Bi-directional Beamforming Bit Error Ratio Analysis for Wireline Backhaul Networks

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***Abstract*—The next generation of digital subscriber line (DSL) standard will require the development of enabling technologies to exploit currently unused higher frequencies in the very and ultra high frequency bands over a shorter copper drop. At these higher frequencies, the indirect channels produced by the electromagnetic coupling (EMC) between pairs in a binder cable may be as strong as, or stronger than, the direct channels. In this work, we exploit the isomorphism between this wireline environment and the well-studied multipath wireless models to propose a full duplex wired MIMO system for the legacy copper connection in a point-to-point backhaul network. The proposed system achieves self-interference suppression and exploitation of the diversity offered by the EMC channels through a joint interoperable pre-coding scheme consisting of null space projection (NSP) and maximum ratio combining (MRC). Channel measurements for a 10 pair binder cable are used to evaluate the performance of the proposed system.**

I. INTRODUCTION

The fiber network proliferation has increased in recent years in order to meet the ever-increasing demand from customers, both business and private, for increased broadband data rates [1], [2]. Fiber to the home or premises is the ultimate goal in terms of achievable data rate, but will incur significant costs to the service providers. Instead, the hybrid fiber-copper network has been employed, where the fiber network is extended to a distribution point (DP) in the vicinity of the customer premises, and the existing copper wire infrastructure is used for the last leg of the communications from the DP to the customer premisis equipment (CPE). Recent standards have seen the length of the copper wire drop decreasing as the DP is moved closer to the customer, allowing increases in capacity [3], [4]. Shorter wires offer the potential to expand the region of operation to higher frequency bands, but the channel conditions in these new regions present new challenges.

The MIMO binder channel model [5] has been used in recent standards to model the crosstalk interference between the wire pairs in the binder from DP to CPE. This has allowed cancellation of far-end crosstalk (FEXT) through precoding techniques known as vectoring. In general, the strong near-end crosstalk (NEXT) is avoided through use of time or frequency duplexing. Channel measurements such as those discussed in [6] and those carried out for this paper and presented in Figs. 2 and 3 demonstrate that at the higher frequencies now under consideration for next generation digital subscriber line (DSL) systems, the FEXT paths provide as much or more power to the receiver than the direct path. Thus these paths offer a source of diversity which may be exploited to improve system performance, through for example maximum ratio combining (MRC).

Full duplex (FD) operation has been proposed in the wireless context to improve spectral efficiency by simultaneously transmitting and receiving at both transceivers in the system on the same frequency or frequencies. The potential benefits of FD are clear, but come at the cost of significant self-interference, where the interfering locally transmitted signals having greater power than the desired received signal at the transceiver. In the wireless systems, null-space projection (NSP) has been proposed as a method of self-interference suppression, by use of a precoder, equalizer pair [7], [8]. On the binder MIMO channel under full duplex operation, the self-interference at the transceiver is the NEXT, while the direct and FEXT paths are modelled by the channel matrix between transceivers, as described by Fig. 1. Discussion of recent research on full duplex in the wired context may be found in [9] and in [10] for the single-subscriber case.

In this paper, a full duplex system is developed for the MIMO copper backhaul network, with self interference suppression to deal with NEXT and which is capable of exploiting the diversity offered by the EMC between the pairs, the FEXT channels. The proposed joint interoperable pre-coding scheme consisting of null space projection (NSP) and maximum ratio combining (MRC) is possible as both NSP and MRC techniques share the same functional constraints. The advantage of the proposed system becomes apparent when the spectral efficiency of the high frequency bands over the individual direct channels vanishes due to the extreme scattering levels of the EMC channels. As this inevitably occurs, the multi-pair channel is processed as a MISO system using MRC to harness and steer the EMC scattering energy and maximise the signal-to-noise ratio (SNR) of the system whilst NSP enables full utilisation of the MISO bandwidth system bi-directionally without sacrificing bandwidth through necessary time or frequency guard intervals. Thus, the upper limit of the system bandwidth is extended and hence the capacity of the system is increased by the proposed joint pre-coding method. The proposed system is evaluated through direct use of channel

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measurements in a simulation environment to demonstrate the effectiveness of the proposed approach in a practical scenario.

