Applications for Distributed Beamforming

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Abstract

Distributed beamforming is a transmitting technique in which a cluster of independent transmitter form an antenna array in order to increase signal strength in the receiver. Synchronization between transmitting antennas is implemented in an iterative fashion using feedback from the receiver.

While interest toward distributed beamforming is growing rapidly, there are no working applications implemented. Furthermore, very little suggestions have been made on in what kind of systems and in which kind of scenarios this technique could be used.

In this paper, we present case studies on prospective applications for distributed beamforming. We will compare distributed beamforming with other transmission methods and explain why it is the optimal solution for given cases.

Index Terms:distributed beamforming, wireless communication, ad-hoc networks, sensor networks.

I. INTRODUCTION

In recent years, the interest towards different kinds of flexible wireless communication networks has grown. A substantial amount of research has been made in the areas of ad-hoc, sensor, and cognitive networks. Unlike in traditional wireless communications systems, such networks can function partly or completely without base stations or other kinds of centralized network management. Thus, by using new communication systems it is possible to implement completely new kinds of wireless network applications.

Distributed beamforming (DBF) [1], [2], is a simple beamforming method designed for ad-hoc networks. In DBF, several independent transmitting nodes collaborate to form an antenna array. The phase synchronization of the array is implemented iteratively, using random phase changes in each transmitter. After every round of phase adjustments, the receiver measures the power of the resulting sum signal and sends a single bit of feedback indicating whether the signal level increases or not. Based on the value of the feedback bit, the transmitter nodes store or discard the latest phase adjustments and continue the process with a new set of adjustments. Ultimately, the received signal strength reaches a level obtainable with coherent combining.

In this paper, we discuss possible use scenarios and applications for DBF. We analyze its strengths and weaknesses and compare it to other similar algorithms. Based on this analysis, we then present case studies on situations where DBF could be used. In each case study we describe how the system in question can be implemented using DBF. We also explain why DBF is the best suited solution for that particular case.

The remainder of this paper is organized as follows: in Section II we specify our system model and introduce the DBF algorithm. We also present simulation results to analyze the performance of the algorithm. In Section III we discuss more closely the properties of DBF, and as a comparison, briefly present some alternative transmitting methods. In Section IV, we introduce possible use scenarios for the described beamforming system and analyze the effect of DBF by calculating link budgets for considered systems. Finally, in Section V, we present a number of prospective future research topics on the subject.

II. DISTRIBUTED BEAMFORMING

We will now shortly explain the system model used in this paper. For simplicity, we only consider transmission from the cluster of nodes to a fixed receiver, which can for example be a base station in a cellular network or a WLAN access point, i.e. the transmission takes place in the uplink. It is assumed that transmissions inside the cluster are easily implemented due to the short distance between the nodes. Furthermore, signal transmission from the base station to the nodes is not considered here, since the base station has a high transmission power, and the data to be transmitted contains only one bit per transmission. The scenario is illustrated Fig.1.

A. System Model

Without loss of generality and for increased simplicity, we use single carrier representation throughout this paper.

Let there be K transmitting nodes, each equipped with a single antenna. The sum signal sensed at the receiver at time index l is

$$y[l] = \sum_{k=1}^{K} h[l]_k w[l]_k x[l] + \eta[l], \tag{1}$$

where $h[l]_k$ is the channel response from transmitter k to the receiver at time l, $w[l]_k$ is the beamforming component for transmitter k, $x[l]$ is the transmitted training symbol, and $\eta[l]$ is the received noise component. We divide the channel response into amplitude and phase components,

$$h[l]_k = |h[l]_k| \exp(i\psi[l]_k), \tag{2}$$

and set $|w[l]_k| = 1$. We can now write

$$w[l]_k = \exp(i\phi[l]_k). \tag{3}$$

Combining (1), (2) and (3) we have

$$y[l] = \left[\sum_{k=1}^{N} |h[l]_k| \exp(i\phi[l]_k + i\psi[l]_k)\right] x[l] + \eta[l]. \tag{4}$$

The total received power reaches its maximum value when the signals from the transmitters are summed constructively. That is,

$$\phi[l]_k + \psi[l]_k = \text{Constant}. \tag{5}$$

We remind that since the transmit power of an individual transmitter is low, the channel cannot be determined accurately enough in order to calculate coefficients ϕ. We will next describe an algorithm to calculate ϕ in an iterative fashion with minimal feedback from the receiver.

