Algorithms for closed-loop feedback based distributed adaptive beamforming in wireless sensor networks

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Abstract—**We study a closed-loop feedback based approach to distributed adaptive transmit beamforming in wireless sensor networks. Three algorithms to achieve sufficient phase synchronisation of carrier signals are considered. In particular, we study the impact of normal and uniform distributions for the phase alteration probability on the performance of the synchronisation process. Both distributions are studied for various probability distributions and variances. Furthermore, a local random search heuristic is studied for various sizes of the search neighbourhood.**

I. INTRODUCTION

A central issue in wireless sensor networks is the forwarding of gathered information from the network to an external receiver. When the receiver node is mobile and requests information in a spontaneous ad-hoc manner, wireless transmission is required. As power consumption is typically a major constraint in wireless sensor networks, the transmission range for this transmission is strictly limited. However, by properly superimposing transmit signal components of distinct nodes the transmission range of a sensor network can be increased.

This approach was studied by various research groups. The solutions proposed cover random schemes as multi-hop [1], [2], [3], Data flooding [4], [5], [6], [7] and cluster based [8], [9], [10] techniques as well as collaborative beamforming [11] or cooperative/virtual MIMO for wireless sensor networks [12], [13], [14], [15].

While the random schemes do not consciously impact the direction of the transmission beam, in virtual MIMO, single antenna nodes cooperate to establish a directed beam from a multiple antenna wireless network [13], [12], [14]. While virtual MIMO has capabilities to adjust to different frequencies and is highly energy efficient [15], [16], it requires accurate time synchronisation, complex transceiver circuitry and signal processing that might surcharge the power consumption and processing capabilities of simple sensor nodes.

A simpler approach is the one-bit feedback closed-loop synchronisation considered in [17], [18], [19]. The authors describe an iterative process in which the source nodes randomly adapt the carrier phases of their base band transmit signal. This random process is guided by a one-bit feedback on the synchronisation quality that is computed by the destination node.

In [20] this process was also implemented and verified in a network of three transmitters and one receiver at 60 GHz. It was shown that this process converges to an optimum with probability 1 [19]. Furthermore, the runtime of the approach is studied in [19], [21]. An asymptotic upper bound of $\mathcal{O}(n \cdot k \cdot \log n)$ on the expected optimisation time in a network of n nodes with k distinct phase offsets at the transmitting nodes was proved in [22]. In this consideration carrier phases are altered uniformly at random from the transmitting nodes during several iterations of the synchronisation process. This is in contrast to various prior studies that considered a normal distribution on the phase alteration process [17], [18]. For the normal distribution the expected asymptotic synchronisation time was not yet derived. In [19] the expected synchronisation time of this process was expected to rise linearly in the number of nodes. However, a central assertion of the proof was left open. We study the impact of normal and uniformly distributed phase alteration processes on the optimisation speed of distributed adaptive beamforming in wireless sensor networks.

II. DISTRIBUTED ADAPTIVE BEAMFORMING IN WIRELESS SENSOR NETWORKS

In distributed adaptive beamforming in wireless sensor networks an individual node i in a network of size n cooperates with other nodes to reach a distant receiver by superimposing its individual carrier signal $\Re\left(m(t)e^{j(2\pi(f+f_i)t+\gamma_i)}\right)$ with carrier signals transmitted from other nodes. The approach constitutes a closed-loop feedback technique that is attained in an iterative process. During each iteration, following a random distribution, each transmit node i adds random phase and frequency offsets γ_i', f_i' to its carrier phase γ_i and frequency f_i. According to the random distribution it is possible that all, some or no node adjusts the phase or frequency of its carrier signal. The nodes then transmit to the destination simultaneously. From this received superimposed sum signal $\Re\left(RSS_{sum}m(t)\sum_{i=1}^{n} e^{j(2\pi(f+f_i)t+\overline{\gamma_i})}\right)$ the receiver estimates the level of phase synchronisation achieved (e.g. by SNR or comparison to an expected signal). At the end