II. SYSTEM MODEL

The modelled transmission scenario in this paper consists of a two-port network communicating over N bundled twisted copper pairs, see Fig. 1. The far-ends of each pair, being the primary communication channel, are connected to transceivers operating with a specific duplexing scheme, e.g. TDD, FDD, etc., to avoid the reflections due to imperfect channel excitation. FDD was widely adopted for DSL technologies operating in the high frequency (HF) band whilst TDD is used for the current generation of DSL, i.e., G.fast. Both of the aforementioned duplexing schemes limit the efficiency and the capacity of the transmission system. Therefore this paper attempts to push the limits of the current state of the art beyond capability by enabling full duplex operation to exploit the full potential capacity of the channel bi-directionally.

On the other hand, each communication channel was classically treated as an orthogonal spatial channel for the frequencies below the HF band since the electromagnetic coupling (EMC, mainly FEXT) between the communication channels was tolerable. Unfortunately, this behaviour fails to persist over the very high frequencies (VHF) and beyond into the ultra high frequencies (UHF) when the desired signals become weakly bounded to their initial pairs and subsequently the propagating signals across the pairs become strongly intertwined over the multi-pair channel. It will be shown later in this paper that the FEXT coupling between 2 adjacent pairs becomes more dominant than the end-to-end coupling of a single pair beyond a specific critical frequency. For this reason, in addition to FD, MRC is proposed to harness the scattering capacity of the channel ensemble represented by FEXT. This implies that the signal processing is isomorphic to the well-known multipath MIMO channel in the wireless domain.

A. Full Duplex Transmision

In order to enable FD operation, NSP is adopted to derive the necessary digital spatial filters (DSFs) for each transmitter, denoted by $\mathbf{F}_{\mathrm{p}} \in \mathbb{C}^{N\times 1}$, and receiver, denoted by $\mathbf{G}_{\mathrm{p}} \in \mathbb{C}^{1\times N}$, in the MIMO system,where $\mathrm{p} \in \{\mathrm{a},\mathrm{b}\}$ is the port index. Each DSF is directly dependent on the eigenvectors of the self-coupling channel, e.g. see $\mathbf{H}_{\mathrm{aa}} \in \mathbb{C}^{N\times N}$ in Fig. 1. The construction method proceeds by factorising the channel to its eigenvalues and eigenvectors by applying Singular Value Decomposition (SVD), i.e. $\mathbf{H}_{\mathrm{aa}} = \mathbf{U}_{\mathrm{aa}}\mathbf{\Sigma}_{\mathrm{aa}}\mathbf{V}_{\mathrm{aa}}^H$, where $\mathbf{U}_{\mathrm{aa}} \in \mathbb{C}^{N\times N}$ and $\mathbf{V}_{\mathrm{aa}} \in \mathbb{C}^{N\times N}$ are orthonormal matrices $\because$ $\mathbf{U}_{\mathrm{aa}}^H\mathbf{U}_{\mathrm{aa}} = \mathbf{U}_{\mathrm{aa}}\mathbf{U}_{\mathrm{aa}}^H = \mathbf{I}$ and $\mathbf{V}_{\mathrm{aa}}^H\mathbf{V}_{\mathrm{aa}} = \mathbf{V}_{\mathrm{aa}}\mathbf{V}_{\mathrm{aa}}^H = \mathbf{I}$. While $\mathbf{\Sigma}_{\mathrm{aa}} \in \mathbb{R}_+^{N\times N}$ is a diagonal matrix which contains the eigenvalues of the channel in descending order. This technique applies strict constraints on the number of the unique data streams which is bounded by the dimensions of the MIMO system, the detailed analysis is presented in [7]. The self-coupling interference model can be formulated as follows:

