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Poster Paper

Implementation and Testing of Co-Operative Schemes on a Real-Time DSP-Based Testbed

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Abstract: Experimental and simulation results on well-known co-operating relaying schemes such as: amplify-and-forward (AF), detect-and-forward (DF), co-operative maximum-ratio combining (CMRC), and distributed space-time coding (DSTC) are presented in this paper. A novel relaying scheme named "selection relaying" (SR), in which one of two relays are selected base on path-loss, is also tested.
We also implement the modes "Selective" and "Antenna Diversity". The "Selective" option is designed to avoid forwarding of erroneous frames.
In our measurements, all co-operative relaying schemes above increase the coverage area as compared with direct transmission. The features "Antenna diversity" and "Selective" improve the performance. Good performance is obtained with CMRC, DSTC and SR.

1. Introduction

Co-operative relaying has been a hot-topic in theoretical research for a long time while experimental results are scarce. Implementation challenges occur with respect to synchronisation in time and frequency. In theoretical studies such issues are generally overlooked while they play an important role in real-world implementations. Propagation conditions also play a role. In most theoretical papers path-loss and shadowing is not taken into account and all channels are assumed to be Rayleigh fading only - with the same mean SNR between every two nodes. In this paper we address these issues by an implementation exercise on a DSP-platform combined with measurements in an office environment. We compare these results with simulations of our schemes. Applications of the techniques presented herein include coverage extension of cellular base-stations in indoor as well as outdoor scenarios and co-operation among satellites. Previous implementation results include [1] where the authors implement a cooperative coding scheme ([2]). In the paper the proposed scheme is compared with a traditional non-cooperative one while transmitting frames of a video clip. From the experiments, they observed that cooperation increases the quality of the video clip.
In this paper we implement classical co-operative schemes such as amplify-and-forward (AF), decode-and-forward (DF), co-operative maximum-ratio combining (CMRC) and

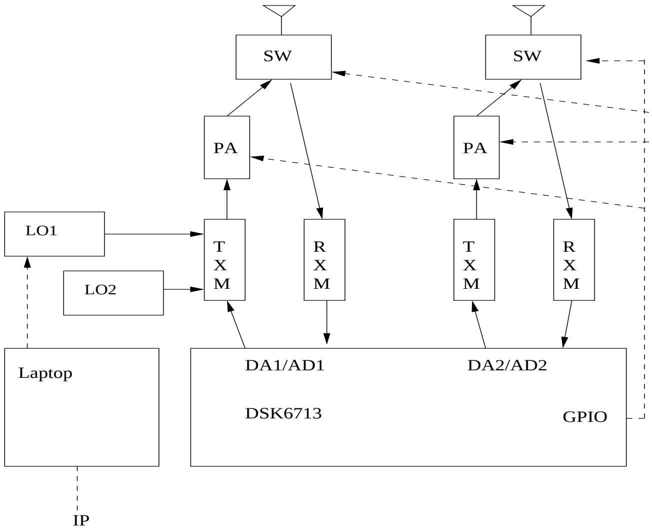

Figure 1: Schematic of a node. The acronyms are: RF-switch (SW), power amplifier (PA), transmitter module (TXM), receiver module (RXM) and general purpose input/output (GPIO).

distributed-space-time coding (DSTC) using Alamouti coding. In addition we implement a novel scheme called "selection relaying" (SR). For benchmark purposes we also include direct transmission (i.e. no relaying). The schemes AF, DF and CMRC involve three nodes: source, relay and destination while DSTC and SR involves four nodes: source, two relays and destination. The level of innovation of the paper is that of demonstrating practical results of existing and novel relaying schemes. The expected impact is an increased understanding of practical issues among researchers working on relaying.

2. The Implementations

The testbed is described in detail in the report [3] and therefore we will only summarise its features. The testbed has four nodes which are general-purpose i.e. they can act as source, relays and destination on demand. The nodes have two transmitters and two receiver chains. Time division duplex is used and thus either the transmitter or receiver chain is connected to the antenna, see Figure 1. More details can found in the report [3].

