CARRIER PHASE SYNCHRONIZATION OF MULTIPLE DISTRIBUTED NODES IN A WIRELESS NETWORK

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ABSTRACT

In this work we present a method for achieving global carrier phase synchronization in a wireless network of distributed, autonomous nodes. Other authors who have investigated this problem mainly focus on a master/slave strategy based on one master broadcasting a sinusoidal reference signal to all slaves. We follow a slightly different approach where the slaves concurrently or sequentially transmit a broadband sequence to the master. Receiving the conjugate complex of the bounced-back signal, each slave can locally determine the phase difference between its own and the master's local oscillator (LO). This information suffices to allow for coherent cooperation.

The broadband nature of the used sequences makes our approach robust to deep fades in a frequency-selective environment. We revisit the popular strategy for global carrier phase synchronization using the sinusoidal reference and compare it to our own approach. A potential application then stresses the benefits of our scheme.

1. INTRODUCTION

In recent years a lot of research has been done in the field of cooperative wireless communication, where a number of autonomous nodes cooperates in order to increase the link reliability and/or the data rate. We distinguish between coherent and noncoherent schemes. While the coherent ones are phase-aware, taking for example the phase information of the channel estimate into account, noncoherent schemes are not. Examples of papers discussing coherent cooperative communication are, e.g., [1], [2] and [3]. In [1] the authors show that coherent cooperative relaying with a finite number of single-antenna relays can actually achieve full spatial multiplexing gain. The authors of [2] and [3] investigate several coherent cooperative relaying strategies for MIMO amplify-and-forward nodes that allow for spatial multiplexing. They compare the ergodic capacity of schemes that are based on channel inversion with schemes that utilize QR decomposition and subsequent successive interference cancellation (SIC) to orthogonalize several users.

Coherent cooperative schemes certainly promise higher performance gains compared to the noncoherent ones. They are, however, more complex and more demanding to implement as they not only require a global carrier frequency but also a global carrier phase reference. This is because the independent phase offsets of the individual local oscillators (LOs) introduce an unknown phase shift to the baseband signals. An interesting problem therefore is how to achieve global carrier phase synchronization in a distributed wireless network. Furthermore we want to investigate the impact of estimation errors on distributed beamforming. In [4] the authors use the theory of random arrays to assess the performance of distributed, collaborative beamforming. They investigate a cluster of randomly placed nodes that is to collaboratively transmit signals such that they add up coherently in the target direction.

A scheme to synchronize the carrier frequency and phase of a pair of two nodes is presented in [5]. In [6] the authors investigate how to provide a global carrier phase to a cluster of multiple sensor nodes that are to beamform to a remote destination. They present a simple algorithm where one master node broadcasts a sinusoidal reference signal. The distance between the master and each slave introduces an individual phase shift to the signal. When the slaves bounce back the signal, the master can obtain information about these phase shifts. Feeding this knowledge back to the slaves, they can adjust their oscillators accordingly. The same problem has also been addressed by [7]. The authors investigate how phase estimation errors affect the gains achieved by distributed transmit beamforming. One of the drawbacks of this approach is that the computational load mainly lies on the master node. In a heterogeneous network, not all nodes might thus be suited to act as master. This restricts the set of potential master nodes. Another problem that arises in a frequency-selective environment is when the reference signal is in a deep fade, the phase offset estimation becomes very inaccurate.

We follow a slightly different approach where all slaves transmit a broadband signal to the master which bounces back the complex conjugate of its received signal. The slaves are now able to locally generate information about the phase difference between their own and the master's local oscillator. This information is enough to allow for coherent cooperative communication. As each slave does the required calculations locally the computational load is distributed equally among the whole network. Furthermore our approach is robust against deep fades as we use a broadband signal and can thus exploit frequency diversity.

Notation: We use square brackets $[\cdot]$ to indicate discrete-time signals. $\circledast$ denotes convolution, $(\cdot)^*$ complex conjugation, $|\cdot|$ the absolute value, and $(\cdot)^{\mathrm{H}}$ the Hermitian transpose. Boldface letters indicate vectors and $\mathrm{E}_x[\cdot]$ is the expectation with respect to x. We use $\angle\{x\}$ to denote the phase of x.

