

Research Article

Efficient MAC Protocols for Wireless Sensor Networks Endowed with Directive Antennas: A Cross-Layer Solution

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Received 21 October 2006; Revised 21 March 2007; Accepted 11 May 2007

Recommended by Mischa Dohler

This paper deals with a novel MAC layer protocol, namely, directive synchronous transmission asynchronous reception (D-STAR) able to space-time synchronize a wireless sensor network (WSN). To this end, D-STAR integrates directional antennas within the communications framework, while taking into account both sleep/active states, according to a cross-layer design. After characterizing the D-STAR protocol in terms of functional characteristics, the related performance is presented, in terms of network lifetime gain, setup latency, and collision probability. It has shown a remarkable gain in terms of energy consumption reduction with respect to the basic approach endowed with omnidirectional antennas, without increasing the signaling overhead nor affecting the setup latency.

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1. INTRODUCTION

Wireless sensor networks (WSNs) [1] have been attracting a great deal of scientific interest in the last decade, making this approach an enabling technology for intelligent environments instrumenting. The deployment of networks comprised of tens up to hundreds of sensors currently represents an affordable solution to some challenging problems: environmental sensing, productive chains control, real-time phenomena monitoring, safety and rescue applications.

Though WSNs represent a special case of the more general wireless ad hoc networks paradigm [2], they present specific constraints, as for the limited energy, storage, processing, and communication capabilities, the low degree of mobility, and the presence of a small number of sinks. In addition, a novel paradigm, namely, distributed wireless sensor and actor networks (WSANs) [3], has been recently proposed, which joins ad hoc and sensor networks features to achieve enhanced capabilities of observing, data processing, and decision making.

All WSN applications claim at pursuing reliable tasks even though such networks rely upon intrinsically *unreliable* actors. This challenging paradox might be overcome through careful system design, with particular regard to the communications and control protocols. It is of particular rele-

vance whenever advanced interaction and sensing schemes are applied, as it happens in the case of WSANs or mobile WSNs.

To this end, some promising issues to be addressed are the management of both sleep and active states, the introduction of directional antennas and their integration within the communications framework [4]. As these aspects belong to both the physical (PHY) and the medium access control (MAC) layers, they might be joined to reach an overall energy efficiency; it could be feasible by jointly managing the duty cycle δ and the transmitting (receiving) antenna gain G_t (G_r). The way to accomplish this goal effectively relies on the so-called *cross-layer* protocol design principle [5]. However, the increased system complexity needs to be addressed and possibly limited as well as the capability of quickly setting up an end-to-end communication path.

This paper aims at filling this gap by proposing a novel MAC layer protocol, namely, directive synchronous transmission asynchronous reception (D-STAR), that broadens the previously introduced STAR MAC approach [6] towards the management of directive antennas. To this end, the cross-layer principle has been adopted to allow the adaptation of physical parameters (as the antenna main lobe pointing) according to the link-to-link communications channel features. In addition, D-STAR MAC provides a nodes' logical

synchronization explicitly taking into account the antenna capabilities.

The paper is organized as follows: in Section 2, the characteristics of the proposed D-STAR MAC protocol are described. To this purpose, some preliminary remarks on existing MAC protocols for WSNs are given in Section 2.1, while the benefits achievable by the adoption of directive antennas are briefly summarized in Section 2.2. Finally, Sections 2.3 and 2.4 deal with the proposed approach, giving a deep insight in terms of functional characteristics, finite state machine (FSM) description, and the related protocol time charts for different use cases. The overall communications protocol performance is presented, in terms of network lifetime gain, setup latency, and collision probability, in Section 3. Finally, some conclusions are drawn explaining the future directions of the present research activity.

2. PROPOSED MAC PROTOCOL

2.1. Related work

WSNs differ from wireless ad hoc networks because of a higher degree of more constraints: nodes are indeed characterized by limited resources such as energy, storage, processing, and communication capabilities [1, 4]. To cope with these impairments, there has been a lot of interest in novel protocols design for using smart antennas in ad hoc networks [2]. In fact, smart antennas allow the energy to be transmitted or received in a particular direction instead of disseminating it in all directions. This helps in achieving significant spatial reuse and, thereby, increasing the capacity of the network. Finally, it has been recently proved that the integration of several antennas on sensor hardware platforms is feasible with minimal additional cost [7]. However, the MAC and the network (NWK) layers must be modified and made aware of the presence of enhanced antennas in order to exploit their use. This might be accomplished by means of the cross-layer principle [5], as widely adopted in recent wireless networks design [8]. It is possible to classify medium access protocols into two classes [9]:

- (i) *scheduled* access,
- (ii) on demand or *unscheduled* access.

The former mechanism attempts to schedule transmissions in advance to reduce the possibility of collisions. On the other hand, unscheduled access is based on contention access; in particular, the IEEE 802.11 MAC protocol adopts carrier sensing (CS) to reduce the extent of packet losses due to collisions.

