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

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### Abstract

*Wireless environmental systems, such as those used in smart cities and smart grids, will be much easier and cheaper to set up thanks to the new long-range WLANs. The new IEEE 802.11ah WLAN standard makes use of 900MHz ISM-band transmission bands and supports multi-antenna MIMO-OFDM. Precoding selection is a technique used to expand cellular networks' range. Solutions are discussed and evaluated. This research focuses on the Grassmannian and the Kerdock manifold because of their efficiency and clarity. The Kerdock manifold has been found to be more efficient due to its decreased quantized codeword's and improved SNR, whereas the Grassmannian manifold may provide an optimum codeword distance. The suggested Kerdock manifold has been shown to improve range by 2-3 dB in both simulation tests and real-world evaluations.*

### 1. Introduction

There has been a substantial uptick in studies involving environmental devices recently. Including smart towns and other digital places, many government-funded studies are focusing on smart networks. The actualization of ubiquitous and clever technologies networks need cheap, widespread cellular connectivity to break into new markets. License exempt unlicensed radio channels offer hope for wireless devices to provide truly pervasive access. The use of lesser radio-frequencies to enable a larger service region and more users is also on the rise. More wide devices connected to the network. One promising option is the rapidly developing sub-1GHzWLAN. Possibilities for cellular connectivity that have been envisioned. Due to the forthcoming IEEE 802.11ah standard, hundreds of WLANs will be supported. STAs operating on the 900 MHz ISM band carrying frequencies used by the science and medical communities. On top of that, this benchmark will pave the way for a new generation of portable gadgets, Wi-Fi monitors. In this article, we examine an important sub-1GHz WLANs, specifically how to extend their wireless coverage even further. These latest Wireless local area networks (WLANs) make use of transmission methods that benefit from multi-antenna systems. This kind of multi-input Multiple-input, multiple-output (MIMO) systems maximize data throughput over extended distances by employing a number of

Transmission advances. Different situations where talking is involved. Increasing the distance between A WLAN access point (AP) and a station typically results in a decrease in data transmission due to a decrease in signal to noise ratio (SNR). (STA). In MIMO systems, the range can be expanded by taking advantage of the channel's unique qualities through the use of one of several diversification methods. Therefore, the primary focus of this research is on ways to increase the benefits of variety. It is important to note that preceding methods assessed, and enhancements in transmission studied. Additionally, a cutting-edge IEEE 802.11ah-based software-defined-radio (SDR) we suggest a WLAN prototype that can be used to test out new preceding techniques in the real world. These Codebook selection methods that extend the range of sub-1 GHz WLANs are proposed in the research. And furthermore Changes to the preceding are suggested that have the potential to increase penetration even further. It is demonstrated that by using a sophisticated codebook picking method, the SNR can be improved. Two to three dB increases have been reported for proceeding. Furthermore, an innovative SDR-based IEEE 802.11ah WLAN prototype has been built with the codebook selection applied, and it has been tried in real-world scenarios. Situational realities. The remaining sections of the report are structured as follows. The most recent improvements in WLAN preceding are discussed in Section 2 of this paper. The multi-antenna WLAN preceding method is presented in Section 3. In Section 4, we provide some theoretical context for WLAN preceding. Section 5 describes the prototype IEEE 802.11ahWLAN built on software-defined radios. The findings from our analysis are presented in Section 6. Finally, this effort is brought to a close in Section 7.