2. PROBLEM DESCRIPTION

We use a simple example to shortly recall the impact of a carrier phase offset on distributed beamforming. Consider a network of two wireless nodes N_1 and N_2 acting as sources and a destination D with free running LOs. They are provided with the same frequency normal f_{c} but, with respect to a global reference, exhibit a phase offset of φ_1, φ_2, and φ_{D}, respectively. N_1 and N_2 are to transmit the baseband signal $s(t)$ such that both signals add up coherently at D. The channels $\mathrm{N}_1 \to \mathrm{D}$ and $\mathrm{N}_2 \to \mathrm{D}$ are frequency flat with channel coefficients h_1 and h_2, respectively.

When node i transmits the baseband signal $s(t)$ to the destination, the latter receives

$$d_i(t) = h_i s(t) e^{j(-\varphi_{\mathrm{D}}+\varphi_i)}. \quad (1)$$

Note that also the channel estimates always include the unknown LO phase offsets. When D broadcasts a channel estimation sequence, N_1 and N_2 are only able to learn

$$\widehat{h}_1 = h_1 e^{j(\varphi_D - \varphi_1)} \text{ and } \widehat{h}_2 = h_2 e^{j(\varphi_D - \varphi_2)}, \quad (2)$$

respectively. In order to achieve a coherent addition of the signal $s(t)$ from both nodes at the destination, the sources transmit $s_1(t) = \widehat{h}_1^* s(t)$ and $s_2(t) = \widehat{h}_2^* s(t)$, respectively. The signal arriving at the destination is then

$$d(t) = \left(|h_1|^2 e^{j(-2\varphi_D + 2\varphi_1)} + |h_2|^2 e^{j(-2\varphi_D + 2\varphi_2)} \right) s(t) \quad (3)$$

with

$$|d(t)|^2 = |s(t)|^2 \left(|h_1|^4 + |h_2|^4 + 2\cos\left(2\varphi_1 - 2\varphi_2\right) |h_1|^2 |h_2|^2 \right). \quad (4)$$

For any $\varphi_1 \neq \varphi_2$ the cosine term is smaller than one and consequently introduces a penalty for the received signal power. Any distributed beamforming approach will thus suffer from the presence of a phase difference of the LOs of all participating nodes.

3. PHASE SYNCHRONIZATION SCHEME

In this section we recapitulate a scheme achieving global carrier phase synchronization in a distributed wireless network that was treated for example in [6] or [7]. It is based on a master/slave architecture and, because the master node has to cope with the better part of the computational load, we call it **M**aster-**B**ased scheme (MB). We then present a slightly different approach which we call **S**lave-**B**ased scheme (SB) because the computational load is distributed equally among all slave nodes. We omit noise in this section and assume channel reciprocity for at least two channel uses.

Consider a set of $N + 1$ wireless nodes out of which one node is assigned master M while all other nodes are slaves S_i, $i \in \{1, 2, \ldots, N\}$. It makes sense to choose the master node according to the quality of its channel to the slaves. However, the choice of the master node out of the whole set of nodes is out of the scope of this paper.

3.1. Master-Based Scheme

The master broadcasts a sinusoidal reference signal. It arrives at each slave with a phase offset of $\varphi = \varphi_M - \varphi_{S_i} + \varphi_{h_i}$, where φ_M is the LO phase of the master, φ_{S_i} the LO phase of the respective slave, and φ_{h_i} a phase offset due to the propagation delay between master and slave. Having received the reference signal, the slaves sequentially bounce it back to the master. When their LO phases stay constant, the master receives a signal from which it can estimate $2\varphi_{h_i}$. Denoting the estimation error by

$$\psi_{i,\text{error}}^{(\text{MB})} := 2\Delta\varphi_{h_i} \quad (5)$$

we can write the estimate as $2\widehat{\varphi}_{h_i} = 2\varphi_{h_i} + 2\Delta\varphi_{h_i}$. M calculates

$$\frac{1}{2}\left(2\widehat{\varphi}_{h_i}\right) = \begin{cases} \varphi_{h_i} + \Delta\varphi_{h_i} & \text{for} \quad \varphi_{h_i} < \pi \\ \varphi_{h_i} + \Delta\varphi_{h_i} - \pi & \text{for} \quad \varphi_{h_i} \geq \pi \end{cases} \quad (6)$$

and feeds this information back to each belonging slave. The slaves in turn use this information together with the received reference signal to generate a phase synchronized oscillator signal. Their LO phase offset is then

$$\begin{aligned} \varphi_{R_i} &= \varphi_M + \varphi_{h_i} - \widehat{\varphi}_{h_{SR_i}} = \\ &= \begin{cases} \varphi_M - \Delta\varphi_{h_i} & \text{for} \quad \varphi_{h_i} < \pi \\ \varphi_M - \Delta\varphi_{h_i} + \pi & \text{for} \quad \varphi_{h_i} \geq \pi \end{cases} \end{aligned} \quad (7)$$