Various approaches have been proposed for addressing the drawbacks of the original IEEE 802.11 MAC in the presence of directional antennas, as directional MAC (DMAC) [10] or multihop MAC (MMAC) [11] to mention a few, while other solutions have been proposed for scheduled access, as the receiver-oriented multiple access (ROMA) [12] protocol. It is worth noticing that the use of directional antennas might also affect routing algorithms and the scheduling of transmissions. Although there have been some works related to *ad hoc* networks, this area still remains open for

future research in WSNs. For instance, a forwarding approach that exploits the use of directional antennas is proposed in [13] for WSNs. It tries maximizing efficiency and minimizing energy consumption by favoring certain paths toward the sink by using switched beam antennas.

All the previously proposed protocols are highly dependent on the antenna beam width; by carefully selecting the appropriate beam width, one obtains a tradeoff between robustness and load incurred in the network.

2.2. Smart antennas features

The adoption of smart antennas in a wireless network allows the gain maximization toward the desired directions by concentrating the energy in a smaller area, with a transmitted power decreasing, a received power increasing, a power consumption reduction, a coverage range increasing, and an error probability reduction.

In addition to this, the use of smart antennas in WSNs is highly desirable for several reasons: higher antenna gain might compensate the reduced coverage range due to higher frequencies (for realizing small size nodes) or preserve connectivity in networks and efficiently use the node energy thus increasing its lifetime.

We can note these benefits by observing the following relationships for the gain:

$$G_{\text{dir}} > G_{\text{omni}}, \quad (1)$$

the received power:

$$P_r > P_t G_t G_r \left(\frac{\lambda}{4\pi} \right)^2 \frac{1}{d^n}, \quad (2)$$

the coverage range:

$$R_{\text{dir}} = R_{\text{omni}} \left(\frac{G_{\text{dir}}}{G_{\text{omni}}} \right)^{2n}, \quad (3)$$

the transmitted power:

$$P_{t,\text{dir}} = P_{t,\text{omni}} \left(\frac{G_{\text{omni}}}{G_{\text{dir}}} \right)^2, \quad (4)$$

the receiver sensitivity:

$$S_{\text{dir}} = S_{\text{omni}} \left(\frac{G_{\text{dir}}}{G_{\text{omni}}} \right)^{2n}, \quad (5)$$

and finally the bit-error rate (BER):

$$\begin{aligned} \text{BER}_{\text{dir}} &= Q \left(\sqrt{\frac{2P_{r,\text{dir}}}{T_b N_0}} \right), \\ \text{BER}_{\text{omni}} &= Q \left(\sqrt{\frac{2P_{r,\text{omni}}}{T_b N_0}} \right), \\ \text{BER}_{\text{dir}} &< \text{BER}_{\text{omni}}. \end{aligned} \quad (6)$$

Moreover, the management of smart antennas performed by a channel access scheme permits the reduction of the power radiation toward undesired direction; this could reduce the interference caused by other transmissions as well as the collision probability.

2.3. STAR MAC protocol

Taking the IEEE 802.11 distributed coordination function (DCF) [14] as a starting point, several more energy efficient techniques have been proposed in literature to avoid excessive power waste due to the so-called *idle listening* effect. These are based on the periodical preamble sampling performed at the receiver side to leave a low-power state and receive the upcoming messages, as in the WiseMAC protocol [15]. Derived from the classical contention-based scheme, several protocols (S-MAC [16], T-MAC [17], and DMAC [18]) have been proposed to address the idle listening overhead by synchronizing the nodes, and by implementing a duty cycle within each slot.

Resorting to the above considerations, a class of MAC protocols, named synchronous transmission asynchronous reception (STAR), particularly suited for a *flat* network topology,¹ has been derived in [6], taking into account the benefits of both WiseMAC and S-MAC schemes. In particular, it joins the power saving capability, due to the introduction of a duty cycle (S-MAC), together with the communication advantages provided by the offset scheduling (WiseMAC), without an excessive signaling overhead nor requiring a strict synchronization as it happens in the S-MAC protocol. According to the STAR MAC protocol, each node might be either into an *idle* mode, in which it remains for a time interval T_l (listening time), or in an energy saving *sleeping* state for a T_s (sleeping time). The transitions between states are synchronous with a period called frame equal to $T_f = T_l + T_s$ partitioned in two subintervals; as a consequence, a duty cycle function can also be introduced:

$$\delta \doteq \frac{T_l}{T_l + T_s}. \quad (7)$$

To provide full communication capabilities to the network, all the nodes need to be weakly synchronized, this means that they are aware at least of the awakening time of all their neighbors. To this end, during the setup phase, each node, while discovering the network topology, asynchronously broadcasts a synchronization message. As the setup phase is expired and the virtual links couple of nodes have been established, each node sends frame by frame one synchronization message to each of its neighbors known to be in the listening mode (synchronous transmission). On the other hand, its neighbors periodically awake and enter the listening state independently (asynchronous reception). The header of the synchronization message contains the following fields: a node unique identifier, the message sequence number, and the *phase* ϕ , that is, the time interval after which the sender claims to be again in the listening status waiting for both the synchronization and data messages from its neighbors.

¹ It means that the network is comprised of *homogeneous* nodes that do not require to be *clustered*.

