Archives of Transport System Telematics

Volume 5

Issue 3

September 2012

Optimization of Channel Access in Wireless Sensor Networks

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ABSTRACT

The objective of the work presented in this paper is to analyse the problem of deployment of TDMA wireless sensor networks in the area of transport telematics from the communication subsystem optimization perspective. The problem of broadcast scheduling has been outlined and a heuristic algorithm has been designed for the optimization of radio channel access control using the TDMA method. The channel utilization was the main optimization goal while eliminating primary and secondary conflicts between the broadcasting stations.

KEYWORDS: wireless sensor networks, TDMA, broadcast scheduling, optimization

1. Introduction

The merging of Internet, communication, information, transportation and industrial control technologies together with the latest technical advances in this areas opened the road for a new generation of economically undemanding sensors and actuators capable of high degree of spatial and temporal resolution and accuracy highly required in telematic applications. The technology for sensing and control includes fields of electric and magnetic sensors, seismic sensors, radiofrequency sensors, electro-optic and infrared sensors, radars, sonars, lidars, and localization and navigation sensors.

The sensing technology is of a high growth potential not only in science or control, but also in a wider spectrum of applications related to monitoring and protection of critical transportation infrastructure, power industry, goods processing, public health, environment and other areas.

A sensor network is an infrastructure consisting of sensing (measuring) and/or acting, computing and communication elements providing functions for measuring, monitoring and reacting on events in a specified operating environment. The basic components of a sensor network is a set of distributed or localized sensors, interconnecting network (usually wireless), central data aggregating node, and a set of computing resources responsible for data correlation, trends monitoring, states determination, and data mining. In this context the sensing and computing nodes are considered as a part of the sensor network, but in fact, a part of the computations may be performed by the network itself. Because of a potentially huge amount of gathered data, algorithmic methods for data processing and communication control play a significant role. The communication and computation infrastructure is specific in dependence on deployment environment and application.

2. Wireless Sensor Networks

Multiple technology implementations utilize the principle of aggregation nodes gathering data from a defined sensor field and sending them to a final point for analysis, for longer distances making use of public wired or wireless network (Fig. 1).

The structure of a wireless sensor network node is dependent on the required functionality in a given application. Fig. 2 depicts a basic node configuration, while the mandatory blocks are marked grey, the optional ones are white. In case of implementation of an active element, the node is referred to as a wireless sensor/actuator. Regarding the possible topological structures of a wireless sensor network it is evident, that a node can operate as a data source (measured data, position information etc.), data receiver (actuator), and as a router (forwarding data from neighboring nodes).

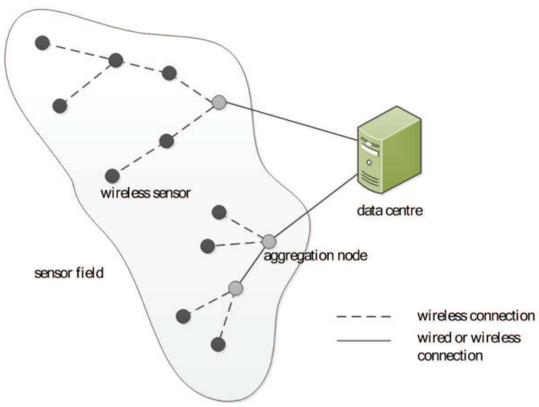

Fig. 1. Example of wireless sensor network configuration

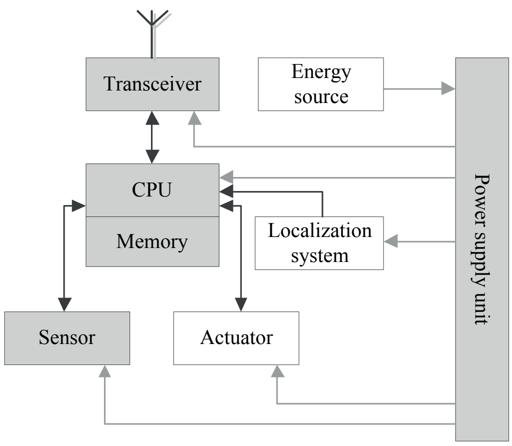

Fig. 2. Structure of a wireless sensor node

The classification of wireless sensor networks is based on a set of characteristic factors [1], according to which the individual configurations can be segmented as follows:

- according to distance from base station (data centre)
  - single-hop,
  - multi-hop,
- according to data dependency
  - aggregating,
  - non-aggregating,
- according to sensor nodes distribution
  - deterministic,
  - dynamic (random),
- according to control scheme
  - autonomously configurable,
  - non-autonomously configurable,
- according to application area
  - industrial automation,
  - transportation (Car2Car, Car2Infrastructure) [6],
  - intelligent buildings,
  - environment,
  - public health,
  - security,
  - military,
  - and others.

