Layered Multiplexed-Coded Relaying: Design and Experimental Evaluation

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***Abstract*—We consider layered DF cooperation in a relay-aided wireless multicast network. Spliting the source-message into two equal layers, we provide unequal power allocation to the individual layers through a simple mapping operation on a QAM constellation. The layering process thus allows the destinations to partially recover the message from the source's transmissions. At the relay, we propose a multiplexed-coded approach that, with a single transmission, caters for the disparity in the number of layers decoded at different destinations. In addition to simulations, we validate the performance gains of the proposed strategy through a system-level implementation using software-defined radios. Catering for real-world factors such as carrier and timing synchronization, we conduct over-the-air experiments in an indoor office environment and find that the proposed scheme can achieve a frame-error-rate that is 25% of that with conventional two-hop DF relaying.**

I. Introduction

Relaying in wireless networks can improve throughput, increase coverage, and provide better quality-of-service (QoS) [1]. The most popular of relaying strategies is the two-hop decode-and-forward (DF) approach in which the transmission is split into two orthogonal time-slots of equal duration. During the first-time slot, the source transmits to the relay. The relay decodes, and forwards the message to the destination in the second time-slot. The destination then attempts to recover the source message solely from the relay's transmissions. An alternate strategy, which we will refer to as joint DF, is for the destination to perform joint decoding on the signal received from the relay and the source. Using information theoretic analysis, this approach can be shown to always outperform two-hop DF. However, its widespread adoption is hampered by issues such as the need for perfect channel estimates, increased computational complexity, as well as large memory requirements at the destination for storing the signal received during the first time-slot. As a result, two-hop DF relaying has received larger traction among standardization bodies. For example, two-hop DF relaying has been proposed in IEEE 802.16m [2] as well as LTE-Advanced [3] as a means of increasing coverage and/or improving QoS.

In this paper, we propose a layered multiplexed-coded DF (LMDF) scheme that has a significantly improved performance over that of two-hop DF, without incurring the practical issues associated with joint DF. At the source, LMDF splits the source message into two equal layers. Encoding them individually with identical convolutional codes, we achieve unequal error protection (UEP) through superposition with unequal power allocation. Targeting a multicast environment with a single relay, the layering allows some of the destinations to recover a portion of the source message using the signal received during the first time-slot. This is opposed to the conventional unlayered approach which only allows an all-or-nothing decoding. It is important to point out that the use of superposition for relaying has been explored in several existing works. However, almost all these works have a theoretical exposition, focusing on the optimization of power and rate allocation while assuming global channel state information. For instance, [4] investigates superposition coding with optimal power and rate allocations for relaying to increase diversity and decrease the outage probability while the work in [5] targets spectral efficiency through superposition coding relaying based on known channel state information. On the other hand, the work in [6] focuses on minimizing expected distortion with efficient relaying through superposition coding of layers at the source node and successive decoding at the destination. As opposed to most of the existing literature on layered superposition-coded communications, we do not delve into the theoretical intricacies. Instead, we utilize a simple, yet an effective system-level approach in which superposition is achieved by a mapping operation of the two coded layers to appropriate bit-planes of quadrature amplitude modulation (QAM) transmission; a process we refer to as superposition mapping (SM).

At the relay, LMDF employs multiplexed coding [7] of the two decoded layers. Without requiring any feedback from the destination, multiplexed coding allows all relay-to-destination channel resources to be utilized for decoding of the layer that the destination had not been able to recover in the first time-slot. This is particularly attractive in a multicast environment in which the relay, with a single transmission, can simultaneously service multiple destinations, each having previously decoded varying amounts of data from the source. At the same time, given that the relay has decoded both layers, the performance of LMDF is no worse than that of conventional two-hop DF relaying. We implement the multiplexed-coded approach using an off-the-shelf convolutional code. At the destinations, simple hard-decision Viterbi decoding rules are employed for decoding of the multiplexed codebook. The closest that any existing work comes to the proposed LMDF scheme is the so-called network modulation strategy of [8], in which a software mapping scheme for achieving UEP was developed for QAM constellations. However, the strategy in [8] requires channel feedback from participating nodes, based on which a constellation is chosen to service only *one* particular user. On the other hand, LMDF is capable of simultaneously servicing many diverse destinations *without* requiring global CSI.