$$\mathbf{y}_{\mathrm{aa}} = \overbrace{\mathbf{G}_{\mathrm{a}} \underbrace{\mathbf{H}_{\mathrm{aa}}}_{\mathbf{U}_{\mathrm{aa}}\mathbf{\Sigma}_{\mathrm{aa}}\mathbf{V}_{\mathrm{aa}}^H} \mathbf{F}_{\mathrm{a}}}^{\approx 0} \mathbf{x}_{\mathrm{a}}, \qquad (1)$$

and the full system model in the presence of NSP becomes:

$$\mathbf{y}_{\mathrm{a}} = \mathbf{G}_{\mathrm{a}}\left(\mathbf{U}_{\mathrm{aa}}\mathbf{\Sigma}_{\mathrm{aa}}\mathbf{V}_{\mathrm{aa}}^H\mathbf{F}_{\mathrm{a}}\mathbf{x}_{\mathrm{a}} + \mathbf{H}_{\mathrm{ab}}\mathbf{F}_{\mathrm{b}}\mathbf{x}_{\mathrm{b}} + \mathbf{n}_{\mathrm{a}}\right), \qquad (2)$$

where $\mathbf{x}_{\mathrm{a}} = [x_{\mathrm{a}}^1, x_{\mathrm{a}}^2, ..., x_{\mathrm{a}}^{N_{\mathrm{a}}}]^T$ and $\mathbf{x}_{\mathrm{b}} = [x_{\mathrm{b}}^1, x_{\mathrm{b}}^2, ..., x_{\mathrm{b}}^{N_{\mathrm{b}}}]^T$ are the complex symbols transmitted at nodes $\mathtt{a}$ and $\mathtt{b}$, respectively.

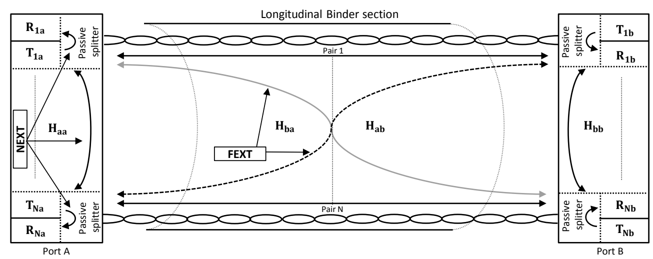

Fig. 1. Bi-directional full duplex 10 pair wired communication system with Null-space projection for NEXT and self-coupling cancellation

The goal in designing these filters is to obtain $\mathbf{G}_{\mathrm{p}}\mathbf{H}_{\mathrm{pp}}\mathbf{F}_{\mathrm{p}} = \mathbf{0}$, for $\mathrm{p} \in \{\mathrm{a},\mathrm{b}\}$, which is referred to as NSP [11]. In designing $\mathbf{F}_{\mathrm{p}}$ and $\mathbf{G}_{\mathrm{p}}$, it is necessary to choose these filters such that they satisfy $\min \|\mathbf{G}_{\mathrm{p}}\mathbf{H}_{\mathrm{pp}}\mathbf{F}_{\mathrm{p}}\|_F^2$, where $\|.\|_F$ is the Frobenius norm.

