Cross-Layer Interaction Between the Application, Routing and MAC Layers for Wireless Sensor Networks

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***Resumo*—This paper proposes a network protocol that relies on cross-layer interaction between the Medium Access Control (MAC), Network and Application layers for wireless sensor networks (WSN). The protocol uses Time Division Multiple Access (TDMA) with varying time intervals, which, in conjunction with a routing protocol, defines the operation of network nodes and its relationship with the application layer. Simulation results indicate a reduction on the end-to-end delay and on the network average delay. The network power consumption is also reduced.**

I. INTRODUCTION

Wireless Sensor Networks (WSN) are composed of small sensor devices which obtain information from the surrounding environment, cooperate using multihop communication and transmit the data to a central processing unit. The WSNs are used to monitor places where the human presence is impossible or unwanted [1].

The WSNs are composed of several nodes equipped with energy cells, usually small batteries, and limited processing capacity and memory [2]. Such limitations demand protocols that can make efficient use of the scarce resources. The literature indicates that the cross-layer interaction protocol performance supersedes the traditional layered protocol architecture [1] [3] [4] [5].

The cross-layer interaction follows two patterns: complete union of functionalities between two or more layers, or information sharing between different layers. A few papers discuss the impact of the physical layer on the network layer and the link between the MAC and network layers [6], [7]. The network and MAC layers received more attention in the literature [6], [7], [8], [9], [10], [11], [12]. Other combinations include MAC, transport, topology control and energy management [6], [4], [13], [5].

While some cross-layer algorithms aim at minimizing the node energy consumption, other factors must be analyzed, such as: network layer delay and interference between the physical and MAC layers. Moreover, most studies deal with network layers, but the application layer can also influence the network performance.

This paper proposes a new cross-layer interaction model that involve the application, MAC and network layers. The interaction between the layers' functionalities is complete. Numerical simulation present the interaction impact on the average delay and energy consumption of the network. Section II describes the network structure and the components, and the layers' interaction model. Section III shows the simulation results. Conclusions and future research are presented in Section IV.

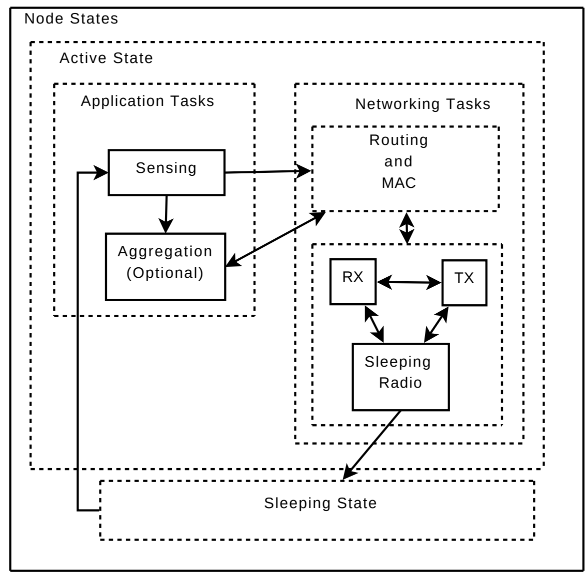

Figura 1. Node block diagram.

II. THE LAYERS' INTERACTION MODEL

In the literature a WSN is described as a collection of sensor nodes that obtain information from the environment and forward it to a central point (sink node) [2]. The sink node receive data directly from the sensor, or through intermediate nodes. In the following the structure of the simulator nodes and the interaction model are presented.

A. Node structure

Figure 1 shows the reference block diagram.

It is possible to divide the nodes' tasks and states in three main categories: node state, application tasks and network tasks, which are shown in Figure 1. The node state represent the operation mode of a certain node in the network. There are three states:

- Active — In the active state the node is on, its circuits are operational, and is executes network or application tasks. The energy consumption is highest. From now and them the node must switch to another state, to save energy. This periodicity defines the duty cycle;
- Sleeping — All nodes remain in this state most of the time, because it saves energy. Only the essential circuits are on and the node does not execute application tasks;
- Idle — When the node is not operational and the battery needs replacement. Is is not shown in Figure 1.

The main application tasks ares:

- Read sensor data — In this task the application collects information from the environment;
- Data aggregation — Information is gathered and expressed in a summary form, for a variety of purposes. This optional task, used to save energy and optimize the network load, was not considered in this paper.