In addition to evaluating performance results of LMDF through simulations, we go a step further and carry out a system-level implementation of LMDF using software-defined radios (SDR). Catering for real-world issues such as carrier and timing offsets, we conduct over-the-air experiments in an indoor office environment with two destinations. Experimental results indicate that LMDF can achieve a frame-error-rate (FER) that is 25% of that with two-hop DF relaying. Although experimental prototyping of relaying has been carried out before [9], [10]to the best of our knowledge, this work is the first in the literature to experimentally evaluate the benefit of layering in a cooperative multicast environment.

The remainder of this paper is organized as follows. In Section- II, we provide a general overview of the proposed LMDF scheme and the principles on which it is based. Based on these principles, a system-level implementation using off-the-shelf convolutional codes is described in Section- III. Experimental results are described in Section- IV, while Section- V concludes the paper.

II. The Layered Multiplexed-Coded DF Scheme

We consider a wireless multicast network consisting of a single source wishing to send the same message to multiple destinations. The transmissions are aided with the help of a single relay. The cooperation takes place over two orthogonal time-slots of equal duration. During the first time-slot, only the source transmits, while during the second time-slot, only the relay transmits. In the following subsections, we separately describe the encoding/decoding operations of the proposed scheme at the source, the relay, and the destinations.

A. Layering at the Source through Superposition Mapping

Layering at the source can be accomplished by splitting the message sequence into multiple layers and encoding them with independent error correction codes. In this paper, we restrict our attention to a bi-layer strategy in which the message $\mathbf{m}$ of length k is split into two portions $\mathbf{m}_1$ and $\mathbf{m}_2$ of lengths k_1 and k_2, respectively, as shown in Fig. 2. The layers are then encoded with binary error correction codes of rates $\frac{k_1}{n}$ and $\frac{k_2}{n}$, each generating length-n coded binary sequences $\mathbf{c}_1$ and $\mathbf{c}_2$, respectively. The coded sequences are then mapped to unit-energy constellations of complex symbols X_{s1} and X_{s2}. The transmitted symbol is obtained after superposing the two coded symbols with different power allocations with the transmitted symbol X_s obtained as

$$X_s = \sqrt{\alpha P} X_{s1} + \sqrt{(1-\alpha)P} X_{s2}, \tag{1}$$

where $0 \leq \alpha \leq 1$ is the fraction of the overall transmitted power P allocated for $\mathbf{m}_1$. The purpose of layering is to provide UEP to the two layers such that the probability of the destination recovering one of the two layers is higher than the probability of recovering the entire message $\mathbf{m}$ had unlayered coding been deployed. We observe that the UEP is induced because of two factors: the unequal coding rate, and the unequal power allocation. For LMDF, we exploit only the disparate power allocations between the two layers and force their code rates to be the same. Thus, we split the message $\mathbf{m}$ into two equal parts, and encode them with an identical encoder. With X_{s1} and X_{s2} drawn from a 4-QAM constellation, we use SM to induce superposition with unequal power allocation through a simple mapping operation of the coded sequences $\mathbf{c}_1$ and $\mathbf{c}_2$ to a higher-order QAM constellation. More specifically, we observe that an M-QAM constellation of power P with $M = 4^k$ can be obtained as a superposition of k 4-QAM constellations. Any symbol X on the M-QAM constellation can be written as

$$X = \sqrt{\frac{3P}{2^{2k}-1}} \sum_{i=1}^{k} 2^{i-1} X_i, \tag{2}$$

where $X_1, \ldots, X_k$ are symbols drawn from 4-QAM constellations. For instance, a 16-QAM constellation is composed of a superposition of two 4-QAM constellations in which the 4-QAM constellation corresponding to the most-significant bits (MSBs) has twice the amplitude (with natural bit-mapping) of the one corresponding to the least significant bits (LSBs). Thus, mapping $\mathbf{c}_1$ to the LSBs and $\mathbf{c}_2$ to the MSBs would induce the superposition operation of (1) with $\alpha = \frac{1}{5}$. The concept can also be generalized to mapping of two 4-QAM layers to the $k \geq 2$ of an $M = 4^k$-QAM constellation. Under the assumption that the 16 constellation points obtained after the mapping maintain the same symmetry around the real and the imaginary axis, it can be shown that the mapping allows the flexibility to achieve superposition with any $\alpha \in \mathcal{A}$, where

$$\mathcal{A} = \left\{ \frac{2^{2i}}{2^{2i} + \left(\sum_{\substack{j=0 \\ j \neq i}}^{k-1} b_j 2^j \right)^2} \;\middle|\; b_j = \pm 1, i, j = 0, \ldots, k-1 \right\}$$