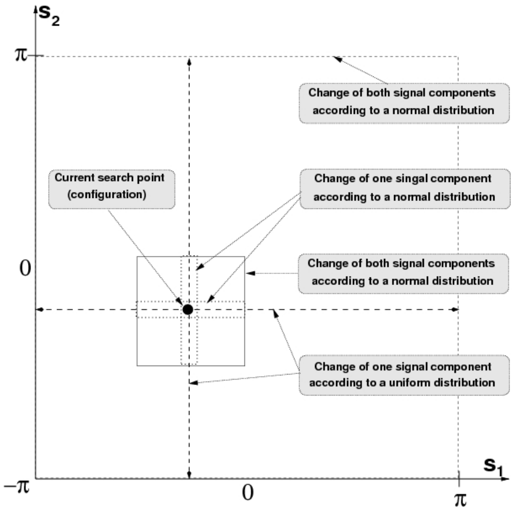

Fig. 1. A point in the search space (configuration of transmit nodes) spanned by the phase offsets of the carrier signals s_1 and s_2

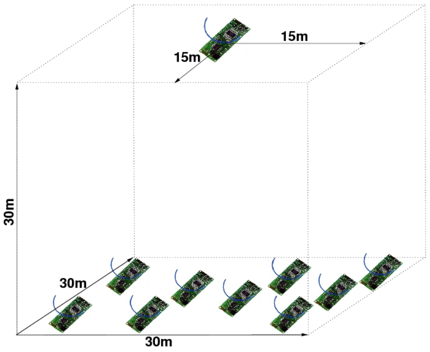

Fig. 2. Base configuration of the simulations conducted.

of each iteration, the receiver broadcasts this estimation as a channel quality indicator to the network. Nodes then sustain their (adapted) carrier phases $\gamma_i + \gamma_i'$ and frequencies $f_i + f_i'$ when the feedback has improved to the feedback obtained during the last iteration or else reverse them.

These steps are repeated until a stop criteria is met. Possible stop criteria are, for example, the maximum iteration count or sufficient quality of the estimated channel.

The exact implementation of the phase alteration process in each iteration impacts the performance of the optimisation approach. Generally, two parameters are of importance. One is the number of nodes altering their carrier phase and frequency in each iteration and the other is the probability distribution applied on the alteration of phases and frequencies of one carrier signal.

When we illustrate the search space of the algorithm with respect to these parameters we observe that they effectively impact the neighbourhood size of the search approach (see figure 1). When the probability to alter the carrier phase of a single node is low, few carrier signals are altered in one iteration. In the figure this might translate to the situation that the phase offset of only one carrier signal is altered. The new search point then differs from the recent one in only one dimension. When a uniform distribution is implemented, all points along this dimension are equally probable while for a normal distribution the most probable points are near to the recent search point as specified by the variance of the probability distribution utilised to alter phase and frequency offsets. When, however, the mutation probability is increased, so that more often several carrier signals (in the figure, for example, both carrier signals s_1 and s_2) are altered, the new search point is drawn from a region in the search space. In the case of the uniform distribution the whole search space might constitute this region. Consequently, a smaller probability for nodes to alter their phase and frequency or a smaller variance for the random process to alter these parameters increases the probability to draw a search point that is near to the recent one.

We expect that a moderate size of the neighbourhood (i.e. probability to alter phase or frequency of one carrier signal and variance for the random process to alter these values) is beneficial at the start of the synchronisation. The initial search point or the initial synchronisation of carrier phases is typically far away from the optimum. Therefore, many search points have a higher fitness value (are better synchronised) than the initial one. Consequently, since the probability to improve the fitness value is high, it might be beneficial to increase the neighbourhood size so that also bigger improvements are possible. Later in the optimisation process, however, when the optimum is near, most search points reduce the fitness value so that the probability to increase it is best for search points drawn from a small neighbourhood. The results obtained in simulation studies in section III also indicate towards the correctness of this assumption.

