Limitations, performance and instrumentation of closed-loop feedback based distributed adaptive transmit beamforming in WSNs

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***Abstract*—We study closed-loop feedback based approaches to distributed adaptive transmit beamforming in wireless sensor networks. For a global random search scheme we discuss the impact of the transmission distance on the feasibility of the synchronisation approach. Additionally, a quasi novel method for phase synchronisation of distributed adaptive transmit beamforming in wireless sensor networks is presented that improves the synchronisation performance. Finally, we present measurements from an instrumentation using USRP software radios at various transmit frequencies and with differing network sizes.**

I. INTRODUCTION

A much discussed topic related to wireless sensor networks is the energy consumption of nodes as this impacts the lifetime and also dimension, weight and cost of the sensor nodes. A major goal in the design of sensor nodes is therefore to cut down the energy consumption of nodes. Ideally, a power consumption at which power harvesting techniques provide sufficient energy for operation of the node is desired. This aim requires nodes that operate at very low power levels of not more than several ten microwatts. This means that also the transmission power and consequently the transmission range of individual nodes is strictly limited.

A greater transmission distance can then be achieved when a sufficient number of nodes superimpose their carrier signals. This is especially useful in large scale sensor networks since the number of potentially available nodes in such a network is increased. By combining RF transmit signal components, a set of transmitting nodes in a sensor network can cooperate to increase the maximum transmission range of a network. One approach to superimpose transmit signals is to utilise neighbouring nodes as relays as proposed in [1]. Cooperative transmission is then achieved by Multi-hop [2], [3], Data flooding [4] and cluster based [5], [6] approaches.

Alternatively, in round-trip synchronisation based techniques [7], [8], the destination sends beacons in opposed directions along a multi-hop circle in which each of the nodes appends its part of the overall message. Beamforming is achieved when the processing time along the multi-hop chain is identical in both directions. This approach, however, does not scale well with the size of a network.

Also, by virtual MIMO techniques in wireless sensor networks [9], [10], single antenna nodes may establish a distributed antenna array to generate a MIMO channel. Virtual MIMO is energy efficient and adjusts to different frequencies [11], [12].

In all these implementations, a dense population of nodes is assumed. A large scale sensor network, however, might be sparsely populated by nodes as additional nodes increase the installation cost. Alternative solutions are approaches in which a synchronisation among nodes is achieved over a communication with the remote receiver. This means that communication among nodes is not required for synchronisation so that also sparsely populated networks can be supported.

Dependent on the communication scheme between the receiver and the network, we distinguish between closed-loop and open-loop feedback based approaches.

In the former scheme, carrier synchronisation is achieved in a master-slave manner. The receiver corrects the phase-offset between the destination and a source node [13]. This approach is applicable only to small network sizes and requires sophisticated processing capabilities at the source nodes.

For the feedback based closed-loop synchronisation scheme, a computationally modest approach was presented in [13], [14]. The authors propose an iterative process in which source nodes randomly, but guided by a one-bit feedback on the synchronisation quality adapt their carrier phases.

A preparatory requirement for closed-loop feedback based distributed adaptive beamforming in wireless sensor networks is that the power level of the asynchronously received RF sum signal (but not necessarily the signal strength of one single carrier) is above thermal noise and interference. As transmit nodes do not communicate with each other, information about the synchronisation process has to be obtained from received signal measurements. This is possible only when the received signal strength exceeds the noise level considerably. In section III we study the impact of the transmission distance on the feasibility of distributed adaptive transmit beamforming in wireless sensor networks. In section IV we introduce an algorithm that exploits this property and greatly improves the synchronisation performance. Finally, in section V, we detail

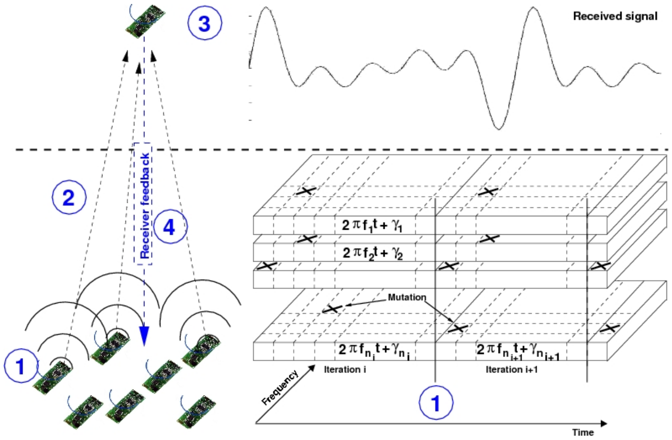


Fig. 1. The proposed solution to closed-loop distributed adaptive transmit beamforming

an instrumentation of distributed adaptive transmit beamforming in wireless sensor networks by USRP software radios.

