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# Codebook Selection Strategies in Long-range Sub-1 GHz WLANs

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**Abstract**

The new long-range WLANs will enable a simple and cost-efficient setup of wireless ambient systems, including smart city and smart grid communication networks. The emerging IEEE 802.11ah WLAN standard utilizes carrier frequencies at 900 MHz in the ISM-band and facilitates multi-antenna MIMO-OFDM. In order to further increase the wireless coverage, precoding selection strategies are proposed and analyzed. The Grassmannian and the Kerdock manifold are in the focus of this study due to their simplicity and effectiveness. Whereas the Grassmannian manifold may provide an optimal codeword distance, the Kerdock manifold has been found to be more effective due to its reduced quantized codewords combined with an increased SNR. Simulation studies as well as real-world evaluation results indicate a 2-3 dB increase of precoding gains when the proposed Kerdock manifold is applied, thus increasing the coverage. The codebooks have been evaluated in a SDR-based IEEE 802.11ah WLAN prototype.

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*Keywords:* Sub-1 GHz; WLAN; IEEE 802.11ah; long-range; precoding; codebook.

## 1. Introduction

Recently, research about ambient systems has increased significantly. Smart spaces, including smart cities and smart grids, are in the focus of numerous national research projects. In particular, the realization of ambient and smart networks requires ubiquitous and cost-efficient wireless access in order to penetrate a wide market area. License-exempt wireless systems, which operate in unlicensed radio bands, are potential candidates to provide ubiquitous access. In addition, there is a trend to utilize lower radio-frequencies to support a wider coverage area and to serve a larger number of associated wireless terminals. The emerging sub-1 GHz WLAN is an appropriate candidate for such envisioned wireless access scenarios. The upcoming IEEE 802.11ah standard allows the support of hundreds WLAN STAs using carrier frequencies in the 900 MHz industry, scientific and medical (ISM) band. In addition, this standard will facilitate the emerge of a new class of wireless devices, so-called Wi-Fi sensors. This paper focuses on a critical aspect of sub-1 GHz WLANs, and that is how to further increase the wireless range of such WLANs. These new WLANs utilize communication protocols that take advantage of using multi-antenna systems. Such multiple-input multiple-output (MIMO) systems utilize various transmission gains in order to increase the data rate in long rage communication scenarios. When increasing the wireless range, usually the data rate is limited due to the decline of

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the signal to noise ratio (SNR) while increasing the distance between WLAN access point (AP) and station (STA). In MIMO systems, various diversity schemes allow to exploit channel characteristics and thus, to increase the coverage. Hence, the improvement of diversity gains are of primarily interest in this study. In particular, precoding schemes are evaluated and transmission gains are analyzed. Further, a novel software defined radio (SDR) based IEEE 802.11ah WLAN prototype is proposed, that allows the practical evaluation of novel precoding schemes in real-world. This study proposes codebook selection strategies, which increase the wireless range in sub-1 GHz WLANs. In addition, precoding modifications are proposed, which can further improve the coverage. It is shown that the SNR can be increased by an advanced codebook selection scheme. Reported precoding gains are in the range of 2-3 dB. In addition, the codebook selection has been implemented in a novel SDR-based IEEE 802.11ah WLAN prototype and tested in real-world scenarios. The rest of the paper is organized as follows. Section 2 gives an overview of related work on recent advantages in WLAN precoding. In Section 3, the precoding scheme in multi-antenna WLANs is introduced. Section 4 outlines the theoretical background of precoding in WLANs. Section 5 introduces the SDR-based IEEE 802.11ah WLAN prototype. Section 6 discusses the evaluation results. Finally, Section 7 concludes this work.

