Combining for cooperative WLANs – A reality check based on prototype measurements

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***Abstract*—Many cooperative relaying systems combine signals received over multiple paths. For this task, in literature usually Maximum Ratio Combining (MRC), or one of its derivatives, is assumed. We show that these complex techniques are not required in Wireless Local Area Network (WLAN) scenarios with slowly fading channels. Instead, simply selecting the "best" decoded packet achieves similar performance. This Packet Selection Combining (PSC) is more practical than MRC as it is independent on channel-knowledge, does not limit the choice of the modulation scheme, and avoids complex Physical layer (PHY) implementation. Our real-time transceiver prototype demonstrates PSC's feasibility; measurements in an indoor scenario show its high performance and validate our theoretical results.**

I. Introduction

Cooperative relaying is a promising approach to improve the error rate in WLANs or cellular networks. At high mobility, interleaving or Automatic Repeat Request (ARQ) efficiently avoids transmission errors. However, at low mobility such time-diversity techniques only cope poorly with the long burst errors caused by the slowly varying channels. Here, cooperative relaying introduces additional diversity gains by transmitting a single packet over multiple, spatially independent channels. Combining the received packets exploits spatial diversity which, unlike coding, *exponentially* improves the error rate in the order of cooperating nodes [1].

This makes cooperative relaying an important technique to compensate for the lack of time diversity in low-mobility indoor or urban scenarios. A basic cooperation procedure is illustrated in Fig. 1. Here, a relay overhears the source's packet in a first phase. If correctly received, the relay forwards this packet to the destination in a second phase. Finally, the destination combines both packets to gain spatial diversity.

This simple example illustrates that cooperative relaying demands for some additional effort at the cooperating nodes. At the Medium Access Control (MAC) layer, a protocol has to coordinate the relay's transmission. At the destination's PHY, many cooperation schemes perform combining. These combining techniques and their application in practical cooperative systems are the focus of this paper.

In particular, we show that in low mobility scenarios complex PHY combining provides no significant performance gain compared to very simple so-called Packet Selection Combining (PSC). With PSC, the destination simply selects the first correctly decoded packet. Unlike standard PHY combining techniques – such as MRC, Equal Gain Combining (EGC), or Chase Combining (CC) – this simple method has several advantages:

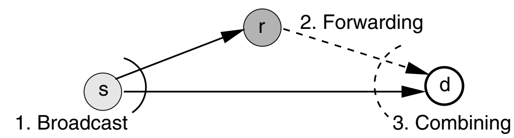

Fig. 1. Steps of cooperative relaying with three single antenna nodes. Source s and relay r cooperate via half-duplex channels to reach destination d.

- PSC can be implemented solely at the link layer: Unlike all other mentioned combining techniques, PSC requires no PHY changes (cp. Sec. II). Its implementation is almost trivial and requires no additional functions.
- PSC considers the coding gain within its combining decision. This is not the case with MRC, EGC, and similar schemes, which can weaken their performance [2].
- Unlike MRC and its derivatives, PSC's performance does not depend on channel estimation quality.
- Unlike MRC and EGC, PSC does not require s and r to use equal modulation. Consequently, PSC does not limit the choices and performance of adaptive modulation.

Therefore, PSC seems very appealing. It has not the limitations of the above combining schemes and allows device manufacturers to implement cooperative relaying only at the MAC processor (or at network driver level). While this avoids time-intense and error-prone extensions of the PHY baseband processor, it is only efficient if PSC achieves a performance similar to PHY combining.

To show that this is indeed the case in low mobility scenarios we compare MRC and PSC in three steps: For a first insight, we derive their theoretic error performance bounds which show only a slight offset in uncorrelated fading channels (Sec. III). Second, we study more realistic *autocorrelated* fading channels by accurate, symbol-wise simulation. This allows us to compare PSC's and MRC's performance in various low and high mobility scenarios (Sec. V).

