Performance Analysis of Receive Collaboration in TDMA-based Wireless Sensor Networks

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Abstract— **This paper presents a general framework to enable the implementation of receive collaboration in wireless sensor networks (WSN). The framework also allows the evaluation of collaborative channel equalization (CCE) performance as one aspect of receive collaboration. Our analysis shows that the use of receive collaboration to receive signals from remote sources is energy efficient with reasonable computational load and memory consumption. However, the increased time delay is a restricting parameter, which limits the application of receive collaboration to a small number of cooperating nodes and to rather short data streams.**

Keywords-*receive collaboration; wireless sensor network; channel equalization; TDMA*

I. INTRODUCTION

Due to the limited and nonrenewable batteries of the sensor nodes in WSNs, energy efficiency is one of the most important issues of the network and protocol design in WSNs.

The application of array processing schemes [1-4] in wireless communication applications is beneficial in terms of energy efficiency and reliability. In WSNs, array processing schemes are applicable during a cooperation of a group of neighbouring nodes. Obviously, synchronization, sharing the signals via local communications and processing capabilities to process the transmitted/received signals are some necessities of the sensor nodes.

Due to the limitations of WSNs, array processing schemes are applicable by cooperation of the sensor nodes which increases the amount of inter-node communications. In [5] and [6], a general framework for implementation of array processing schemes is developed. According to this idea, a group of sensors cooperate to improve signal reception. Collaborative channel equalization is also suggested as an aspect of receive collaboration. The use of array processing schemes in transmit mode is considered as distributed beamforming in [7-9]. It is shown that both receive and transmit collaboration are effective methods to decrease and distribute the energy consumption.

Despite of its energy efficiency, the increased computational load and memory consumption of receive collaboration limit the applications. However, increase in its applications is expected due to future advances in hardware design.

In [5], receive collaboration is introduced as a way to increase the energy efficiency of WSNs in receive mode. According to this new idea, a group of neighboring nodes cooperate to improve the reception of a signal by applying array processing schemes like channel equalization. Based on this idea, it is applicable to improve the quality of the received signal at a fixed value of transmitted SNR or to reduce the transmitted power without any decrease in the quality of received signal. The implementation of receive collaboration and CCE in CDMA based WSNs are introduced in [6]. It is shown that due to the large amount of spreading and despreading during CDMA based local communications, the computational load and memory requirements of receive collaboration increase more than linearly. Therefore, the processing capability and available memory of the nodes are the two restricting parameters to develop receive collaboration in CDMA based networks.

In TDMA-based protocols, a TDMA frame is divided into time slots and each node is assigned one. The transmission schedule allows nodes to send and receive without collision. In TDMA based MAC protocols the interference between adjacent wireless links is guaranteed to be avoided. Thus, the energy waste coming from packet collisions is diminished. In [10-12] some TDMA based MAC protocols for sensor networks are studied. Although the use of TDMA in local communications requires exact synchronization of cooperating nodes, it is an efficient way of mitigating the limitations of CDMA based networks.

The objective of this work is to develop and evaluate receive collaboration in TDMA based WSNs. To do so, in the next section, we propose a general framework for implementation of receive collaboration in TDMA based WSNs. This framework is a primary step to implement the array processing schemes. To evaluate the performance, advantages and disadvantages of receive collaboration, CCE is considered in Section III as an aspect of receive collaboration. According to CCE, after aggregation of the received signals at the processing node, a channel equalization scheme is applied on the signals to decrease undesired effects of the transmission channel. In this section, energy efficiency, computational load, time delay and memory requirements of the proposed framework are evaluated. It also includes some simulations. Finally, Section IV concludes this paper.

II. RECEIVE COLLABORATION FOR TDMA BASED WSNS

In the following subsections, a general framework for implementation of receive collaboration in TDMA based WSNs is developed.

A. Data Reception

The first step of receive collaboration is the reception of an impinging signal from the remote node. In TDMA based networks, various methods may be considered to manage the reception and transmission timing of the nodes.

In the following steps, it is assumed that the cooperating nodes transmit their signals only in their corresponding time slot whereas they are ready to receive the impinging signals both in their time slots and in the common time slot.

B. Announcement

After reception of the impinging signal, one of the cooperating nodes is selected as the processing mode to handle the receive collaboration. New processing node is selected by a reference node which can be the previous processing node or cluster-head in the cluster based networks. An announcement message containing the ID of the new processing node is broadcasted through the other cooperating nodes in the common time slot.