II. DISTRIBUTED ADAPTIVE BEAMFORMING

Closed-loop feedback based distributed adaptive beamforming in wireless sensor networks is an iterative approach to synchronise RF transmit signal components for their relative phase offset. We assume that, for a network of size n, initially the carrier phase offsets γ_i of transmit signal components $\Re\left(e^{j(2\pi(f+f_i)t+\gamma_i)}\right);\ i \in \{1..n\}$ are arbitrarily distributed. When a receiver requests a transmission from the network, carrier phases are synchronised in an iterative process.

1) Each node i adjusts its carrier phase offset γ_i and frequency offset f_i randomly
2) Source nodes transmit simultaneously as a distributed beamformer.
3) The receiver estimates the level of phase synchronisation of the received RF sum signal (e.g. by SNR or comparison to an expected signal).
4) The level of synchronisation is broadcast to the network. Nodes sustain their phase adjustments if the feedback has improved or else reverse them.

These four steps are iterated repeatedly until a stop criteria is met (e.g. maximum iteration count or sufficient synchronisation). Figure 1 illustrates this procedure. Observe that this approach has modest computational requirements for nodes in the network. In each iteration, only a single random decision is taken and possibly the phase offset of the carrier is altered by an arbitrary amount. Furthermore, inter-node communication is not required for the synchronisation process. It is even possible to synchronise a set of nodes that are out of reach of each other (Although in this case a coordinated transmission of identical data subsequent to the synchronisation is not possible).

III. IMPACT OF THE TRANSMISSION DISTANCE

In the following section we study the impact of the transmission distance on the performance and feasibility of distributed adaptive transmit beamforming in wireless sensor networks.

TABLE I

CONFIGURATION OF THE SIMULATIONS CONDUCTED. P_{RX} IS THE THE RECEIVED SIGNAL POWER, d IS THE DISTANCE BETWEEN TRANSMITTER AND RECEIVER AND λ IS THE WAVELENGTH OF THE SIGNAL

Property	Value
Node distribution area	$30m \times 30m$
Mobility	stationary nodes
RF frequency	$f_{RF} = 2.4$ GHz
Transmission power of nodes	$P_{TX} = 1$ mW
Gain of the transmit antenna	$G_{TX} = 0$ dB
Gain of the receive antenna	$G_{RX} = 0$ dB
Iterations per simulation	10000
Identical simulation runs	10
Thermal noise power (AWGN)	-103 dBm
Pathloss calculation (P_{RX})	$P_{TX}\left(\frac{\lambda}{2\pi d}\right)^2 G_{TX}G_{RX}$

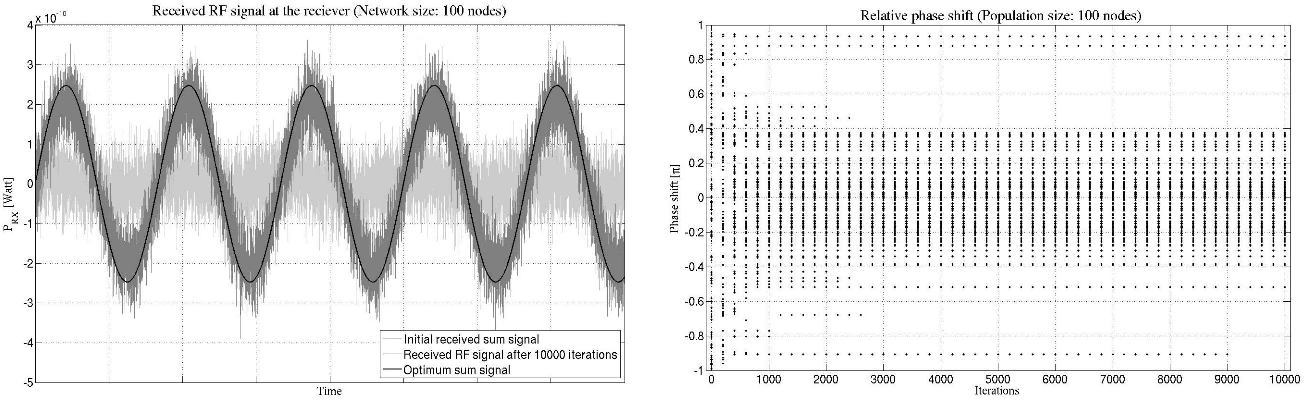
Beamforming can be utilised to increase the transmission range of cooperating nodes. When it is, however, implemented by a closed-loop phase synchronisation technique in which transmit nodes do not cooperate directly but utilise the receiver feedback for synchronisation, the high relative noise figure at increased distance might prevent a useful feedback as improvements by phase alterations of individual RF signal components can be obstructed.