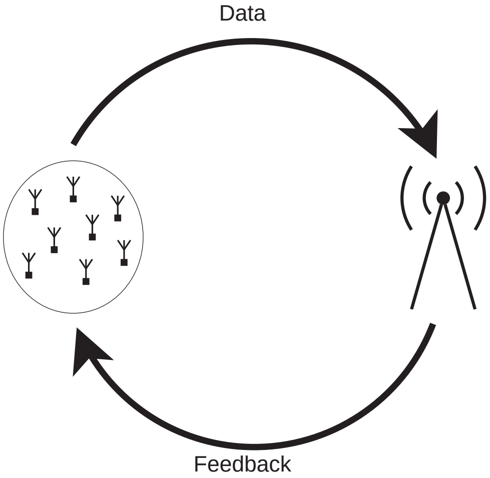

Fig. 1. A typical DBF use scenario: a cluster of transmitters sends a training signal to the receiver. The receiver responds with a feedback signal.

B. Iterative phase correction algorithm

To gain maximum signal power at the receiver, (5) must be fulfilled, i.e. a suitable value of ϕ for each transmitter must be calculated. In other words, the transmitted signals must be synchronized.

Because it is not possible to detect the channel accurately, we cannot calculate ψ directly. The beamforming coefficients are therefore calculated recursively using a stochastic approach. We denote by $\theta[l]_k$ the best known value for the channel phase correction term ϕ_k at time index l. The phase correction term for the $(l+1)$:th iteration is calculated by adding a random change δ into the best known values

$$\phi[l+1]_k = \theta[l]_k + \delta[l+1]_k. \tag{6}$$

Note that every transmitter adjust its own δ independently, which means that there is no need for a centralized algorithm. After receiving the sum signal, the receiver broadcasts a feedback bit to the transmitters, indicating whether the received power level improved or not compared to best power level achieved so far. The transmitters then continue the process by updating their best known correction terms according to

$$\theta[l+1]_k = \begin{cases} \theta[l]_k & \text{feedback} = 0 \\ \theta[l]_k + \delta[l+1]_k & \text{feedback} = 1. \end{cases} \tag{7}$$

In other words, the random change is kept if it improved the reception, otherwise it is canceled.

We illustrate the convergence of the algorithm with a series of simulation results. In Fig. 2, the received signal power is plotted as function of iterations. In Fig. 3, the number of iterations needed to reach 80 % of maximum reception power (i.e. the power obtainable with coherent combining) with different numbers of transmitters is shown.

Several improvements have been proposed to the above described basic DBF scheme, for example in [3] and [4], faster convergence was achieved with a more efficient use of the feedback bit. In [5], time overhead was minimized by transmitting frames consisting of several symbols with different phase correction terms. In [6], DBF was utilized in an OFDM system.

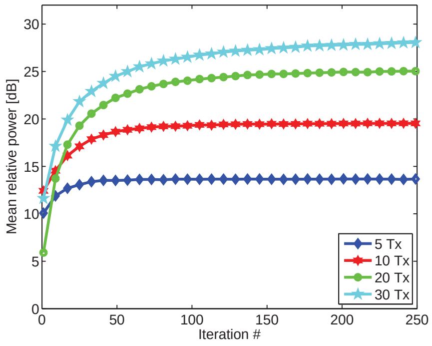

Fig. 2. Convergence of the DBF algorithm. The received signal power as function of iteration loops with different numbers of transmitters.

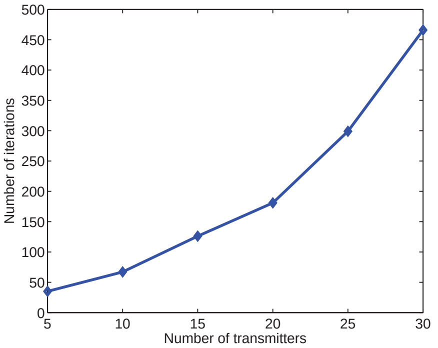

Fig. 3. Convergence time of the DBF algorithm. The number of iterations needed to achieve 80 % of maximum reception power with different numbers of transmitters inside the cluster.