Finally, we validate our analytic and simulation results by real-world measurements (Sec. V). Therefore, we design and implement a real-time transceiver prototype for *cooperative* WLANs using either PSC or MRC (Sec. IV). This implementation demonstrates the feasibility and high performance of the lightweight PSC approach. From this reality check we can conclude that – for the relevant low mobility case – complex PHY development is not required to efficiently integrate cooperative relaying into today's wireless technology.

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II. COMBINING AND COOPERATIVE RELAYING

We now summarize standard and recent literature on combining and cooperation and detail the studied techniques.

A. A simple cooperative relaying protocol with combining

We focus on the cooperation protocol described in Sec. I, where the relay overhears, re-encodes, and forwards only correct packets which the destination combines with the direct link's copies [1]. This protocol is practical as it can be efficiently implemented [1, 3] and requires no Channel State Information (CSI) feedback towards the transmitters. In literature, this simple method functions as a building block and main benchmark for more sophisticated cooperation schemes, e.g., including adaptive modulation, coding, or feedback [4, 5].

Due to its high relevance and to focus on combining instead of protocol gains, we consider only this basic cooperation protocol. Thus, we assume that only two signals are combined, i.e., only a single relay is employed. Moreover, we assume that (1) the relay uses a Cyclic Redundancy Check (CRC) to test the complete received packet, (2) if the packet is correct, forwards an identical copy of the first packet, and (3) uses the same power, code, and transmission rate (i.e., repetition coding) for this forwarding. Consequently, both phases are of equal duration and transmission power.

B. Pre-decoder combining

Combining multiple signals at symbol or soft-bit level *before* channel decoding is an important approach to achieve diversity gains. Assuming coherent reception, the signals are in phase and can be combined linearly by a sum of the received signals $y_1(t)\dots y_N(t)$, i.e., $y(t) = \sum_{j=1}^{N} a_j y_j(t)$ where each signal is weighted by its combining coefficient $a_1 \dots a_N$. Using this notation, three important linear combining techniques were classified by Brennan in his seminal paper [6].

With Selection Combining (SC), the receiver selects the "best" of the N signals. Thus, SC defines $a_k = 1$ for channel k with the highest instantaneous Signal-to-Noise Ratio (SNR) γ_k, while all other weights are 0. In practice, this technique is usually simplified by selecting the signals with the highest power instead of SNR [6]. In this case, no additional channel knowledge is required.

MRC is a more sophisticated technique where each weight is $a_j = \sqrt{y_j^2(t)/n_j^2(t)}$, i.e., proportional to the signal's Root Mean Square and inversely proportional to the mean square noise. If these coefficients are used to calculate y as above, its instantaneous SNR $\gamma = y^2/n^2$ is equal to the sum of the (linear) SNR of all combined signals. Consequently, from all linear combining schemes, MRC yields maximum SNR and, thus, Bit Error Rate (BER) performance. However, this requires accurate knowledge of the noise and signal power which is not easily available in many receivers.

EGC simplifies MRC by adding all signals at equal weight, i.e., $a_j = 1$ for $j = 1,\dots,N$. Although EGC is more practical than MRC, it achieves significantly lower performance if N is small [6]. This is the case for cooperative relaying, where typically not many relays transmit per cooperation cycle to limit the multiplexing loss for repeated packets.

Unfortunately, the above schemes can only combine signals of the same modulation type. As this limits the choices and, thus, performance of adaptive modulation, techniques to combine different modulation types were proposed recently; cp. [7] and references therein. Here, multiple QAM signals with different numbers of bits/symbol are combined at the soft-bit level. Optimal soft-bit combining schemes almost achieve MRC's performance *while* combining different modulation types [7]. However, even suboptimal variants are of higher complexity than MRC and still demand accurate CSI [7].

From all these linear combining schemes, we choose to compare PSC only to MRC since, in theory, neither the simpler SC, EGC nor the more sophisticated soft-bit based techniques reach a higher performance than MRC [6, 7].