An illustration of this is shown in Fig. 1, in which the two layers choose, through SM, 16 symbols of a 64-QAM constellation such that the resultant symbols are the superposition of two 4-QAM constellations. The amplitude of one of the constellations is six times that of the other, thus achieving $\alpha = \frac{1}{37}$. It is important to note that an even greater flexibility can be achieved if we relax the constraint of the symmetry around the real and imaginary axis being the same. Moreover, a similar methodology can be utilized to induce superposition of more than two layers as well.

B. Multiplexed Coding at Relay

The relay must decode the superposed layers of the source for onward forwarding to the destination. Optimal decoding of the two layers can be achieved through a joint decoding operation, and under same cases through a multi-stage decoder that employs successive interference cancellation [11]. However,

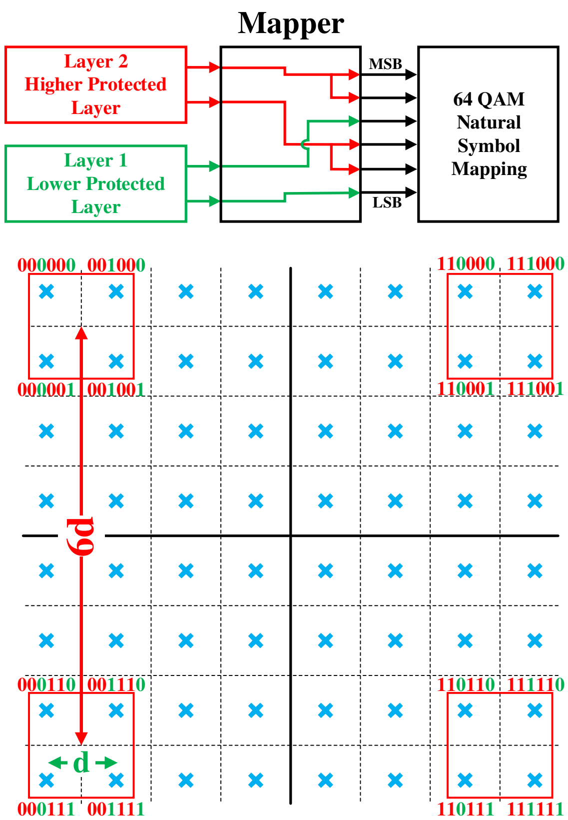

Fig. 1. An illustration of how appropriate symbol mapping of two layers to a 64-QAM constellation induces superposition of two 4-QAM constellations with unequal power allocation.

keeping low computational complexity to be of paramount importance, we use a suboptimum but a simple decoding approach. The approach relies on parallel recovery of both layers, as shown in Fig. 3. The case where the relay is able to decode only one of the two layers is not of great interest. This is because the source-destination channel is typically considered to be weaker than the source-relay link. As a result, if the relay is unable to recover a layer, as indicated by a cyclic redundancy check (CRC), the destination would have been unable to do so as well because of which cooperation will be of no benefit. Thus, we will describe only the case where the relay has been able to recover both layers successfully.

The most straight-forward approach is for the relay to re-encode the decoded layers and transmit them using superposition coding. However, we note that because of the layering operation, it is possible for the destination to have recovered one of the two layers. In such a situation, the power that the relay allocates in transmitting the layer already decoded at the destination goes to waste. Had feedback from the destination been available at the relay (as is assumed in [8]), the relay would have dedicated all its transmission energy in transmitting the other layer. With the proposed LMDF scheme, we harness the power of multiplexed coding [7] to achieve the functionality of having all transmission power dedicated to the destination's un-decoded layer *without* requiring any feedback. Multiplexed codebooks can be considered as two-dimensional tables with the rows indexed by one of the layers, and the columns by the other. Given the two layers, multiplexed coding outputs the codeword selected by the given row and column index. If the destination has not been able to decode any layer from the source's transmission, it searches the two-dimensional codebook for the appropriate codeword. If Y_{d2} is the baseband signal received at a destination, information theoretic analysis dictates that successful decoding is achievable if the coding rate R at the relay satisfies