There are several approaches that can be used for this purpose as in [7], [11]–[13]. We apply the method of [12], and in order to apply spatial multiplexing to obtain orthonormal streams, the filters are constrained such that $\mathbf{F}_{\mathrm{p}}^H\mathbf{F}_{\mathrm{p}} = I$ and $\mathbf{G}_{\mathrm{p}}\mathbf{G}_{\mathrm{p}}^H = I$. This can be achieved, as in [12], by choosing

$$\mathbf{F}_{\mathrm{p}} = \mathbf{V}_{\mathrm{pp}}\mathbf{S}_{\mathrm{p}} \quad \text{and} \quad \mathbf{G}_{\mathrm{p}} = \mathbf{T}_{\mathrm{p}}\mathbf{U}_{\mathrm{p}}^H, \qquad (3)$$

where $\mathbf{S}_{\mathrm{p}}$ and $\mathbf{T}_{\mathrm{p}}$ represent the binary column and row selection matrices, respectively. The optimum design for these two matrices can be achieved by satisfying the following conditions: $\mathbf{S}_{\mathrm{p}}^H\mathbf{S}_{\mathrm{p}} = I$, $\mathbf{T}_{\mathrm{p}}\mathbf{T}_{\mathrm{p}}^H = I$, $\mathbf{T}_{\mathrm{p}}\mathbf{S}_{\mathrm{p}} = \mathbf{0}$, and $\mathbf{G}_{\mathrm{p}}\mathbf{H}_{\mathrm{pp}}\mathbf{F}_{\mathrm{p}} = \mathbf{T}_{\mathrm{p}}\mathbf{\Sigma}_{\mathrm{pp}}\mathbf{S}_{\mathrm{p}}$. Furthermore, we propose applying maximum-ratio combining after NSP to the received signal in order to improve the SNR [14, p. 230-233]. This is can be achieved by combining the desired incoming signals, which contain the direct signal in addition to the indirect signal created by the far-end cross talk (FEXT). It is worth mentioning that exploiting NSP to mitigate the interference along with MRC to enhance the power of the desired incoming signal will maximise the SNR for the proposed system which consequently improves the overall system performance.

On the other hand, NSP introduces a normalisation problem since the $\mathbf{F}_{\mathrm{p}}$ may apply non-unity weighting factors to the desired signals. This problem will be revisited and resolved in the following section.

B. Transmission Modeling

The transmission model in this paper attempts to recover the frequencies which experience high levels of attenuation over the direct channels whilst being overwhelmed by the severity of the scattering and the nature of the EMC from the neighbouring pairs. This behaviour, as mentioned earlier in this paper, is analogous to the multipath effect of the wireless channels, which can be exploited as information channels via diversity combining techniques.

In [15], for instance, MRC has been studied for multi-pair copper channels. The initial research outcomes suggest that the scattering capacity can be prolific towards the upper edges of the VHF and beyond into the UHF bands. Intuitively, diversity/scattering combining, e.g. via MRC, can force the current state of the art system bandwidth beyond its limits and hence its capacity. In this paper, MRC is introduced alongside NSP since both techniques are operable under similar degrees of freedom. For each FD channel there must be a channel reserved to enable NSP, hence the ensemble carries only one unique data stream. Likewise, for each beamed channel, one unique data stream can be communicated. Hence, enabling one technique subsequently enables the other.

In order to use FEXT as information channels, the coupled transmission must be coherent. Hence the MRC pre-codes the support signals to arrive at one destination in phase with the desired signal. This can be carried out by applying the unity transpose conjugate of the channel (widely known as Hermitian) to the desired signal to align the phase and avoid power amplifications. Hence the generic transmission model in the absence of NSP is given by:

$$\mathbf{y}_{\mathsf{a}} = \mathbf{H}_{\mathsf{ab}} \underbrace{\mathbf{P}_{\mathtt{MRC}}}_{\text{is the MRC pre-coder } \frac{\mathbf{H}_{\mathsf{ab}}^H}{|\mathbf{H}_{\mathsf{ab}}^H|}} \mathbf{x}_{\mathsf{b}} + \mathbf{n}_{\mathsf{a}}, \tag{4}$$

where $\mathbf{P}_{\mathtt{MRC}}$ has to be a unit vector/matrix, i.e. $\mathbf{P}_{\mathtt{MRC}}\mathbf{P}_{\mathtt{MRC}}^H = I$.