C. Decoder combining

Unlike the above pre-decoder schemes, combining *during* channel decoding is not limited to specific modulation types. Here, Chase Combining (CC) [2] is a very relevant approach operating on redundancy bits extracted from multiple received packets. Therefore, CC relies on specific rate-compatible and convolutional codes which allow to decode packets with arbitrary re-inserted redundancy. Although applying CC in cooperative relaying schemes has shown large benefits in theory [4], it sets high constraints on the usable codes [4] and significantly increases PHY complexity [2].

D. Post-decoder combining

Recently, lightweight techniques for packet combining *after* channel decoding were developed. Unlike post-decoder or decoder combining, here the actual decoder result can be considered in the combining decision. So far, post-decoder combining schemes comparing the error vector of decoded packets have been proposed; cp. [8] and references therein. While measurements show high performance with AWGN channels, these approaches are limited to specific block codes and to specific relaying protocols in wireless sensor networks.

Although decoder and post-decoder combining seems very promising, this short literature review shows that the current approaches are complex or can only be employed to a limited set of systems or codes. Thus, we focus on PSC which simply selects the first correct packet after decoding. More formally, from each of K decoded packets $p_1,\dots,p_k,\dots,p_K$ the first packet p_k which passes an error test, e.g., a CRC, is selected. Complexity can be limited by not decoding all later received packets $p_{k+1},\dots,p_N$.

This simple post-decoder packet combining scheme has not been concisely discussed in literature so far. In this paper, we show that its implementation at the link layer is simple and that it achieves almost MRC's BER performance at low mobility. Finally, we have to note that PSC is strongly related to SC since we can regard PSC as a packet-level SC after decoding. We will use this analogy in our analysis in the next session.

III. Combining with uncorrelated channels: Outage analysis

We now compute the outage probability of the cooperation protocol (Sec. II-A) with either MRC or SC in the form of PSC (Sec. II-D). Outage probability is used as a measure of packet error rate at a certain transmission rate [9].

In this section, we assume all channels to experience slow, quasi-static fading. Each channel remains constant within one block's duration, the blocks are spatially independent, not correlated in time, and experience Additive White Gaussian Noise (AWGN). This channel model is given as

$$y_{i,j} = h_{i,j}x_{i,j} + n_{i,j} \tag{1}$$

where $x_{i,j}$ and $y_{i,j}$ are the inputs and outputs of the channels, respectively; $i \in \{s,r\}$, $j \in \{r,d\}$, and $i \neq j$; $h_{i,j}$ is the fading coefficient and $n_{i,j}$ is the AWGN component which is $\mathcal{N}(0,N_0)$ distributed. The channel's instantaneous SNR is given by $\gamma_{i,j} = |h_{i,j}|^2 \frac{P_t}{N_o}$, where $\frac{P_t}{N_o}$ is the mean transmit SNR.

Consider a direct transmission of packets from node i to j at an information rate R. For this transmission, an outage event occurs when the channel's Shannon capacity is less than R, or equivalently, when $\gamma_{i,j}$ is less than a threshold SNR given by $\gamma_{thr} = 2^R - 1$ [9]. Assuming channel i,j to be Rayleigh distributed, the outage event probability is given by

$$P_{out} = P(\gamma_{i,j} < \gamma_{thr}) \quad = \quad 1 - \exp\left(-\frac{\gamma_{thr}}{\Gamma_{i,j}}\right) \tag{2}$$

where $\Gamma_{i,j}$ is the average SNR. In the following, we compute the outage probabilities for SC and MRC schemes.

A. Selection Combining (SC)

At the end of the cooperation cycle, the destination might have received two copies of the same packet from the source and relay. With SC it selects the one with stronger instantaneous SNR value and an outage occurs if the maximum of the two SNR values is below the SNR threshold. Note that in this outage analysis SC represents PSC as, here, the channel does not change inside a packet and the ideal coding is assumed.