C. Synchronization

Random distribution of the cooperating nodes causes random time delays in local communications. Therefore, in advance of the aggregation of the received signals, cooperating nodes should be synchronized. Similar to the CDMA based networks [5], during the synchronization step, the processing node estimates the time delays of local communications and assigns new time slots to the cooperating nodes to increase the efficiency of the receive collaboration. Proper time delays should be applied to the new time scheduling to avoid overlapping.

To do so, processing node broadcasts a synchronization message via the common time slot. It can both detect the time slots of the cooperating nodes and estimate the time delays of local communications based on the feedbacks from cooperating nodes. To properly estimate the time delays, the synchronization message should be short enough to avoid overlapping due to different time delays. Finally, the processing node computes a new scheduling for the cooperating nodes and informs them via their previous time slots. Reception of the acknowledgements from the cooperating nodes confirms proper time slots allocation.

Various time slot scheduling methods can be suggested to avoid overlapping due to different time delays of local communications. As the simplest method, some guard bands are considered among the time slots. Assuming the length of the guard bands to be equal to the maximum time delay of local communications overlap-free local communication is guaranteed. Despite of its simplicity, this method is not time-efficient. In another method, non-processing nodes are sorted according to their time delays and the node with smaller time delay would belong to the first time slot and so on. Although this method increases the efficiency of time scheduling, it is not completely efficient due to gaps among the received time slots. As an efficient method, it is possible to designate the time slots such that they have no overlap at the processing node, meanwhile there is no gap among the received time slots by the processing node. The length of the time slots depends on the method used in the aggregation step. It is discussed in more detail in the next subsection.

D. Aggregation

In this step, received signals by the cooperating nodes are aggregated at the processing node. Proper array processing scheme is applied mostly by combination of these signals after applying weighting coefficients which are generated recursively based on the aggregated signals. In this paper, the least squares constant modulus algorithm (LS-CMA) [13-14] is considered as the channel equalization scheme. LS-CMA estimates optimum weighting coefficients by minimizing the following cost function with respect to w_k, the $1\times M$ vector of weighting coefficients, which corresponds to k-th sample of the aggregated signal

$$J(\mathbf{w}_k) = E\left[\left(|y_k|^2 - 1\right)^2\right] \quad (1)$$

here, $E[.]$ denotes the expected value and y_k, the channel equalizer output is in the form

$$y_k = \mathbf{w}_k \cdot \mathbf{x}_k^H \quad (2)$$

where x_k is the $1\times M$ vector containing the k-th sample of received signals. The operator H is the conjugate transpose operator.

According to the stochastic gradient methods [15], the weight vector in each time instant is updated based on its previous value and the gradient of the cost function. In practice, w_k is updated recursively as follows

$$\mathbf{w}_{k+1} = \mathbf{w}_k - \mu \cdot \mathbf{x}_k \cdot \left[|y_k|^2 - 1\right] \cdot y_k \quad (3)$$

In this equation, μ is the step size of the algorithm, a constant parameter to control the convergence rate of the algorithm. After convergence of the algorithm to its optimum weighting coefficient, w_{opt}, it has small variations due to the variation of the effective parameters on the aggregated signals. It enables the processing node to apply w_{opt} for some parts of the aggregated signals.

To start the aggregation step, processing node broadcasts a request for aggregation. After receiving the aggregation request, each non-processing node sends its signal to the processing node via its corresponding time slot. Assuming to be enough samples at the first part of aggregated signals for convergence, w_{opt} is achieved and used to generate the output of the channel equalizer.

Depending on the criticality of the power supply and computational capability of the processing node and also energy consumption of the local communications, it is possible to distribute the computational load. To do so, processing node sends the coefficients to the corresponding nodes. Each node sends its signal to the processing node after applying the weighting coefficient.

Due to the simple and low cost construction of sensor nodes, it is not applicable to implement exact synchronization modules for the cooperating nodes. Therefore, especially for higher data rates, there are some synchronization errors during local communications.

The question is that how much is the ability of CCE in the case of imperfect synchronization. Despite the performance degradation of CMA based channel equalizer due to random distribution of the cooperating nodes, it is shown that CMA is still helpful for such applications [5]. Since channel equalization is not based the nodes' positions, it is possible to model the synchronization errors as some changes in the nodes' position. However the synchronization error should be small enough to have correlated signals at the processing node in data aggregation step.