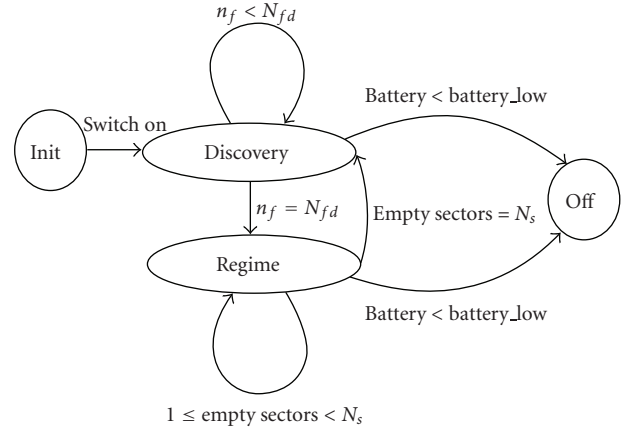


FIGURE 1: Finite state machine description of the proposed D-STAR protocols, involving the transitions occurring among *init*, *discovery*, *regime*, and *off* phases.

2.4. Directive STAR MAC protocol

The proposed directive STAR (D-STAR) MAC protocol expands the STAR MAC concept to achieve a time-space synchronization.² The network infrastructure is built up by means of joining together *bidirectional* links; to allow communications inside a WSN, each node sends to its neighbors its own phase ϕ as it happens in STAR approach, while the angular position is implicitly taken into account at the receiver and transmitter sides.³

To give an exhaustive description of the D-STAR protocol, it is possible to refer to the state diagram given in Figure 1. According to it, every node wakes up independently of the other ones, entering an initial idle mode (*init*), in which it remains for a time interval necessary to perform the elementary CPU operations and to be completely switched on ($T_{init,j}$). Then it switches into the *discovery* phase where it tries to recognize its neighbors and to establish a logical synchronization with them. Within this phase, the operation mode of j th node is duty cycled with a periodic succession of listening and sleeping subperiods, whose durations are $T_{l,j}$ and $T_{s,j}$, respectively.⁴

For the sake of generality, it has been supposed that the generic j th node has a specific frame period $T_{f,j}$ and duty cycle δ_j (and of course listening $T_{l,i}$ and sleeping $T_{s,i}$ subperiods) with $j = 1, \dots, N$, where N is the total number of nodes

² It is worth noticing that this approach, like the STAR protocol, is mainly suited for *flat* networks in which there are no cluster heads distributing a time frame and for densely deployed networks with a number of neighbors per node greater than ten [6].

³ Since there is not a common angular reference system, each node upon the reception of a packet is able to identify the angular position of the sender with respect to its own system; this information is stored and used to transmit to that node.

⁴ The abrupt introduction of this operation mode allows a remarkable power saving as an unnecessary long listening phase is avoided, while more attention might be devoted to also minimize the setup latency.

in the network. Moreover, it has been assumed that the wake up time is randomly selected by each node.

To provide an affordable and robust approach, during the initial setup (*discovery*) phase each node remains in a *listening* mode for a time interval equal to

$$T_{\text{setup}} \geq 2\max_j \{T_{f,j}\}. \quad (8)$$

The minimum value for T_{setup} has been chosen equal to $2\max_j \{T_{f,j}\}$ since it has been assumed that $T_{\text{init},j} \leq T_{f,j}$.

In the *discovery* phase, each node begins to *broadcast* one *hello* message to each angular sector (i.e., the coverage area within a certain side lobe) sending its *ID* and *phase*; then it waits for a fixed time duration τ_s in search of reply messages⁵ and switches to the following angular sector, repeating the procedure until T_{setup} is expired. In particular, each node sends the *hello* messages with a period

$$T_{\text{broad}} \leq \min_j \{T_{l,j}\}. \quad (9)$$

As a consequence, the number of *hello* messages sent by the j th node during the *discovery* phase is equal to

$$N_{\text{broad}} \geq \frac{T_{f,j}}{\min_i \{T_{l,i}\}} N_s, \quad (10)$$

where N_s is the number of nonoverlapping angular sectors of the transmitter antenna.⁶ The value of the *phase* ϕ sent is strictly related to the time interval remaining to exit the *discovery* phase and enter the duty-cycled mode.

It is worth noticing that as N_s increases the cost of *hello* messages transmission is predominant with respect to the cost of the listening mode for the vast majority of hardware platforms available on the market. This justifies a posteriori the simplified exit condition from the setup phase.

The overall messages exchange related to the *discovery* phase is represented in Figure 2. In particular, it has been assumed that Node A has four neighbors belonging to four different angular sectors. Node A begins the channel sensing procedure and then it sends one *hello* message per angular sector. Upon the successful reception of this message, each node adds Node A to the list of its own *active* neighbors. The procedure is repeated until the *discovery* phase is expired, that is, for a time interval $T_{\text{setup}} = 2T_f$.⁷ In Figure 1 the transition from the *discovery* to the *regime* phase occurs when the condition $n_f = N_{fd}$ is satisfied, where n_f is the

number of frame periods spent from the beginning of the *discovery* phase and N_{fd} represents its maximum value.