In the preceding, $\mathbf{H}_{\mathsf{ab}}^H$ and $|\mathbf{H}_{\mathsf{ab}}|$ are the Hermitian (transpose conjugate) and the absolute operation for $\mathbf{H}_{\mathsf{ab}}$. The channel matrices are defined as $\widetilde{\mathbf{H}}_{\mathsf{aa}} \in \mathbb{C}^{N_{\mathsf{a}} \times N_{\mathsf{a}}}$ for the NEXT and self-coupling and $\mathbf{H}_{\mathsf{ab}} \in \mathbb{C}^{N_{\mathsf{a}} \times N_{\mathsf{a}}}$ for the FEXT. In this paper, we employ M-ary quadrature amplitude modulation (QAM) as the modulation scheme to produce the symbols $\mathbf{x}_{\mathsf{a}}$ and $\mathbf{x}_{\mathsf{b}}$. Additionally, $\mathbf{n}_{\mathsf{a}}$ in (4) represents additive white Gaussian noise (AWGN) at node a with zero mean and variance equal to $\sigma_{n_{\mathsf{a}}}^2 I$, i.e. $\mathbf{n}_{\mathsf{a}} \sim \mathbb{CN}(0, \sigma_{n_{\mathsf{a}}}^2 I)$.

The incorporation of MRC into the FD system implies that $\mathbf{P}_{\mathtt{MRC}}$ has to be the last processing unit before the Inverse Discrete Fourier Transform (IDFT). Such a configuration leaves $\mathbf{F}_{\mathsf{b}}$ behind $\mathbf{P}_{\mathtt{MRC}}$ which alters and scales the phase and the amplitude of the desired signal and subsequently corrupts the transmission system. We tackle this problem with the following steps:

1) introduce a binary matrix, **B**, to identify the desired destination of beam channel. In the case that pair one is selected, column 1 of **B** is set to 1 and zeros elsewhere.

$$\mathbf{y}_{\mathsf{a}} = \mathbf{H}_{\mathsf{ab}}\mathbf{B}\mathbf{P}_{\mathtt{MRC}}\mathbf{x}_{\mathsf{b}} + \mathbf{n}_{\mathsf{a}}, \tag{5}$$

2) modify the self-coupling interference by merging it with the MRC pre-coder as follows:

$$\tilde{\mathbf{H}}_{\mathsf{aa}} = \mathbf{H}_{\mathsf{aa}}\mathbf{B}\mathbf{P}_{\mathtt{MRC}}, \tag{6}$$

This is followed DSF by the design as detailed earlier in Section A. This step ensures that $\mathbf{F}$ is always unity and implies no power adjustment. However, it may alter the phase of the final precoded signal yet this is not as problematic as the $\mathbf{G}$ at the receiving end. Thereafter, the combined FD and MRC models can be re-written as:

$$\mathbf{y}_{\mathsf{a}} = \mathbf{G}_{\mathsf{a}}\left(\tilde{\mathbf{H}}_{\mathsf{aa}}\mathbf{F}_{\mathsf{a}}\mathbf{x}_{\mathsf{a}} + \mathbf{H}_{\mathsf{ab}}\mathbf{B}\mathbf{P}_{\mathtt{MRC}}\mathbf{F}_{\mathsf{b}}\mathbf{x}_{\mathsf{b}} + \mathbf{n}_{\mathsf{a}}\right), \tag{7}$$