The symbol- and sample-rate used are 9600Hz and 48kHz, respectively. The power level used for transmitting payload data is -20dBm. This results in a transmitted power spectral density of -30dbm/kHz. This is comparable to what can be expected to be the case in future wireless LAN-type applications which may use 20dBm transmit power over a 100MHz bandwidth, [4], which also gives -30dBm/kHz power spectral density.

The system is synchronised by the following procedure. One of the nodes, usually the source, sends a synchronisation sequence. The other nodes detect it and adjust their frame time and frequency offset, accordingly. The synchronization offset error that remains after the aforementioned procedure is up to one sample and it is treated separately by each scheme described in the following sections.

Scheme	A	S
Direct	Yes	No
AF	No	No
DF	Yes	Yes
CMRC	Yes	No
DSTC	Yes	Yes
SR	Yes	No

Table 1: Availability of "Antenna Diversity" and "Selectivity" modes in the implemented schemes

The transmissions and receptions of the nodes are frame-based. For example, the frame structure for the case of AF and DF is shown in Fig. 2. In general, the payload frames consist of 48 quadrature pulse shift keying (QPSK) symbols (TX for transmit and RX for receive) which are a combination of uncoded and training symbols. The training ones are used mainly for channel estimation, synchronization and, depending on the scheme, signal to noise ratio (SNR) estimation and signal integrity checks. There are also idle frames during which processing of received signals occurs. The frames labeled as "6" are also idle and are inserted for testbed-related reasons.
The destination for all schemes, except DSTC, employs maximum ratio combining (MRC) for combining the signal received by the source and the relays and then performs detection based on the maximum likelihood criterion.
We have introduced two modes of operation. Specifically, in the first one, the receiving nodes (i.e. relays and destination) can use either one or two antennas. This feature is called "Antenna Diversity" and is denoted as "A". When two antennas are used, MRC is employed. The second mode is called "Selectivity" and is denoted as "S". In this case, the relays perform an integrity check in their received signal from the source using an estimate of the SNR. If the value is lower than a threshold then the relay does not transmit anything to the destination. This mode is used mainly for avoiding forwarding errors to the destination by the relays. Table 1 shows in which schemes the two modes are available.
In the following, a brief description of the implemented schemes is provided about the frame structure and treatment of the offset error.

2.1 Amplify-and-forward, Detect-and-forward and Cooperative Maximum Ratio Combing

The AF scheme uses three nodes, a source, a relay and a destination. The frame structure of the transmissions and receptions performed by them is shown in Fig. 2. Initially, in *Phase 1*, the source sends two frames to the relay and the destination, respectively. The relay processes the signal by scaling the sample amplitudes in order to be consistent with the maximum allowable amplitude of the transmitter. Then, in *Phase 2*, the relay uses the next two TX48 frames to send the data to the destination.
The frame structure of the DF scheme is similar to AF. The difference is that the relay does not scale the received signal, instead it performs detection in an attempt to reconstruct the source data. In this case, depending on the quality of the source-relay channel, detection errors might occur.
The CMRC scheme [5] was proposed as a suboptimum but efficient way to take into consideration the possible errors in the relay. The frame structure of CMRC is similar

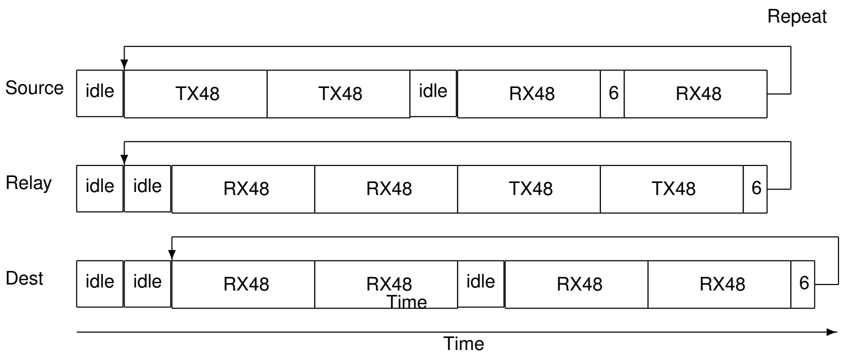

Figure 2: Frame structure of AF and DF schemes.