$$R < I\left(X_r; Y_{d2}\right) \tag{3}$$

On the other hand, if the destination had been able to decode one of the layers, it searches for potential codewords *only* in the row or the column indexed by the layer already decoded. Thus, prior knowledge of one of the layer reduces the search space, thus aiding decoding of the other layer. It can be shown that with prior knowledge of layer-2 [7], multiplexed coding can allow successful decoding of layer-1 if its coding rate $R_1 = \frac{R}{2}$ (for the case of equal-length layers) satisfies

$$R_1 < I\left(X_r; Y_{d2}\right). \tag{4}$$

In other words, multiplexed coding will induce all resources on the relay-destination link to be allocated to layer-1 without the relay ever knowing that the destination had already decoded layer-2. The biggest advantage of the proposed approach is in a multicast setting. Given the heterogenous channel conditions, the destinations could have recovered a disparate number of layers during the first time-slot. What is needed in this scenario is a universal transmission from the relay that not only services (without any coding loss) those destinations that have no prior knowledge of any layer, but also those that were able to recover one of the two layers. Multiplexed coding achieves this objective perfectly.

C. Decoding at the Destinations

Destinations in the first time-slot attempt to decode the source message using the same parallel decoder as that employed at the relay. If one of the two layers is recovered successfully, the destination stores the recovered binary information sequence for subsequent processing in the next time-slot. On the other hand, it discards all receive/decoding information corresponding to the other layer. We point out that compared to joint DF that requires the destination to store all *complex* symbols received during the first time-slot, LMDF requries the destination to store only *binary* data. As a result, the proposed LMDF scheme possesses significantly smaller memory requirements than joint DF. Having received symbols from the relay during the second time-slot, the destination uses the decoded layers' information to collapse the relay's multiplexed codebook to a one-dimensional code and uses it to decode the second layer. If on the other hand the destination was unable to recover any layer in the first time-slot, it attempts to decode both layers by running decoding over the relay's two-dimensional codebook.

III. System-level implementation of LMDF

In addition to verifying the performance gains of LMDF through simulations, our goal in this paper is also to carry out its prototype implementation using SDRs and verify its superiority through over-the-air experiments. While not discounting the importance of simulations, the purpose of this prototyping is to experimentally demonstrate that the proposed LMDF strategy can significantly outperform conventional two-hop DF in real radio environments without relying on simplistic models or assumptions that are typically employed in simulations. Thus, in order to carry out the system-level implementation, we must cater for imperfections in real-world RF equipment such as carrier and timing offsets. In the following subsections, we first describe the packetization process as well as details of the baseline modem that caters for these system-level issues. We then describe a simple implementation of the LMDF scheme using off-the-shelf convolutional codes.

A. Packetization and Baseline Modem

For the system-level implementation, we utilize packetized transmissions. Each packet is preceded by two concatenated 13-bit Barker code sequences $(1,1,1,1,1,0,0,1,1,0,1,0,1)$ with each bit mapped to the diagonal points of a 4-QAM constellation. This preamble sequence is utilized at the receiver for frame synchronization, phase ambiguity resolution, as well as gain control to normalize the effect of channel attenuation. The frame size for the source's message is chosen to be 128 bytes. The message is split into two equal layers along with addition of an 8-bit CRC to each layer, which is then followed by convolutional encoding. The two codeword sequence are each fed into inter-layer pseudo random interleavers, followed by the SM operation so as to induce superposition with unequal power allocation. The resulting symbols are appended alongside the preamble symbols to form a sequence of symbols belonging to one packet. For the case of single-layer transmission (as that from the relay), the coded bit-streams after interleaving, ismapped to an M-QAM constellation in a conventional manner.