There are some drawbacks to this scheme:

- In a frequency selective environment the master reference signal might be in a deep fade for some of the nodes. As a consequence, the phase synchronization will be very imprecise.
- The scheme does not benefit from multiple antennas at the slaves. The estimate of $2\varphi_{h_i}$ has to be calculated for each slave antenna individually.
- The master node has to perform much more calculations than the slaves. This means that the computational load is not distributed equally among the network. As a consequence, there are systems where not every node is suited to act as master. Restricting the set of potential master nodes is surely disadvantageous.
- In a mobile environment the overhead to synchronize a large number of nodes might be prohibitive as the slaves are synchronized sequentially.

3.2. Slave-Based Scheme

In our scheme all slaves transmit a sequence $p_i[t]$ to the master node which bounces back the conjugate complex of the received signal. From its own received signal, each slave can then locally generate an estimate of $-2\varphi_{S_i} + 2\varphi_M$ which is two times the difference between the LO phases. When all slaves transmit their sequence $p_i[t]$ *concurrently* to the master, the whole scheme takes two timeslots, independent of the number of nodes. However, the slaves cause interference to each other which degrades the quality of the phase estimation. No interference occurs when the slaves transmit their sequences *sequentially* to the master node. The phase estimation thus improves, but we need $2N$ channel uses to synchronize a network of N slaves.

We use cyclically shifted m-sequences when synchronizing the carrier phase of all slaves at the same time. Let $m[t]$ be an m-sequence of length T_m. Slave i uses the sequence $p_i[t] = m_i[t]$, where we get $m_i[t]$ by shifting $m[t]$ cyclically by $\left\lfloor (i-1)\frac{T_m}{N} \right\rfloor$ samples. Due to the correlation properties of the m-sequence we get

$$\sum_{t=1}^{T_m} p_i[t] p_j^*[t] = \begin{cases} T_m & \text{for} \quad i = j \\ -1 & \text{for} \quad i \neq j \end{cases} \quad (8)$$

Thus the interference generated by all other slaves $S_{j,j\neq i}$ to S_i can be made small when T_m is large. We use m-sequences because they have, apart from the small dc component, a flat spectrum. That means that they have the same power in all frequency bins and we gain from frequency diversity.

We use a tapped delay line to model the impulse response of the channel from slave i to the master node. It is denoted by $h_{S_iM}[t]$ and has a length of T_h taps. We assume that all nodes are perfectly frequency matched and only consider baseband signals for the sake of simplicity. For the concurrent synchronization strategy the details of the procedure are as follows:

0) Initially, every slave S_i is assigned one sequences $p_i[t]$ that is generated as described above.
1) All slaves S_i transmit their baseband signal $s_i^{(\text{tx})}[t] = p_i[t]$ simultaneously to the master node.
2) The master receives the superposition of all signals which are rotated by its own LO phase offset φ_M and the LO phase offset of each slave φ_{S_i}. The received baseband signal is

$$d^{(\text{rx})}[t] = e^{-j\varphi_M} \sum_{i=1}^{N} \left(p_i[t] \circledast h_{S_iM}[t] \cdot e^{j\varphi_{S_i}} \right). \quad (9)$$

3) The master calculates

$$d^{(\mathrm{tx})}[t] = \left(d^{(\mathrm{rx})}[-t+T_{\mathrm{h,m}}]\right)^* \quad (10)$$

and broadcasts it to all slaves. We use $T_{\mathrm{h,m}} = T_{\mathrm{m}} + T_{\mathrm{h}} - 1$ to make the transmit signal causal.