## 2. Related Work

The transmission performance in MIMO systems is greatly influenced by the selected precoding technique. Nojima, *et al.,* [1] compared the precoding improvements of channel inversion (CI) and block diagonalization (BD) precoding schemes under realistic channel conditions. It was shown that the BD precoding scheme outperforms the CI precoding, which was simulated for very high throughput (VHT) wireless local area networks (WLAN) IEEE 802.11ac multi-user (MU) multiple input multiple output (MIMO) that use orthogonal frequency division multiplexing (OFDM). Lou, *et al.,* [2] analyzed the transmission performance of implicit and explicit channel state information (CSI) methods, which have been specified in IEEE 802.11ac in which a compressed beam-forming report based on singular value decomposition (SVD) is assumed. The comparison included overhead and packet error rate (PER) performance measures. It was shown, that explicit feedback requires a high precision feedback mode which incurs larger overhead. If accurate calibration is available, using implicit feedback would allow to reduce the signaling overhead. An hybrid CSI transmission scheme was proposed that would allow faster calibration updates with without incurring additional overhead. Precoding is classified in linear and non-linear schemes. Riera-Palou, *et al.,* [3] refer to linear precoding in MIMO-OFDM based on deterministic CSI information at the transmitter (CSIT). It was shown that spreading the CSI information over a group of OFDM sub-carriers instead of a per sub-carrier basis, would utilize all the diversity a wireless channel can provide. Performance analysis of non-linear precoding schemes are reported [4]. Non-linear precoding schemes, such as dirty paper coding, have been found as an alternative to linear precoding schemes, facilitating higher channel capacity. However, due to the high complexity, such schemes are not considered in WLAN protocols. Next, when precoding is executed at the transmitter, complex multiplication between the data stream and the codebook requires computing power, which is analyzed by Yue, *et al.,* [5]. The impact on the codeword computation and the use of hardware resources are considered. A simple binary shift rather than a binary-to-binary operation is proposed to execute the multiplication and division of codeword and data signal processing. Codebooks include the unitary space vector quantization (USVQ) [6], Grassmannian and LTE-A R10 discrete Fourier transform (DFT) codebook [7], whereas the USVQ can adapt to channel dynamics and performs better than Grassmannian or DFT codebooks [5]. The IEEE 802.16e codebook has shown good performance in uncorrelated channels, whereas DFT codebooks are more suitable for correlated channels [8]. Codebook performance in millimeter-wave broadband WLANs has been reported by Liang, *et al.,* [9] discussing the challenges on codebook selection strategies and channel capacity improvements in high data rate WLANs.

## 3. Precoding in multi-antenna WLANs

The knowledge on channel state determines the performance in MIMO systems. In order to provide channel state information to the transmitter, the receiver sends quantized channel information by using fixed codebooks and send them to the transmitter [8].

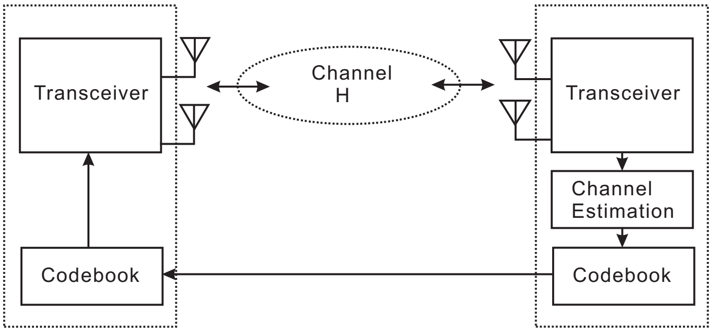


Fig. 1. Illustration of a closed-loop MIMO transmitter and receiver configuration with codebook selection.

### 3.1. Channel State Information (CSI)

In order to enable a more reliable transmission or higher throughput, it has been shown that the availability of CSI information at the transmitter in MIMO systems is beneficial[3]. The transmitter uses the CSI data in order to precode the transmit data signal to optimize a predefined performance metric. The use of linear transmit and receive filters optimizes the transmission characteristic under a linear processing constraint. Wireless transmission performance improvement is obtained by exchanging information about the wireless channel condition between sender and receiver. In MIMO WLANs, the receiver sends channel state information (CSI) to the transmitter. CSI information is affected by channel estimation error and feedback errors. The sending of CSI information adds additional overhead to a wireless system, which can significantly affect its transmission efficiency. Hence, CSI information is compressed by few number of bits in order to reduce the feedback overhead.