III. SIMULATION RESULTS

We have implemented the scenario of distributed adaptive beamforming in Matlab for a network of 100 transmit nodes that are placed uniformly at random on a $30m \times 30m$ square area. The receiver is located $30m$ above the centre of this area (cf. figure 2).

The transmission power of transmit nodes is set to 1 mW with no antenna gain at the transmitter or receiver. Environmental noise (AGWN) is set to -103 dBm as proposed in [23] and the pathloss is calculated by the Friis free-space equation as

$$P_{rx} = P_{tx} \left(\frac{\lambda}{2\pi d} \right)^2 G_{tx} G_{rx}$$

Receiver and transmit nodes are stationary. The base configuration for all simulations is summarised in table I. Frequency and phase stability are considered perfect. We study the impact of a uniform or normal distribution of the phase alteration process on the performance of distributed adaptive beamforming in wireless sensor networks.

We experience good synchronisation after about 3000 iterations (cf. figure 4). For every configuration of the network the simulation we conducted 10 identical simulation runs

TABLE I

BASE 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	$30m \times 30m$
Location of the receiver	$(15m, 15m, 30m)$
Mobility	stationary nodes
Base band frequency	$f_{base} = 2.4$ 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 simulations	6000
Identical simulation runs	10
Random noise power	-103 dBm
Pathloss calculation (P_{rx})	$P_{tx}\left(\frac{\lambda}{2\pi d}\right)^2 G_{tx}G_{rx}$

with 6000 iterations. One iteration consists of the network transmitting for few signal periods, feedback computation at the receiver, feedback transmission and feedback interpretation at the network. It is possible to perform these steps within few signal periods. The time consumed for a complete synchronisation of 6000 iterations is therefore in the order of milliseconds for a base band signal frequency of 2.4 GHz.

Simulation results show the median and the standard deviation. Signal quality at the receiver is measured by the RMSE between the received signal and an expected optimum signal.

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

In this formula, τ was chosen to cover several signal periods. The terms $s_i = RSS_i \Re\left(m(t)e^{j(2\pi(f+f_i)t+\overline{\gamma_i})}\right)$ and $s_{opt} = nRSS_{sum} \Re\left(m(t)e^{j(2\pi f_{opt}t+\gamma_{opt})}\right)$ represent the i-th signal component of the received sum signal and the expected optimum signal, respectively. The optimum signal is calculated as the perfectly aligned and properly phase shifted received sum signal from all transmit sources. For the optimum signal, noise is disregarded. Figure 3 depicts the optimum sum signal, the initial received sum signal and the signal of synchronised carriers after 6000 iterations when phase alterations are chosen according to a per node uniform distribution with mutation probability $\frac{1}{n}$.

Figure 4 illustrates the phase offset of received signal components for an exemplary simulation run. In this simulation, phase alterations are chosen according to a per node uniform distribution and nodes alter their phase with probability 0.01. For $n = 100$ transmit nodes this translates to an average number of 1 transmitting node in every iteration. We observe that after 6000 iterations about 95% of all carrier signals have a relative phase offset of +/- 0.1π. The median of all variances of the phase offsets for simulation runs with this configuration is 0.2301π after 6000 iterations.

In the first set of simulations we considered the impact of the mutation probability on the synchronisation performance when new transmit phase offsets are drawn according to a uniform distribution.