Based on these classifications it is obvious that different combinations of the defined classification factors lead to an extensive and diverse set of possible configurations. This implies varied requirements on network characteristics, priority of key parameters, and specific problems.

3. Broadcast Scheduling in TDMA Networks

A wireless sensor network can be represented by a graph $G=(V,E)$, where $V=\{v_1, v_2,\ldots,v_i,\ldots, v_N\}$ is a set of nodes, while N is number of nodes and $E = \{e_1, e_2,\ldots,e_L\}$ is a set of undirected edges, where L is number of undirected edges [4]. The existence of an edge between two nodes means, that these nodes are able to directly mutually receive broadcast packets transmitted by the other node. The connectivity between network nodes can be expressed by a symmetric matrix **C** with dimension $N\times N$, called connectivity or adjacency matrix, where the element

$$c_{ij} = \begin{cases} 1, & \text{if } v_i \text{ and } v_j \text{ are connected} \\ 0, & \text{otherwise} \end{cases}$$

In case two nodes are directly connected, we say they are one hop away. Let us suppose time divided into slots and a frame with constant length. The transmission of a single packet takes one time slot. A TDMA frame consists of a fixed number of such time slots. Packets can be transmitted simultaneously without conflict in the same time slot only if no interference occurs. If an optimal TDMA transmission scheme is determined, the frame is repeated. Let us denote this TDMA frame by a matrix **T** with dimensions $M\times N$, which elements

$$t_{mj} = \begin{cases} 1, & \text{if } v_j \text{ transmits in time slot } m \\ 0, & \text{otherwise} \end{cases}$$

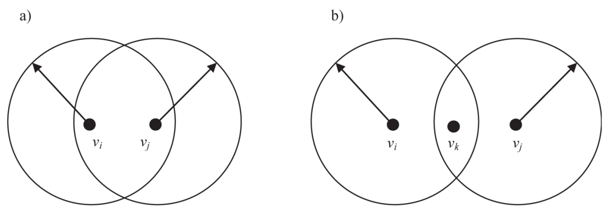

Fig. 3. **Primary a) and secondary b) conflict**

If node v_i transmits a packet, none of its neighbors, i.e. nodes a single hop away, is permitted to transmit at the same time, which would cause a primary conflict or direct collision [2] (Fig. 3a). All nodes which are two hops away from node v_i are also not permitted to transmit simultaneously with node v_i, seeing that this would lead to a secondary conflict or hidden collision (Fig. 3b) because of a multiple reception on intermediate nodes.

All these nodes one or two hops away from node v_i are referred to as broadcast zone of node v_i [3]. A set of these nodes is denoted B_i. It is evident, that the need of elimination of interferences requires, that none of the nodes located in B_i can transmit simultaneously with node v_i. Fig. 4 illustrates the principle of creation of broadcast zone for node v_4 (grey area B_4) and node v_8 (area B_8). The broadcast zone of node v_4, denoted as B_4, contains all nodes which are one or two hops away from node v_4. That means that it delimits a set of nodes, by which transmission primary or secondary conflicts would occur. Based on this concept it is possible to form a compatibility matrix **D** with dimensions $N \times N$, which elements are given

$$d_{ij} = \begin{cases} 1, & \text{if } v_j \in B_i \\ 0, & else \end{cases}$$

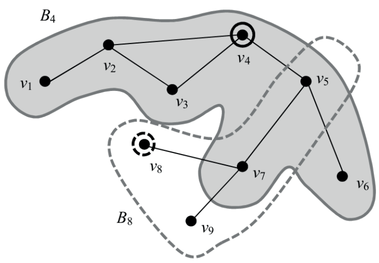

Fig. 4. The principle of broadcast zones

The goal is to find the shortest TDMA cycle fulfilling the following requirements:

- each node has to transmit during a TDMA cycle at least once

$$\sum_{m=1}^{M} t_{mi} \geq 1 \quad \text{for } \forall i \qquad (1)$$

- to avoid primary conflicts a node must not transmit and receive packets in the same time slot,
- a node must not receive two or more transmissions simultaneously, which eliminates secondary conflicts.