The network tasks distribute the data, transmitting the information between the nodes. They are:

- TX — When the node transmits information;
- RX — When the node receives information;
- Sleeping – When there are no tasks to execute, and the transmitter is shut off.

It is important to notice that the application and network tasks can only be performed while the node is in the active state. Therefore, it is important to synchronize all the tasks to avoid switching states. The TX and RX states also demand energy.

The MAC and network layers are closely related in a WSN, and each depends on the other to improve efficiency [4]. There is no single combination of MAC and routing protocols that can produce the best performance in every scenario, which indicates that the best approach is the joint development of both layers [14].

B. Interconnecting the MAC and Network Layers

This paper presents a cross-layer approach, involving the application, network and MAC layers. The MAC and network layers form a single layer which shares information with the application layer, to improve the performance of the network. A TDMA scheme, with variable time intervals, is used in the approach to make the communication between the nodes feasible, in a multihop topology, as shown in Figure 1.

The network can be segmented to simplify the analysis of each route. For example, the route formed by the nodes Sink-3-9-20 is called string topology, as shown in Figure 3 [2].

Some properties of the network topologies:

- Nodes that are close to the sink are subject to heavier traffic than distant nodes, because they act as routers for the remaining nodes;
- Nodes that are close to the sink must be in the active mode for longer periods;

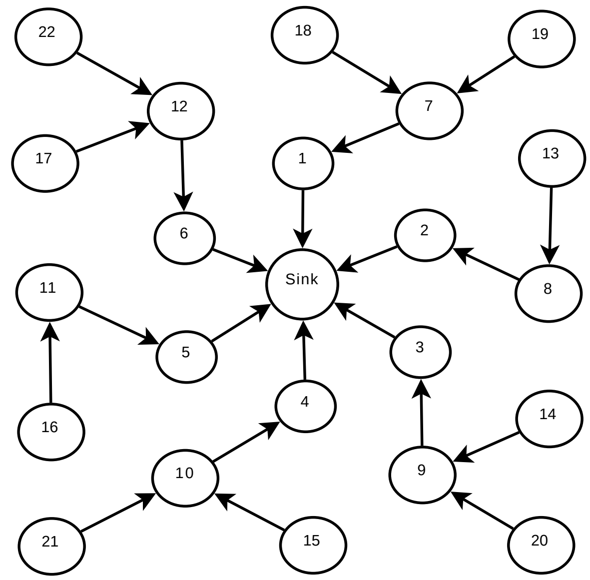

Figura 2. Network topology.

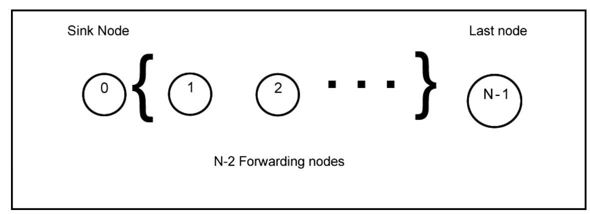

Figura 3. The string topology.

- Nodes that are close to the sink suffer more interference;
- A distance vector algorithm can be used to create routes.

In the proposed approach the TDMA model is used to avoid collisions between neighboring nodes. But, the proposed TDMA model has variable time intervals to allow longer time periods for the nodes that are closer to the sink node. And the duration of the interval t is used as a weight in the routing algorithm. The number of hops indicates the distance between a specific node and the sink node.

At each node a value d is subtracted from t, and this indicates the existence of another hop in the path. Because t is used as a weight in the algorithm, as it increases along the path, the route cost decreases. This is exactly the opposite of the traditional approach. The value of d can be computed using

$$n(b/p) < d < c/m, \tag{1}$$

in which n is the maximum number of nodes for each network segment, for example, the set of nodes {Sink,4,10, 15, 21} in Figure 2 represents a network segment with $n = 4$; b is the transfer rate between two nodes; p is the maximum number of data packets; c is the maximum dimension of the TDMA cycle; and m is the maximum number of neighbors from which a node can route data. In Figure 2, node 10 has only two neighbors which use it as router. As an example of the topology formed by the nodes Sink-3-9-20 in Figure 2 it

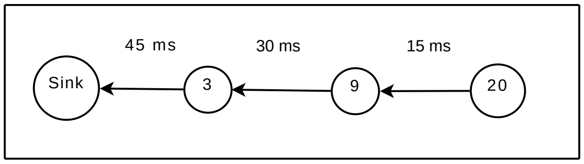

Figura 4. Scenario for the connections between nodes Sink-3-9-20.