Once the *discovery* phase is expired, each node enters the *regime* phase, according to Figure 1. The reference node then sends *hello* messages in a unicast way to the neighbors belonging to different angular sectors, according to the phase ϕ transmitted in previous *hello* message. In addition to that, several *hello* messages are sent in background with the proper period to unknown neighbors in the empty angular sector. Upon the replying of a node, a *logical channel* is established and j th node can adopt the unicast or the multicast approach, according to the STAR+ approach [6]. Again, the transmitted phase value ϕ is the time interval after which the sender claims to be again in the listening status, as previously introduced in Section 2.3. It might be pointed out that the D-STAR protocol is able to prevent the so-called *deafness* problem,⁸ under the hypotheses that the transmitted phase values ϕ are correct, the local clocks do not present a remarkable time drift and the antenna switching is ideally performed.

The channel access is managed by means of the carrier sense multiple access with collision avoidance (CSMA/CA) scheme, as specified in [19]. Before transmitting a packet toward a certain angular sector, a node first listens to the channel: if no transmitted packets are detected, it assumes that the channel is idle and starts transmitting. Otherwise, it must wait and try again to transmit in that sector after a random time interval until a maximum number of attempts has been reached. This mechanism is very effective in reducing collisions, while the problem of *hidden node* [2] is still partially unsolved [20].

Each node remains in the *regime* phase until there is at least one neighbor, otherwise if there are no active neighbors (i.e., the number of empty angular sectors is equal to N_s)⁹ it reenters the *discovery* phase in search of connectivity. In Figure 3, the signaling occurring within the *regime* phase is pointed out following the illustrative topology introduced above. In particular, the channel sensing mechanism and the unicast sending of one *hello* message per neighbor node are shown, according to both the destination's angular sector and duty cycle.

To complete the protocol characterization, whenever a node battery is depleted, this node turns off, entering an *off* phase.¹⁰ This is again represented in Figure 1.

3. PERFORMANCE ANALYSIS

To evaluate the performance of the proposed D-STAR protocol, extensive numerical simulations have been conducted over a realistic scenario in compliance with the pi-

⁵ Once the communication is logically established with this node, the following *hello* messages sent to it in a *unicast* way are able to also reach the other nodes within the same angular sector.

⁶ If no additional information is provided during the *discovery* phase, the value of $\max_i \{T_{f,i}\}$ might be estimated by the generic j th node on the basis of its own characteristics (i.e., $\max_i \{T_{f,i}\} \equiv T_{f,j}$) and the same is true for $\min_i \{T_{l,i}\}$ (i.e., $\min_i \{T_{l,i}\} \equiv T_{f,j}$). These values could be further refined upon receiving *hello* messages from neighbor nodes containing this information.

⁷ It implies that the *hello* message sending is repeated twice.

⁸ This effect takes place when the transmitter fails to communicate to its intended receiver, because the receiver's antenna is oriented in a different direction.

⁹ It might be due to the fact that a node could have joined the network extremely late or even have changed its position.

¹⁰ This transition could indifferently occur starting both from the *discovery* phase and from the *regime* phase.