to DF apart from the existence of an intermediate phase during which the relay sends to the destination an estimated value of the SNR related to the source-relay channel. This enables the destination to (partially) compensate for erroneous decisions made by the relay.

Finally, concerning the way that the synchronization error is treated, is similar to all aforementioned schemes. To be more specific, before transmitting the useful data, a synchronisation phase is executed where the source first sends a frame with training symbols only to the relay and destination. Those are used to estimate the best sampling phase of the source signal. The relay, after receiving the training signal from the source, sends a training signal so that the destination can be synchronised as well. Twelve symbols are used to achieve the synchronisation.

2.2 Distributed space-time coding

The DSTC scheme uses a source, two relays and a destination. The frame structure of the transmissions and receptions of the four nodes is identical to the AF one (Fig. 2) except that a second relay is added. The processing at the relays is similar to the DF scheme. However, in this case, the relays transmit simultaneous at *Phase 2* employing the Alamouti coding where each relay plays the role of one antenna in the conventional Alamouti scheme [6].

By following the synchronization procedure that was described in the previous section, a single offset at the destination might not fit for both relays since they transmit simultaneously in the second phase. Therefore, in the case of DSTC, the adjustment of the timing, which is made at the relays, is calculated in the destination. Then, it is fed back to the relays in a special frame.

2.3 Selection Relaying

In this scheme, the source sends information to the destination using two relays. There are three phases in this frame structure. In the first phase, the source broadcasts its data to the other nodes. Each relay, apart from detecting the received signal, calculates an average signal to noise ratio ($ASNR_i$, $i = 1, 2$) which is related to the corresponding source-relay channel. In the second phase, the best relay is selected. Specifically, each relay sends its estimated $ASNR_i$ value to the destination. The destination based on the received signals, also, calculates two new SNR_i ($i = 1, 2$) values corresponding to relay-destination channels. Using this information, the destination decides which relay has a better overall source-relay-destination channel and informs the relays about which is going to be active in the third phase. The decision is based on the rule

$$i_{best} = arg \max_{i=\{1,2\}} \{ \min\{ASNR_i, SNR_i\}\}. \tag{1}$$

In the third phase, the selected relay retransmits the information detected in the first phase. The destination, then, combines the received signal with the one from the first phase using MRC and performs the final detection of the transmitted data.

The relay usage, in this scheme, is reduced by 50% compared with DSTC as only one relay out of two is chosen. The idea behind the scheme is that channel variations are composed of short-term variations, due to Doppler fading, and long-term variations, due to obstacles between the nodes e.g., walls. With the proposed scheme we should be able to select the best relay when the difference in channel conditions between the two relays is large due to the long-term properties, even though time delays may somewhat alter the propagation conditions between the moment of selection and usage.

3. Measurement Results

A measurement campaign was conducted in an indoor office environment (Fig. 3). In order to be able to compare all five schemes and the direct one with different modes, a measurement procedure consisting of "measurement runs" was developed. Within each measurement run twenty-four different configurations were run in sequence (i.e. four combinations of modes for each of the six schemes), some of which are identical because not all modes are available to all schemes (Table 1). Each measurement run was conducted under stationary conditions meaning that there were no people moving between the nodes and the nodes were standing still. This is not a requirement for the schemes to work - but this makes it more likely that the schemes see the same propagation channels. The fact that some configurations in one measurement run are identical can be used to verify the similarity of the channel conditions under which the different configurations are tested. A total of 47 measurement runs were conducted. The positions of the two relays and the destination were changed between every run.