III. PERFORMANCE EVALUATION

CCE is an aspect of receive collaboration in which the processing node applies a channel equalization method to decrease undesired transmission channel effects. In this section, the effect of CCE on some critical parameters of WSN such as energy efficiency, computational load, time delay and memory consumption are considered.

To better visualization of the analysis of this section, some simulations are also presented. The assumptions of this section are listed below:

- Duration of the transmitted signal: 1 *ms*
- Number of the cooperating nodes: 50
- The distance between remote and cooperating nodes: 2 *km*
- Primary time slot duration in local communications: 100 μs
- The number of primary time slots in the primary scheduling: 100
- New time slot duration: 50 μs
- Number of the time slots in the new scheduling: 50
- Radius of the disk containing the nodes: 50 *m*
- Node density: $6.4 \cdot 10^{-6}$ $nodes/m^2$
- Carrier frequency of the remote node: 20 *MHz*
- BER of interest at the processing node: 0.01

These parameters are constant unless it is mentioned. To focus on CCE, we avoid using any coding technique in our simulations.

A. Energy Efficiency

Energy efficiency is the relative improvement of using CCE reception method which is defined as follows

$$e = \frac{E_{noCCE} - E_{CCE}}{E_{noCCE}} \tag{4}$$

where E_{noCCE} and E_{CCE} are energy consumption of non-CCE and CCE based reception method.

In the case of non-CCE based reception method, one of the cooperating nodes receives the impinging signal from the remote node. According to the Friis equation, the transmission loss is

$$L_{LR} = 20\log(L) + 20\log(f_d) + 32.44 \tag{5}$$

where L (*km*) is the distance between remote and cooperating nodes and f_d (*MHz*) is the carrier frequency of the remote node. Without the use of CCE, to achieve a fixed BER at the receivers, received SNR should be higher than a threshold SNR_{noCCE} which is estimated in [5]. Therefore, the transmitted power is

$$P_{noCCE} \geq L_{LR} + SNR_{noCCE} + N \tag{6}$$

where, N is the noise power at the receiver. All parameters in equation (6) are in dB. If the duration of the transmitted signal is T_d, the total energy consumption in the case of using no CCE is

$$E_{noCCE} = P_{noCCE} \cdot T_d \tag{7}$$

In the case of using CCE, to meet the BER of interest, the SNR at the receiver should be equal to or greater than SNR_{CCE}. Similar to the discussion above, the energy consumption at the transmitter is equal to

$$E_{rec} = P_{rec} \cdot T_d \tag{8}$$

where

$$P_{rec} \geq L_{LR} + SNR_{CCE} + N \tag{9}$$

In the second step, a reference node selects the new processing node and introduces it to the other cooperating nodes by broadcasting an announcement message. The energy consumption of this step is

$$E_{ann} = P_m \cdot T_m \tag{10}$$

where T_m is the duration of the managing messages like announcement or synchronization. For simplicity, we assume the same length for these messages. P_m is also the required transmission power for local communications. Assuming the required SNR at the receivers during local communications to be SNR_{SR}, we have

$$P_m \geq L_{SR} + SNR_{SR} + N \tag{11}$$

In (11), all of the parameters are in dB. L_{SR} is the maximum transmission loss in local communications which corresponds to the maximum inter-node distance in the virtual array. It is calculated similar to (5).

During the synchronization step, the processing node broadcasts a synchronization message and receives some feedbacks from the cooperating nodes. It contains M local transmissions. After estimation of the time delays of the local communications, the processing node generates new more time-efficient scheduling and informs the other cooperating nodes during M-1 local transactions. Reception of some acknowledgements from the cooperating nodes needs also M-1 local communications. Therefore, the synchronization step is performed during 3M-2 local communications and its energy consumption is

$$E_{syn} = (3M - 2) \cdot P_m \cdot T_m \tag{12}$$

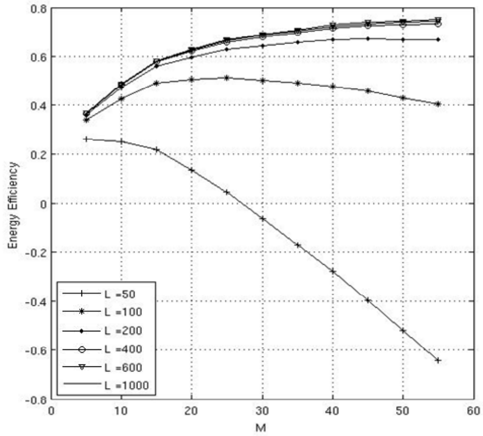

Figure 1. Effect of increasing the number of cooperating nodes on the energy efficiency for different values of *L*