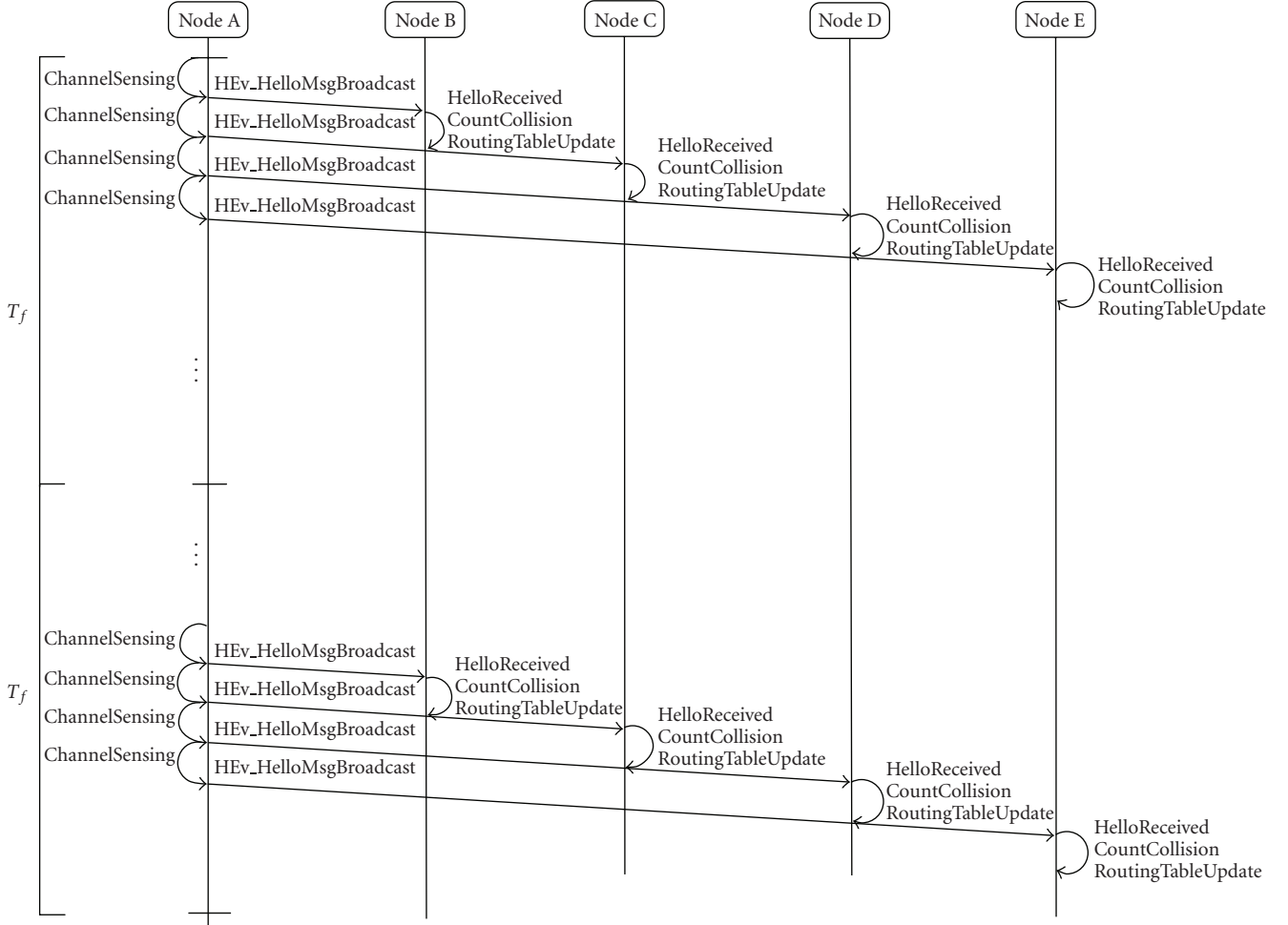


FIGURE 2: Message passing occurring within the *discovery* phase of the proposed D-STAR protocols.

lot site developed by EU Integrated Project “GoodFood” [21]. The simulated system has been developed by means of *network protocol simulator (NePSing)*, that is, a C++ framework specifically designed for modeling the evolution of a time-discrete, asynchronous network [22]. The most relevant simulation parameters are summarized in Table 1. The adopted antenna model is an *ideal* switched beam antenna. A group of almost nonoverlapping beams has been created that together result in omnidirectional coverage, so that the patterns’ main lobes are adjacent. The microcontroller at each node is able to scan the channel according to the D-STAR protocol, switching to the correct beam corresponding with the user wishing to communicate at that time. Only a single beam pattern is employed at any given time. In particular, the antenna has been conceived so that to cover a fixed arc or sector of, say, π , $\pi/2$, $\pi/3$, and $\pi/4$ radians, thus providing increased gain over a restricted range of azimuths as compared to an omnidirectional antenna. Besides, WSN nodes are supposed to be deployed only in a 2D scenario.

The adopted approach has been conceived to minimize the power consumption, thus enhancing the network

lifetime.¹¹ To this end, a duty-cycled operation and directive antennas have been introduced and properly managed to allow full connectivity through time-space synchronization. However, the D-STAR protocol is also able to minimize the setup latency, as the *discovery* phase duration T_{setup} is upper bounded by twice the maximum frame period value, as explained in (8).

To give an insight on the protocol energy efficiency, in Figure 4, the lifetime as a function of the number of network nodes has been pointed out in the case of omnidirectional antennas (i.e., the basic STAR MAC protocol), and directive antennas with two or four angular sectors, respectively. The remarkable gain provided by the introduction of directive antennas could be noticed; in particular, it is almost equal to 4 or 16 in the case of two or four angular sectors, respectively, in accordance with analytical predictions. Nevertheless, performance gets worse as the number of nodes increases, due to

¹¹ As to our purpose, the *network lifetime* has been assumed in a strict sense, that is, as the time interval after which the first node is turned off.