Each scheme transmitted ten payload frames of 48 symbols. The channel estimates obtained during these frames were saved and made available for post-processing. We also calculated the bit error rate (BER) and the number of clock-cycles used by the DSPs. Relay 2 generally has a better channel to the source while relay 1 has better channel to the destination. The worst channel is that between the source and the destination. Finally, the SNRs are very low which represents challenging conditions.

The most straightforward way of comparing the different schemes is to look at the bit error rate statistics over the 47 measurement runs. In Table 5, we show the "outage probability" i.e. the probability that a received frame has one or several bit errors. Table 3 shows the corresponding results when we allow 5% bit errors. Here, we point out that the scenario we are interested in is for uncoded data.

The last four columns of the table are related to the four combinations of the antenna diversity and selectivity modes. The parentheses next to some of the outage probability values indicate if a mode is actually present to this specific configuration of the scheme.

In order to make a fair comparison of the direct scheme, which has a duty-cycle of about two times that of the other schemes, we assume that the direct scheme repeats every frame two times and that the receiver is able to determine which of the two copies of

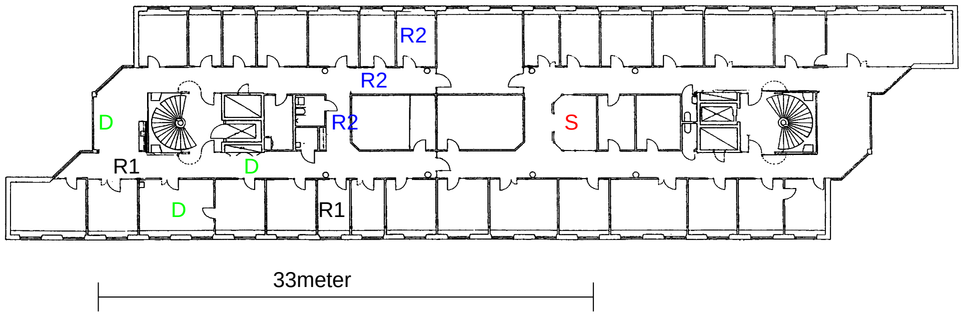

Figure 3: Some of the positions of the nodes used during the measurements. S=source, R1=relay 1, R2=relay 2, D=destination

Scheme	**(Antenna Diversity, Selectivity)**			
	(Off,Off)	(On,Off)	(Off,On)	(On,On)
Direct	70	62 (A)	71	64 (A)
AF	57	56	57	57
DF	61	52 (A)	54 (S)	49 (A,S)
CMRC	53	42 (A)	52	43 (A)
DSTC	53	34 (A)	38 (S)	26 (A,S)
SR	34	23 (A)	36	26 (A)

Table 2: Outage probability: The percentage of frames with one bit error or more. The notations (A), (S), (A,S) indicate when the corresponding configuration is actually present in the scheme (according to Table 1)

the same frame has the least number of bit errors (this reduces outage probability from 74% to 70%).
As already mentioned, some of the configurations are actually identical. For instance, the second row of Table 5 shows the results for AF repeated four times. The difference between multiple values for the same configuration are in the range 0-3%. This shows that the relative comparisons between the different configurations based on Table 5 are meaningful. We may immediately conclude that the features "Selective" and "Antenna Diversity" consistently improve the performance. The performances of CMRC is better than that of AF. The performance of DF and CMRC is similar if the "Selective" feature is switched on. Likewise, the performances of DSTC and SR are very similar, again assuming the "Selective" feature is switched on.