III. COMPARISON TO ALTERNATIVE SYSTEMS

For succesful implementation of the DBF algorithm, its strengths and weaknesses must be known. Also, it is important to know what are the alternatives for DBF and in which ways they are better or worse compared to it.

A. Benefits

The main benefit of DBF is its simplicity. The computational power needed to perform the algorithm is minimal in either end of the transmission link. Also, very little information is needed about the system in the nodes that it is comprised of. Knowledge of channel parameters is not required. Furthermore, the transmitter does not need information on how many cooperating nodes it has around it. The number of transmitting nodes can even change in the middle of transmission without causing any problems to system.

These properties make DBF practical in almost any wireless system. The question that arises at this point is when DBF is the best available method.

B. Implementation challenges

As seen before, the DBF algorithm takes quite many iterations to converge. With accurate channel information or a more organized way of iterating transmitting parameters, the convergence could speed up considerably. On the other hand, according to [2], the convergence is linearly dependent on the number of transmitting nodes. This means that the DBF algorithm is fully scalable.

C. Alternatives

In distributed beamforming, a cluster of independent nodes cooperatively send a common signal to a single receiver. For comparison purposes, we now present two alternative systems that could be used in the same applications.

The first alternative is a system in which each transmitting node is connected to the base station individually. This kind of configuration is used for example in cellular networks. In such networks, the transmitting power of an individual node is higher compared to DBF. Higher transmitting power leads to higher power use and ultimately to shorter battery life. On the other hand, there is no need for synchronization or routing between mobile terminals. Therefore this system is simple to implement.

The second alternative is a wireless multi-hop routing network. In such a network, the transmitted signal is relayed through a number of nodes. As in DBF, the transmitting power can be kept at a low level. However, the arrangement of routing is challenging: since there is always just one node sending, the distance between two nodes can not be too long. A situation in which a number of nodes is located far away from the base station could be problematic for a network of this kind.

IV. IMPLEMENTATION

In this section, we will give a few examples on what kind of systems could benefit from using DBF. We will also point out why DBF is the most suitable solution for these example systems.

A. Sensor networks

A sensor network is a wireless ad-hoc network consisting of a number of sensors capable of measuring, transmitting and receiving data. Because of limited battery life, and the price of an individual sensor, it is important that both the transmitting power and the power used for signal processing is kept as low as possible.

In a DBF based sensor network, it is possible to keep the transmission power of an individual sensor low. Also, through DBF gain, the signal range can be extended. As an example, we calculated the increase of signal range for a sensor group with more than 10 sensors transmitting with DBF. First, we calculated the link budget for such a system. The link budget calculations are presented in Table I. The decibel values used in the calculations were taken from [7]. We calculated the path loss components by using a formula provided in the WINNER 2 channel model [8] D1. The path loss as a function of distance is shown in Fig. 4, along with maximum signal ranges for the system with and without DBF. In this example, the signal range almost tripled by using DBF.

The biggest challenge for using DBF in a sensor network is a high number of test transmissions required in the synchronization phase. Therefore, synchronizing the transmitters increases the initial power consumption, which can in some sense contradict with the base assumptions. On the other hand, considering that the sensors are meant to be used for an extended period of time and that transmissions to the base station occur rarely, only actual data transmissions are performed after the initial synchronization phase. As long as the nodes are not moving, the channel parameters change only a little, making it possible to use phase correction parameters that were achieved earlier. Furthermore, the correction parameters can be

TABLE I
LINK BUDGET A FOR SENSOR NETWORK

Tx power	0 dBm
Antenna gain	0 dB
DBF gain	20 dB
Receiver sensitivity	-85 dBm
Fading margin	7 dB
Tolerated pathloss with DBF	98 dB
Tolerated pathloss without DBF	78 dB

tracked during every transmission, therefore the system can update itself to prevent problems caused by minor changes in channel conditions.

In a sensor network, using direct connection to the receiver would require substantially higher transmission power, thus shortening the battery life. On the other hand, a multi-hop routed network would require a complex routing algorithm and upkeep of routing tables, making individual sensors more complex and expensive to produce.

