards it to a satellite terminal. The terminal transports the collected data received through the satellite transponder to the monitoring centre. As the importance of different measurements may vary, it is necessary to have different priorities in the transmitter terminal. Hence, we propose our Satellite Proportional Dropper (SPD) algorithm [2], which determines the data delivery priorities for the data types existing in the network. Moreover, each sensor node is battery operated, so the available energy is limited. Given that, it usually impossible to replace or recharge batteries, consequently energy conservation is crucial for sensors.

An efficient MAC protocol offers the ability to improve the energy consumption of WSNs, as it directly controls the transceiver operation of each sensor device. Therefore, many existing protocols concentrate on reducing the sources of energy waste. The first source is caused by collisions, which occur when two or more nodes attempt to transmit simultaneously. The need to re-transmit a packet that has been corrupted by collision increases the energy consumption. The second source of energy wastage is idle-listening, where a node listens for traffic that it is not sent. This energy expended monitoring a silent channel can be high in several sensor applications. The third source of waste is overhearing, which occurs when a sensor node receives packets that are destined for other nodes. The fourth is caused by control packet overheads, which are required to regulate access to the transmission channel. Sending and receiving control packets consumes energy too, and less useful data packets can be transmitted. The fifth source is over-emitting where the destination node is not ready to receive during the transmission procedure, and hence the packet is not correctly received. Finally, the transition between different

operation modes, such as sleep, idle, receive and transmit, can result in significant energy consumption. Limiting the number of transitions between sleep and active modes leads to a considerable energy saving. [6]
As outlined above, the choice of MAC protocol is the major factor affecting the performance of a WSN. The key goal of this work is to explore the existing MAC protocols under our scenario, in terms of energy consumption, throughput and energy efficiency. Therefore, we decide to simulate it under IEEE 802.11, TDMA, SMAC and IEEE 802.15.4. Now, it is necessary to briefly describe the main functionalities of each protocol, before we proceed in the performance analysis.
The standard IEEE 802.11 [5] with Carrier Senses Multiple Accesses (CSMA) is designed for conventional wireless networks, such as wireless Internet. In CSMA mode, before sending its own message, each sensor node first senses the channel to see whether or not there are on going transmissions from the other nodes. This is done in an attempt to avoid collision with others. However, this does not completely avoid collisions since the two nodes may transmit simultaneously if they are not able to detect each other transmissions. One mechanism to solve this problem is the Ready To Send (RTS) and Clear To Send (CTS) handshake.
TDMA [6] divides the use of the channel into fixed time slots and schedules the transmission of the active nodes among these time slots based on the nodes' demands and the total resources available. It requires strict synchronization among nodes and a centralized control to coordinate the use of channels. As a result, TDMA requires a large overhead in order to maintain synchronization between sensors nodes and to exchange local information, such as the network topology and the communication pattern.
The basic idea of the SMAC [4] is that each sensor node generates a local sleep-wake message and broadcasts the information to neighboring sensors through the exchange of synchronization packets. If a sensor receives a sleep-wake schedule from other sensors before it broadcasts its own, it will operate under the received schedule instead of the one generated locally. As a result, the network will design virtual clusters that contain sensor nodes running a common sleep-wake schedule. The concepts of messages-passing, where long messages are divided into frames and sent in a burst achieve energy savings by minimizing the communication overhead at the expense of unfair sharing of the wireless medium. Also, SMAC employs CSMA and RTS/CTS mechanisms for collision avoidance.
In contrast to the other protocols, IEEE 802.15.4 [8] focuses on sensor devices with limited energy resources. In our experiments, we use the centralized or star topology, where a single node operates as a Personal Area Network (PAN) coordinator to control node association in the network. The resource reservation occurs mainly through the PAN coordinator. Data transfer from PAN to device uses more packets, but the receiving device still initiates the transfer. The node first sends a data request command to the PAN coordinator meaning that the data transfer may occur. Then, the PAN node may transmit an acknowledgment indicating it received the message successfully. After that the PAN coordinator transmits the data message according to the CSMA mechanism. In addition, sensors node in an 802.15.4 network operate in a beacon enabled mode, where the PAN coordinator periodically broadcasts a beacon for synchronization and management purposes. Beacon enabled PANs utilize the synchronization provided by the message to perform slotted channel access.
For completeness, it is necessary to take into account several assumptions, in order to achieve the forest fire detection application:

- All the nodes are homogeneous in terms of battery and transmission range.
- The network consists up to 30 randomly deployed nodes.
- All the nodes in the network are static.
- An omnidirectional antenna is installed in each sensor node and the transmission range is defined at 15m.
- Each node has a unique ID in the network.
- The data rate is low enough so that there will not be queuing delay in sensor nodes.
- Packets communicated through the network are small and of constant size.