4) Slave i receives the baseband signal

$$s_i^{(\mathrm{rx})}[t] = d^{(\mathrm{tx})}[t] \circledast h_{\mathrm{S}_i\mathrm{M}}[t] \cdot e^{j\left(-\varphi_{\mathrm{S}_i}+\varphi_{\mathrm{M}}\right)}. \quad (11)$$

5) Knowing all used phase estimation sequences $p_i[t]$, each slave computes $c_i[t] = p_i[t] \circledast s_i^{(\mathrm{rx})}[t] = c_i^{(\mathrm{S})}[t] + c_i^{(\mathrm{I})}[t]$. The signal part $c_i^{(\mathrm{S})}[t]$ is given by

$$c_i^{(\mathrm{S})}[t] = p_i[t] \circledast p_i^*[-t+T_{\mathrm{h,m}}] \circledast \circledast h^*_{\mathrm{S}_i\mathrm{M}}[-t+T_{\mathrm{h,m}}] \circledast h_{\mathrm{S}_i\mathrm{M}}[t] \cdot e^{j\left(-2\varphi_{\mathrm{S}_i}+2\varphi_{\mathrm{M}}\right)}. \quad (12)$$

and the interference part by

$$c_i^{(\mathrm{I})}[t] = \sum_{l=1, l\neq i}^{N} p_i[t] \circledast p_l^*[-t+T_{\mathrm{h,m}}] \circledast \circledast h^*_{\mathrm{S}_l\mathrm{M}}[-t+T_{\mathrm{h,m}}] \circledast h_{\mathrm{S}_i\mathrm{M}}[t] \cdot e^{j\left(-\varphi_{\mathrm{S}_i}-\varphi_{\mathrm{S}_l}+2\varphi_{\mathrm{M}}\right)}. \quad (13)$$

Analyzing (12) we define

$$c_{\mathrm{p}_i}^{(\mathrm{S})}[t] = p_i[t] \circledast p_i^*[-t+T_{\mathrm{h,m}}] \quad (14)$$

and obtain $c_{\mathrm{p}_i}^{(\mathrm{S})}[T_{\mathrm{m}}] = T_{\mathrm{m}}$ due to the correlation properties of the m-sequences. Furthermore we write

$$c_{\mathrm{h}_i}^{(\mathrm{S})}[t] = h^*_{\mathrm{S}_i\mathrm{M}}[-t+T_{\mathrm{h,m}}] \circledast h_{\mathrm{S}_i\mathrm{M}}[t] \quad (15)$$

and have $\angle\left\{c_{\mathrm{h}_i}^{(\mathrm{S})}[T_{\mathrm{h}}]\right\} = 0$. Using (14), (15), and the associativity of the convolution we get

$$\angle\left\{c_i^{(\mathrm{S})}[T_{\mathrm{m}}+T_{\mathrm{h}}-1]\right\} = -2\varphi_{\mathrm{S}_i} + 2\varphi_{\mathrm{M}}. \quad (16)$$

Assuming that the interference is small because of the correlation properties of our transmit sequences, we approximate $\widehat{\psi}_{\mathrm{S}_i,\mathrm{M}} = \angle\{c_i[T_{\mathrm{h,m}}]\}$. Slave i now has an estimate of $\psi_{\mathrm{S}_i,\mathrm{M}} = -2\varphi_{\mathrm{S}_i} + 2\varphi_{\mathrm{M}}$ with phase estimation error

$$\psi_{i,\mathrm{error}}^{(\mathrm{SB})} = \widehat{\psi}_{\mathrm{S}_i,\mathrm{M}} - \left(-2\varphi_{\mathrm{S}_i} + 2\varphi_{\mathrm{M}}\right). \quad (17)$$

For the sequential synchronization strategy we simply have to omit the interference term (13).

It is enough for each slave S_i to know twice the phase difference $-2\varphi_{\mathrm{S}_i}+2\varphi_{\mathrm{M}}$ instead of $-\varphi_{\mathrm{S}_i}+\varphi_{\mathrm{M}}$ in order to achieve the coherent addition of all signals at the destination. Note that we again face the π-ambiguity as described in Section 3.1. Compared to the MB scheme, we observe some advantages:

- Due to the broadband nature of the phase estimation sequences we can benefit from the frequency diversity present in a frequency selective channel.
- Multiple slave antennas provide a diversity gain by simple antenna selection. This is because we determine the LO phase offset which is the same for all employed antennas.
- As the computational load is distributed equally among the network, any simple amplify-and-forward node can be assigned master.
- By dynamically adjusting the sequence length T_{m}, we can trade estimation accuracy (T_{m} large) for system resources (T_{m} small).

