Low-Power Multihop Routing for Wireless Sensor Networks

Zdravko Karakehayov

Abstract – **This paper presents ALS-MAC, a medium access control protocol for wireless sensor networks. The protocol 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 two dedicated modes of operation for data intensive traffic which assign temporary priority to nodes with many or long buffered packets. We study collision-free concurrent data transmissions and multihop optimization schemes under ALS-MAC.**

Keywords – Wireless sensor networks, MAC protocol, Low-power routing

I. INTRODUCTION

Distributed sensor networks are made up of a large number of small sensing nodes which cooperatively perform complex tasks. Environmental monitoring, healthcare, building automation, surveillance and rescue missions are applications where wireless ad-hoc networks provide benefits that we would not otherwise be able to obtain.

The interaction between the nodes is based on wireless communication. Sensor-actuator networks employ sensors to gather information and actuators to perform appropriate actions in a area of interest. 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. Consequently, it would be beneficial to forward the packet via several hops instead a single link.

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. Location-aware nodes and radios with variable power levels would help alleviate both collision and overhearing.

In this paper we present a MAC protocol for wireless sensor networks, ALS-MAC. The protocol achieves good scalability and collision avoidance by utilizing contention-based advertising slots mapped to scheduled-based transmission slots. ALS-MAC provides extra opportunities for collision-free data transmissions and low-power multihop routing which we study for non-regular topologies.

II. 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], [3]. TRAMA, another MAC protocol, reduces energy consumption by avoiding collisions via a distributed election scheme [4]. ExOR (Extremely Opportunistic Routing) is a routing method developed to reduce the total number of transmissions taking into account the actual packet propagation [5]. DTA, data transmission algebra, has been developed to generate complex transmission schedules based on collision-free concurrent data transmissions [6]. Multihop optimization has already been studied for simple linear settings [7], [8]. In related research we studied multihop optimization for general topologies under a simplified 802.11 MAC protocol [9].

Zdravko Karakehayov is with the MCI-CPD, University of Southern Denmark, Grundtvigs Alle 150, DK-6400, Sønderborg, Denmark, E-mail: zdravko@mci.sdu.dk

III. NOTATION

Assume that the nodes of a wireless sensor network are members of the following set: $N = \{N_1, N_2, N_3, ... N_{n(N)}\}$. 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 $d(k, m_{i,j})$. Routing algorithms are employed to determine the next hop node of N_i, N_i^{+1}. The distance between N_i and its next hop N_i^{+1} is *d*(i,+1). Likewise, the distance between N_k and the halfway point between N_i and N_i^{+1} is $d(k, m_{i,+1})$. R is the radio communication range.

A statement **power**(*d*(i,j)) in the pseudocode listing adjusts the transmit power according to the distance *d*(i,j) to save energy. A statement **send**$(N_i \rightarrow N_j)$ indicates a packet forwarding from node i toward node j.

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

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

IV. 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.

V. ALS-MAC PROTOCOL

We propose a single channel MAC protocol suitable for location-aware sensor networks. 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.

L-mode. A node generates a L-beacon when the number of packets it has already buffered is greater than a predefined threshold. The beacon announces a number of slots equal to the number of buffered packets. Addressed nodes send ACK frames in the same order they have been indicated in the beacon. Neighbors that are not involved in the advertised traffic are still allowed to participate. However, ALS-MAC discipline requires they to follow collision-free SDMA with regard to the advertised links. L-mode allows to transmit very long packets when a single data frame utilizes a complete transmission section.

S-mode. S-beacons are broadcast by nodes which have no packets to transmit. The motivation behind S-beacons is to maintain synchronization. When a node does not receive beacons for a predefined number of periods, it generates a S-mode frame. If neighbors have buffered packets, they exchange control and data frames in the same way they do after normal beacons.

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.

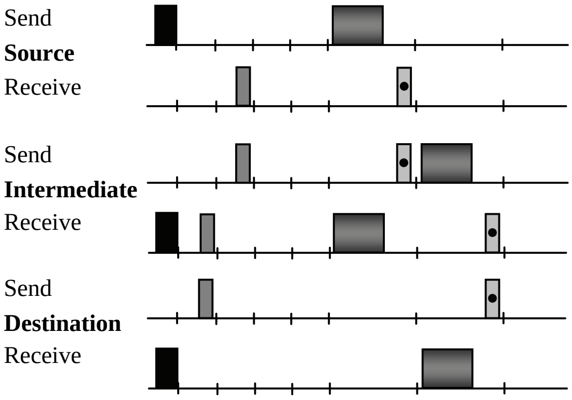

Fig. 1. Forwarding under M-mode

VI. ENERGY MODEL

The energy used to send a bit over a distance *d* may be written as $E = ad^n$, where *a* is a proportionality constant [10], [11]. The radio parameter *n* is a path loss exponent that describes the rate at which the transmitted power decays with increasing distance. Typically, *n* is between 2 and 4 [10]. $E = ad^n + b$ emerges as a more realistic model. The *b* constant is associated with specific receivers, CPUs and computational algorithms. The power consumption of a turned on receiver is yet another constant, $\mathrm{P_R}$.

VII. MULTIHOP OPTIMIZATION

Fig. 2 shows a partitioning of the link in the general case, the intermediate node is neither equally spaced from S and D, nor located on the line SD.