### 3.2. Precoding strategies

Precoding methods at transmitting nodes which are based on full channel state information result in significant delay time and signaling overhead. As an alternative, the codebook based precoding in a MIMO system alleviates the problem of delay time and channel estimation errors[5]. The transmission performance of a closed-loop wireless system with *limited* or *quantized* feedback can be improved by using a codebook based transmit beam-forming scheme[11,12]. Fig. 1 illustrates a closed-loop MIMO transmitter and receiver WLAN with feedback. Wireless transmission in orthogonal frequency division multiplexing (OFDM) MIMO systems can only reach higher data rate regimes when down-link channel state information (CSI) is available to the transmitter prior to the transmission. Precoding is applied to the signal on the sender side. At the receiver side traditional MIMO detection schemes are applied, such as minimum mean square error (MMSE) and vertical Bell laboratories layered space time (V-BLAST) decoder. In general, precoding schemes can be classified in two groups namely, *linear* precoding and *non-linear* precoding schemes. Linear precoding schemes are known for their simplicity and are easy to apply to wireless communication systems. IEEE 802.11ac supports both, the CI and BD precoding scheme. Non-linear precoding schemes are selected when data rate is the primary concern. High throughput can be achieved by some of non-linear precoding schemes, including the Tomlinson-Harashima (THP) and vector perturbation (VP). However, they are well known for their system complexity and not applied to the IEEE 802.11 protocols[4].

## 4. Theoretical background on precoding

Precoding is used in MIMO systems with limited feedback. Further, precoding can be considered as a form of beam-forming. Multiple signal streams are precoded and emitted via multiple antennas giving a different weighting for each data stream with the intent to increase the received signal at the receiver. When precoding is used a precoding matrix $\mathbf{F}$ is defined as

$$\mathbf{y} = \mathbf{HFs} + \mathbf{n}, \tag{1}$$

where $\mathbf{H}$ is the $N_t \times N_r$ complex Gaussian channel matrix and $\mathbf{y}$ the received signal. $\mathbf{H}$ can be modeled as Kronecker spatial correlated Rician and Rayleigh channel, separated in line of sight (LOS) and non-line of sight (NLOS) components given as

$$\mathbf{H} = \sqrt{\frac{1}{1+K}\mathbf{H}_{LOS}} + \sqrt{\frac{K}{1+K}\mathbf{H}_{NLOS}}, \tag{2}$$

were $\mathbf{H}_{NLOS}$ is given by [13]

$$\mathbf{H}_{NLOS} = [\mathbf{R}_{rx}]^{1/2}\,[\mathbf{H}_{iid}]\,[\mathbf{R}_{tx}]^{1/2}, \tag{3}$$

with $\mathbf{R}_{tx}$ and $\mathbf{R}_{rx}$ as the correlation matrices at the transmitter and receiver side, the channel model factor $K$ (channel model values taken from [14]), and $\mathbf{H}_{iid}$ as the random complex Gaussian variables of unit variance and zero mean. $\mathbf{F}$ is the precoding matrix (in Frobenius form) of $N_r \times N$ where $M < \min(N_t, N_r)$. The input signal vector $\mathbf{s}$ is a $N \times 1$ matrix, and $\mathbf{n}$ the noise vector. Under the assumption of limited feedback and minimum mean squared error criteria, the optimal precoder is designed by applying the complex *Grassmannian* packaging where the chordal distance between any two codewords $\mathbf{F_1}$ and $\mathbf{F_2}$ is maximized with [10]:

$$d(\mathbf{F_1}, \mathbf{F_2}) = \frac{1}{\sqrt{2}} \left\| \mathbf{F_1}\mathbf{F_1^*} - \mathbf{F_2}\mathbf{F_2^*} \right\|_F. \tag{4}$$

Two lineary dependent vectors have the chordal distance zero, whereas two orthogonal vectors have the maximum chordal distance equal to 1. A codebook $C$ is finite set of $n$ vectors, called codewords $c$ in which all the codewords maximize the minimum distance $d$ between any two codewords in the entire vector set [5].