Using this packet selection, the overall outage event, O_{sc}, of SC is given by [10]

$$\begin{aligned} O_{sc} \quad &= \quad \left[\left(\gamma_{s,r} > 2^{2R}-1\right) \bigcap \left(\mathbf{max}\left(\gamma_{s,d}\,,\,\gamma_{r,d}\right) < 2^{2R}-1\right)\right] \bigcup \\ &\quad\quad \left[\left(\gamma_{s,r} < 2^{2R}-1\right) \bigcap \left(\gamma_{s,d} < 2^{2R}-1\right)\right] \end{aligned} \tag{3}$$

where $\cap$ and $\cup$ are the logical 'AND' and 'OR' operations, respectively. The first line in (3) shows the outage event at the destination when the relay correctly receives the source's packet (i.e., $(\gamma_{s,r} > 2^{2R} - 1)$). Similarly the second line shows the outage event when the relay wrongly decodes the source's packet, i.e., $(\gamma_{s,r} < 2^{2R} - 1)$. The outage probability, $P_{sc} = P(O_{sc})$, of the event in (3) is then

$$\begin{aligned} P_{sc} \quad &= \quad P\left[\gamma_{s,r} > 2^{2R}-1\right] P\left[\gamma_{s,d} < 2^{2R}-1\right] P\left[\gamma_{r,d} < 2^{2R}-1\right] \\ &\quad\quad +P\left[\gamma_{s,r} < 2^{2R}-1\right] P\left[\gamma_{s,d} < 2^{2R}-1\right]. \end{aligned} \tag{4}$$

Each probability term in (4) can be computed from (2) with the new threshold SNR $2^{2R} - 1$ instead of $2^R - 1$.

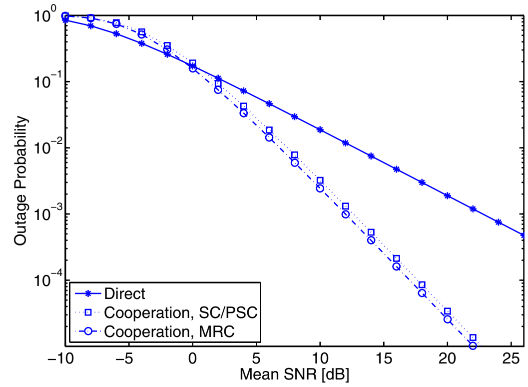

Fig. 2. Outage probability vs. mean SNR with SC and MRC. Here, $\Gamma_{s,r} = \Gamma_{s,d} = \Gamma_{r,d}$ and information rate $R = 1/4$ bits/s/Hz are used.

B. Maximum-Ratio Combining (MRC)

When MRC is used, the destination combines packets received from the source and relay, i.e., the instantaneous SNR of the resulting packet will be the sum of the instantaneous SNRs of the two packets. The overall outage event and probability, O_{mrc} and $P_{mrc} = P(O_{mrc})$, respectively, are given by

$$\begin{aligned} O_{mrc} \quad &= \quad \left[\left(\gamma_{s,r} > 2^{2R}-1\right) \bigcap \left(\left(\gamma_{s,d}+\gamma_{r,d}\right) < 2^{2R}-1\right)\right] \bigcup \\ &\quad\quad \left[\left(\gamma_{s,r} < 2^{2R}-1\right) \bigcap \left(\gamma_{s,d} < 2^{2R}-1\right)\right] \\ P_{mrc} \quad &= \quad P\left[\gamma_{s,r} > 2^{2R}-1\right] P\left[\left(\gamma_{s,d}+\gamma_{r,d}\right) < 2^{2R}-1\right] + \\ &\quad\quad P\left[\gamma_{s,r} < 2^{2R}-1\right] P\left[\gamma_{s,d} < 2^{2R}-1\right]. \end{aligned} \tag{5}$$