EVALUTION OF RESULTS

The satellite terminal is linked with the wireless ad-hoc sensor network in order to transmit the sensed data to the monitoring center. The maximum number of sensor nodes are used is 30, which means that the number of sensor nodes are varied and consequently the topology of the network. In addition, the data rate of each node is set at 250 kbps and the packet size at 60 bytes, since in our case it is necessary to transmit only data information, such as the location and the fire at the given moment. In this application we utilize Ad-hoc On-demand Distance Vector routing (AODV) as the underlying routing protocol. AODV [9] has the basic route-discovery and route-maintenance and uses the hop-by-hop routing, sequence numbers and beacons. The node that wants to know a route to a given destination generates a route request. The route request is forwarded by intermediate nodes that also create a reverse route for itself from the destination. Once, the request reaches a node with route to destination it generates a route reply containing the number of hops requires reaching destination. All nodes that participate in forwarding this reply to the source node create a forward route to destination.
We evaluate our model under the exponential traffic generation and the simulation time is set at 100 sec. The initial energy of each sensor device is configured in 100mJoule, since it is expected to consume it during our experiment. The power

consumption model is installed in each sensor device, as it is showed in table 1.

Table 1. Energy model of wireless sensor node

Mode of Sensor	Ratio
Sleep Power	0.001
Idle Power	0.8
Receive Power	0.8
Transmit Power	1.0
Transition Power	0.2

Figure 1 shows the simulated average energy consumption per node, for a different numbers of sensor nodes during the monitoring period. The first result of interest is that the 802.15.4 protocol consumed less energy than the other three protocols. The second observation is that 802.11 MAC uses more than that used by S-MAC and TDMA, when the traffic load is low. Since, idle listening always happens; energy conservation from periodic sleeping is very limited. SMAC achieves energy savings mainly by avoiding overhearing and efficiently transmitting a message. Additionally, 802.15.4 outperforms SMAC and a good explanation is that SMAC has synchronization overhead of sending and receiving SYNC packets. At last, the columns descend slightly with increasing number of sensor nodes in TDMA and SMAC protocols.

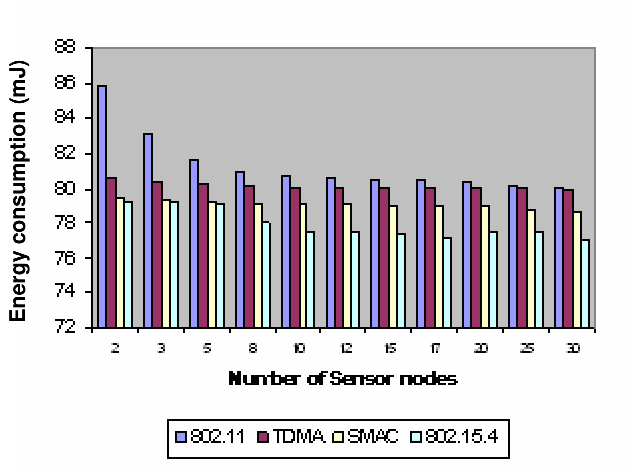

Figure1. Measured energy consumption of MAC protocols

In figure 2 illustrates the throughput for each MAC protocol with different numbers of sensor nodes. It is known that throughput usually depends on many aspects of networks such as power control, scheduling strategies, routing schemes and network topology. It is calculated by dividing the packets that were successfully received (in bits) in all sensor nodes of the network by the monitoring period. It is clearly shown that the 802.11 protocol CSMA/CA mechanism has the maximum throughput in all scenarios compared with the other three protocols. Furthermore, TDMA and SMAC have almost the same throughput, with TDMA performing slightly better than SMAC. On the other hand, 802.15.4 has the lowest throughput in all simulations, since this protocol is designed specifically for low data rate networks. Also, it is expected that the throughput is increased proportionally to the number of nodes and this observation is confirmed in the following chart [6] Moreover, there are some deviations as shown in figure 1 since, as number of sensor nodes is increased; the behavior of physical layer and its interactions with the MAC layer are complex.

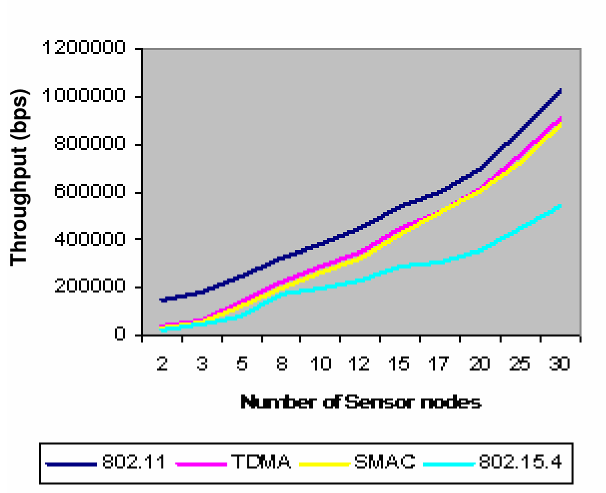

Figure 2. Comparison of throughputs for 802.11, TDMA, SMAC and 802.15.4

Figure 3 shows a graph of energy efficiency as the traffic rates increases. Energy efficiency is estimated by dividing the average energy remained per node by the initial energy. Note that the curves ascend slightly with increasing the number of sensor nodes in TDMA and SMAC protocol. However, in 802.11 the curve increase rapidly in the first 10 nodes and after that is more stable. This is caused by the overhearing avoidance mechanism that puts nodes into sleep whenever an unrelated communication takes place within radio range. Moreover, as shown in the figure the energy consumption of SMAC is relatively independent of the number of sensor nodes, as the periodic sleep plays a major role for energy savings.