### 4.1. Codeword generation

In the case where only limited CSI information is available at the transmitter, codeword based precoding becomes an effective solution. A set of codebooks is defined, e.g., off-line, and is stored at the transmitter and receiver. After every transmission only the index is sent back in form of few bits to the transmitter to inform about the codebook selection [5]. The elements in the codebook $C$ are referred as *codewords* $c$, such as

$$C^k = \left\{c_0^k, \ldots, c_n^k\right\}. \tag{5}$$

The transmitter collects all reported indexes of the codeword and determines which codeword increases the link capacity. A precoding selection algorithm selects the codewords, $c \in C$ for and input signal vector $v$, with minimum chordal distance given by

$$c = \operatorname*{argmin}_{c \in C} d\,(v, \bar{c}\,) \tag{6}$$

In order to minimize the mean squared error the chordal distance has to be maximized. The transmitter uses the codebook elements as the precoding matrix for the beam-forming operation.

### 4.2. Codeword selection strategies

MIMO systems use fixed codebooks which consists of a construction of preselected codewords that have been decided on specific criteria. In independent and identically distributed (iid) wireless channels, the *Grassmannian* line packing provides maximum distance between any two codewords [10]. Other codebooks are useful when correlation is present. Such codebooks are useful for specific system configuration, e.g., short-range, indoor, etc. However, if the wireless communication system is located outside, other affects may impact the transmission performance which may be optimized by a different set of codebooks and codewords. In particular, long-range WLANs suffer from signal degradation and fading. Thus, it is essential to apply robust codewords which allow an increase of signal strength. In addition, an intelligent precoding matrix index (PMI) selection allows further improvements. A precoder is used as an error-corrector that is inferred by a code sequence that is the sum of a set of sequences composed of the m-sequence codeword and the elements of an arbitrary sequence, the signal sequence. In order to apply the sequence set, who elements are the sequences sums of a linear error-correcting code, it is recommended to have a sequence set that has a large minimum distance. Such sequence sets include the *Kasami* sequence, *Gold* sequence, *Stiefel* sequence, and *Kerdock* sequence. Such code sequences have a minim distance of

$$\frac{2^{2m} - 2^{m}}{2}, \tag{7}$$

where the total code length $L$ is $2^{2m}$ (when the index part is even). In case where the minimum distance is

$$2^{2m} - 2^{m}, \tag{8}$$

the total code length $L$ is $2^{2m+1}$ (when the index part is odd). For instance, if the total code length is 16, the minimum distance is 6.

### 4.3. Selected codebooks

The chordal distance of the codewords has to be maximized in order to minimize the mean squared error. In cases where the input is symmetric, the quantization of a codebook may use the symmetry. The codebook may be designed to take advantage of such symmetry by selecting codewords which reduce the quantization error. The Grassmannian space $Gr(n, k)$ is the set of k-dimensional subspaces in an n-dimensional vector space. The Grassmannian codebook (code-bits=2) is widely used in LTE and in some WLANs and is given as

$$\begin{aligned} \mathbf{c}_0^G &= \begin{bmatrix} -0.1612 - j0.7348 & -0.5135 - j0.4128 \\ -0.0787 - j0.3192 & -0.2506 + j0.9106 \end{bmatrix}, \\ \mathbf{c}_1^G &= \begin{bmatrix} -0.2399 + j0.5985 & -0.7641 - j0.0212 \\ -0.9541 & 0.2996 \end{bmatrix}. \end{aligned} \tag{9}$$