We evaluate $P\left[\left(\gamma_{s,d} + \gamma_{r,d}\right) < 2^{2R} - 1\right]$ using [1, App. I]

$$\begin{cases} 1 - \left[\left(\frac{\lambda_u}{\lambda_u - \lambda_v}\right)\exp\left(-\lambda_v w\right) + \left(\frac{\lambda_v}{\lambda_v - \lambda_u}\right)\exp\left(-\lambda_u w\right)\right] \\ 1 - (1 + \lambda w)\exp\left(-\lambda w\right) \end{cases}. \tag{6}$$

The terms $\lambda_u = \frac{1}{\Gamma_{s,d}}$ and $\lambda_v = \frac{1}{\Gamma_{r,d}}$ are the parameters of the two exponentially distributed random variables. The first equation is used when $\lambda_u \neq \lambda_v$ and the second when $\lambda_u = \lambda_v = \lambda$; $w = 2^{2R} - 1$ is the threshold SNR.

Fig. 2 shows numerical results for the outage probability of MRC and SC at equal mean SNR on each link. Comparing both combining schemes to direct transmission, shows that either of them achieves the diversity order of two. As a result of the modeled quasi-static, uncorrelated fading channels MRC performs only slightly better than SC.

IV. Prototype implementation

To demonstrate PSC's feasibility and performance in real measurements, we implemented a cooperative WLAN transceiver prototype with PSC and MRC. This implementation and the used platform is described in this section.

A. Platform and cooperative transceiver design

We implemented our cooperative WLAN transceiver prototype using the SORBAS Software Defined Radio (SDR) platform [11]. Based on a powerful hard-software design, SORBAS runs a fully programmable IEEE 802.11g stack in

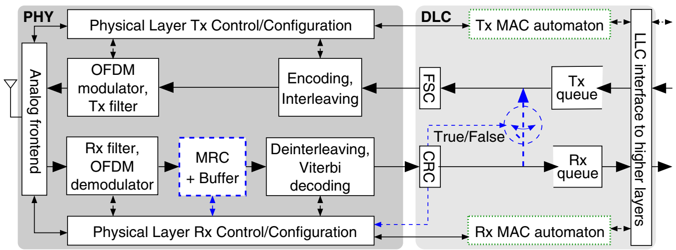

Fig. 3. Cooperative IEEE 802.11g transceiver design with control (small arrows) and data connections (large arrows). To support cooperation, dotted parts are changed and dashed parts are added. For measurements, the MRC block can be deactivated.

real time, reaches full transmission rate, and allows developers to modify all link layer, MAC, and PHY baseband functions.

On this platform we integrated the simple cooperation protocol from Sec. II-A into the MAC, PSC at the link layer, and MRC at the PHY. Fig. 3 summarizes these extensions. As discussed in Sec. II-A, only the basic variant of the cooperation protocol was implemented. At the link layer, the relay's forwarding decision is represented by a switch which is triggered by the CRC's result. If the relay forwards a correct packet, this switch circumvents the Rx and Tx queues to avoid reordering and delays for the forwarded packet. At the MAC, the cooperation protocol needs to include wait and signaling cycles into the Rx and Tx automates to avoid collisions of relayed packets, to find relays, and to invoke and maintain the cooperation cycle. Details of our extensions and on further indoor and outdoor measurements are provided in [3].

B. Implementing combining techniques

To compare both techniques, PSC as well as MRC are implemented and can be each switched on or off. MRC is implemented at the PHY and operates on the digital modulation symbols prior to decoding. It is implemented as linear combining as described in Sec. II and employs noise and power measurements from the radio frontend to calculate the weights. Since these measurements are provided only once per PHY frame, the weights remain equal for the complete packet. Although suboptimal, such implementation represents the typical case, as in most systems noise and power are measured only once per frame over the preamble. Nevertheless, the combining operation is performed for each symbol per frame.