## 2. Related Work

The communication efficiency of MIMO systems is highly sensitive to the preceding method that is used. In a study conducted under genuine channel circumstances, Nominal et al. 1 contrasted the preceding enhancements of channel inversion (CI) and block diagonalization (BD). It has been demonstrated that the BD preceding method is superior to Very high throughput (VHT) WLANs based on IEEE 802.11ac multi-user (MU) multiple input multiple output (MIMO) that employ orthogonal frequency division multiplexing have been tested with CI preceding. (OFDM). Transmission efficacy of both implicit and explicit channel state information (CSI) techniques, as defined in IEEE 802.11ac, was evaluated by Lou et al. 2 under the assumption of singular value decomposition (SVD)-based compressed beam-forming report. Overhead and PER (packet error rate) efficiency metrics were used in the analysis. It was demonstrated that clear feedback necessitates a higher-overhead, higher-precision feedback option. It is possible that the communication burden could be decreased by using implied input if precise tuning is already in place. It was suggested that a mixed CSI communication method be used to expedite calibration changes without significantly increasing latency. Both linear and non-linear preceding methods exist. Linear proceeding in MIMO-OFDM using predictable CSI information at the emitter is mentioned by Riera-Palou et al. (CSIT). It was demonstrated that all the variety available in a wireless channel could be exploited by distributing the CSI data across a set of OFDM sub-carriers rather than using each one individually. The effectiveness of non-linear preceding methods is analyzed in detail4.

## 3. Preceding in multi-antenna WLANs

In MIMO networks, success or failure depends on how well one understands the channel state. The receiver transmits discrete channel information using preset codebooks to the emitter 8 in order to report the current status of the channel.

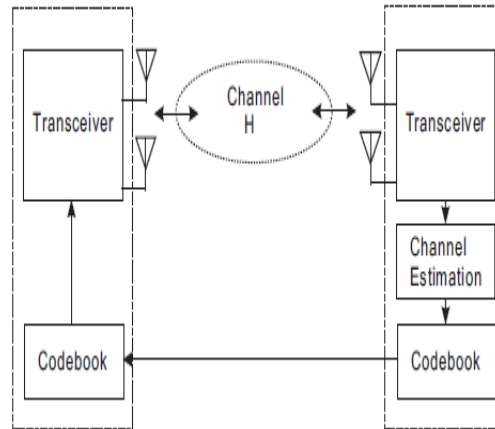


Fig. 1. Illustration of a closed-loop MIMO transmitter and receiver configuration with codebook selection.

### Channel State Information (CSI)

It has been demonstrated that having CSI information available at the emitter in MIMO systems improves broadcast reliability and throughput<sup>3</sup>. The emitter takes advantage of the CSI information to precede the transmission data signal in order to maximize some a priori performance measure. Transmission and reception using linear filters maximizes the desired propagation property within the bounds of linear processing. By sharing wireless channel state data between the transmitter and recipient, wireless communication efficiency can be improved. Channel status information (CSI) is transmitted from the recipient to the sender in MIMO WLANs. Channel prediction mistake and return flows impact CSI data. Sending CSI information can greatly reduce the transfer effectiveness of a wireless network due to the extra latency it introduces. In order to lessen the burden of the feedback system, CSI data is reduced by a small number of bits.

### Preceding strategies

Transmitting node preceding techniques based on complete channel state information introduce substantial latency and signalling overhead. Instead, a MIMO system can reduce latency time and channel prediction mistakes with preceding based on a codebook.<sup>5</sup> Closed-loop wireless technology propagation efficiency using a codebook based broadcast beam-forming scheme<sup>11, 12</sup> can help with restricted or timed input. The feedback cycle between a MIMO emitter and recipient WLAN is depicted in Fig. 1. Higher data rate modes for wireless transmission in orthogonal frequency division multiple input multiple output (OFDM) MIMO systems can only be attained if the sender has access to down-link channel status information (CSI) before transmission. The transmitter performs preceding on the transmission. Minimum mean square error (MMSE) and the vertical Bell laboratories layered space time (V-BLAST) encoder are examples of conventional MIMO detection methods used at the receiver. Linear preceding and non-linear preceding algorithms are the two broad categories into which preceding methods fall. Since they are so straightforward, linear preceding methods are frequently used in wireless networks. Both the CI and BD preceding schemes are supported by IEEE 802.11ac. To maximize throughput, non-linear preceding techniques are preferred. Tomlinson-Hiroshima (THP) and vector perturbation are two examples of non-linear preceding methods that can attain high output. (VP). However, they have not been used with the IEEE 802.11 protocols<sup>4</sup> due to the intricacy of the systems involved.