3) detection and equalisation has to take into account the end-to-end channel estimation as shown below:

$$\tilde{\mathbf{H}}_{\mathsf{ab}} = \mathbf{G}_{\mathsf{a}}\mathbf{H}_{\mathsf{ab}}\mathbf{B}\mathbf{P}_{\mathtt{MRC}}\mathbf{F}_{\mathsf{b}}, \tag{8}$$

re-writing equation 7,

$$\mathbf{y}_{\mathsf{a}} = \underbrace{\mathbf{G}_{\mathsf{a}}\tilde{\mathbf{H}}_{\mathsf{aa}}\mathbf{F}_{\mathsf{a}}}_{\text{NSP}}\mathbf{x}_{\mathsf{a}} + \tilde{\mathbf{H}}_{\mathsf{ab}}\mathbf{x}_{\mathsf{b}} + \mathbf{G}_{\mathsf{a}}\mathbf{n}_{\mathsf{a}}, \tag{9}$$

finally, signal detection is obtained by applying the pseudo inverse of the channel $\tilde{\mathbf{H}}_{\mathsf{ab}}$ as follows:

$$\tilde{\mathbf{x}}_{\mathsf{b}} = \tilde{\mathbf{H}}_{\mathsf{ab}}^H\left(\tilde{\mathbf{H}}_{\mathsf{ab}}.\tilde{\mathbf{H}}_{\mathsf{ab}}^H\right)^{-1}\mathbf{y}_{\mathsf{a}}. \tag{10}$$

III. CHANNEL MEASUREMENTS

In this section, the cable channel measurements are presented. The measurements were taken using a two-port vector network analyser for a BT cable with 10 twisted pairs of wire, with each wire having diameter 0.5mm. Direct, FEXT and NEXT channels were evaluated. The channel frequency responses are provided in Figs. 2 and 3. In both figures, all of the direct channels are shown, while in Fig. 2 the FEXT channels are also included. This figure confirms that above 150Mhz, the crosstalk signals have comparable or greater strength than the direct channel. These measurements demonstrate the need for novel approaches to allow signalling at these frequencies, motivating the proposed use of MRC to construct a MISO system to offer improved SINR and thus to improve the performance and offer increased bandwidth in the system. Fig. 3 shows the channel frequency response of the same direct channels, along with the NEXT and self-coupling interference channels. This figure demonstrates the extremely challenging channel conditions introduced by the indirect EMC channels. In standards to date, including the recently announced G.fast standard, NEXT is avoided by use of either TDD or FDD. However, this solution sacrifices significant spectral efficiency. These points motivate the jointly proposed NSP approach to allow FD operation.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, the simulation study for the proposed jointly pre-coded full-duplex wired transceiver is presented. The bi-directional operation is investigated, with ports a and b of Fig. 1 transmitting simultaneously in the same frequency band.