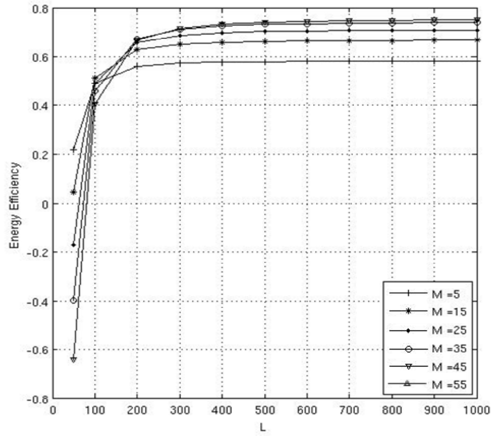

Figure 2. Effect of increasing the distance between remote and cooperating nodes on energy efficiency for different values of *M*

At the aggregation step, all of the non-processing nodes send their data to the processing node. Depending on the length of data stream and the time slot intervals, this step is performed in several time slots. The energy consumption of this step is

$$E_{agg} = (M-1) \cdot P_m \cdot T_d \tag{13}$$

Therefore, the energy consumption of CCE based reception method is

$$E_{CCE} = [(3M-1) \cdot T_m + (M-1) \cdot T_d] \cdot P_m + T_d \cdot P_{rec} \tag{14}$$

By substitution of (14) in (4) and some simplifications, energy efficiency is achieved as (15).

Fig. 1 illustrates the effect of increasing the number of cooperating nodes on energy efficiency. In all situations, the area in which the cooperating nodes are distributed is the same. Therefore, increasing the number of nodes is the same as increasing the node density. In this figure, energy efficiency is calculated for different values of L (the distance between remote and cooperating nodes). As seen in this figure, when $L = R$, increasing of M has negative effect on the energy efficiency such that CCE is inefficient for $M \geq 30$. Although CCE decreases the transmitted power by the remote node, the energy consumption of local communications grows up by increasing the number of cooperating nodes. In CCE, energy consumption can be divided into two parts; energy consumption by the remote node (E_{RN}) and that of local communications (E_{LC}). For small values of L, due to the small values of transmission loss, both E_{RN} and E_{noCCE} are rather small. Therefore E_{LC} plays key role in energy efficiency.

Moreover, Fig. 1 shows that by increasing of L (in the case of proper transmission range) the energy efficiency improves. It is because of the higher increment rate of E_{RN} rather than E_{LC}. Finally E_{LC} can be neglected for higher values of L and therefore the curves are saturated.

Increasing of L has no effect on the computational load and memory consumption and its effect on the time delay is neglectable. Therefore, it can be said that the application of CCE in long range communications is more beneficial than that of in short distances.

Fig. 2 shows the effect of increasing the distance of the remote node on the energy efficiency for different values of the number of cooperating nodes. All of the curves saturate by increasing of L, but increasing of M increased both the distance in which saturation happens and the final value of the energy efficiency. As mentioned before, by increasing of L, E_{RN} increases whereas E_{LC} remain constant such that after some increase in L, E_{LC} become neglectable and the curves approach to their final value. Increasing of M increases E_{LC}. Therefore, saturation happens in larger values of L. On the other hand, for small values of L, $E_{LC} > E_{RN}$. Therefore energy efficiency descends significantly. Since increases by M, using less cooperating nodes yields better results.

B. Time Delay

In the case of using no CCE, one of the cooperating nodes receives the impinging signal from the remote node. Therefore, the needed time for no CCE based reception method is $T_{noCCE} = T_d + L/C$ where T_d is the length of transmitting data sequence by the remote node, L is the distance between receiver node and the remote node and C is the free space wave propagation speed. In CCE-based reception method, the time delay of the first step is equal to T_{noCCE}. Neglecting the time delay of selecting the processing node, needed time for announcement is $T_{ann} = T_m + d_{max}/C$, where d_{max} is the maximum inter-node distance among the cooperating nodes.