We place a receiver at several transmit distances to the wireless sensor network in mathematical simulations. Table I summarises the base configuration of the simulations. 100 nodes have been placed uniformly at random on a space of $30m \times 30m$. The receiver distance is altered in various simulation runs from 100 to 300 meters. We assume a direct line of sight between the network and a remote node. Interference between the direct signal components is calculated as the sum of the distinct received carrier signal components.

Simulation results are depicted in figure 2. In 100 meters distance, the aligned sum signal after 10000 iterations of the algorithm is well distinguishable from thermal noise (cf. figure 2(e)). Also, within about 3000 iterations, the phases of all transmit signal components are within 0.2π (cf. figure 2(f)). According to the Friis transmission equation utilised to calculate the pathloss of individual signal components in our simulation setting, the received signal strength is equal to the noise level of $-103dBm$ already at about 90 meters distance.

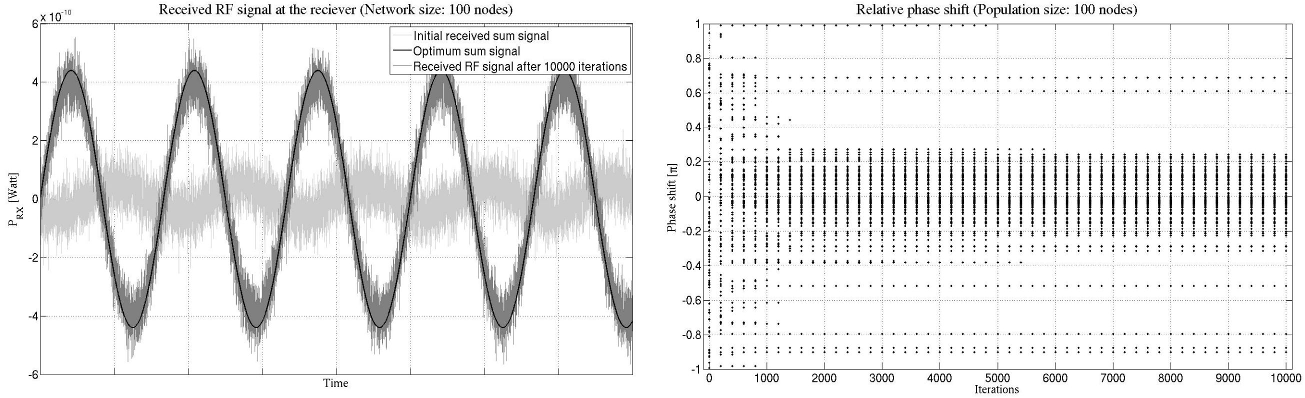
For distances of 150 meters and 200 meters, the relative noise figure is already easily above the received signal strength of an individual signal component. An alignment of signal components is, however, still feasible by distributed adaptive transmit beamforming. After 10000 iterations, the received sum signal is easily distinguishable although the phase synchronisation between signal components is less complete (cf. figure 2(b) and figure 2(d)).

At this synchronisation level we can imagine simple modulation schemes to transmit data over the channel so that we conclude that distributed adaptive transmit beamforming is feasible at distances where single signal components are below the noise level. Observe also that the level of synchronisation after about 3000 iterations does not improve significantly in