MRC needs to buffer all modulation symbols of the first received PHY frame in order to combine it with the symbols of the consecutive frame(s). With PSC such additional buffering is not required. Here, only a single correct packet passes the CRC and is, thus, selected. After this decision, the link layer signals the PHY to ignore the data part of all further packets received in the same cooperation cycle. The next cooperation cycle is detected by still decoding the PHY preamble. This procedure avoids useless de-interleaver and decoding operations and, thus, saves energy in a mobile device.

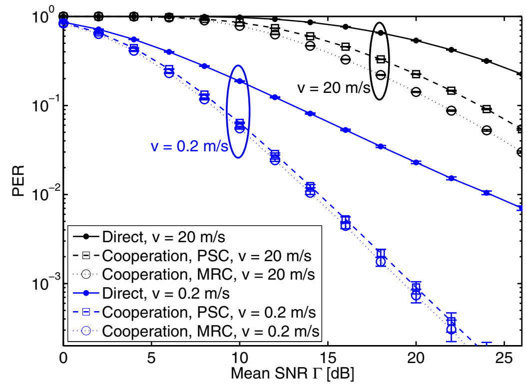

Fig. 4. Simulation results for autocorrelated fading: Comparing end-to-end PER of cooperative relaying with PSC and MRC for varying mean SNR Γ and a high and low speed v. Mean results and 95% confidence intervals

V. Combining with Autocorrelated Channels: Measurement and Simulation Results

In this section, we focus on a more realistic type of fading where the channel's autocorrelation depends on the mobility in the propagation environment. We, first, study high and low mobility by simulation. Then, we provide measurement results for an indoor scenario at low mobility.

A. Simulation assumptions and results

To model autocorrelated fading channels we use the "land mobile" model (Tbl. 2.1 in [9]) with a Bessel-like Autocorrelation Function (ACF). This widely-used model is suitable for mobile scenarios with many scatterers and provides us with autocorrelated, Rayleigh-distributed channel coefficients for each symbol time. Consequently, depending on the current state of the ACF, the channel may change at each symbol time and, thus, even *inside* a packet. Note that this behavior is neither captured by the block fading model in Sec. III nor in most analytic work [1, 4, 10]. The channel's ACF is parameterized by the maximum Doppler shift reflecting the maximum speed v inside the propagation environment. We vary v between 1 and 40 m/s resulting in channel coefficients highly and little correlated in time, respectively.

At the PHY we assume IEEE 802.11g parameters and functions. A symbol is transmitted in 4 μs at a carrier frequency of 2.4 GHz in 20 MHz bandwidth. The transmission rate is 18 Mbit/s using IEEE 802.11g's OFDM mode, coherent QPSK modulation, and a punctured convolutional code at rate $3/4$.

For these assumptions, Fig. 4 shows the end-to-end Packet Error Rate (PER) obtained at the link layer of the destination. At a low speed, cooperative relaying with both combining schemes improves direct transmission's PER by up to two orders of magnitude at high SNR. This high diversity gain is expected from literature and Sec. III. Moreover, there is no significant performance difference between PSC and MRC. This, again, reflects our analytic results for quasi-static channels in (Fig. 2). At higher speed, however, MRC outperforms PSC by up to 2 dB. Nonetheless, with such temporally uncorrelated channels, cooperative relaying reaches only poor PER and

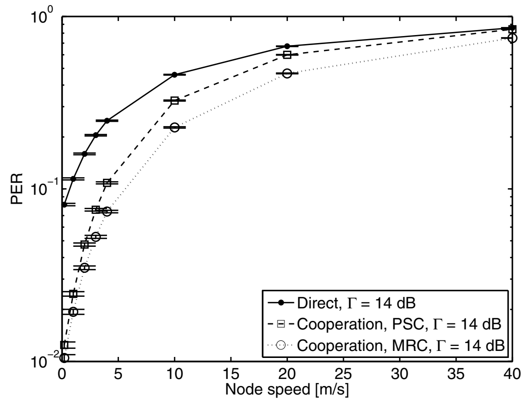

Fig. 5. Simulation results for autocorrelated fading: Comparing end-to-end PER of cooperative relaying with PSC and MRC for varying speed v and a fixed mean SNR of $\Gamma = 14\,\text{dB}$. Mean results and 95% confidence intervals

