SPACE DIVISION MULTIPLE ACCESS FOR WIRELESS SENSOR NETWORKS

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This paper deals with medium access control protocols for wireless sensor networks. The protocol in focus, ALS-MAC, employs beacons to synchronize internode communications. Scalability and collision avoidance are achieved via contention-based advertising slots mapped to scheduled-based transmission slots. ALS-MAC has dedicated modes of operation for data intensive traffic which assign temporary priority to nodes with many or long buffered packets. Also, ALS-MAC is capable of establishing multihop links within a single beacon period. We study collision-free concurrent data transmissions under ALS-MAC. The efficiency of the developed algorithms is proved via simulations.

Keywords: Wireless sensor networks, MAC protocol, low-power routing, SDMA

1. INTRODUCTION

Distributed sensor networks are made up of a large number of small sensing nodes which cooperatively perform complex tasks. The interaction between the nodes is based on wireless communication. Since the energy is a scarce and usually non-renewable resource, the functionality of distributed sensor-actuator networks must be viewed from low-power perspective. Normally, the nodes have a limited radio footprint and packets are forwarded in a multihop manner. When a node receives a packet it applies a routing algorithm to select a neighbor for forwarding. Different criteria can guide the local decision. One approach is to choose the closest to the destination neighbor.

The greater than linear relationship between transmit energy and distance promises to reduce the energy cost when the radio link is partitioned. Nodes calculate the distance and tune their transmit power accordingly.

Medium access control (MAC) mechanism has a significant impact on the energy efficiency. Currently available MAC protocols for wireless sensor networks can be broken down into two major types: contention based and scheduling based. While under contention-based protocols nodes compete among each other for channel access, scheduling-based schemes rely on prearranged collision-free links between nodes. There are different methods to assign collision-free links to each node. Links may be assigned as time slots (TDMA), frequency bands (FDMA), or spread spectrum codes (CDMA). However, size and cost constrains may not permit allocating complex radio subsystems for the node architecture. Logically, TDMA scheduling is the most common scheme for the domain of wireless sensor networks. The limited communication range of network nodes provides an extra opportunity for collision-free interaction, space division access (SDMA). Two major cases of redundant energy consumption are associated with contention-based communication. Collision occurs when two or more nodes transfer data to a single node at the same time. Overhearing is the situation when a node receives a packet which is not directed to it.

In this paper we discuss algorithms for collision-free concurrent data transmission under ALS-MAC. Parallel transmissions are closely related to multihop optimization, the process of partitioning the link into several power-efficient hops.

2. RELATED WORK

Previous approaches have studied MAC protocols and multihop low-power routing separately. Span, a distributed, randomized algorithm declines the power consumption via short advertising periods and long beacon cycles [1]. S-MAC medium access control protocol establishes a low duty cycle operation in nodes [2]. TRAMA, another MAC protocol, reduces energy consumption by avoiding collisions via a distributed election scheme [3]. ExOR (Extremely Opportunistic Routing) is a routing method developed to reduce the total number of transmissions taking into account the actual packet propagation [4]. DTA, data transmission algebra, has been developed to generate complex transmission schedules based on collision-free concurrent data transmissions [5]. In related research we studied multihop optimization for general topologies under a simplified 802.11 MAC protocol [6]. Also, we introduced ALS-MAC in an attempt to reduce collisions and overhearing [7].

3. NOTATION

Assume that the nodes of a wireless sensor network are members of the following set: $\mathrm{N} = \{\mathrm{N}_1, \mathrm{N}_2, \mathrm{N}_3, \ldots \mathrm{N}_{n(\mathrm{N})}\}$. Nodes are placed in a rectangular region of *X* by *Y*. The distance between node i and node j is d(i,j). The distance between node k and the halfway point between node i and node j is $d(\mathrm{k}, \mathrm{m}_{\mathrm{i,j}})$. Routing algorithms are employed to determine the next hop node of $\mathrm{N_i}$, $\mathrm{N_i^{+1}}$. The distance between $\mathrm{N_i}$ and its next hop $\mathrm{N_i^{+1}}$is d(i,+1). Likewise, the distance between $\mathrm{N_k}$ and the halfway point between $\mathrm{N_i}$ and $\mathrm{N_i^{+1}}$ is $d(\mathrm{k}, \mathrm{m}_{\mathrm{i,+1}})$. R is the radio communication range.