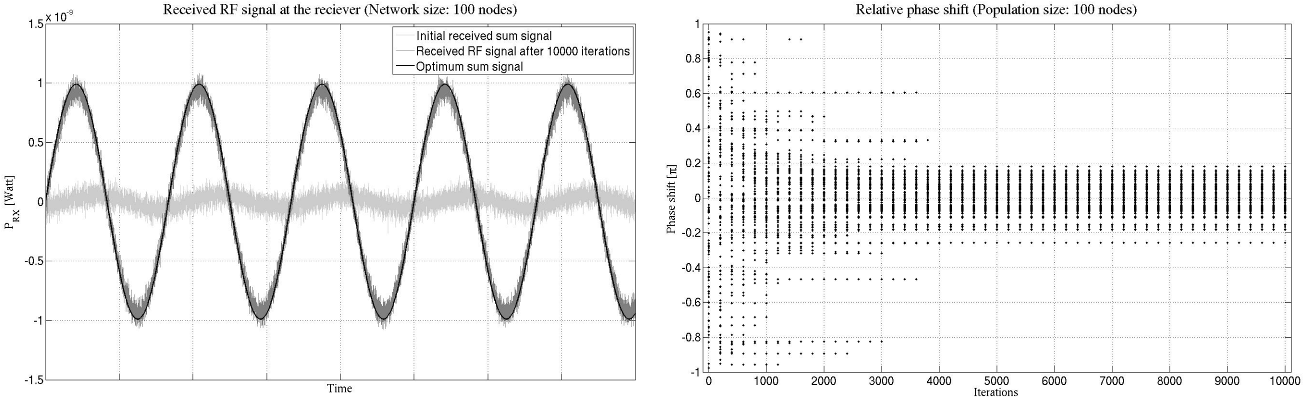
(a) Receiver distance: 200 meters – Received RF signal

(b) Receiver distance: 200 meters – Relative phase shift of signal components



(c) Receiver distance: 150 meters – Received RF signal

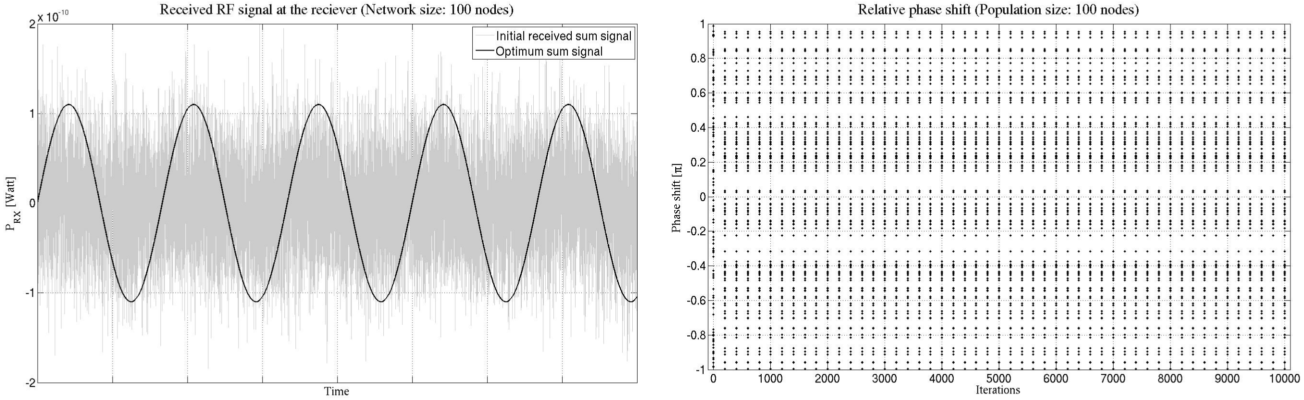
(d) Receiver distance: 150 meters – Relative phase shift of signal components



(e) Receiver distance: 100 meters – Received RF signal

(f) Receiver distance: 100 meters – Relative phase shift of signal components

Fig. 2. RF signal strength and relative phase shift of received signal components for a network size of 100 nodes after 10000 iterations. Nodes are distributed uniformly at random on a $30m \times 30m$ square area and transmit at $P_{TX} = 1mW$.



(a) Receiver distance: 300 meters – Received RF signal

(b) Receiver distance: 300 meters – Relative phase shift of signal components

Fig. 3. RF signal strength and relative phase shift of received signal components for a network size of 100 nodes after 10000 iterations. Nodes are distributed uniformly at random on a $30m \times 30m$ square area and transmit at $P_{TX} = 1mW$. As the optimum signal is hardly above noise level, an optimisation is not possible.

all three cases so that after few thousand iterations the network can be assumed to be synchronised. At an RF frequency of 2.4 GHz this translates to a synchronisation speed that is easily in the order of milliseconds, even when we allow 1000 RF signal periods per iteration. When the distance between the network and the receiver, however, becomes too large, a synchronisation might be infeasible. Figure 3 depicts some results from a simulation in which the receiver is separated by 300 meters from the network. We observe that signal phases are not adapted in this case so that an optimisation was not possible. After some initial phase alterations in the first 200 iterations, the impact of the noise seems more serious than the effect of phase alterations of single RF signal components so that phase offsets remain constant for the course of the simulation.

