Cooperative Diversity for Ultrawideband Networks

Jaime Adeane and Ian J. Wassell
Computer Laboratory, University of Cambridge
J. J. Thomson Avenue, Cambridge CB3 0FD, UK
Email: ja316@cam.ac.uk; ijw24@cam.ac.uk

Wasim Q. Malik
Department of Engineering Science, University of Oxford
Parks Road, Oxford OX1 3PJ, UK
Email: wasim.malik@eng.ox.ac.uk

***Abstract*— We propose the use of cooperative communication among single-antenna users to enhance the performance of ultrawideband networks. We consider the amplify-and-forward cooperative protocol in the multiband OFDM setting using practical channel measurements.**

I. Introduction

While ultrawideband (UWB) offers high information rates for wireless communication and sensor networks, the EIRP limits on UWB devices severely affects its coverage radius [1]. One approach to improve the UWB coverage is by using multiple antennas at the transmitter and receiver sides, referred to as MIMO diversity [1]. However, the practical implementation of MIMO systems is difficult, especially the integration of multiple antennas in a physically compact terminal.

An alternative is provided by a cooperative network configuration, which relies on multiple nodes, each comprising a single-antenna system, to provide transmit diversity [2]–[4]. The users relay messages to each other and propagate redundant signals over multiple paths in the network. This redundancy enables the receiver to average out the channel fluctuations due to fading, shadowing, and other interference. The separation between the spatially distributed user terminals helps create the signal independence required for diversity.

The current state of the art in UWB technology does not consider cooperative transmission. In this paper we show that forming cooperative networks between UWB devices enhances the network reliability in a variety of scenarios. We adopt the multiband orthogonal frequency division multiplexing (MB-OFDM) UWB transmission scheme. The results are based on realistic UWB channels obtained from indoor measurements.

II. Signal model

The system under consideration consists of two or more cooperating users transmitting to a single destination, as shown in Fig. 1. Each receiving node estimates and maintains the instantaneous channel fading coefficients. Coherent detection with maximum ratio combining (MRC) is employed. The constituent narrowband channels of the OFDM UWB system between the nodes and from each node to the destination are mutually independent. The i^{th} node is allocated frequency band f_i, in which it transmits in two consecutive timeslots: one timeslot is used for its own data and the other for relaying its partner's data. In the n^{th} timeslot, node 1 transmits $b_1(n,k)$ on subcarrier k, and the received signal at node 2 is

$$y_2(n,k) = \sqrt{E_b/2}\; h_{12}(n,k)b_1(n,k) + w_2(n,k),$$

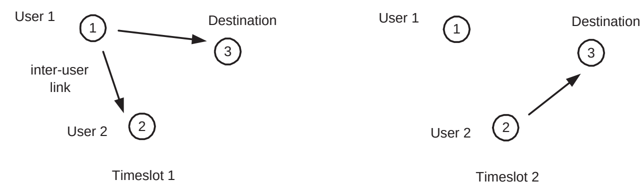

Fig. 1. System model for communication with two cooperating nodes.

where E_b is the energy per transmitted bit in the case of direct (non-cooperative) transmission, $b_1 \in \{\pm 1\}$ is the BPSK modulated information symbol with unit energy, $h_{ij}(n,k)$ captures the effect of pathloss and block fading on transmissions from node i to node j at time n and subcarrier k, and $w_j(n,k)$ models the additive white Gaussian noise at the receiver with variance N_0. Note that in the 2-node cooperation scheme, the energy available per bit for the cooperative scheme is half of that for the direct transmission scheme to maintain the total power consumption. Node 2 amplifies the received signal by the relay gain, α_2, and transmits $d_2(n+1,k) = \alpha_2 y_2(n,k)$ in the $(n+1)^{\text{th}}$ timeslot. During the two consecutive time frames, the destination, i.e., node 3, receives the signal

$$y_3(n,k) = \sqrt{E_b/2}\; h_{13}(n,k)b_1(n,k) + w_3(n,k)$$

in the n^{th} timeslot, and in the $(n+1)^{\text{th}}$ timeslot, we have

$$\begin{aligned} y_3(n+1,k) &= h_{23}(n,k)d_2(n+1,k) + w_3(n+1,k) \\ &= \sqrt{E_b/2}\; h_{12}(n,k)h_{23}(n+1,k)b_1(n,k) \\ &\quad + \alpha_2 h_{23}(n+1,k)w_2(n,k) + w_3(n+1,k). \end{aligned}$$

One choice is to amplify $y_2(n,k)$ to the node 2's transmit signal power level before relaying it to node 3, i.e., [2]

$$\alpha_2^2(n,k) = \frac{1}{h_{12}(n,k)^2 + 2N_0/E_b}. \quad (1)$$

Let us define the signal-to-noise ratio (SNR) between users i and j as $\rho_{ij} = |h_{ij}|^2 E_b/(2N_0)$, where $i \neq j$. After combining the received signals from the direct and the 2-hop paths for two consecutive timeslots using MRC, the SNR is

$$\rho_{MRC} = \rho_{13} + \frac{\rho_{12}\;\rho_{23}}{\rho_{12} + \rho_{23} + 1} = \rho_{13} + f(\rho_{12}, \rho_{23}),$$

where we have dropped the suffix (n,k) for notational simplicity. With BPSK modulation, the conditional probability of

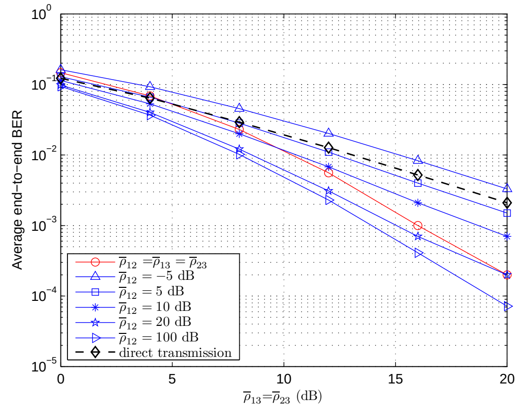

Fig. 2. Two-node cooperation with symmetrical user-destination channel configuration, $\overline{\rho}_{13} = \overline{\rho}_{23}$.