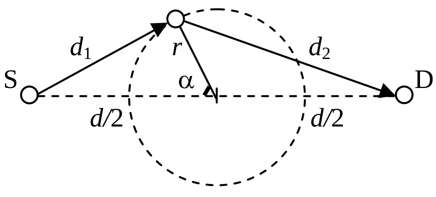

Fig. 2. Partitioning the link in the general case

Theorem 1. Let the energy per bit sent over a distance *d* scales as $ad^4 + b$. The power consumption of a turned on receiver is $\mathrm{P_R}$. The bit rate is B. Referring to Fig. 2, if the distance

$$d \geq ((8\mathrm{P_R} + 8b\mathrm{B})/7a\mathrm{B})^{1/4} \tag{2}$$

and the distance between the intermediate node and the halfway point between S and D

$$r \leq \left(-1.25d^2 + \left(2d^4 - 0.5a^{-1}\mathrm{B}^{-1}\mathrm{P_R} - 0.5a^{-1}b\right)\right)^{1/2}\Big)^{1/2} \tag{3}$$

the two-hop communication requires less energy than the direct link.

Proof. We must prove when the following inequality holds. Suppose the communication range is R, the packet has *p* bits and signaling frames are *q* bits long. The advertising part of the beacon period is $\mathrm{T_A}$ and the number of slots is n(S).

$$\begin{aligned}
&q(a\mathrm{R}^4 + b) + p(ad_1^4 + b) + \mathrm{T_A P_R} + 2(q/\mathrm{B})\mathrm{P_R} + 2q(ad_1^4 + b) \\
&+ p(ad_2^4 + b) + (\mathrm{T_A}/\mathrm{n(S)})\mathrm{P_R} + \mathrm{T_A P_R} + (p/\mathrm{B})\mathrm{P_R} + (q/\mathrm{B})\mathrm{P_R} \\
&+ 2q(ad_2^4 + b) + (\mathrm{T_A}/\mathrm{n(S)})\mathrm{P_R} + \mathrm{T_A P_R} + (p/\mathrm{B})\mathrm{P_R} \\
&+ (\mathrm{n(N_S^R)} - 2)((\mathrm{T_A}/\mathrm{n(S)})\mathrm{P_R} + \mathrm{T_A P_R}) \leq q(a\mathrm{R}^4 + b) + p(ad^4 + b) + \mathrm{T_A P_R} \\
&+ (q/\mathrm{B})\mathrm{P_R} + 2q(ad^4 + b) + (\mathrm{T_A}/\mathrm{n(S)})\mathrm{P_R} + \mathrm{T_A P_R} + (p/\mathrm{B})\mathrm{P_R} \\
&+ (\mathrm{n(N_S^R)} - 1)((\mathrm{T_A}/\mathrm{S})\mathrm{P_R} + \mathrm{T_A P_R})
\end{aligned} \tag{4}$$

$$d_1 = \left(d^2/4 - dr\cos\alpha + r^2\right)^{1/2} \tag{5}$$

$$d_2 = \left(d^2/4 + dr\cos\alpha + r^2\right)^{1/2} \tag{6}$$

Thus, we get

$$16a\mathrm{B}r^4 + 8ad^2\mathrm{B}\left(1 + 4\cos^2\alpha\right)r^2 - 7ad^4\mathrm{B} + 8\mathrm{P_R} + 8b\mathrm{B} \leq 0 \tag{7}$$

Since the threshold value for the distance *r* will vary with α, we take the worst case, $\cos\alpha = 1$. Then the inequality has solutions if and only if $d \geq ((8\mathrm{P_R} + 8b\mathrm{B})/7a\mathrm{B}))^{1/4}$. Using the quadratic formula,

$$r \leq \left(-1.25d^2 + \left(2d^4 - 0.5a^{-1}\mathrm{B}^{-1}\mathrm{P_R} \text{ - } 0.5a^{-1}b\right)^{1/2}\right)^{1/2} \tag{8}$$

VIII. SDMA UNDER M-MODE

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:

$$\mathrm{G} = \left\{\mathrm{L_1, L_2, L_3, \ldots L_{n(G)}}\right\} \tag{9}$$

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

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

if $\mathrm{n(S) > n(G) - 1}$
  return $\mathrm{j = n(S) - (n(G) - 1)}$
end if
for $0 \leq \mathrm{j} \leq \mathrm{n(S) - 1}$ **do**
  if $\mathrm{MIN}\left[\mathrm{d(L_{j+1}, N_i), d(L_{j+1}, N_i^{+1}), d(L_{j+2}, N_i), d(L_{j+2}, N_i^{+1})}\right] >$ $\mathrm{MAX}\left[\mathrm{d(L_{j+1}, L_{j+2}), d(N_i, N_i^{+1})}\right]$
    return j
  end if
end for
 $\mathrm{j = n(S)}$

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

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

2: **return** $j = n(S) - (n(G) - 1)$

3: **end if**

4: $m = n(S)$

5: $s = 0$

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

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

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

9: **end if**

10: **end for**

11: $j = m$

Algorithm 3 is an improvement of Algorithm 2 that aims to decline the impact of radio irregularity on wireless links [12]. 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.

IX. Conclusion

This paper presents ALS-MAC, a low-power medium access control protocol. The protocol achieves scalability and collision avoidance via variable transmit power levels and a correspondence between contention-based and scheduled-based slots. ALS-MAC has a special mode to support multihop low-power routing. We proved that any node located within a certain area can be successfully employed to partition the communication link. We discussed algorithms for collision-free parallel data transmissions under ALS-MAC.

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