IV. A SOLUTION BY SOLVING MULTIVARIABLE EQUATIONS

Despite the respectable results that the global random search heuristics show, the performance of these random approaches is not optimal. The reason for this is that the global random search heuristic does not use the properties of the search space and the fitness function. We design an optimisation scheme that better exploits the problem characteristics and is able to speed up the synchronisation performance.

The algorithm is based on the idea that a node should compute the effect of its own carrier phase offset on the total RF sum signal. For this scheme it is essential that at one time only one single transmit node adapts its phase offset. This is ensured through a low mutation probability and by comparing the feedback value with an expected feedback as detailed below. the following four steps are repeatedly iterated by the algorithm.

1) The node altering its phase superimposes its transmission in three consecutive iterations with the RF sum signal and stores the phase-fitness-tuples
2) It then calculates the phase offset with the optimum fitness value for its transmit RF signal component
3) In the following iteration the node adapts this value
4) If the received fitness value deviates from the calculated one by more than 1% the original phase offset is restored as this might indicate that another node had also altered its phase offset

So, why shall this algorithm find an optimum faster than a global random search heuristic and why is it correct?

From the node's point of view, there are two signals on the medium. Its own transmitted signal and the superimposed sum signal from all other RF transmit signal components. Since with every superimposed transmission the receiver provides additional information by calculating and transmitting a feedback value, the node can learn the optimum phase offset of its own carrier signal relative to the superimposed sum signal, provided that the latter does not change significantly.

Observe that, when the RF frequency of all RF signal components is identical, also the superimposed sum signal shows this frequency. Furthermore, it exists one optimum phase offset for the transmit signal of a node i so that the fitness value reaches its optimum value. From this phase offset the fitness value decreases symmetrically when the phase offset is chosen smaller or greater. Consequently the fitness function when all but one phase offset are kept constant is a sine function:

$$\mathcal{F}(\Phi_i) = A \sin(\Phi_i + \phi) + c \tag{1}$$

In this formula, A is the amplitude, Φ_i the phase offset of the RF transmit signal component of node i, ϕ is the phase offset of $\mathcal{F}_i$ and c is an additive term. For a node i this is an equation with three unknown variables. Consequently, with three distinct measurements the optimum phase offset Φ_i^{opt} can be calculated. Figure 4 depicts the variation of the actual fitness curve to the calculated fitness curve when all but one node keep their phase offset constant.

The fitness is measured by the RMSE of the received RF sum signal to the RF sum signal that could be expected when

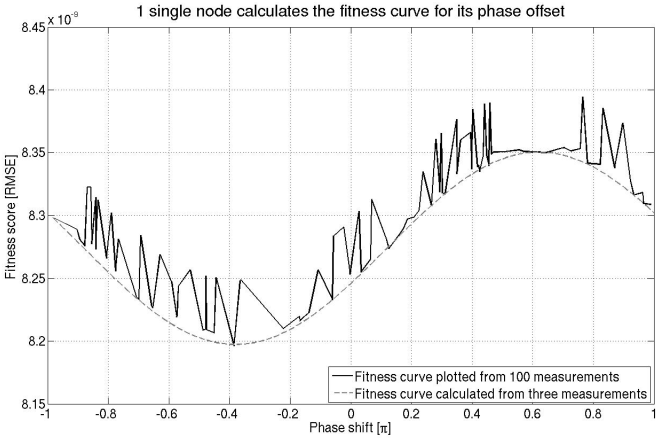


Fig. 4. Deviation of the calculated fitness curve to the measured fitness curve

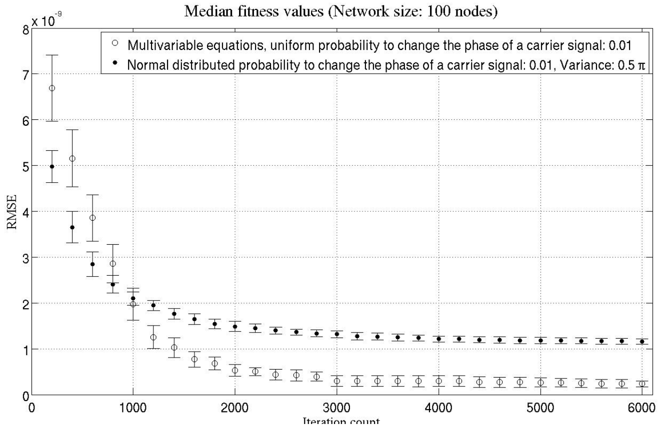


Fig. 5. Performance of the proposed optimisation algorithm for distributed adaptive beamforming in wireless sensor networks

signal phases are perfectly aligned:

$$RMSE = \sqrt{\sum_{t=0}^{\tau} \frac{\left(\sum_{i=1}^{n} s_i + s_{noise}(i) - s^*\right)^2}{n}}. \quad (2)$$