## 4. Theoretical background on preceding

When the amount of input in a MIMO system is low, preceding is used. It's also possible to think of preceding as a type of beam-forming. In order to boost the detected signal at the recipient, multiple signal streams are preceded and broadcast using multiple antennas, each with a unique weighting scheme. For the purposes of preceding, a preceding Definition of Matrix F

$$y = HFs + n, \quad (1)$$

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

$$H = \sqrt{\frac{1}{1+K}} H_{LOS} + \sqrt{\frac{K}{1+K}} H_{NLOS}, \quad (2)$$

$$H_{NLOS} = [R_{rx}]^{1/2} [H_{iid}] [R_{tx}]^{1/2}, \quad (3)$$

With  $R_{tx}$  and  $R_{rx}$  as the correlation matrices at the transmitter and receiver side, the channel model factor  $K$  (channel model values taken from [14]), and  $H_{iid}$  as the random complex Gaussian variables of unit variance and zero mean.  $F$  is the preceding matrix (in Frobenius form) of  $N_r \times N_t$  where  $M < \min(N_t, N_r)$ . The input signal vector  $s$  is an  $N \times 1$  matrix, and  $n$  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 codeword's  $F_1$  and  $F_2$  is maximized with [10]:

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

The chordal distance between two linearly dependent vectors is zero, while the greatest chordal distance between two orthogonal vectors is 1. A codebook  $C$  is a finite set of  $n$  codeword's  $c$  such that the minimal distance  $d$  between any two codeword's in the set is maximized.

Creating Codeword's, Section 4.1 When only a small amount of CSI data is accessible at the emitter, codeword-based precoding can be a useful alternative. Both the sender and the recipient have access to a collection of codebooks that were previously specified, presumably off-line. The number is the only information sent back to the sender after each transfer to indicate which codebook was used [5]. Codeword's  $c$ , for example, relate to components in the  $C$  codebook.

$$C^k = \{c_0^k, \dots, c_n^k\}. \quad (5)$$

$$c = \underset{c \in C}{\operatorname{argmin}} d(v, \bar{c}) \quad (6)$$

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

### Codeword selection strategies

MIMO systems use fixed codebooks which consists of a construction of preselected codeword's 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 effects may impact the transmission performance which may be optimized by a different set of codebooks and codeword's. In particular, long-range WLANs suffer from signal degradation and fading. Therefore, it is crucial to employ strong codeword's that enable a boost in signal power. Further enhancements can be achieved via the careful choosing of a preceding matrix index (PMI). In order to rectify errors detected by the code sequence, which is the union of all sequences containing the m-sequence, a precoder is employed. Codeword and the constituent parts of a completely made-up string, the signal string. For practical purposes, it is preferable to have a sequence set with a high minimum distance, whose components are the sequence sums of a linear error-correcting code. Included in this category are such sequences as the Kasami, Gold, Stiefel, and Kerdock sequences. The smallest gap between two such code sequences is

$$\frac{2^{2m} - 2^m}{2}, \quad (7)$$

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

The total code length  $L$  is  $22m+1$  (when the index part is odd). For instance, if the total code length is 16, the minimum distance is 6.

**Selected codebooks**

To achieve a small mean squared error, it is necessary to optimize the choral distance of the codeword's. Quantization of a codebook may take advantage of uniformity in the incoming data. Codeword's that minimize quantization error could be purposefully chosen when creating the codebook to take advantage of such harmony. To Grassmanians, The subspaces of dimension  $k$  in a vector space of size  $n$  make up the space  $Gr(n, k)$ . LTE and some WLANs typically use the Grassmannian codebook (code-bits=2), which is defined as

$$\begin{aligned} c_0^G &= \begin{bmatrix} -0.1612 - j0.7348 & -0.5135 - j0.4128 \\ -0.0787 - j0.3192 & -0.2506 + j0.9106 \end{bmatrix}, \\ c_1^G &= \begin{bmatrix} -0.2399 + j0.5985 & -0.7641 - j0.0212 \\ -0.9541 & 0.2996 \end{bmatrix}. \end{aligned} \tag{9}$$

As an alternative to Grassmannian, this paper proposes the use of the Ker dock manifold in long-range WLANs. The Ker dock 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

$$c_0^K = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, c_1^K = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}, \tag{10}$$

$$c_0^{Kmod} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, c_1^{Kmod} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 + j \\ 1 + j & 1 - j \end{bmatrix}. \tag{11}$$