4. APPLICATION: DISTRIBUTED BEAMFORMING

Consider a scenario with a cluster of $N+1$ wireless sensor nodes employing only one antenna each. One of the nodes wants to transmit data to a remote destination. Due to their small size and limited power supply, a single node out of the cluster is not able to reach the destination on its own. However, when they cooperate to form a distributed array, the sensor nodes are able to cover a much larger distance using distributed beamforming. In the previous section we treated a frequency-selective propagation channel to develop the slave-based phase synchronization scheme. Now we are interested in the impact of the phase estimation error on the performance of the present scenario. For the data transmission it suffices to consider frequency-flat Rayleigh fading channels. This can for example be achieved by employing OFDM modulation. We assume that all channel coefficients are independent, complex normal random variables with zero mean and variance σ_{h}^2. The channels from source S_0 to relay S_i and from relay S_i to destination D are denoted by $h_{\mathrm{S}_0\mathrm{S}_i}$ and $h_{\mathrm{S}_i\mathrm{D}}$, respectively.

In order to achieve a coherent addition of all signal at the destination, all nodes have to transmit the same information but with a different precompensation factor g_i to compensate for their individual propagation channel to the destination and their LO phase offset.

The question arises how the transmit data can be shared among the nodes. One approach that certainly suggests itself is to distribute this information wirelessly. In **Fig. 1** we depict the above mentioned scenario. One node out of the whole set of sensors S_i,

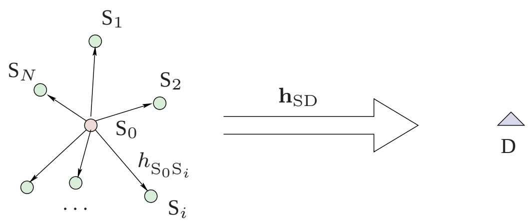

Fig. 1. Distributed beamforming scenario

$i \in \{0,\ldots,N\}$ is assigned *master*. It is to provide a global phase reference to the *slaves* as described in Section 3.2. Assume that sensor node S_0 wants to transmit the data burst $s[t]$ to the remote destination D. For the sake of simplicity we assume that S_0 also acts as master node. All other nodes $\mathrm{S}_i, i \in \{1,\ldots,N\}$ act as amplify-and-forward (AF) relays forming a distributed antenna array. Transmission from source to destination then follows a two-hop traffic pattern consuming two timeslots.

Timeslot 1: The source node S_0 broadcasts $s[t]$ to all relays, where $\mathrm{E}_t\left[|s[t]|^2\right] = \sigma_{\mathrm{s}}^2$. S_i receives

$$s_i^{(\mathrm{rx})}[t] = s[t]e^{j\left(\varphi_{\mathrm{S}_0}-\varphi_{\mathrm{S}_i}\right)}h_{\mathrm{S}_j\mathrm{S}_i} + n_{\mathrm{R}_i}[t], \quad (18)$$

where $n_{\mathrm{R}_i}[t]$ is circular symmetric, additive, white, Gaussian noise (AWGN) with variance $\sigma_{\mathrm{n}_{\mathrm{R}_i}}^2$. Assume that all relays have learned

$\widehat{\psi}_{\mathrm{S}_i,\mathrm{S}_0}$ as described in Section 3.2 and, assuming channel reciprocity, have an estimate of their channel from the source,

$$\widehat{h}_{\mathrm{S}_0\mathrm{S}_i} = h_{\mathrm{S}_0\mathrm{S}_i} e^{j\left(\varphi_{\mathrm{S}_0} - \varphi_{\mathrm{S}_i}\right)} \tag{19}$$

and to the destination,

$$\widehat{h}_{\mathrm{S}_i\mathrm{D}} = h_{\mathrm{S}_i\mathrm{D}} e^{j\left(\varphi_{\mathrm{D}} - \varphi_{\mathrm{S}_i}\right)}. \tag{20}$$

They can calculate a gain factor compensating the concatenation of both channels and their carrier phase offsets according to

$$g_i = \gamma_i \cdot \tilde{g}_i = \gamma_i \cdot \widehat{h}^*_{\mathrm{S}_0\mathrm{S}_i} \widehat{h}^*_{\mathrm{S}_i\mathrm{D}} e^{j\widehat{\psi}_{\mathrm{S}_i,\mathrm{S}_0}}. \tag{21}$$

The factor

$$\gamma_i = \sqrt{\frac{P_{\mathrm{R}}}{|\tilde{g}_i|^2 \sigma_{\mathbf{s}}^2 \sigma_{\mathrm{h}}^2 + |\tilde{g}_i|^2 \sigma^2_{\mathbf{n}_{\mathrm{R}_i}}}} \tag{22}$$

is a locally computed scaling factor ensuring that the average transmit power of node S_i is equal to P_{R}.