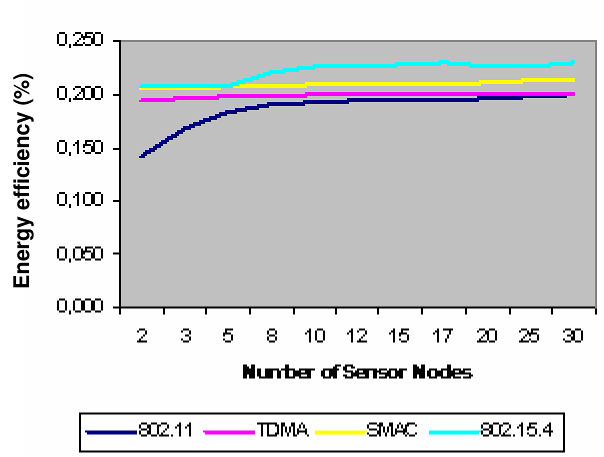

Figure3. Energy efficiency of MAC protocols is estimated by dividing the remained energy by the initial energy.

Besides, in figures 1 and 3 the 802.15.4 protocol has the best energy property and outperforms

802.11, TDMA and SMAC protocols. The reason is that it does not send RTS/CTS packets and increases the remained energy due to control packet overhead. But, TDMA protocol in terms of energy efficiency consumed almost the same amount of energy under the entire traffic pattern and it uses less energy than 802.11. Finally, it is interesting to note that SMAC adjusts the sleep time according to low duty cycle (10%). Also, SMAC avoids overhearing by letting interfering sensor nodes to transit in the sleep mode, once receiving RTS or CTS messages. This is in contrast to 802.11 and TDMA where nodes spend more and more time in idle listening when the traffic changes and consume more energy.

Finally, it is necessary to state important observations for the performance of the MAC protocols, under our investigation. Firstly, IEEE 802.11 is not appropriate for sensor networks due to the energy inefficiency. This is because the sensor devices consume energy due to the high percentage of time spent in idle-listening mode without receiving any measurements. The control protocol overhead which conventional wireless networks can tolerate, becomes very large when used in sensor networks where our application may only generate a few bytes of data per message. However, 802.11 achieved high throughput at varying traffic loads compared with other protocols.

Secondly, TDMA has a natural advantage of collision-free medium access, but includes clock drift problems and decreased throughput due to idle slots. The main drawback of TDMA is the synchronization of the nodes and adaptation to topology changes, where changes are caused by insertion of new nodes, limited battery power and sleep messages. Therefore, the slot assignments should be done regarding such possibilities and it is not easy to accomplish it, since all nodes must agree on it.

Thirdly, SMAC offers many advantages supporting its utilization in sensor networks. According to our study it is shown that is more energy efficient than the IEEE 802.11 and TDMA protocol. The energy consumption caused by idle-listening is reduced and time synchronization overhead is prevented by sleep schedules messages. Locally synchronizing sensor nodes minimizes the problem of coordinating sensor nodes for communication and may provide adequate synchronization and clustering for other protocols. Hence, SMAC can scale easily since the sensor nodes do not require any wide-scale coordination by using beacon messages, and hence do not have to forward or share large amounts of state information. However, SMAC has some drawbacks since sleep and listen schedules are predefined and constant, which decrease the efficiency of the protocol under variable traffic load. Another disadvantage comes from the static duty cycle of SMAC, as sensor nodes may not change their duty cycle based on traffic or density conditions and thus consume more energy than required and affects the protocol performance.

Lastly, IEEE 802.15.4 is an energy efficient protocol favouring low data rate and low power consumption applications, which is very desirable in a WSN with non-reachable batteries. While 802.15.4 focuses on applications similar to sensor networks, several problems exist for its use in sensor networks. The standard defines the operation of network devices for star topologies where devices can directly communicate with the PAN coordinator. Most sensor networks will have too many devices spread over too great a geographical area for all devices to use a single PAN coordinator. So, in large scale sensor networks experiences scalability problems. Besides, it suffers from hidden terminal problem due to the lack of RTS/CTS messages.

CONCLUSIONS

In this paper, the key goal was to study the effect of MAC protocols for WSNs, in terms of energy consumption, throughput and energy efficiency. We have compared the performance of four widely used MAC protocols (IEEE 802.11, TDMA, SMAC and IEEE 802.15.4) used in sensor networks for energy conservation. To evaluate the general performance of the above protocols, we consider a forest fire detection application in ns-2 and carried out a numerous simulations with different numbers of sensor nodes. Our performance analysis shows that although 802.15.4 outperforms better than the other three protocols in terms of energy consumption and energy efficiency, it is not very stable once the number of sensors nodes increases, since it suffers from scalability problems. However, SMAC is more stable as the traffic rate increases. Our future direction in the area of MAC layer will be to propose and design a new energy efficient protocol.

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