The transmission of the announcement message is postponed until the next common time slot which at the worst case, it causes a time delay of $M'T'_S$, where M' and

$$e = \frac{(SNR_{noCCE} - SNR_{CCE}) \cdot T_d - [(3M-1) \cdot T_m + (M-1) \cdot T_d] \cdot P_m}{20\log L + 20\log f_d - 32.44} \tag{15}$$

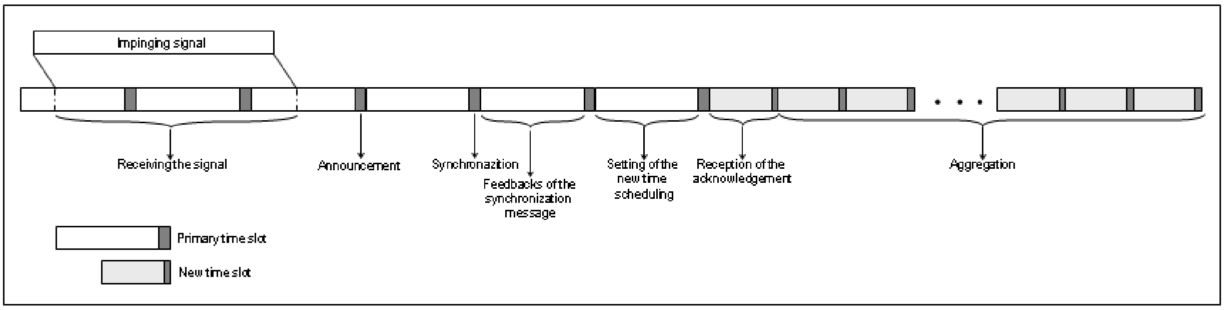

Figure 3. Time delay of the receive collaboration in TDMA based WSNs

T_S' are the number and duration of the time slots of each frame in the primary scheduling.

At the synchronization step, the processing node broadcasts the synchronization message in the common time slot and receives the feedbacks from the cooperating nodes in their corresponding time slots. The processing node sends new time scheduling information to the cooperating nodes via their primary time slots. Finally, the processing node receives some acknowledgements from the cooperating nodes. Therefore the total time delay of the synchronization step is $T_{syn} = 3M'T_S' + MT_S$, where M and T_S are the number and duration of the time slots in the new time scheduling. Finally, at the aggregation step, all of the nodes send their data to the processing nodes, which is performed in $M \cdot T_d$.

Fig. 3 represents the consuming time of different steps of receive collaboration. According to this figure, the time delay of CCE is equal to

$$T = \frac{L}{C} + 4M' \cdot T_S' + (M+1) \cdot T_d + M \cdot T_S \tag{16}$$

In equation (16), the time delays of local communications are neglected.

Fig. 4 illustrates the time delay of CCE. It is shown that the time delay increases linearly by increasing the duration of the received signal from the remote node. This increase is mostly because of the serial aggregation of the signals in the aggregation step due to the use of TDMA in local communications. It is why the increment rate of the time delay curves increase by increasing of the number of cooperating nodes.

C. Memory Consumption

Fig. 5 shows the memory consumption of receive collaboration. As expected from the Table 1, the curves are linear. It shows that increasing of M has approximately linear effect on the memory consumption. Generally, it can be said that memory consumption is not a critical issue in TDMA based WSNs.

According to receive collaboration steps, memory consumption of the non-processing nodes is low. The memory consumption of the processing node depends on the length of the signal transmitted by the remote node.

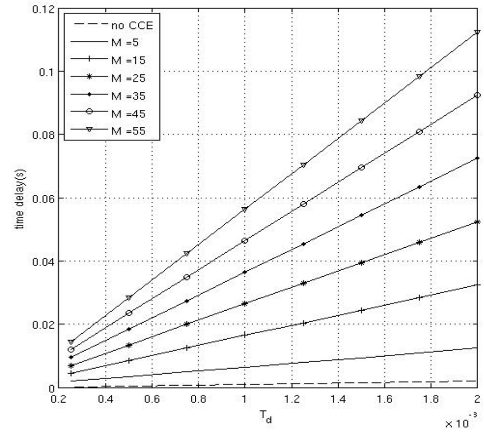

Figure 4. Effect of increasing the duration of the received signal on the time delay