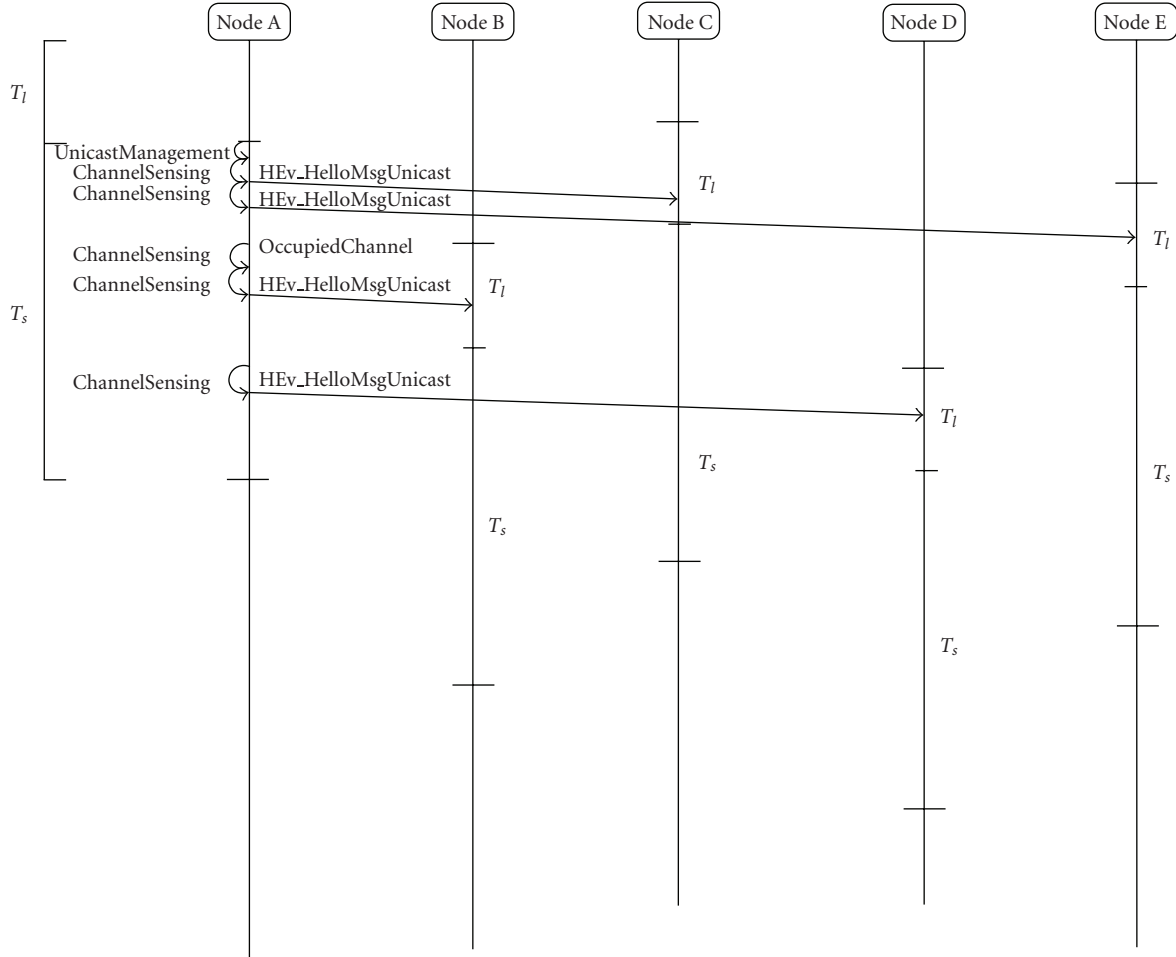


FIGURE 3: Message passing occurring within the *regime* phase of the proposed D-STAR protocols.

the presence of packet collisions that implies packets retransmissions and transmitted power wasting. It is not surprising that the network lifetime is extremely high,¹² as only the MAC layer operations have been simulated, that is, the *hello* message sending, thus with a very low network load. This choice better highlights the benefits of the proposed scheme with respect to the basic approach (i.e., with omnidirectional antennas).¹³

In Figure 5, the same comparisons have been performed with respect to the duty cycle value which has been varied over a commonly adopted range of [1%, 5%]. Without pointing out again the noticeable gain, it is possible to highlight that lifetime remains constant no matter what the duty cycle is, as the larger the listening time the greater the receiving cost and the lower the collision probability.

¹² For instance it is equal to two and a half years in the worst case.

¹³ However, to complete the present analysis, the D-STAR protocol might be integrated in future works with the Network layer to take into account the packet forwarding that is undoubtedly the most relevant cause of power consumption.

Finally, in Figure 6, the network lifetime as a function of the frame period duration T_f is shown. Within a usual operation range for T_f from 10 seconds up to 90 seconds, the lifetime has a linear increase, as the listening subperiod duration T_l is also proportional to T_f and it mostly affects the overall power consumption.

The energy efficiency of the proposed D-STAR protocol can be evaluated by also focusing on the collision probability that depends upon the node density and the presence of the *hidden nodes*. The underlying CSMA/CA mechanism might fail indeed if neighbor nodes get extremely close or if two or more nodes not belonging to the same coverage area attempt to transmit toward the same node.

To get an insight on this aspect, in Figure 7, the collision probability as a function of the number of network nodes is depicted, again in the case of omnidirectional antennas and directive antennas with two, four, six, eight possible angular sectors, respectively. It could be noticed that the adoption of omnidirectional antennas minimizes the packets collisions, even in the case of densely deployed nodes, while the converse is true for directive antennas mostly due to the presence

TABLE 1: Parameters values adopted within the numerical simulation campaign.