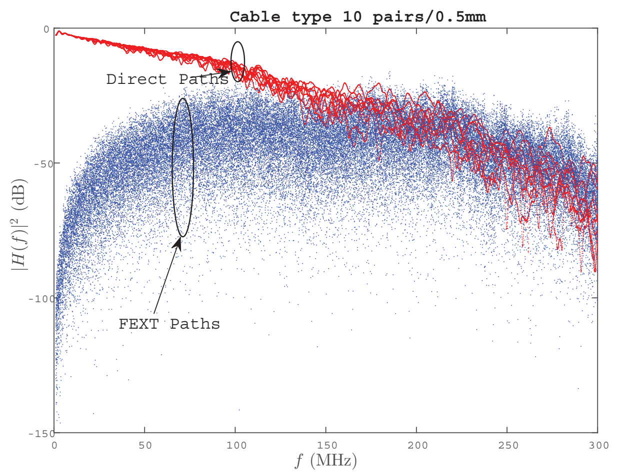

Fig. 2. Plot of power of direct and FEXT paths for the channel measurements

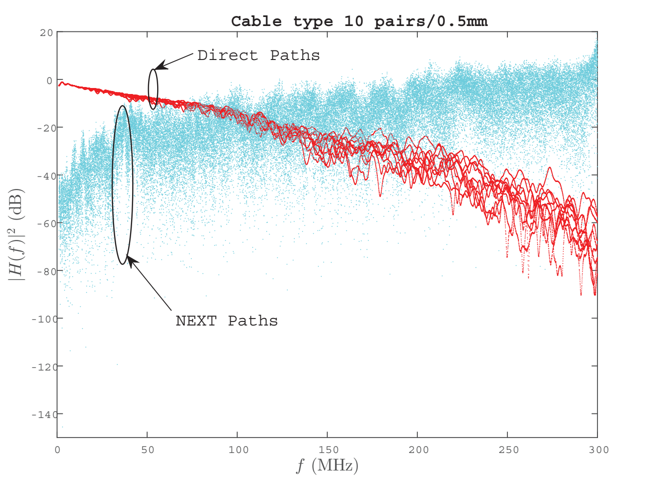

Fig. 3. Plot of power of direct and NEXT paths for the channel measurements

The received signal at port a is impaired by NEXT and self-coupling due to the near-end transmitting terminals, and this interference is mitigated by the proposed NSP suppression approach. The signal is additionally subject to FEXT, and the proposed MRC approach combines the direct channel with the indirect paths resulting from this FEXT to exploit the available diversity of the multi-pair channel.

An uncoded M-QAM modulation scheme is used for the simulated digital subscriber line (DSL) environment, for a number of modulation orders, as presented in Figs. 4 and 5. There are 10 twisted pairs in the cable between the ports. In the simulated DSL system, the channel impairments used to test performance, i.e., the direct channel path losses, self-coupling and NEXT, and FEXT, are taken directly from the channel measurements. In addition, randomly generated additive noise is included. Figs. 4 and 5 demonstrate error rate performance for the proposed full-duplex system under these conditions. In each case, the proposed NSP approach is applied to mitigate the self and NEXT interferences, while the performance results for the proposed system both with and without MRC are provided. These results clearly demonstrate that a significant performance enhancement is offered when the indirect FEXT channels are exploited constructively under MISO operation. The merge of NSP with MRC reveals that we can obtain an additional 12 dB gain at BER=10^{-4} resulting from maximising the combining of the direct desired path with the indirect coupling, FEXT, which is taken place between the wires. In addition, in both Fig. 4 and Fig. 5, the uncoded performance of the considered modulation schemes on an additive white Gaussian noise (AWGN) channel is provided as a reference.

Fig. 6 attempts to evaluate the maximum diversity gain of the system using Time Division Duplex (TDD) instead when all the pairs are steered into pair 4 and compared to zero-forcing. The simulated results, using 2^6-QAM, demonstrates that we can obtain about 22 dB gain at BER=10^{-4} by applying MRC with conventional zero forcing without NSP. This means that there is approximately a 10 dB loss caused by NSP. The reason behind this is that the transmitting end spatial filer, $\mathbf{F}$, may reduce the coherence of the transmission by altering the phase of the signals and subsequently the likelihood of achieving optimal constructive EMC. At the receiving ends, the spatial filer $\mathbf{G}$ plays a major role in degrading the MRC gain by amplifying the noise, since its coefficients are not unity. Fig. 6 additionally provides a direct comparison between the error rate performances of the FD NSP system and the TDD system. However, these results should be viewed in the context of the spectral efficiency and overall system capacity improvements of the FD system.

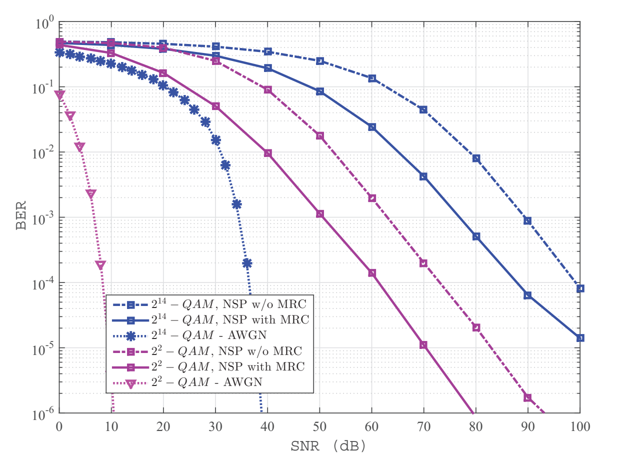

Fig. 4. SNR vs. BER of 2^2-QAM and 2^{14}-QAM for 10-pairs ($D = 0.5$mm) FD bi-directional wired system with NSP-MRC