D. Computational Load

In TDMA based networks computational load is not a critical issue. Assuming no encoding at the cooperating nodes, the computational load is limited to the generation of proper scheduling for the cooperating nodes (computational load of the selection of new processing node and estimation of the time delay of local communications are neglected). Therefore, the computational load of receive collaboration is:

$$O_{RC}^{A} = (M-1) \cdot L_d \tag{17}$$

and

$$O_{RC}^{M} = M \cdot L_d \tag{18}$$

where O_{CCE}^{A} and O_{CCE}^{M} are the number of additions and multiplications and L_d is the number of data symbols. The computational load of the array processing scheme should be considered. Assuming the number of iterations for convergence of LS-CMA is L_{con} and after convergence the weighting coefficients are valid for all of received signal. According to (2) and (3), the number of additions and multiplications of LS-CMA is

$$O_{LS-CMA}^{A} = M \cdot L_{con} + (M-1) \cdot L_d \tag{19}$$

and

$$O_{LS-CMA}^{M} = (M+3) \cdot L_{con} + M \cdot L_d \tag{20}$$

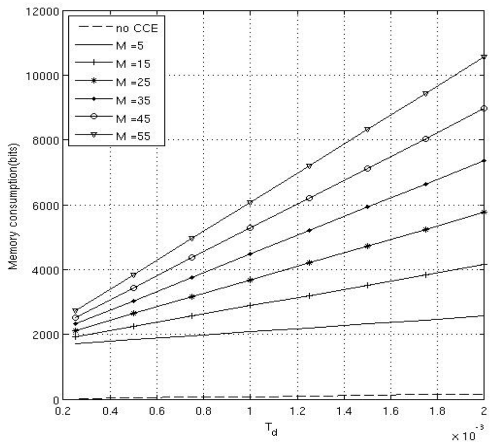

Figure 5. Effect of increasing the duration of the received signal on memory consumption

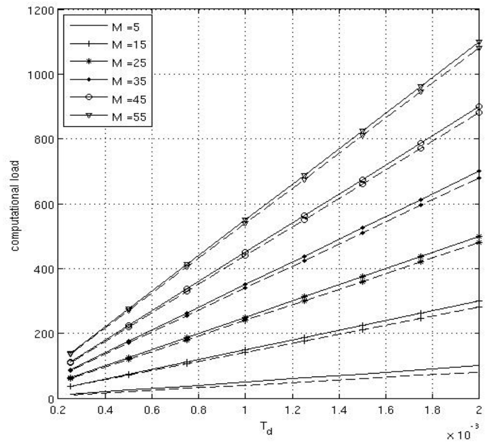

Figure 6. Effects of increasing *L* on the computational load for different values of *M*

Our simulations show that increasing the length of received signal (T_d) has no considerable effect on the energy efficiency. But it increases the computational load. Fig. 6 shows that the number of additions and multiplications are approximately the same. These parameters increase linearly by increasing the duration of the received signal. The highest value of this parameter corresponds to the longest signal duration and largest number of cooperating nodes which is less than $3 \cdot 10^5$ addition and multiplication.

IV. Conclusion

The performance of receive collaboration and collaborative channel equalization in TDMA based WSNs are investigated. It is shown that when the transmitter node is at the short distance (smaller than the virtual array radius) from the virtual array, the energy efficiency of CCE is negative, but it grows up by increasing the distance until 10 times of the virtual array radius. Although the computational load and memory consumption of CCE is very low, increasing of the time delay by increasing the number of cooperating nodes or by increasing the length of received signal is a limiting parameter of CCE.

In TDMA based WSNs, receive collaboration is completely useful to receive short data streams. Reasonability of receive collaboration to receive rather long data streams is due to the acceptable time delay at the cooperating nodes. Moreover, the efficiency of receive collaboration improves by increasing the distance between cooperating nodes and the remote node.

Acknowledgment

The authors would like to acknowledge partial funding by the European Commission for the ICT project CHOSeN ”Cooperative Hybrid Objects Sensor Networks” (Project number 224327, FP7-ICT-2007-2) within the 7th Framework Program. We would further like to acknowledge partial funding by the ’Deutsche Forschungsgemeinschaft’ (DFG) for the project ”Emergent radio” as part of the priority program 1183 ”Organic Computing”.

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