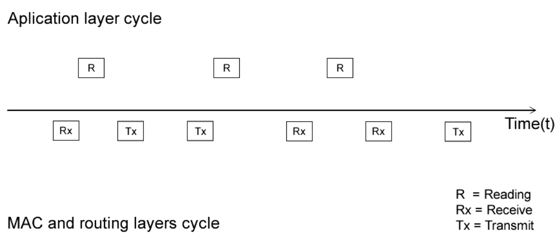

Figura 5. Comparing the application, network and MAC layers duty cycles.

is possible to obtain the scenario shown in Figure 4.

Therefore, in the proposed algorithm the MAC and network layers must be united in a complete union of functionalities. The next section explains how the cross-layer works.

C. Application Layer Relationships

In general, for some of the network protocols found in the literature, there is a relationship between the MAC and network layers. But the application layer can also establish a relationship with those layers. This is shown in Figure 5, that illustrates the application duty cycle, which is different from the MAC and network duty cycles. This can have an important impact on the network latency. The nodes can change to the active state several times, in different periods, for application and network tasks, and influence the energy consumption.

In the proposed approach, the application layer is synchronized with the network and MAC layers, Therefore, before the execution of the TX/RX tasks by the MAC layer, the application layer executes its activities and only then the network layer completes its tasks. The proposed duty cycle is defined in Figure 6. In this case, the application layer relaxes the execution of its tasks to adapt to the adequate timing, in accordance with the other layers' schedule, and taking advantage of the only period in which the node is active.

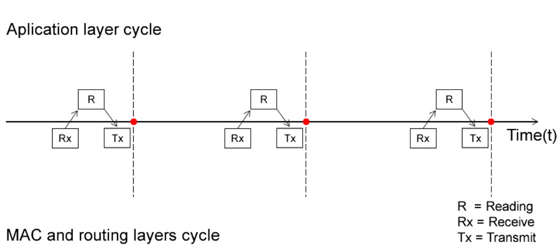

Figura 6. Application tasks synchronized with the network layer schedule.

D. Node synchronization and the cross-layer model

The TDMA scheme, explained in Section 2.2, can also be used to define the node synchronization, because the the cycle differentiation between the nodes is established according with the distance from the Sink. The TDMA slot synchronization and the weight adjustment for the routing algorithm are done dynamically. Suppose A is a node that routes information from B to C. The proposed protocol follows steps are:

1a) *Neighbors are found*: At this point, node A (which is Sink or is already synchronized with another node) transmits a broadcast packet that contains information on the slots (start, size, number and an free slot);

1b) *Topology control*: Nodes B and C decide if they will establish the neighborhood with A;

2a) Nodes B and C adjust themselves according to Inequality (1). The value d can be computed taking the node residual energy into account;

2b) Nodes B and C compete to find a free slot, as they send requests to associate;

3a) Node A allocates free slots to B and C;

3b) Nodes B and C adjust themselves and scale their tasks according to the slot allocated by A.

The routing policy is defined in step (2a). For instance, nodes B and C could have found node D, which has a bigger slot. Nodes B and C then decide between A and D. The routing protocols are part of a whole block. In case of faults or if new nodes are inserted, step (1a) is executed again. The relationship with the application layer begins in step (3b), in which the application receives information on the start of the slot that carries the transmission from B to A.

Finally, the node synchronization can affect the TDMA based protocol efficiency, because the slot is fixed for the duration of the transmission. If there is a clock delay in one node, node A can transmit while node B is not waiting for.

III. Results

The OMNET++ simulator was used to implement the algorithms and protocols to evaluate the proposed model [15]. In the simulations the nodes, except the Sink, are sources of periodic events. After the event is produced, the application sends the data immediately thorough the network layers, and there is no delay to transmit the information. All nodes share the sale features and the clocks are fully synchronized.

The following parameters are used in the simulations:

- Total simulation time: 360 seconds;
- Periodicity: 4 seconds;
- A radio transmitter is simulated, and $b = 25$kbit/s;
- The number of hops in the network varies from 3 to 12, and the string topology is used;
- Packet size in the application layer $p = 64$bits;
- Maximum number of nodes in a certain network segment $n = 15$;
- Maximum number of neighbors routed by a node $m = 5$;
- TDMA cycle size $c = 2.1$ seconds.