V. CONCLUSIONS

In order to offer greater bandwidth over shorter loops, the higher (VHF and UHF) frequency bands are considered in this paper. However, it was demonstrated through the use of channel measurements that at these operating regions, the spectral efficiency over the individual direct channels vanishes

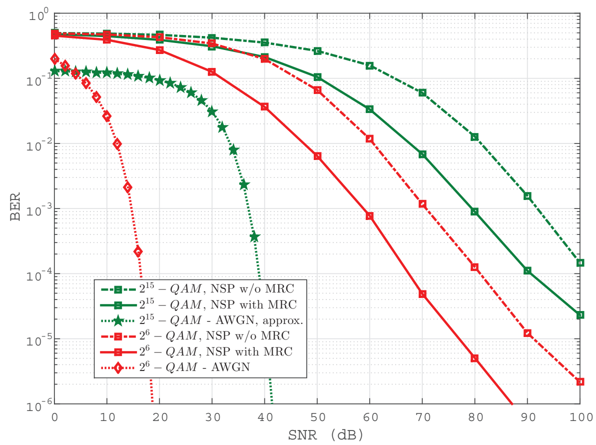

Fig. 5. SNR vs. BER of 2^6-QAM and 2^{15}-QAM for 10-pairs ($D = 0.5$mm) FD bi-directional wired system with NSP-MRC

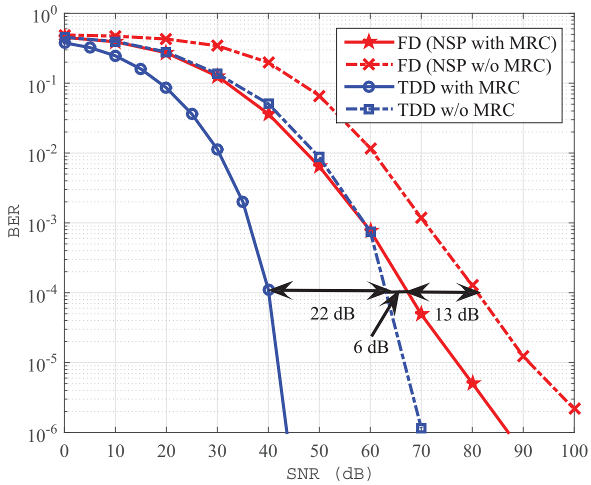

Fig. 6. SNR vs. BER of 2^6-QAM for 10-pairs ($D = 0.5$mm) TDD and FD bidirectional wired system with and without MRC

TABLE I
SIMULATION SETTING

Channel Type	10/0.5mm (pairs-count/dimeter)
Channel length	BT Cable, 25 m
System bandwidth	1-300 MHz
Tone spacing (DMT)	51750 Hz
Modulation	QAM

due to high scattering levels of the EMC channels. As this is an unavoidable characteristic of the copper wire binder environment, an alternative mode of operation was proposed whereby the multi-pair channel is processed as a MISO system using MRC to harness and steer the scattering energy and maximise the SNR of the system. The jointly proposed NSP approach allows full use of the constructed MISO system bi-directionally, with the added benefit of removing the need for any time or frequency guard intervals. As a result, the upper limit of the system bandwidth is extended through the increased capacity of the system offered by the proposed joint precoding method. Finally, we would like to stress that although NSP and MRC are interoperable, since both consume equal numbers of dimensions from the MIMO system, NSP restricts the use case scenarios of MRC to point-to-point systems whilst reducing the coherence of the transmission and amplifying its noise levels.

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