B. Mobile network gap filler

At present, mobile connection is available almost everywhere. Finding the signal with a mobile phone is hardly an issue anymore. However, there are still areas without proper network coverage, mostly far away from large cities. Gaps in network coverage can also occur if one or more base stations go out because of technical reasons. Natural disasters, such as earthquakes, can also cause base stations to go offline. In such a scenario, DBF along with a cluster of mobile devices, could be used as a gap filler for the mobile network. For example, consider a case in which there is a group of users residing outside the network coverage area, e.g. hiking in the wilderness. This kind of scenario prevents both the uplink and downlink signal from reaching their respective receivers. By using DBF at the mobile devices and robust coding in downlink transmission of the feedback bit, the group might be able to send one-way distress messages to the base station in case of emergency, even if a voice call or a text message can not be sent from an individual device.

We illustrate the effect of using DBF in a mobile system similarly as we did earlier for a sensor network. The corresponding link budget calculations are presented in Table II. We assume that there are 5 mobile phones in one DBF cluster, which gives a DBF gain value of 12 dB. The other decibel values were chosen to approximately correspond those from the UMTS standard [9]. The value of the path loss component as a function of distance is plotted in Fig. 5. The presented link budget calculation results imply that in this scenario, the transmitting range can be doubled by using DBF.

In this use scenario, DBF is the only option, since by definition, direct connect is not possible and multi-hop routing is not reliable since it is unlikely that there are enough mobile stations available to relay the transmission all the way to the basestation.

V. FUTURE RESEARCH

In this paper, we have discussed properties of the DBF algorithm and proposed possible use scenarios that could be implemented. However, there are also a number of interesting topics yet to be researched and analyzed, concerning different variations of the DBF algorithm. We will now conclude this paper by listing a few potential areas for future research.

TABLE II
LINK BUDGET FOR A MOBILE NETWORK USING DBF

Tx power	20 dBm
Antenna gain	0 dB
DBF gain	12 dB
Receiver sensitivity	-100 dBm
Fading margin	7 dB
Tolerated pathloss with DBF	125 dB
Tolerated pathloss without DBF	113 dB

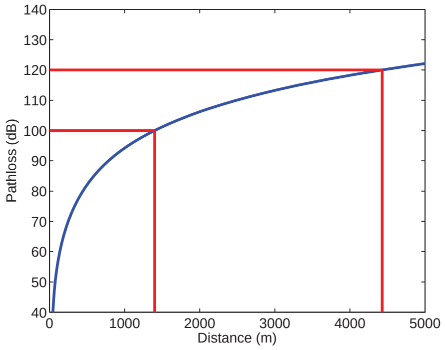

Fig. 4. Pathloss in a sensor network. Corresponding maximum communication ranges are plotted for DBF and non-DBF cases.

Past research concerning DBF has not considered the effect of device mobility extensively. Since temporal variation of the channel properties affects the convergence speed of the algorithm, i.e. the channel response changes during the transmitter phase synchronization and therefore finding the optimal phases is harder, device mobility has a definite impact on system performance.

Before DBF can be fully implemented in a complete system, a proper analytical treatment concerning the system performance must be performed. At the moment of writing this paper, there is none available. Unfortunately, the analysis for DBF seems to be very complex and difficult to develop.

In real-world applications, network security is likely to be an issue when using the DBF algorithm because the original transmitted signal is shared between the nodes. In the simple systems like those we have proposed as examples, hijacking the transmitted signal would be fairly easy. However, network security is probably easy to be implemented in the higher layers of the network system.

VI. ACKNOWLEDGEMENTS

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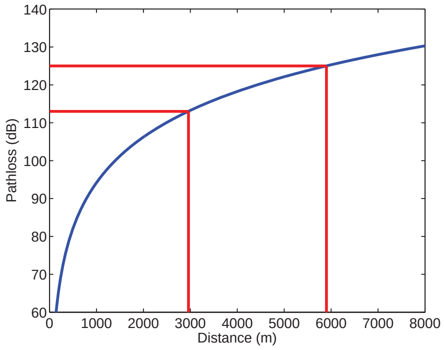

Fig. 5. Pathloss in an UMTS network. Corresponding maximum communication ranges are plotted for DBF and non-DBF cases.

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