The packetized symbols are modulated with a discrete-time pulse-shaping interpolation filter. We focus on narrow-band single carrier modulation, for which we use a root-raised cosine (RRC) filter operating at four samples per symbol and a roll-off factor of 0.5. The discrete-time output of the pulse shaping filter is passed to the SDR for carrier modulation and onward transmission over the air. At the receiver, the complex baseband symbols, as provided by the SDR, are passed through a RRC filter operating at two samples per symbol. The first step we implement is that of frame synchronization, in which we use an autocorrelation based approach to detect the start-of-packet. The known preamble sequence is then used to estimate the channel attenuation, the effect of which is then normalized. For carrier frequency and phase offset compensation, we utilize a phase-locked loop operating at two samples per symbol. For symbol-level timing synchronization, we employ a zero-crossing timing error detector along with a parabolic interpolator [12]. The output of these synchronization blocks is then fed into a symbol-to-bit de-mapper. For the layered demodulator, this de-mapper simply inverts the SM operation to produce two bit-streams, one for each layer.

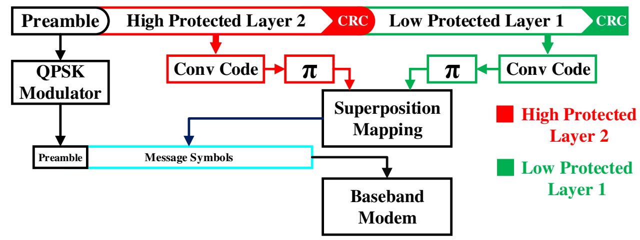

Fig. 2. Block diagram of the operations at the source.

B. LMDF coding using convolutional codes

The overall block diagram of the layered coding at the source is shown in Fig. 2. For error-correction of both layers at the source, we utilize identical off-the-shelf rate-R_s convolutional codes. The encoded bit-streams are packetized and transmitted over the air using the baseline modulator described in the preceding subsection. The block diagram of the relay's processing is shown in Fig. 3, in which a baseline demodulator with SM demapping is employed to produce two bit-streams, each one of which is fed into a hard-decision Viterbi decoder. The destination employs the same decoding structure during the first time-slot, and stores the binary information sequence of the layer it is able to successfully recover. When the relay successfully recovers information sequences of both layers, it encodes the two layers using multiplexed coding. For the purpose, we utilize an off-the-shelf rate-R_r convolutional code. The information bit-sequences corresponding to the two layers are interleaved with the layer-1 and layer-2 bits placed at odd and even indices, respectively. The length-k interleaved sequence is then encoded with the rate-R_r convolutional code. The resulting codeword sequence is interleaved and mapped to an M_r-ary QAM constellation before passing it to the baseline modulator. At the destination, the bit-sequence output from the base-line demodulator is passed to the decoder. In case the destination was unable to recover any layer during the first-time slot, it applies conventional hard-decision Viterbi decoding. This situation corresponds to the information theoretical constraint of (3), which can be practically interpreted as the decoder achieving success if the SNR on the relay-

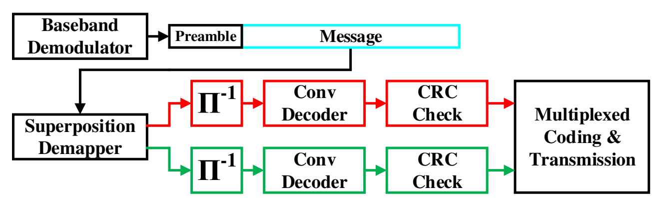

Fig. 3. Block diagram of the operations at the relay.

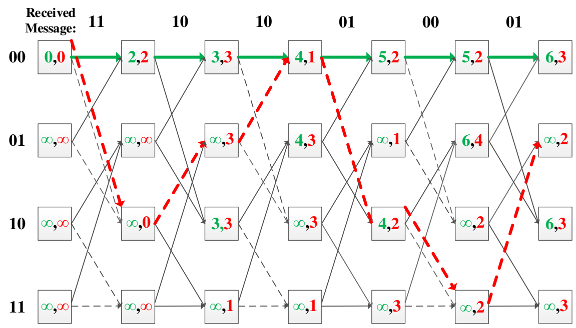

Fig. 4. An illustration of how the received erroneous sequence is correctly decoded to the all-zero codeword assuming prior knowledge of layer-2; incorrectly otherwise.