Timeslot 2: Each relay now transmits the baseband signal $s_i^{(\mathrm{tx})}[t] = s_i^{(\mathrm{rx})}[t] \cdot g_{\mathrm{S}_i}$. The destination receives the superposition of all relay signals

$$d^{(\mathrm{rx})}[t] = \sum_{i=1}^{N} \gamma_i s[t] |h_{\mathrm{S}_0\mathrm{S}_i}|^2 |h_{\mathrm{S}_i\mathrm{D}}|^2 e^{j\left(2\varphi_{\mathrm{S}_i} - 2\varphi_{\mathrm{D}} + \widehat{\psi}_{\mathrm{S}_i,\mathrm{S}_0}\right)} + \\ + \sum_{i=1}^{N} \gamma_i n'_{\mathrm{R}_i}[t] h^*_{\mathrm{S}_0\mathrm{S}_i} |h_{\mathrm{S}_i\mathrm{D}}|^2 + n_{\mathrm{D}}[t]. \tag{23}$$

$n_{\mathrm{D}}[t]$ is AWGN at the destination and $n'_{\mathrm{R}_i}[t]$ is a phase rotated version of the relay noise $n_{\mathrm{R}_i}[t]$. As a phase rotation does not affect the statistics of a circular symmetric random variable, $n'_{\mathrm{R}_i}[t]$ remains AWGN with variance $\sigma^2_{\mathrm{n}_{\mathrm{R}_i}}$. Assuming a perfect phase estimate, i.e., $\widehat{\psi}_{\mathrm{S}_i,\mathrm{S}_0} = -2\varphi_{\mathrm{S}_i} + 2\varphi_{\mathrm{S}_0}$, the signal part of the destination signal is

$$d_{\mathrm{s}}^{(\mathrm{rx})}[t] = e^{j\left(2\varphi_{\mathrm{S}_0} - 2\varphi_{\mathrm{D}}\right)} \sum_{i=1}^{N} \gamma_i s[t] |h_{\mathrm{S}_0\mathrm{S}_i}|^2 |h_{\mathrm{S}_i\mathrm{D}}|^2 \tag{24}$$

which is the coherent addition of all relay signals. The remaining phase offset $2\varphi_{\mathrm{S}_0} - 2\varphi_{\mathrm{D}}$ is the same for all relay signals.

We split (23) into a signal part $d_{\mathrm{s}}^{(\mathrm{rx})}[t]$ and a noise part $d_{\mathrm{n}}^{(\mathrm{rx})}[t]$ and define the average receive SNR as

$$\mathrm{SNR}_{\mathrm{rx}} = \frac{\mathrm{E}_{t,h}\left[|d_{\mathrm{s}}^{(\mathrm{rx})}[t]|^2\right]}{\mathrm{E}_{t,h}\left[|d_{\mathrm{n}}^{(\mathrm{rx})}[t]|^2\right]}. \tag{25}$$

5. SIMULATION RESULTS

We performed Monte-Carlo simulations to assess the performance of our carrier phase synchronization scheme and compare it to the master-based approach using a sinusoidal reference signal. Consider the scenario presented in Section 4. For the phase synchronization we assume a frequency-selective Rayleigh fading channel with impulse response $h_{\mathrm{S}_i\mathrm{M}}[t]$ between the master and all slaves $i \in \{1, \ldots, N\}$. The average path strengths are chosen according to the Hiperlan channel model B [8] with a bandwidth of $100\ \mathrm{MHz}$ and an average root-mean-square (rms) delay spread of $100\ \mathrm{ns}$. It corresponds to a typical large open space environment with non-Line-of-Sight (NLoS) conditions or an office environment with large delay spread. The channel impulse response is normalized such that its total power is on the average equal to 1. We assume a block fading environment, i.e., the channel coefficients stay constant during two transmission cycles. Different channel realizations are temporally uncorrelated. The LO phase offsets φ_{S_i} are modelled as uncorrelated, uniformly distributed random variables, where $-\pi \leq \varphi_{\mathrm{S}_i} \leq \pi$. They are also assumed to stay constant during two transmission cycles and change independently afterwards.