As an alternative to Grassmannian, this paper proposes the use of the Kerdock manifold in long-range WLANs. The Kerdock codebook should be the first choice when computational capabilities are limited combined with limited memory space. The Kerdock manifold consists of 0, $\pm 1$, $\pm j$ which has a low implementation complexity. For a two transmit antenna system the coding constellation is given by

$$\mathbf{c}_0^K = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \mathbf{c}_1^K = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}, \tag{10}$$

with the codebook basis $c_0^K$ and $c_1^K$, with $c_0^K$ as the *scaled* Sylvester-Hadamard matrix.

To further increase the precoding performance, modifications are applied through experimental testing. Modifications are proposed as follows

$$\mathbf{c}_0^{Kmod} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \mathbf{c}_1^{Kmod} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1+j \\ 1+j & 1-j \end{bmatrix}. \tag{11}$$

## 5. IEEE 802.11ah WLAN prototype

A WLAN that is used in infrastructure basic service set (IBSS) mode has an WLAN AP and one or more WLAN STAs associated with a single AP. Without loss of generality, only down-link precoding (AP to STA) performance is in the focus of this paper. The WLAN AP of interest has $N_t$ transmit antennas. The STA has $N_r$ receive antennas. In a $2 \times 2$ MIMO-OFDM system with $N_S = 2$ spatial streams, $N_{t,r} = 2$. The proposed sub-1 GHz WLAN prototype utilizes the IEEE 802.11ah WLAN protocol. IEEE 802.11ah is an upcoming sub-1 GHz WLAN standard that inherits the baseline design from IEEE 802.11ac and IEEE 802.11n and is optimized for extended wireless coverage. IEEE 802.11ah is envisioned to provide IP connectivity to WLAN STAs and WLAN sensors in a wide coverage $\leq$ 1 km. It provides rich data rates (low data rates for sensor applications, $\leq$ 150 kbps, mid/high data rates up to 78 Mbps in countries with high tx power and wide channel bandwidth) and high scalability (hundreds of nodes). A novel signal repetition scheme (MCS 10) is particularly specified in IEEE 802.11ah to enable long-range coverage. Table 5 lists the relevant system parameters of the SDR-based IEEE 802.11ah WLAN prototype. Further details on the prototype and how to setup the SDR platform can be found in our previous literature[20] and references therein.

Table 1. Specification of the SDR-based IEEE 802.11ah WLAN prototype used in this study.

| Parameter | Value | Description |
|---|---|---|
| Center frequency, $f_c$ | 923 MHz | According ARIB STD-T108 [15] |
| Channel bandwidth, $BW$ | 1 MHz | According ARIB STD-T108 [15] |
| Protocol | IEEE 802.11n/ah | IEEE 802.11ah WLAN prototype |
| Modulation | OFDM, 2×2 MIMO | Down-clocked, 1 MHz BW |
| Modulation and Coding Scheme (MCS) | 2 | Beam-form ON (single stream) |
| Number of Tx antennas, $N_t$ | 2 | |
| Number of Rx antennas, $N_r$ | 2 | |
| Number of streams, $N_S$ | 2 | |
| Tx power, $P_{tx}$ | 10 dBm | According ARIB STD-T108 [15] |
| Codebook manifold | Grassmannian, Kerdock (original, modified) | |
| Traffic | ICMP (100 B, 0.3 sending rate) | |
| Wireless link | LOS, 3 m | |
| Software | GnuRadio [18], Hydra [16] | |
| RF front-end | USRP1, SBX [19] | Software defined radio |
| Antenna | VERT900 [19] | 840-970 MHz, omni-directional |