destination link is higher than the decoding threshold of the rate-R_r convolutional code. On the other hand, the even-odd interleaving inherently induces the multiplexed coded nature. The set of 2^k codeword sequences of the code can indeed by rearranged to form a two-dimensional table of $2^{k/2}$ rows and columns, with the rows and columns being indexed by the layer-2 and layer-1 information sequence, respectively. For a fixed layer-2 information sequence, the corresponding row forms a rate-$\frac{R_r}{2}$ code which can be used to decode layer-1 with prior knowledge of layer-2. This corresponds to the information theoretic constraint of (4), which implies that successful decoding of layer-1 will be achieved if the SNR on the relay-destination link is higher than the decoding threshold of the induced rate-$\frac{R_r}{2}$ code; under a good code design, the threshold for this code will be smaller than that of the original rate-R_r code. For efficient decoding on this induced code, we modify the hard-decision Viterbi algorithm to use layer-2 information to aid in layer-1 decoding. In particular, at the even time indices of the trellis, we include only those edges in the metric calculation that correspond to the decoded layer-2 sequence and eliminate all others. Since the convolutional code has memory, the codeword bits at the even time indices still convey some parity-check information about the message bits lying at odd indices, thus aiding the decoding process. This is illustrated in Fig. 4 that shows the decoding process for a received (erroneous) codeword sequence $\{11\ 10\ 10\ 01\ 00\ 01\}$ when the all-zero sequence was transmitted. The thick dashed red curve shows the decoded path without prior knowledge of layer-2, thus resulting in an incorrect decoded sequence. On the other hand, with the same received sequence, decoding with prior knowledge of the layer-2 sequence is indicated by the green path. The edges eliminated due to the prior knowledge of layer-2 are shown as thin black dashed lines at even time indices. We observe that prior knowledge of layer-2 results in correct decoding of layer-1, thus indicating that the decoding threshold of the induced code is indeed smaller than that of the original.

IV. Performance Evaluation

For the prototype implementation, we encode the two layers with an identical rate-$\frac{1}{2}$ convolutional code specified by the polynomials $G_1(D) = 1 + D^2 + D^3$, and $G_2(D) = 1 + D + D^2 + D^3$. For SM, we utilize the constellation and the mapping shown in Fig. 1. For multiplexed coding at the relay, the information sequence is coded with a rate-$R = \frac{1}{2}$ convolutional code that is identical to the ones being used at the source. The multiplexed coded bit-stream is then mapped to an M_r = 16-QAM constellation, thus ensuring that an equal number of symbols are transmitted in the two time-slots. Before experimenting with over-the-air transmissions, we verify the benefit of LMDF over conventional two-hop DF using a simple additive white Gaussian noise (AWGN) channel model. Considering the source-relay channel to be strong enough for the relay to decode both layers with a probability approaching one, we evaluate in Fig. 5 the FER at the destination as a function of the source-destination signal-to-noise ratio (SNR) when the SNR on the relay-destination link is 3 dB higher. In order to estimate the effect of imperfect timing and carrier synchronization, we also include the FER curves for an AWGN channel with these offsets. The FER curves are indicative of the performance of the base-line modem that uses PLL-based methods for synchronization, as described in Section III-A. We observe that at a FER of 2%, LMDF in a simple AWGN setting provides more than 1 dB gain in performance. In addition, with practical synchronization algorithms, the loss in SNR is also approximately 1 dB.

A. Experimental Setup and Evaluation

For experimental prototyping and performance evaluation, we utilize the USRP 2921 from National Instruments [13] interfaced with Mathworks Simulink which performs all base-band processing described in Section III. All transmissions from the source as well as the relay nodes use a sampling frequency of 10^6 samples per second. With four samples per

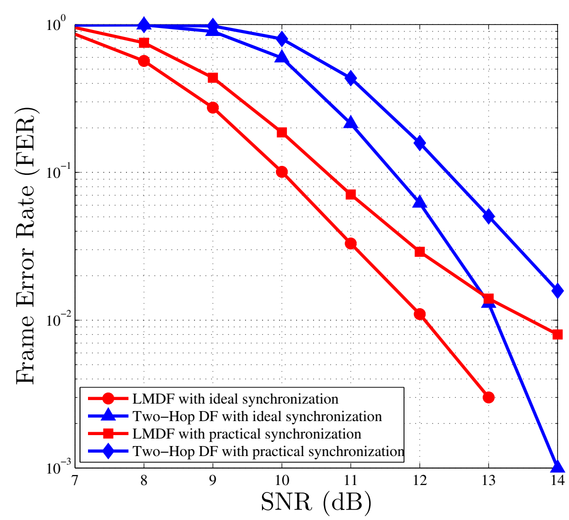

Fig. 5. Simulated FER of LMDF versus two-hop DF as a function of source-destination SNR under an AWGN model. The relay-destination SNR is assumed to be 3 dB higher; the source-relay SNR is assumed to be very high so as to allow recovery of both layers at the relay.