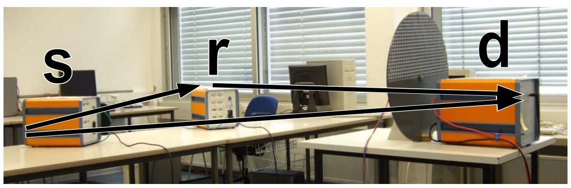

Fig. 6. Indoor scenario with 3 SORBAS SDRs (orange) operating as source s, relay r, destination d.

would be not employed. Here, time-diversity techniques, e.g., interleaving or ARQ, are more effective.

Fig. 5 supports our discussion of Fig. 4. With increasing speed MRC starts to outperform PSC. This makes MRC the preferred scheme at medium mobility of $v = [4, 10]$ m/s while at higher mobility cooperative relaying performs poorly and would be not employed.

B. Experimental setup and measurement results

We used three SORBAS devices to set up the indoor scenario in Fig. 6. All three nodes experience a typical office environment. The nodes were placed in an isosceles triangle with distance 1.44 m between s and r and 2.70 m between s and r to d. Non-Line Of Sight (NLOS) propagation was obtained by shielding the LOS between the nodes. A rotating disk in front of d emulates low mobility, i.e., a constant linear velocity of ≈ 1 m/s. The nodes operate in IEEE 802.11g OFDM mode (without IEEE 802.11b legacy support), at carrier frequency 2.472 GHz, using a single omnidirectional antenna with 5 dBi gain. This basic cooperative WLAN was studied within a large campus environment where approximately 40 neighboring IEEE 802.11g/b legacy terminals affected the interference level but were not employed for communication.

Fig. 7 shows the results for this indoor scenario. These results show the same behavior as our theoretical results for the uncorrelated but quasi-static channels (Fig. 2) as well as our simulation results for low speed (Fig. 4). The diversity gain of cooperation is clearly shown for both combining schemes. Nevertheless, the performance gains of both combining techniques are equal. No significant difference between PSC and MRC is shown by our prototype measurements.

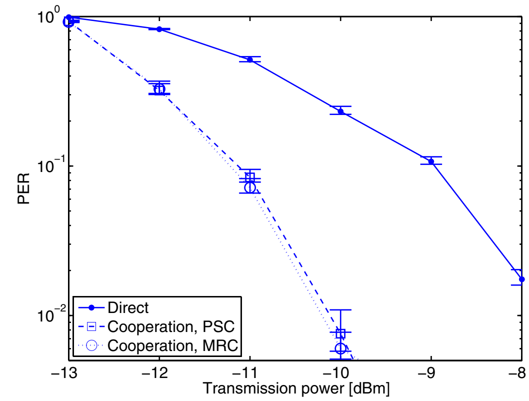

Fig. 7. Measurement results for the indoor scenario: Comparing end-to-end PER of cooperative relaying with PSC and MRC vs. transmission power. Mean results and 95% confidence intervals

VI. Conclusion

Integrating cooperative relaying into wireless transceivers can be done solely at the link layer. PHY combining is not required and not beneficial if these devices operate in low mobility environments, e.g., indoor or urban scenarios. At low mobility, which is the preferred scenario for cooperative relaying, simple post-decoding packet selection at the link layer achieves equal performance as MRC and its derivatives. Thus, time-intense PHY development and complex extensions are not required to integrate cooperation into wireless networks at low mobility. We hope that this practical result motivates device manufacturers and standardization to include cooperative relaying in future WLANs or urban cellular networks.

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