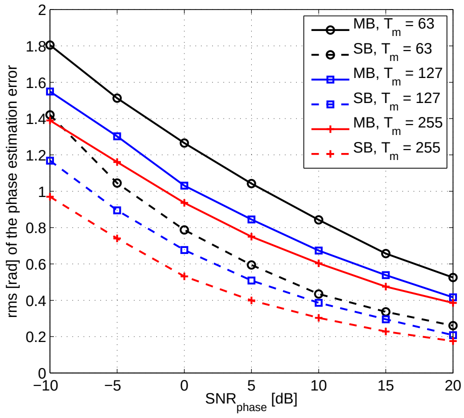

Fig. 2. rms [rad] of $\psi^{(\mathrm{MB})}_{i,\mathrm{error}}$, $\psi^{(\mathrm{SB})}_{i,\mathrm{error}}$ for different values of T_{m}

The phase estimation sequences $p_i[t]$ are chosen such that they use the whole channel bandwidth of $100\ \mathrm{MHz}$. We define the SNR for the phase estimation at slave node i as

$$\mathrm{SNR}^{(i)}_{\mathrm{phase}} = \frac{E_{\mathrm{s}}}{N_0} \mathrm{E}_h\left[\sum_{t=0}^{T_{\mathrm{h}}-1} h_{\mathrm{S}_i\mathrm{M}}[t] h^*_{\mathrm{S}_i\mathrm{M}}[t]\right], \tag{26}$$

where E_{s} is energy per symbol, N_0 the noise power spectral density and $\mathrm{E}_h\left[\sum_{t=0}^{T_{\mathrm{h}}-1} h_{\mathrm{S}_i\mathrm{M}}[t] h^*_{\mathrm{S}_i\mathrm{M}}[t]\right]$ average total channel power.

5.1. Phase Estimation Performance

First, we investigate the accuracy of the LO phase offset correction between master M and slave S_i when the estimation is done sequentially (no interference). **Fig. 2** shows the rms-value in radians of the phase estimation errors $\psi^{(\mathrm{MB})}_{i,\mathrm{error}}$ (see (5)) and $\psi^{(\mathrm{SB})}_{i,\mathrm{error}}$ (see (17)), respectively, versus the phase estimation SNR for different values of T_{m}. Note that the impact of the phase estimation error on the receive SNR is the same for both schemes. This is why we can directly compare them. As expected, the quality of the phase estimation increases with increasing T_{m}. We can observe that the slave-based approach (SB) always performs about 10dB better than the master-based approach (MB) for this channel model. The smaller rms values hint at the frequency diversity we can exploit with our scheme.

In **Fig. 3** we plot the cumulative density function (cdf) of the phase estimation error ψ_{error}. We observe that curves for the slave-based approach (SB) are steeper at the zero-error point and flatten out much later compared to the master-based approach (MB). The chance of a serious misdetection is thus much smaller.

The achievable gain of an antenna selection scheme at the slaves is investigated in **Fig. 4**. For the phase estimation we chose an exponential power delay profile with 10 taps and average total channel power 1 instead of the Hiperlan B channel model. We did this to simulate a scenario with a strong line-of-sight (LOS) component. The

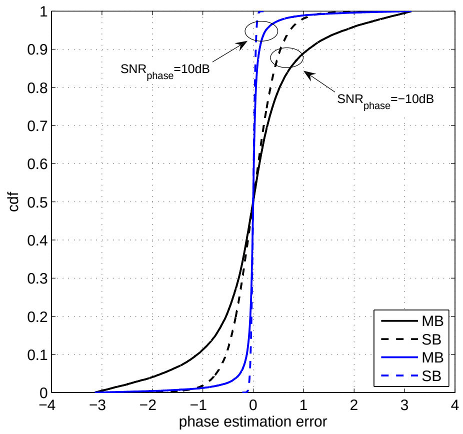

Fig. 3. cdf of $\psi_{i,\mathrm{error}}^{(\mathrm{MB})}$, $\psi_{i,\mathrm{error}}^{(\mathrm{SB})}$ for different $\mathrm{SNR}_{\mathrm{phase}}$ values