Parameter	Value
Monitored Area [m^2]	25×25
Number of nodes	[10, ..., 50]
Number of angular sectors	[1, 2, 4, 6, 8]
Frame duration T_f [s]	[10, 25, 50, 75, 93]
Duty cycle δ [%]	[1, ..., 5]
Transmitted power [dBm]	0
Receiver attenuation [dBm]	-50
Receiver sensitivity [dBm]	-90
Transmitting antenna gain G_t	[0.5, 1, 2, 3, 4]
Receiving antenna gain G_r	[0.5, 1, 2, 3, 4]
Battery initial level [mAh]	2500
Cost of 1 <i>hello</i> packet transmission [mAh]	$6 \cdot 10^{-5}$
Cost of hello pkt reception/channel sensing [mA/s]	$2.777 \cdot 10^{-3}$
Cost of sleeping [mA/s]	$2.97 \cdot 10^{-6}$
Maximum number of CSMA/CA algorithm backoff attempts	6
Time duration of a channel sensing attempt [s]	0.02
Hello packet size (payload) [B]	8
Transmission bit-rate [kb/s]	250
Packet error rate [%]	5
Simulated time interval [s]	86400

of hidden nodes, since the coverage area gets smaller in terms of azimuth and an increasing number of nodes become invisible.¹⁴ However, as the angular resolution increases, a lower number of nodes might overlap with a third node when transmitting and the communication becomes really *point-to-point*. This effect is more evident in the case of directive antennas with a number of possible angular sectors greater than four, since a kind of *spatial blindness* occurs in the case of lower values.¹⁵

The adoption of a medium access scheme following a CSMA/CA approach implies that a new channel sensing is randomly scheduled whenever a channel is not detected as *idle*. This allows for the avoidance of packet collision, whilst reducing the link throughput. To conclude this analysis, Figure 8 points out the probability of finding the channel occupied as a function of the number of deployed nodes. In this case the most conservative scheme, that is, the omnidirectional one, highlights the worst behavior for these parameters being compensated by a better collision probability, while the opposite happens for more directional antennas.

¹⁴ It could be noticed that in any case the maximum value for collision probability remains lower than 2%.

¹⁵ This statement is true in the case of a symmetric link, that is, with the same antenna at the receiver and transmitting sides. Otherwise, the performance is limited by the antenna with the lower directivity.

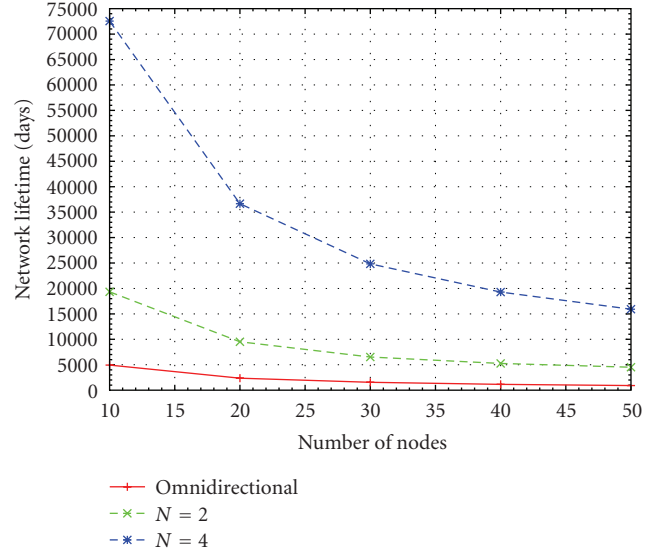


FIGURE 4: Network lifetime as a function of the number of nodes in the case of omnidirectional and directive antennas with π or $\pi/2$ main lobes for $T_f = 93$ seconds and $\delta = 3\%$.

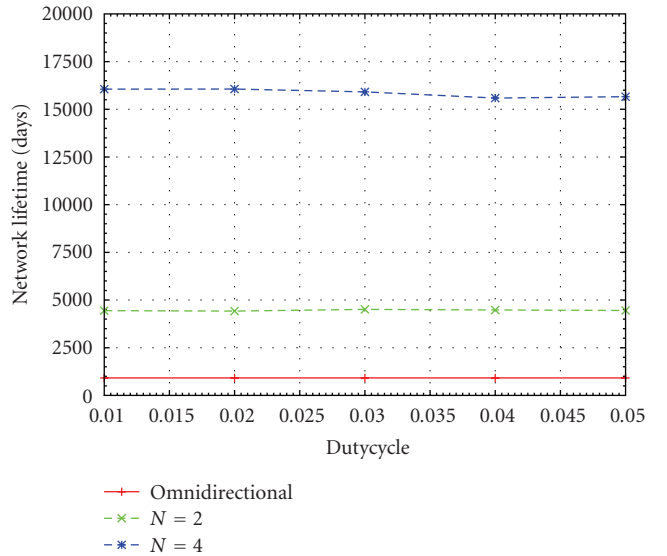


FIGURE 5: Network lifetime as a function of the duty cycle δ in the case of omnidirectional and directive antennas with π or $\pi/2$ main lobes for $T_f = 93$ seconds and 50 nodes.

4. CONCLUSIONS AND FURTHER DEVELOPMENTS

The WSN application is widely considered as the most promising solution for intelligent environments instrumenting, leading to novel communications paradigms. However, this could be pursued by means of effective protocols design, since sensor nodes present specific constraints, as far as the limited resources, the low degree of mobility, and the unattended operations.