The deviation of the calculated fitness curve did not exceed 0.6% when only one node adapts its phase offset. With two nodes simultaneously adapting their phase offset we experienced a deviation of approximately 1.5%. Therefore, node i concludes that it was not the only node to adapt its phase offset when the deviation exceeds 1%. A relatively low share of mutating nodes is achieved by implementing a low mutation probability as, for example, $\frac{1}{n}$. The asymptotic synchronisation time of this algorithm is $\Theta(n)$ as for each transmit signal component the optimal phase offset is calculated in a constant number of iterations. Figure 5 depicts the performance improvement to a global random search approach. The figure depicts the median fitness values over all simulation runs. We observe that the global random search heuristic is outperformed already after about 1000 iterations.

TABLE II
EXPERIMENTAL RESULTS OF SOFTWARE RADIO INSTRUMENTATIONS

	Experiment 1	Experiment 2
Sender	4	3
Mobility	stationary	stationary
Distance to receiver [m]	≈ 0.75	≈ 4
Separation of TX antennas [m]	≈ 0.21	≈ 0.3
Transmit RF Frequency [MHz]	$f_{TX} = 2400$	$f_{TX} = 27$
Receive RF Frequency [MHz]	$f_{RX} = 902$	$f_{RX} = 902$
Gain of receive antenna [dBi]	$G_{RX} = 3$	$G_{RX} = 3$
Gain of transmit antenna [dBi]	$G_{TX} = 3$	$G_{TX} = 1.5$
Iterations per experiment	500	200
Identical experiments	14	10
Median gain (P_{RX}) [dB]	2.19	3.72

V. NEAR REALISTIC INSTRUMENTATION

We have utilised USRP software radios (http://www.ettus.com) to model a sensor network capable of distributed adaptive transmit beamforming. the software radios are controlled via the GNU radio framework (http://gnuradio.org). The transmitter and receiver modules implement the feedback based distributed adaptive beamforming scenario. For the superimposed transmit channel and the feedback channel we utilised widely separated frequencies so that the feedback could not impact the synchronisation performance. Two experiments have been conducted with low and high RF transmit frequencies of 27MHz and 2.4GHz, respectively. Table II summarises the configuration and results of both experiments. After 10 experiments at an RF transmit frequency of 27MHz we achieved a median gain in the received signal strength of 3.72dB for three independent transmit nodes after 200 iterations. This corresponds to half of the optimum gain when carrier phases are exactly synchronised. Although this demonstrates the general feasibility of distributed adaptive transmit beamforming in wireless sensor networks, we expect that further work is required in order to minimise the gap to the optimum case. In 14 experiments with 4 independent nodes that transmit at 2.4GHz the achieved median gain of the received RF sum signal was 2.19dB after 500 iterations. The transmit nodes have been synchronised in their clock but no other communication or synchronisation between nodes was allowed. In future implementations we are planning to utilise GPS for the clock synchronisation of nodes.

VI. CONCLUSION

We have detailed quantitative results on the impact of the transmission distance on the feasibility of distributed adaptive beamforming in wireless sensor networks. In mathematical simulations we could show that the synchronisation of phases of RF transmit signal components is possible even when the signal strength of individual RF signal components is below the thermal noise level. In particular, the noise level does not impact the speed of the synchronisation process. However, the spread of relative phase offsets increases with increasing relative noise level. Furthermore, we presented an $\Theta(n)$ optimisation algorithm for distributed adaptive beamforming in wireless sensor networks and compared its performance in mathematical simulations to a standard random search heuristic.

In a near realistic instrumentation with USRP software radios we successfully demonstrated the general feasibility of distributed adaptive beamforming in realistic settings. To the best of our knowledge it is the first such instrumentation that utilises up to four independent transmit nodes and also the first that also uses a wireless channel for the receiver feedback.

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