Formally then

$$\text{if } t_{mi} = 1, \text{ then } \sum_{j=1}^{N} t_{mj} d_{ij} = 0 \quad \forall m, i \qquad (2)$$

i.e.

$$\sum_{m=1}^{M} \sum_{i=1}^{N} \sum_{j=1}^{N} t_{mi} t_{mj} d_{ij} = 0$$

The latter two conflicts can be avoided by creating a TDMA frame **T** with a structure satisfying the equation (2). A trivial solution satisfying all three constraints is a N-slot TDMA frame, where N different nodes transmit in N different time slots (Fig. 5). At the same time, the value N represents the lower bound of TDMA frame length.

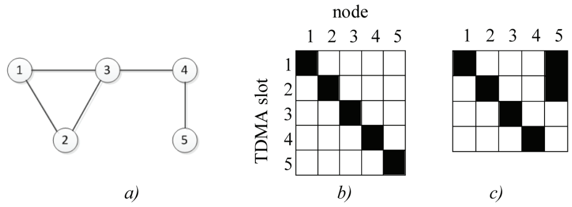

Fig. 5. Example of network topology a), trivial TDMA frame b), optimal TDMA frame c)

The primary optimization criterion is the minimization of TDMA frame length, i.e. M should be as small as possible. One of other possible optimization goals is the maximization of overall number of transmissions. This requirement can be represented by channel utilization index ρ, while

$$\rho = \frac{1}{MN} \sum_{m=1}^{M} \sum_{j=1}^{N} t_{mj} \qquad (3)$$

4. Optimization of TDMA frame

A heuristic algorithm has been designed for optimization of TDMA frame length M fulfilling the constraints (1) and (2), i.e. enabling each node to transmit at least once during a TDMA cycle and elimination both, primary and secondary conflicts.
The algorithm has been tested on a set of testing network topologies [5] with given statistical properties (number of nodes, number of edges, connectivity). The obtained results are summarized in Table 1.

Table 1. Resulting TDMA frames lengths for the individual testing topologies

Testing topology#	Number of nodes N	Number of edges E	min(deg(v))	max(deg(v))	Frame length M
1	100	162	2	8	9
2	300	476	2	9	10
3	500	827	2	11	12
4	100	560	4	18	19
5	300	1795	4	24	25
6	500	2812	2	22	23
7	750	4348	3	24	25
8	1000	5826	3	22	23
9	100	1117	10	38	39
10	300	3809	5	39	40
11	500	6214	5	38	39
12	750	9997	6	49	50
13	1000	13028	7	42	43
14	100	1712	10	56	57
15	300	6076	12	62	63
16	500	10869	15	71	72
17	750	16932	15	70	71
18	1000	22837	15	72	73

Considering the inequality (4) determining the lower bound of TDMA frame length, which can be written as

$$M \geq \max(\deg(v_i)) + 1, \quad i = 1, 2, ..., N \qquad (4)$$

then it is evident, that for the individual testing topologies with the use of the proposed algorithm optimal TDMA frame lengths M have been achieved.

5. Conclusion

The implementation of wireless sensor networks into telematic systems requires definition of priority parameters of these networks. In the first place the reliability of communication has to be satisfied by eliminating conflicts between nodes trying to simultaneously transmit while being within transmission range (primary, direct conflicts) and conflicts occurring during simultaneous broadcast transmission of two nodes to a third node (secondary, indirect conflict).

An algorithm has been proposed to detect primary and secondary conflicts in a given network topology defined by a connectivity matrix.

Analysis of this problem showed suitability of the TDMA medium access mechanism for effective and reliable sharing of common radio-frequency channel between the individual nodes of a wireless sensor network. A simple assignment of a time slot for each node (trivial TDMA frame) leads for higher number of nodes to a drastically ineffective utilization of transmission channel and to a significant delay. The reason is not enabling to transmit nodes which could transmit without to cause a conflict.

The solution of this problem is based on finding such a TDMA frame, which in compliance with the given input data (connectivity matrix, compatibility matrix) enables each network node to transmit at least once during cycle duration (assigns at least one time slot) and at the same time this TDMA frame has a minimal length.

Acknowledgment

The paper was elaborated with support of the Slovak grant agency VEGA, grant No. 1/0453/12 "*Study of interactions of a motor vehicle, traffic flow and road*".

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