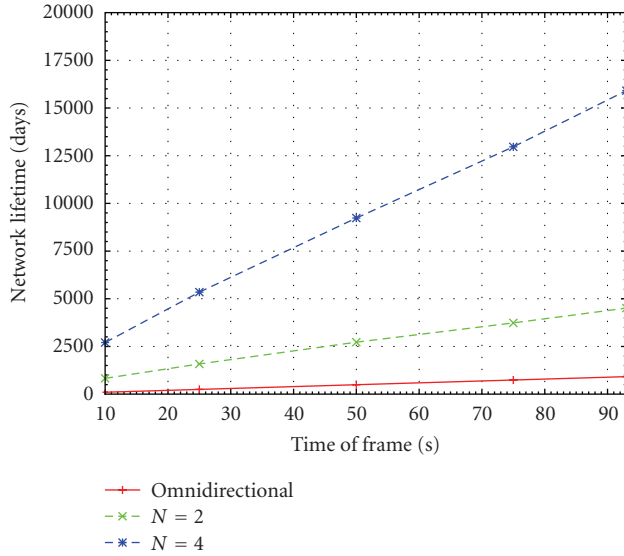


FIGURE 6: Network lifetime as a function of the frame duration T_f in the case of omnidirectional and directive antennas with π or $\pi/2$ main lobes for $T_f = 93$ seconds and 50 nodes.

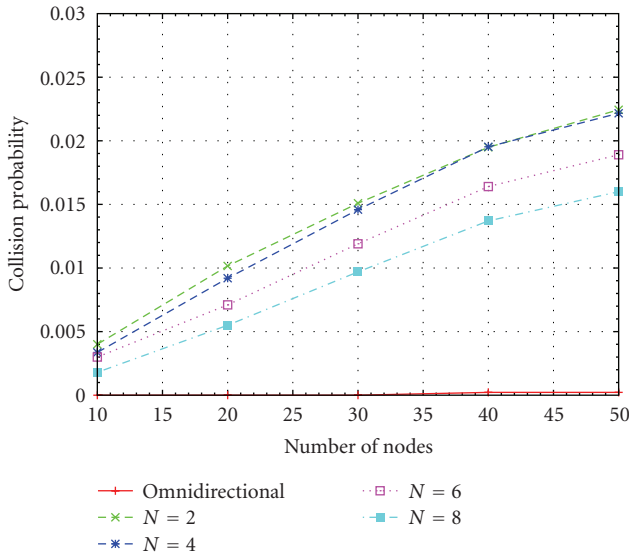


FIGURE 7: Collision probability as a function of the number of nodes in the case of omnidirectional and directive antennas with π , $\pi/2$, $\pi/3$, and $\pi/4$ main lobes for $T_f = 93$ seconds and $\delta = 3\%$.

This paper deals with both the sleep/active states power management, as well as the introduction of directional antennas and their integration within the communications framework, following a cross-layer design. A novel MAC layer protocol, namely, D-STAR is proposed, aiming at expanding the capabilities of previously introduced STAR MAC approach [6] toward the management of directive antennas, without increasing the signaling overhead or affecting the setup latency, but by achieving a reduction in energy consumption.

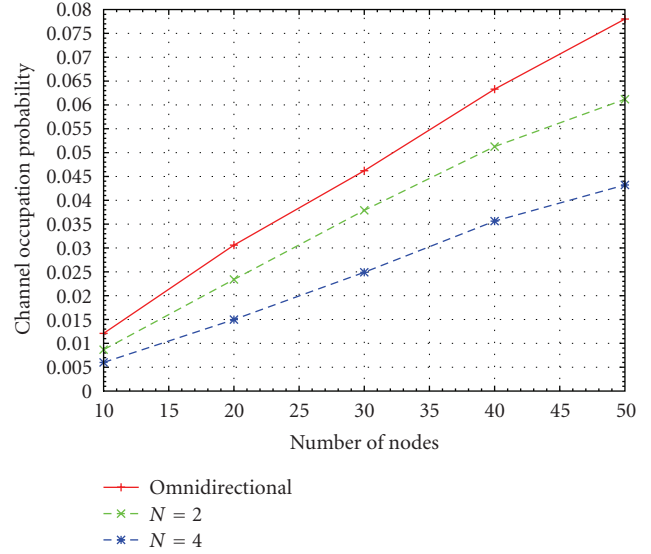


FIGURE 8: Channel occupation probability as a function of the number of nodes in the case of omnidirectional and directive antennas with π and $\pi/2$ main lobes for $T_f = 93$ seconds and $\delta = 3\%$.

The D-STAR protocol has been characterized in terms of functional characteristics, state transitions diagram representation, and the related time charts for different use cases. The overall communications protocol performance is presented, in terms of network lifetime gain, setup latency, and collision probability, pointing out a remarkable gain with respect to the basic approach endowed with omnidirectional antennas.

Future developments of the present research activity might include the protocol implementation and testing over realistic user defined scenarios, like the ones proposed in [21, 23], or the application to critical emergency operations such as [24].

ACKNOWLEDGMENTS

This work was supported in part by the EU Integrated Project FP6-IST-1-508774-IP “GoodFood” as well as by the EU Network of Excellence FP6-IST-4-027738-NoE “CRUISE” and EU STREP FP6-IST-045299-STREP “DustBot.”

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