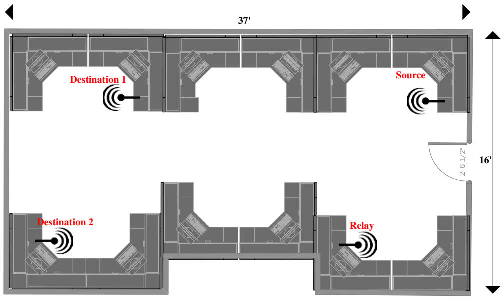

Fig. 6. Floorplan for the indoor office environment.

symbol, this corresponds to a narrowband symbol rate of 250×10^3 symbols per second. For performance evaluation in a multicast setting, we use a total of four USRP modules; the source, relay, and two destinations. We conduct over-the-air experiments in an indoor office environment, the floorplan of which is shown in Fig. 6. The source and the relay were placed in line-of-sight (LOS) separated by approximately 13 feet. On the other hand, the Destination 1 and 2 are each placed in a non-line-of-sight (NLOS) configuration from the source with distances of approximately 23 and 33 feet, respectively. At the same time, the destinations are in NLOS of the relay as well, with the distaces of 14 and 23 feet, respectively. In Fig. 7, we compare the FER performance of the proposed LMDF scheme versus that of conventional two-hop DF. The curves indicate the average FER across the two users as a function of the USRP transmit gain, which is kept the same at both the source and the relay. It is important to note that when computing the FER, we also account for events where the relay has not been able to decode both layers. At the same time, a frame-error event is also recorded in cases where the relay and/or the destinations were not able to detect a valid packet header. We observe that the proposed strategy, under real-world experiments, significantly outperforms conventional two-hop DF. In particular, at a USRP transmission gain of 10 dB, LMDF achieves an FER that is smaller than 25% of the FER of two-hop DF.

V. Conclusion

In this paper, we propose LMDF that achieves significant performance gains over conventional two-hop DF without incurring the computational costs typically associated with joint DF. The scheme relies on layering at the source achieved through a simple mapping operation on a high-order QAM constellation. A key component of the strategy is multiplexed coding at the relay that allows all relay-to-destination channel resources to be allocated to the layer not already recovered at the destination. We develop a system-level implementation of the proposed strategy using off-the-shelf convolutional codes and experimentally verify its performance benefit using SDRs.

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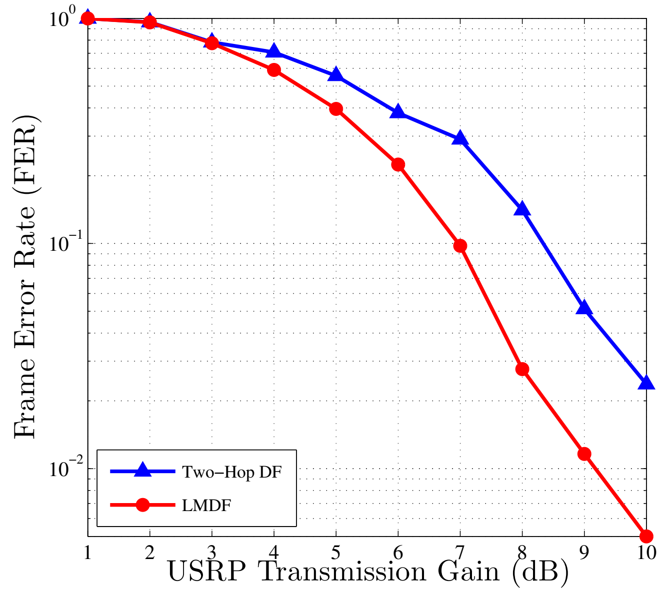

Fig. 7. Comparison of experimental FER results of LMDF and two-hop DF versus the USRP transmission gain (kept the same at the relay and the source). The receive gain at the relay and the destinations is kept constant at 15 dB.

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