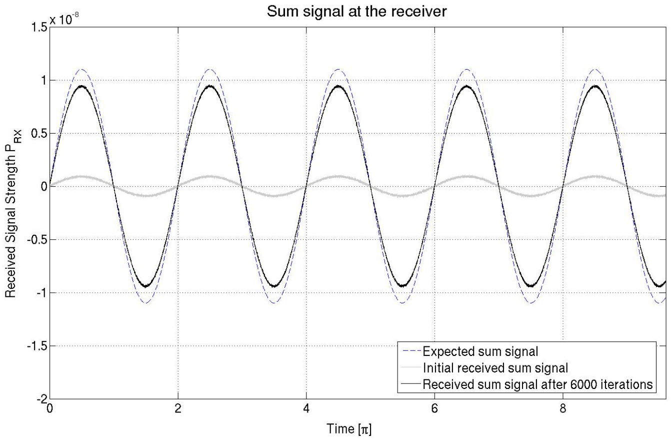

Fig. 3. Received sum signal from 100 transmit nodes without synchronisation and after 6000 iterations. Phase alterations are drawn uniformly at random with mutation probability $\frac{1}{n}$ for each node

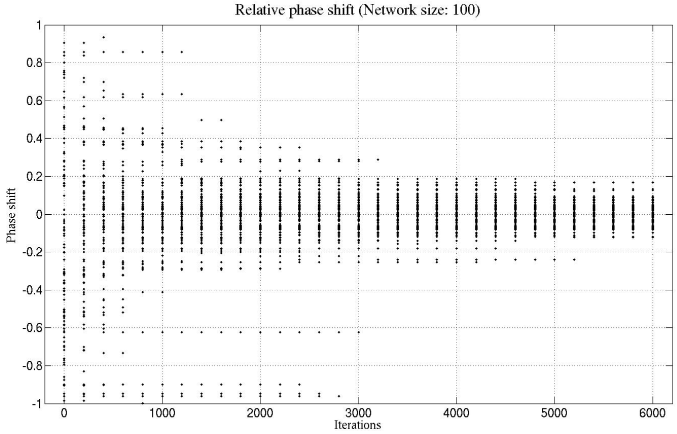

Fig. 4. Evolution of the phase adaptation process for uniform distribution of phase adaptation and 1 percent nodes change

When the average number of carrier signals that are modified in one iteration is altered, this affects the performance of the optimisation approach, as the stepwidth of the random process is changed. We are interested in the optimum percentage of nodes that alter their phase per iteration (mutation probability) when the phase-alteration for each mutating node is drawn according to a uniform distribution. Figure III depicts simulation results for several mutation probabilities.

A mutation probability of κ represents the case that on average $\kappa \cdot n$ out of n transmit signal components mutate (randomly alter their phase offset) in one iteration.

We observe that with a low mutation probability the overall performance of the synchronisation process is improved. At the start of the optimisation, however, higher mutation probabilities are more beneficial. This accounts for the fact that initially many configurations exist that would improve the fitness value as the initial point is not well synchronised with high probability (cf. section II).

Since a mutation probability of 0.01 translates to 1 node to adapt the phase offset of its carrier signal per iteration on

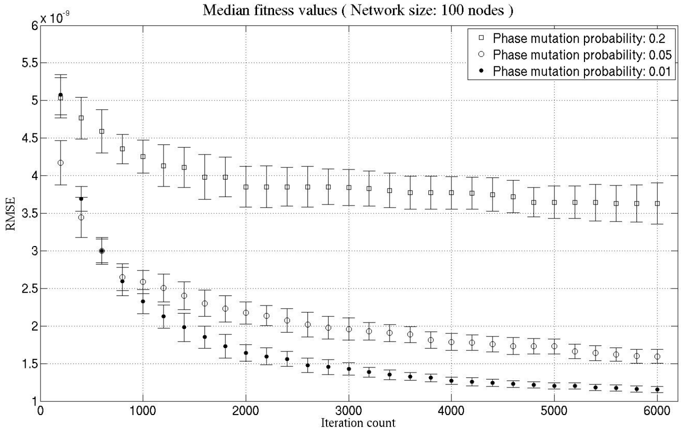

Fig. 5. Performance of distributed adaptive beamforming in a wireless sensor network of 100 nodes and normal and uniform probability distributions on the phase mutation probability. Uniform distribution of phase mutations.