Algorithm 1 $\mathrm{N_i^{+1}} \leftarrow \mathrm{NextHop}(\mathrm{N_i}, \mathrm{N_D}, \mathrm{N_i^R})$

1: **if** $\mathrm{N_D} \in \mathrm{N_i^R}$
2:     **return** $\mathrm{N_D}$
3: **end if**
4: $s = (X^2 + Y^2)^{1/2}$
5: **for** $1 \le \mathrm{j} \le \mathrm{n(N)},\ \mathrm{j} \ne \mathrm{i}$ **do**
6:     **if** $\mathrm{N_j} \in \mathrm{N_i^R}$ and $d(\mathrm{j}, \mathrm{D}) < s$

7: $N_i^{+1} = N_j, \; s = d(j, D)$
8: **end if**
9: **end for**

Algorithm 1 describes a single-hop selection procedure used to find N_i^{+1}, the next hop of N_i. N_D is the final destination. N_i^{+1} is the closest to the destination neighbor of N_i.

4. HARDWARE MODEL

A typical node is built around a low-power microcontroller. Wireless transceivers create physical links between nodes. Hardware provides the following low-power mechanisms.

- Each node is capable of determining its coordinates.
- The receiver and transmitter can be individually enabled and disabled.
- The transmit power can be adjusted gradually.

5. ALS-MAC PROTOCOL

We proposed a single channel MAC protocol suitable for location-aware sensor networks [7]. We call this procedure Advance Local Scheduling, ALS-MAC. In order to save energy, nodes should stay in a sleeping mode as long as possible. Periodically, nodes must wake up and receive the packets buffered for them. ALS-MAC employs beacons to synchronize internode communications. A beacon period, T_B, includes two major sections. The period begins with a contention-based, time-slotted traffic indication window, T_A. During T_A all nodes are listening and pending packets are advertised. The set of slots

$$S = \{S_0, S_1, S_2, ...S_{n(S)}\} \tag{1}$$

In an IEEE 802.11 style, short request-to-send (RTS) and clear-to-send (CTS) control frames are exchanged. The second section of the beacon period is a collection of transmission slots for scheduled access. The number of the slots is equal to the number of the slots in the indication window. Once a node succeeds in establishing a session via RTS and CTS frames in the traffic indication section, it gets an access to the corresponding slot in the data transmission section. Data transmissions are followed by acknowledgement (ACK) frames to confirm successful reception. The one-to-one mapping between advertising and transmission slots allows all nodes to sleep during the second section and wake up to exchange packets only at specific slots.

Along with this essential mode, ALS-MAC is capable of organizing three extra interaction schemes. L-mode and M-mode help to adapt to different traffic demands. S-mode aims merely to keep nodes well synchronized for future sessions.

M-mode. This interaction scheme allows multihop routing within a single beacon period. The beacon indicates one or more routing paths. All involved nodes are within the communication range. Nodes can advertise buffered packets in the following slots or immediately after the beacon if they do not interfere with the routing paths. The main advantage of M-mode is energy-efficient partitioning of the communication links and collision avoidance. Also, M-beacons can be used to send a single packet to multiple nodes.

Fig. 1 shows an example when a source sends a packet to a destination via an intermediate node. Since the routing path has been indicated in the M-beacon, the destination sends CTS in the first advertising slot. The intermediate node receives this frame and sends back its own CTS indicating also the status of the path. As a result, the source will know which nodes are available. The interaction goes on with data packets and acknowledgements.

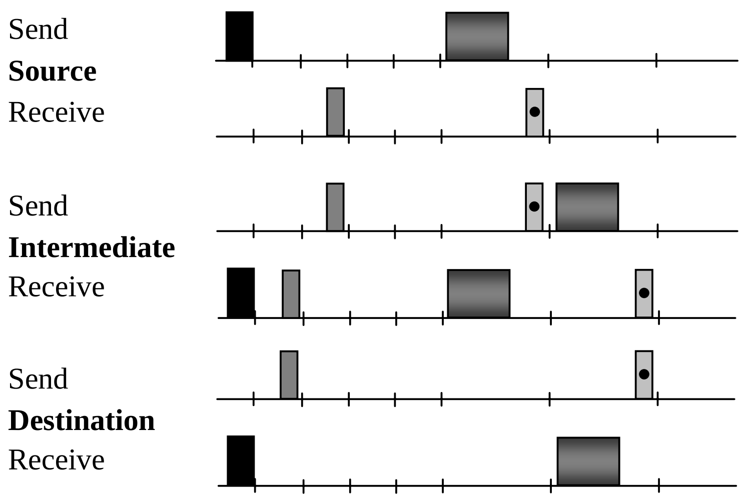

Fig. 1. Forwarding under M-mode

6. SPACE DIVISION MULTIPLE ACCESS

Calculated SDMA under M-mode allows collision-free parallel data transmissions. Assume that a M-beacon includes a single routing path. The locations of the nodes involved constitute the following set:

$$G = \{L_1, L_2, L_3, \ldots L_{n(G)}\} \quad (2)$$

Algorithm 2 describes a search procedure for a collision-free slot. Such a slot can be used to send a packet from N_i to N_i^{+1} in parallel with the advertised in the beacon routing path.

Algorithm 2 $S_j \leftarrow SDMA(N_i, N_i^{+1}, G)$

if $n(S) > n(G) - 1$
  return $j = n(S) - (n(G) - 1)$
end if
for $0 \le j \le n(S) - 1$ **do**
  if

$\mathrm{MIN}[d(L_{j+1},N_i),d(L_{j+1},N_i^{+1}),d(L_{j+2},N_i),d(L_{j+2},N_i^{+1})] >$
$\mathrm{MAX}[d(L_{j+1},L_{j+2}),d(N_i,N_i^{+1})]$

6: **return** j

7: **end if**

8: **end for**

9: $j = n(S)$

Initially, in lines 1-3, we check if the number of available slots is higher than the required number for the transmissions advertised in the beacon. If there are not empty slots, the procedure goes on with comparing the distances between the nodes. As soon as SDMA has been found, the name of the current slot is returned. When the network layout does not allow SDMA, the procedure returns a non-existing slot, $S_{n(S)}$.

Algorithm 3 $S_j \leftarrow \mathrm{SDMA}(N_i, N_i^{+1}, G)$

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if $n(S) > n(G) - 1$

return $j = n(S) - (n(G) - 1)$

end if

$m = n(S)$

$s = 0$

for $0 \le j \le n(S) - 1$ **do**

if
$\mathrm{MIN}[d(L_{j+1},N_i),d(L_{j+1},N_i^{+1}),d(L_{j+2},N_i),d(L_{j+2},N_i^{+1})]$
$-\mathrm{MAX}[d(L_{j+1},L_{j+2}),d(N_i,N_i^{+1})] > s$

$m = j$,
$s = \mathrm{MIN}[d(L_{j+1},N_i),d(L_{j+1},N_i^{+1}),d(L_{j+2},N_i),$
$d(L_{j+2},N_i^{+1})] - \mathrm{MAX}[d(L_{j+1},L_{j+2}),d(N_i,N_i^{+1})]$

end if

end for

$j = m$

Algorithm 3 is an improvement of Algorithm 2 that aims to decline the impact of radio irregularity on wireless links [8]. Radio irregularity is a common phenomenon which arises from multiple factors, such as uncontrolled variations of the transmit power and change of the path loss. In case of parallel transmissions, Algorithm 3 selects the slot which is characterized with longest distance between communicating nodes.

Fig. 2 shows simulation results for three tests. Each test is based on 1500 random deployments. We assume n(G) is equal to 4, 5 and 6 respectively. When the number of hops is increased, the transmit power is decreased and the probability for collision-free transmissions is higher.

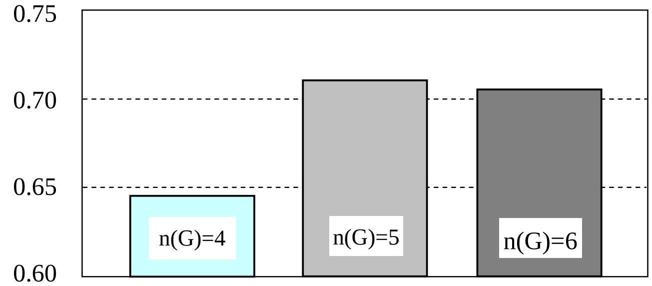

Fig. 2. SDMA success rate

7. Conclusion

This paper expands the feasibility of ALS-MAC M-mode for collision-free concurrent data transmissions. Simulations for example deployments showed that more than 60% of the concurrent transmissions can result in collision-free paths under ALS-MAC.

8. References

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