4. Computational Complexity

All the processing was done on 6713 floating point processor from Texas Instruments which runs at a 225MHz clock. The numbers of clock-cycles consumed per frame for the different configurations are listed in Table 4 and 5 below Table 4 is about the number of clock-cycles in the destination while 5 is about the number of clock-cycles in the relay. It may seem that the amplify and forward technique would require much less computational power in the relay than the other schemes at the relay. However, note that in a TDD implementation the relay must still do synchronisation and subsample the signal

Scheme	(Antenna Diversity, Selectivity)			
	(Off,Off)	(On,Off)	(Off,On)	(On,On)
Direct	64	51 (A)	64	53 (A)
AF	39	37	35	36
DF	47	38 (A)	41 (S)	31 (A,S)
CMRC	46	32 (A)	43	29 (A)
DSTC	42	25 (A)	26 (S)	15 (A,S)
SR	25	14 (A)	28	15 (A)

Table 3: Outage probability: The percentage of frames with 5% bit error or more. The notations (A), (S), (A,S) indicate when the corresponding configuration is actually present in the scheme (according to Table 1)

Scheme	(Antenna Diversity, Selectivity)			
	(Off,Off)	(On,Off)	(Off,On)	(On,On)
AF	7400	7400	7392	7404
DF	2500	3996 (A)	2496 (S)	3996 (A,S)
CMRC	4496	6360 (A)	4492	6352 (A)
DSTC	2788	4860 (A)	2788 (S)	4860 (A,S)
SR	2500	3984 (A)	2504	3984 (A)

Table 4: Number of clock-cycles used per frame at the destination. The notations (A), (S), (A,S) indicate when the corresponding configuration is actually present in the scheme (according to Table 1)

(one sample per symbol instead of five samples per symbol). Moreover, we scale every burst to make optimum use of the available dynamic range.

What should not be forgotten regarding the complexity of relaying schemes is the memory required for storing the signal to be relayed in the relays. In the DF, CMRC and DSTC schemes the required amount of memory are two frames of 96 bits each. In the SR schemes, ten such frames are stored. In the AF technique we need to store the samples of the received signal e.g. using 16 bits for real and imaginary parts respectively (in our implementation we have stored them as floats). Thus, these lead to a memory requirement in the relay of 24 bytes for DF, CMRC and DSTC, 120 bytes for SR and 384 bytes for AF. These number will scale with the bandwidth if multiple subcarriers are introduced.

Other complexities that should be considered are the synchronisation requirements. Here, we have assumed that the transmission will go on for long enough for the overheads during the synchronisation phase to be neglected. This is also a question of the functionality of the upper layers i.e., how the source, relay and destination are set up and how spectrum resources allocated. The DSTC scheme requires the relays to adjust the timing of the transmitted signal so that the signals from both relays to arrive aligned at the destination.

5. Conclusion

We have implemented four well-known cooperative relaying schemes: amplify-and-forward (AF), detect-and-forward (DF), cooperative maximum-ratio combining (CMRC)

Scheme	(Antenna Diversity, Selectivity)			
	(Off,Off)	(On,Off)	(Off,On)	(On,On)
AF	2892	2888	2896	2892
DF	3016	4480 (A)	3432 (S)	5260 (A,S)
CMRC	3484	5340 (A)	3488	5340 (A)
DSTC	2864	4304 (A)	3276 (S)	5076 (A,S)
SR	2520	3976 (A)	2520	3976 (A)

Table 5: Number of clock-cycles used per frame at the relay. The notations (A), (S), (A,S) indicate when the corresponding configuration is actually present in the scheme (according to Table 1)

and distributed space-time coding (DSTC), and one novel scheme selection relaying (SR), see Section 2.. All the five schemes improved the coverage area over direct transmission. The feature "selective" helped improve the performance of DF and and DSTC significantly. Using antenna diversity was also an effective means for improving performance. The greatest performance improvement were achieved using DSTC and SR which utilise two relays. From these results it is evident that DF and DSTC need the "selective" option to function properly. It was noted that CMRC performs better than AF, when counting the number of frames with bit errors while AF performs better than CMRC when a few errors are allowed. Ongoing work includes transmitting over wider bandwidths and exploiting frequency diversity.

6. Acknowledgement

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