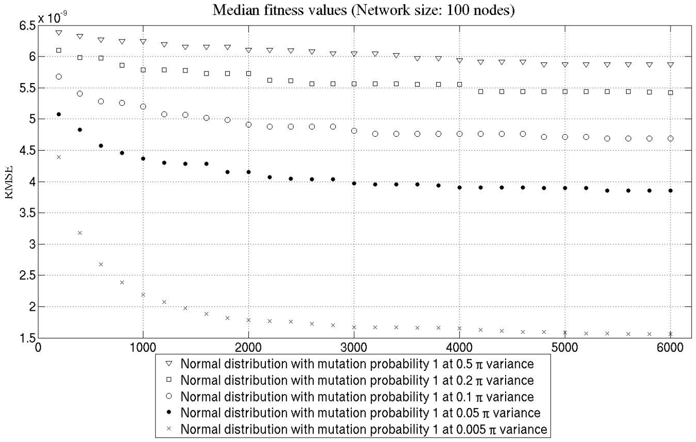

Fig. 6. Normal distribution of phase mutations with mutation probability 1

average, smaller mutation probabilities are not beneficial.

We also considered a normal distribution for the phase alteration as it was applied in [20], [24], [19], [25] and study the impact of the mutation probability and the variance utilised.

Figure 6 shows the performance of this approach with several values for the mutation variance applied to the phase mutation process when all nodes mutate in every iteration (mutation probability of 1). This configuration is identical to the simulations conducted in [20], [24], [19], [25]. For ease of presentation, error bars are omitted in this figure.

We observe that a smaller variance is beneficial for the performance of the synchronisation process. The reason for this is again the reduced neighbourhood size of the search method at smaller variances. In particular, by means of the mutation variance the neighbourhood size can be adapted to an optimum for a given mutation probability.

We approximated the optimum variance for several mutation probabilities. Generally, a higher mutation probability necessitates a smaller variance to achieve the optimum performance.

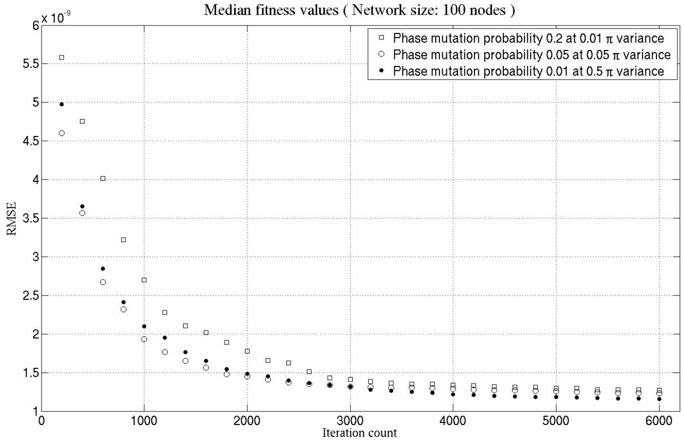

Fig. 7. Performance of distributed adaptive beamforming in a wireless sensor network of 100 nodes and normal and uniform probability distributions on the phase mutation probability. Normal distribution of phase mutations.

Figure III depicts the performance for mutation probabilities of 0.2, 0.05 and 0.01 and near optimum variance, respectively.

For these configurations the performance is similar to the performance of the uniform distribution with mutation probability 0.01.

Summarising, we conclude that the best performance was achieved by small mutation probabilities in which one transmit signal component is altered in every iteration on average. This optimisation performance can be further improved at the start of the synchronisation process when a moderate mutation probability is implemented that is gradually adapted in the course of the synchronisation process.

For the normal distribution the performance is also impacted by the mutation variance so that for a fixed mutation probability the performance can be improved by adopting the variance of the process.

Overall, results for near optimum configurations are similar for normal and uniform distributed phase alteration processes. A straightforward implementation would, for instance, constitute an adaptive phase mutation process with uniform distribution.