## 6. Performance evaluation and discussion

In order to identify the precoding gains of the selected codewords, simulation studies have been conducted. Fig. 2 shows the comparison between Grassmannian and the proposed Kerdock precoding gains. At BER = $10^{-5}$ an in-

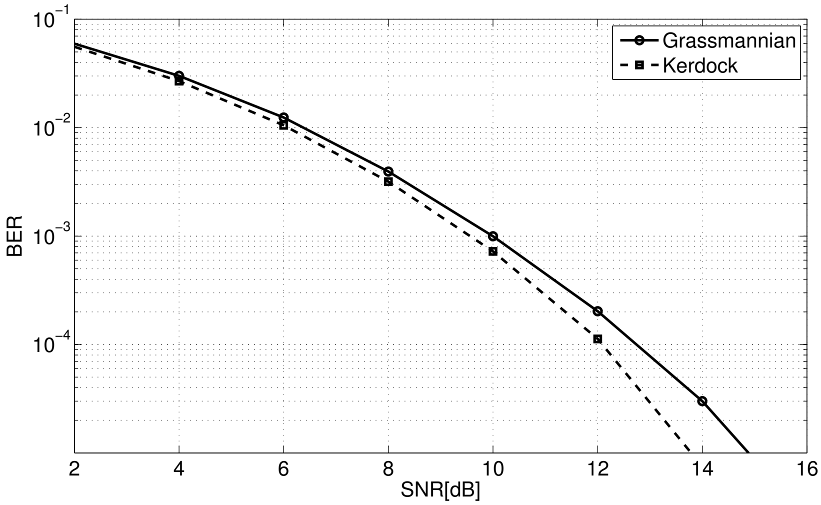


Fig. 2. Illustration of performance comparison between Grassmannian and proposed Kerdock precoding.

creased gain (> 1 dB) over the Grassmannian codebook (Eq. 9) can be observed when the Kerdock codebook is applied (Eq. 10). Next, in Fig. 3 at BER = $10^{-5}$, an increased gain (> 2 dB) over Grassmannian codebook can be observed when the *modified* Kerdock codebook (Eq. 11) is applied. To conclude the study, the proposed codebook selection is implemented in a novel SDR-based IEEE 802.11ah WLAN prototype (Section 5). The codebook performance is evaluated, without loss of generality, in a simple WLAN AP-STA scenario. A single ICMP flow was applied with packet size=100 B in line of sight with 1 m distance between AP and STA. Carrier frequency was selected at $f_c$ = 923 MHz. In addition, beam-form was configured with MCS 2 to execute the precoder. The wireless setup was located in a shielded environment. The results of the delay performance, when Grassmannian, Kerdock, and the modified Kerdock codebooks are applied, are shown in Fig. 4. The figure shows a reduced delay for Kerdock precoding

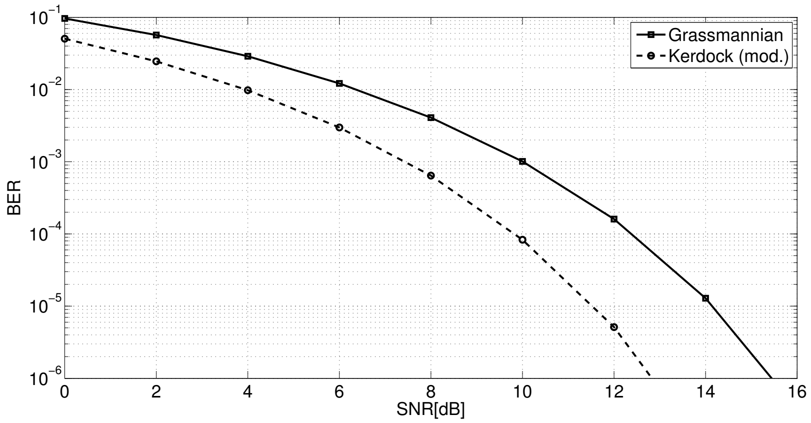


Fig. 3. Illustration of performance comparison between Grassmannian and modified Kerdock.