To compare with the proposed model a traditional approach is also simulated, using TDMA for the MAC protocol, same

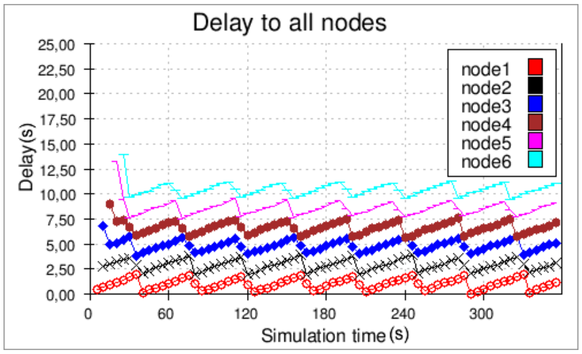

Figura 7. Delay in a six hops network without cross-layer interaction.

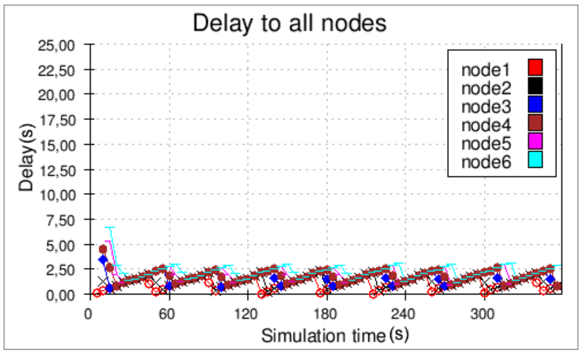

Figura 8. Delay in a six hops network with cross-layer interaction.

parameters, and routing based on the distance vector, but without cross-layer interaction. The results show a lower energy consumption, smaller delay and same scalability.

A. Delay analysis

The first result indicates a larger delay as the node is far away from the sink. Figure 7 shows the average delay for the traditional approach and Figure 8 shows the results for the proposed approach. The cross-layer approach reduces the delay, because the application tasks are executed in synchronism with the network tasks. The delay reduction, for the more distant node, is fourfold.

Another contribution is the interval configuration in the MAC layer. They are organized so that nodes at a distance $n+1$, in terms of hops, from the sink node are allowed to transmit during the next hops, at a distance n, before those nodes have the opportunity to transmit to the respective next hops, at a distance $n-1$. Therefore there is a reduction in the period a message is stored before being transmitted.

B. Energy consumption analysis

Energy consumption by the application and protocols is an important metric. To verify this the OMNET++ Battery Module was simulated [15], using the following parameters:

- Simulation time (120 minutes);
- Radio transmission (8 mW);
- Radio reception (8 mW);
- Sleeping state (1 mW).

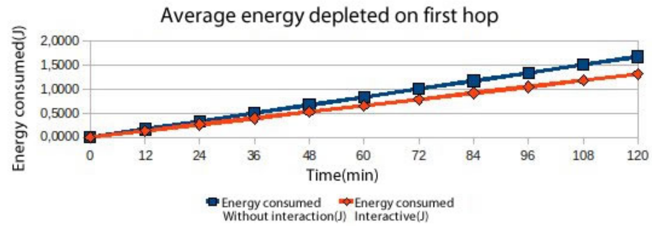

Figura 9. Average energy spent in the nodes.

Figure 9 shows the energy spent by the nodes which in the first network hops. Nodes 1 to 6, in the topology shown in Figure 2. The cross-layer approach saves energy because the synchronism between the application and network layers avoid unnecessary state changes.

IV. Conclusion and Future Work

The layered protocol architecture has been used for a while in computer networks and the sensor networks represent a new paradigm which demand efficient protocols to solve new problems.

This paper deals with the joint construction of three layers of the traditional protocol stack. The numerical simulations indicate that the cross-layer interaction has the potential do significantly reduce the average delay.

The proposed model, which involves the application, MAC and networks layers, used the distance vector algorithm and the TDMA protocol. It worth mentioning that the cross-layer approach is more sensitive to network maintenance [4].

Future work include the approach to define the clusters, and to optimize the cross-layer inter-cluster routing.

Acknowledgment

The authors would like to thank CAPES, CNPq and FINEP. CAPES project PE-087/2008, CNPq $579483/2008-8$, FINEP $01.08.0426.00$ and $04.10.0077.00$.

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