**5. IEEE 802.11ahWLAN prototype**

In infrastructure basic service set (IBSS) configuration, a WLAN consists of a single WLAN AP and one or more WLAN STAs that are all connected to that AP. This study focuses solely on down-link preceding efficiency (from AP to STA) without sacrificing any breadth of coverage. There are  $N_t$  broadcast antennas on the WLAN AP in question. The STA is equipped with  $N_r$  radio receivers. When using  $N_t, r = 2$  in a 22 MIMOOFDM system,  $NS = 2$ . The IEEE 802.11ahWLAN standard is used in the suggested sub-1GHz WLAN prototype. Sub-1GHz WLAN standard IEEE 802.11ah is on the horizon, and it's been designed to provide greater range than its predecessors, IEEE 802.11ac and IEEE 802.11n. WLAN STAs and WLAN devices will be able to access the internet via IP thanks to IEEE 802.11ah's planned 1 km range. It offers both high scaling (supporting data rates of up to 78 Mbps in nations with high tx power and broad channel capacity) and a wide range of data rates (from low data rates for sensing apps, around 150 kbps, to high data rates of up to 1.8 GBps). (hundreds of nodes). IEEE 802.11ah specifies an innovative signal repeat strategy (called MCS 10) for achieving long-range coverage. In Table 5, we can see the prototype's pertinent system characteristics for the SDR-based IEEE 802.11ahWLAN. Our prior literature<sup>20</sup> and sources therein provide further information on the prototype and how to build up the SDR platform.

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 <sup>15</sup>
Channel bandwidth, $BW$	1 MHz	According ARIB STD-T108 <sup>15</sup>
Protocol	IEEE 802.11n/ah	IEEE 802.11ah WLAN prototype
Modulation	OFDM, 2x2 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 <sup>15</sup>
Codebook manifold	Grassmannian, Kerdock (original, modified)	
Traffic	ICMP (100B, 0.3 sending rate)	
Wireless link	LOS, 3 m	
Software	GnuRadio <sup>18</sup> , Hydra <sup>16</sup>	
RF front-end	USRPI, SBX <sup>19</sup>	Software defined radio
Antenna	VERT900 <sup>19</sup>	840-970 MHz, omni-directional

## 6. Performance evaluation and discussion

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

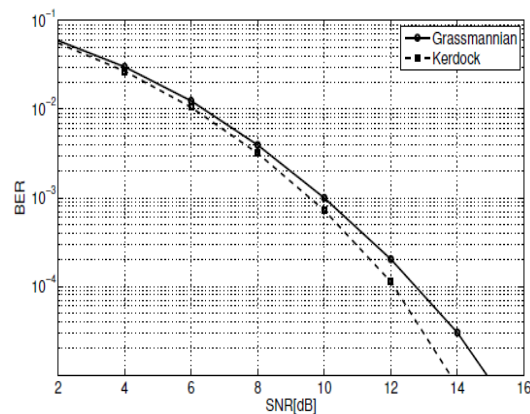


Fig. 2. Illustration of performance comparison between Grassmannian and proposed Kerdock preceding. creased gain ( $> 1$  dB) over the Grassmannian codebook (Eq. 9) can be observed when the Kerdock codebook is applied (Eq. 10). Next, in Fig. 3 at BER =  $10^{-5}$ , an increased gain ( $> 2$  dB) over 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 802.11ahWLAN prototype (Section 5). The codebook performance is evaluated, without loss of generality, in a simpleWLAN AP-STA scenario. A single ICMP flow was applied with packet size=100B in line of sight with 1m 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 proceed. 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 preceding