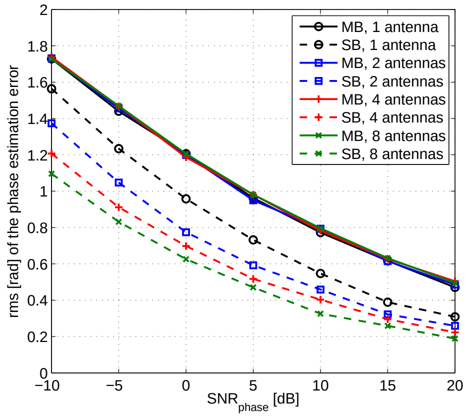

Fig. 4. rms [rad] of $\psi_{i,\mathrm{error}}^{(\mathrm{MB})}$, $\psi_{i,\mathrm{error}}^{(\mathrm{SB})}$ for different number of slave antennas

channel is then not very frequency-selective so we can better observe the effect of the expected antenna diversity. We see that our slave-based approach (SB) in fact benefits from a simple antenna selection scheme.

5.2. Distributed Beamforming

We now investigate the impact of phase estimation errors on the receive SNR at destination D. We have $N = 8$ relays where carrier phase synchronization is performed as in Section 3. The transmit sequence length is $T_{\mathrm{m}} = 63$. In **Fig. 5** we plot the average receive SNR loss with respect to perfect phase synchronization. As reference the receive SNR loss of a system with random LO phases at the relays is shown. For the slave-based approach with sequential synchronization we are nearly perfect even for low phase estimation SNR. The concurrent synchronization at low SNR leads to a loss compared to the master-based approach. However, we only need 2 channel uses. From about $\mathrm{SNR}_{\mathrm{phase}} = 10$ dB there is only a very small performance loss compared to the master-based approach.

6. CONCLUSIONS

We presented a strategy to achieve a global carrier phase synchronization in a distributed, wireless network with autonomous nodes.

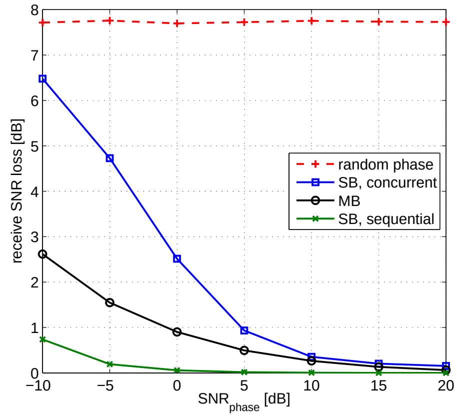

Fig. 5. Receive SNR loss due to inaccurate phase estimation

Our approach is able to exploit frequency diversity and the computational load is distributed equally among the whole network. We showed that the phase estimation is more accurate compared to a scheme employing a sinusoidal reference signal when the environment is frequency-selective. We are furthermore able to dynamically trade phase estimation accuracy for system resources by adjusting the length of the phase estimation sequences.

7. REFERENCES

[1] A. Wittneben and B. Rankov, "Distributed Antenna Systems and Linear Relaying for Gigabit MIMO Wireless," in *Proc. IEEE VTC'04 Fall, Los Angeles*, Sep. 2004.

[2] H. Shi, T. Abe, T. Asai, and H. Yoshino, "Relay Techniques in MIMO Wireless Networks," in *Proc. IEEE VTC'05 Fall, Dallas*, Sep. 2005.

[3] H. Shi, T. Abe, T. Asai, and H. Yoshino, "A Relaying Scheme using QR Decomposition with Phase Control for MIMO Wireless Networks," in *Proc. IEEE International Conference on Communications*, 2005, Seoul.

[4] H. Ochiai, P. Mitran, V. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," *IEEE Transactions on Signal Processing*, vol. 53, no. 11, pp. 4110 – 4124, Nov. 2005.

[5] D. R. Brown III, G. B. Prince, and J. A. McNeill, "A method for carrier frequency and phase synchronization of two autonomous cooperative transmitters," in *IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2005, pp. 260 – 264.

[6] Y.-S. Tu and G. J. Pottie, "Coherent cooperative transmission from multiple adjacent antennas to a distant stationary antenna through AWGN channels," in *Proc. IEEE VTC'02 Spring, Birmingham, Al*, 2002, vol. 1, pp. 130 – 134.

[7] G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in *IPSN'04: Proc. of the Third International Symposium on Information Processing in Sensor Networks*, 2004, pp. 81 – 88.

[8] M. Debbah, J. Gil, P. Fernandes, J. Venes, F. Cardoso, L. Marques, and M. Correia, "Final report on channel models," FLOWS project, 2004, Online available: http://www.elec.york.ac.uk/comms/FLOWS.html.