compared to Grassmannian. The simple codeword configuration of the Kerdock manifold has been found as the reason for the reduced processing delay. The results of the SNR of the Grassmannian, Kerdock, and the modified Kerdock

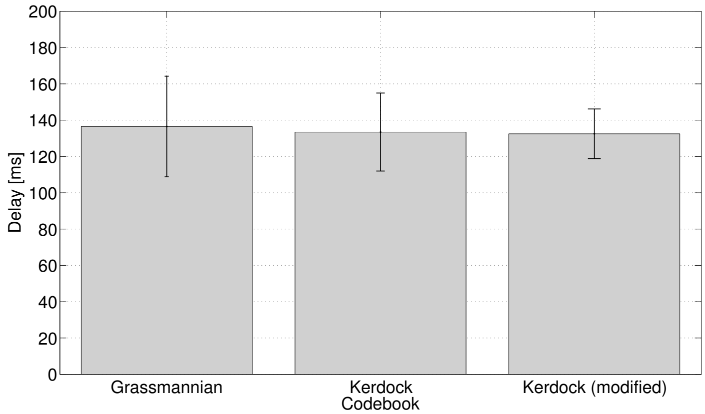


Fig. 4. Illustration of measured delay performance of Grassmannian, Kerdock, and modified Kerdock codebook.

codebooks are shown in Fig. 5. It can be observed that the Kerdock manifold increases the SNR at 2 dB. Further SNR improvement of 1 dB can be observed when the *modified* Kerdock manifold is applied. It can be concluded that the Kerdock manifold adds significant advantages to a WLAN system by reducing transmission delay and increasing the SNR at the receiver at 2-3 dB.

## 7. Conclusions

In this paper, the problem of enhancing the wireless coverage of long-range sub-1 GHz WLANs was considered. In particular, the focus was on enhancing precoding mechanisms, by selecting a codebook which results in higher SNR. The theoretical background on precoding was presented and various precoding schemes were discussed. Details on the Grassmannian manifold was given, which is widely applied in LTE and some WLAN implementations. As an alternative, the Kerdock manifold was introduced, which shows similar precoding performance compared to the Grassmannian, but resulting in less quantized signal overhead. The Grassmannian and the Kerdock manifold precoding performance were evaluated in simulation studies as well as in a practical implementation study of a novel

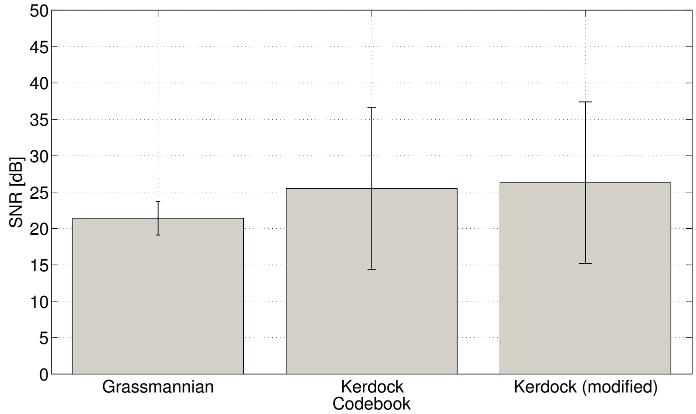


Fig. 5. Illustration of measured SNR of Grassmannian, Kerdock, and modified Kerdock codebook.

SDR-based IEEE 802.11ah WLAN prototype, that uses the IEEE 802.11ah WLAN protocol. It was shown, that the Kerdock manifold outperforms the Grassmannian manifold. In addition to the selecting scheme, modifications on the Kerdock codebook have been proposed, resulting in 2-3 dB precoding gain. Future plans include the testing of higher code-bit constellations and larger antenna arrays using our proposed IEEE 802.11ah WLAN prototype.

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