Since in [26] the search space of distributed adaptive beamforming was classified as weak unimodal, we expect a nearest neighbour search approach to be best suited to achieve fast synchronisation. We implemented and tested a local random search heuristic for this scenario with various neighbourhood sizes. The implementation differs from the normal distribution mainly since it utilises a fixed size neighbourhood instead of a variance on the phase alteration process. Figure 8 shows that the performance is similar to the implementation with uniformly distributed phase alteration probabilities. We therefore conclude that the global random search approaches utilised are already near optimal solutions for distributed adaptive beamforming in wireless sensor networks.

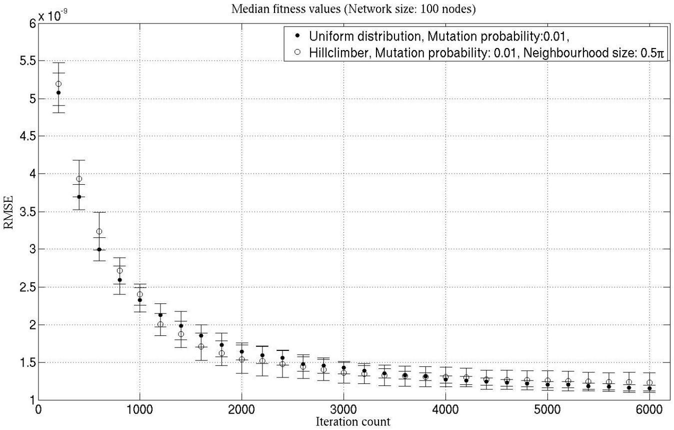

Fig. 8. Comparison of the performance achieved for a uniform distributed phase modification process and a nearest neighbour search approach

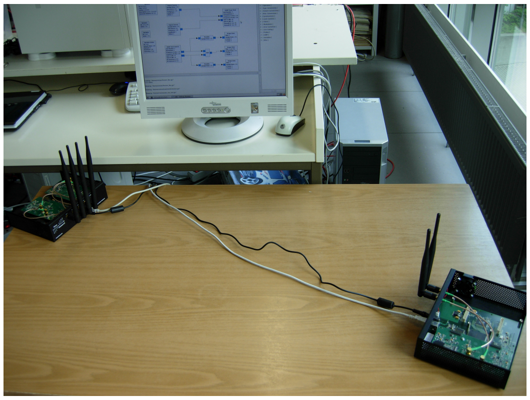

Fig. 9. Two USRP software radios constitute our current small scale scenario

IV. NEAR REALISTIC INSTRUMENTATION

We are currently working on the implemention of the scenario of distributed adaptive beamforming in wireless sensor networks in a laboratory environment with USRP software radios (http://www.ettus.com). The optimisation logic is implemented within the GNU radio framework (http://gnuradio.org). The current environment with one receiver node and two transmit nodes is depicted in figure 9. In the figure, both transmitters are realised by the USRP located on the left. As each USRP supports two full duplex transceivers, a single USRP can model two sensor nodes. We equipped the USRP motherboards with RFX900 transceiver daughterboards that operate in the 900 MHz band. Channel quality measurements are calculated by the RSSI at the receiver node. In contrast to a similar study presented in [20] the channel quality feedback is also propagated over the wireless channel. In our current implementation we utilise a slightly shifted carrier frequency for the feedback channel to enable parallel transmission and reception by the USRP modules. With two USRP software radios we achieved an improvement of about $2.6dB$ in the signal strength when signal phases are aligned with each other.

V. CONCLUSION

We have studied the impact of normal and uniform distributed phase mutation probabilities in a closed loop synchronisation approach for distributed adaptive transmit beamforming in wireless sensor networks. In mathematical simulations quantitative results for a network of 100 low power nodes and one remote receiver are derived. Sufficient synchronisation was possible for both approaches within several milliseconds. We observed that minimum mutation probabilities together with a suitable variance are well suited to achieve optimum synchronisation performance.

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