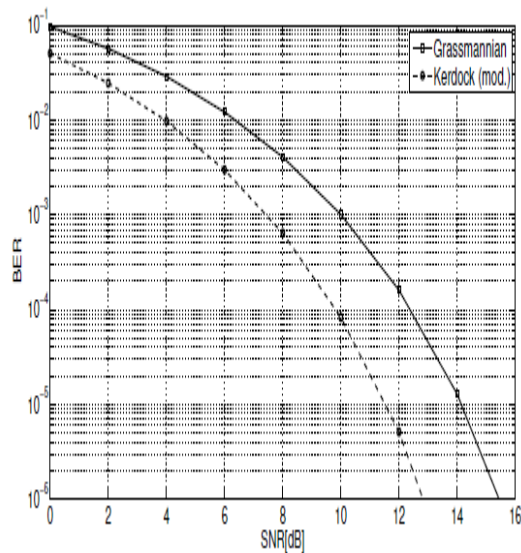


Fig. 3. Illustration of performance comparison between Grassmannian and modified Kerdock. Compared to Grassmannian. The simple codeword configuration of the Kerdock manifold has been found as the reason for the reduced processing delay. The results of the SNR of the Grassmannian, Kerdock, and the modified Kerdock

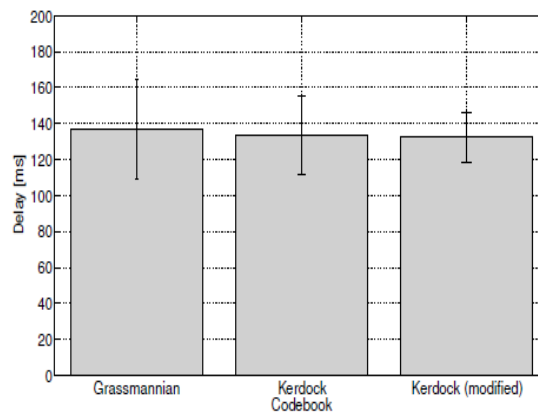


Fig. 4. Illustration of measured delay performance of Grassmannian, Kerdock, and modified Kerdock codebook. Codebooks are shown in Fig. 5. It can be observed that the Kerdock manifold increases the SNR at 2 dB. Further SNR improvement of 1 dB can be observed when the *modified* Kerdock manifold is applied. 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

Improving the wireless penetration of long-range sub-1GHz WLANs is a topic explored in this article. Particular attention was paid to improving precoding processes by choosing a codebook that leads to increased signal-to-noise ratio (SNR). Several preceding methods were reviewed, and their theoretical foundations were laid out. A detail on the Grassmannian manifold, which is used extensively in LTE and some WLAN applications, was presented. The Kerdock manifold was developed as an option to the Grassmannian; it exhibits comparable preceding efficiency while reducing the encoded signal delay. Both theoretical simulations and real-world applications of a new preceding scheme for manifolds like the Grassmannian and the Ker dock were analyzed.

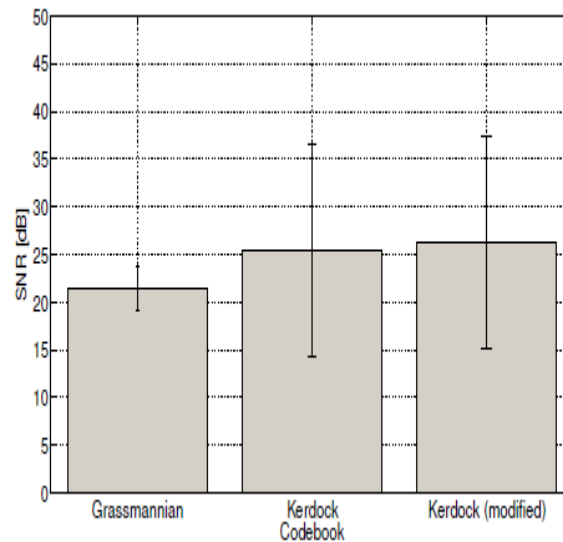


Fig. 5. Illustration of measured SNR of Grassmannian, Kerdock, and modified Kerdock codebook. Prototype of a software-defined radio (SDR) WLAN built on the IEEE 802.11ah standard. Compared to the Grassmannian manifold, the Kerdock manifold was shown to be superior. Modifications to the Kerdock codebook have also been suggested, and together with the choosing method, they result in a 2-3 dB preceding increase. In the near future, we hope to try even more advanced our suggested IEEE 802.11ah WLAN device allows for more code-bit clusters and bigger radio arrangements.

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