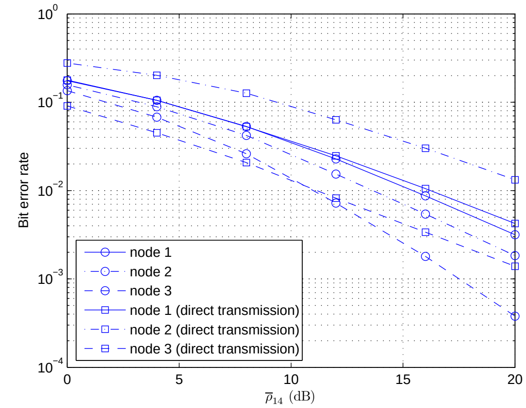

Fig. 3. Node BER performance for three-node cooperation with asymmetrical user-destination channels, $\overline{\rho}_{24} = \overline{\rho}_{14} - 5$ dB, $\overline{\rho}_{34} = \overline{\rho}_{14} + 5$ dB, and different inter-user SNRs, $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, $\overline{\rho}_{23} = 20$ dB.

error for the combined signal can be written as

$$P_e^{AF}(\rho_{MRC}) = \mathcal{Q}\left(\sqrt{2\left\{\rho_{13} + f(\rho_{12}, \rho_{23})\right\}}\right), \qquad (2)$$

where $\mathcal{Q}(.)$ denotes the Q function. It is straight forward to extend this approach to multiple-node cooperation scenarios.

Similarly, for direct (non-cooperative) transmission, the SNR is $\rho_{ij} = |h_{ij}(k)|^2 E_b/N_0$, and the error probability is

$$P_e^{NC}(\rho_{ij}) = \mathcal{Q}\left(\sqrt{2\rho_{ij}}\right). \qquad (3)$$

III. Simulation Results

We perform system simulations to evaluate the average BER of 2- and 3-user cases based on the measured indoor non-line-of-sight UWB channel in [5]. For these two cases, node 3 and node 4 refer to the destination, respectively.

Fig. 2 shows the 2-user cooperation scheme with symmetrical user-destination channels ($\overline{\rho}_{13} = \overline{\rho}_{23}$) and various values of the inter-user link SNRs, $\overline{\rho}_{12}$ where $\overline{\rho}_{ij}$ denotes the average SNR between nodes i and j. For the fully symmetrical case, i.e. when $\overline{\rho}_{12} = \overline{\rho}_{13} = \overline{\rho}_{23}$, the cooperative system achieves over 5 dB gain at $P_e = 10^{-3}$. The inter-user link quality determines the gain from cooperation. When the inter-user link is robust, such as when the users are closely located, cooperation improves the BER performance. At very low inter-user SNR, such as when the inter-user separation is much larger than the user-destination separation, cooperation actually performs worse than direct transmission.

The results for the 3-user case with highly asymmetrical user-destination links and inter-user links are shown in Fig. 3, where $\overline{\rho}_{34} = \overline{\rho}_{24} + 10$ dB $= \overline{\rho}_{14} + 5$ dB, and inter-user SNRs are $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, and $\overline{\rho}_{23} = 20$ dB. In this case the gains of cooperative transmission over direct transmission for user 1, 2, and 3 at $P_e = 10^{-2}$ are 1, 7, and -0.1 dB, respectively. Based on the total BER averaged across the three users, Fig. 4 shows that the cooperative scheme outperforms direct transmission by 4.5 dB at $P_e = 10^{-2}$. We conclude that although not all nodes benefit individually from cooperation, the overall network performance is improved significantly.

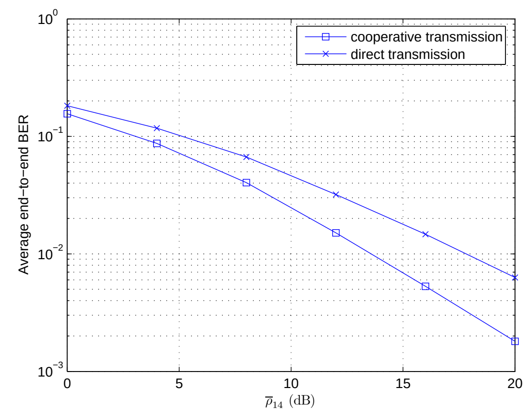

Fig. 4. Network BER performance for three-node cooperation with asymmetrical user-destination channels, $\overline{\rho}_{24} = \overline{\rho}_{14} - 5$ dB, $\overline{\rho}_{34} = \overline{\rho}_{14} + 5$ dB, and different inter-user SNRs, $\overline{\rho}_{12} = 5$ dB, $\overline{\rho}_{13} = 10$ dB, $\overline{\rho}_{23} = 20$ dB.

IV. Conclusion

This paper has analyzed the BER performance of UWB networks with cooperative diversity. We have shown with channel measurements that user cooperation leads to improved performance under some typical network configurations. Our results establish that cooperative diversity can be as beneficial for UWB networks as for conventional narrowband networks.

References

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