On the Applicability of Nonlinear MIMO in Sensor Networks

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Abstract— **MIMO systems have attracted attentions in wireless applications recently because of their potential to dramatically enhance data rates over wireless channel. In this paper, we consider the deployment of Multi-input Multi-output (MIMO) spatial multiplexing systems on sensor networks (SN). Sensor networks are limited in power and complexity. Therefore, brute-force MIMO systems are not suitable to be implemented on them. In contrast, nonlinear MIMO techniques are designed to reduce the complexity of brute-force MIMO systems, so that they could be implemented in sensor networks. Simulation of MIMO maximum likelihood detector (MIMO-MLD) is presented for 2×2 MIMO system in addition to linear reduced complexity MIMO schemes, zero forcing and MMSE. Thereafter, a study of nonlinear MIMO systems in terms of performance and complexity was performed. Finally, all designs were transformed into MATLAB codes compatible with AccelDSP format in order to generate Xilinx blocks that demonstrate different MIMO techniques on hardware. These blocks are then tested for their performance and complexity to be compared with the previous results.**

I. Introduction

In sensor networks, the cost of each node has to be kept as low as possible because the number of nodes deployed in typical applications can be very huge [1]. Moreover, sensor nodes are deployed in remote and dangerous locations and their maintenance such as battery replacement will be unlikely. Therefore, there is a great interest in optimizing and reducing the power consumption of sensor nodes [2]. Nonlinear modulators, such as on-off keying (OOK) [3] and frequency-shift-keying (FSK), are commonly used in sensor nodes design. These techniques use envelop detector which result in major power saving in both transmitter and receiver compared to the other modulation schemes by detecting the amplitude of the received signal using envelope detector traditionally [3].

Even though, the deployment of MIMO networks promises performance enhancements over conventional single-input, single-output (SISO) technology for a fixed radiated power. Recently, the attempts at using MIMO technique in sensor networks have only considered the idea of Virtual MIMO system, where each sensor node is essentially a SISO system but can co-operate with nearby SISO sensor nodes to collectively form MIMO transmission over a given coverage area. This idea improves the error rate performance via the diversity effect, but not the data rate [4] since multiple antenna transmissions are not deployed in each sensor nodes.

To facilitate data rate enhancements in sensor networks, the work in [5] proposes a reduced complexity MIMO system for sensor networks, called nonlinear MIMO, where a nonlinear function of the signal (amplitude or phase) is used for MIMO signal detection at the receiver. Indeed, MIMO systems are well known for their large complexity making brute-force MIMO systems unaffordable at sensor nodes. In order to make them affordable for sensor networks, their complexity and power consumption must be pruned down to a level that matches the requirement of SN. The employment of nonlinear MIMO in SN as considered in [5] is one of the many possible approaches for reducing MIMO complexity to a level that might be affordable by sensor nodes due to their low power consumption and modest complexity [5].

However, the focus of the work in [5] is on characterizing the date rate achievable in sensor networks using NL MIMO. Error rate performances of such scheme or its complexities were not analyzed. In this paper, we present BER performance of the NL MIMO system in [5] and compare this with existing simple MIMO detection schemes such as MIMO-ZF and existing full complexity MIMO schemes such as MIMO-MLD. We show that despite the very simple nature of NL MIMO (simpler than ZF); its error rate performance is much better than ZF.

On the applicability of NL MIMO in sensor networks, we conduct the complexity analysis of the NL MIMO system and compare this information with typical complexities affordable in state-of-the-art sensor networks. We then deduce that for the case of BPSK modulation, NL MIMO scheme would be affordable in sensor networks. Thus, we conclude that NL MIMO implementation as discussed above could be affordable in sensor nodes.

II. MIMO Detection Approaches and Their Complicities

Here, we consider a MIMO system with N_t transmit antennas and N_r receive antennas shown in Fig.1. The received signal vector is represented as:

$$\boldsymbol{y} = \boldsymbol{H}\,\boldsymbol{s} + \boldsymbol{n}$$

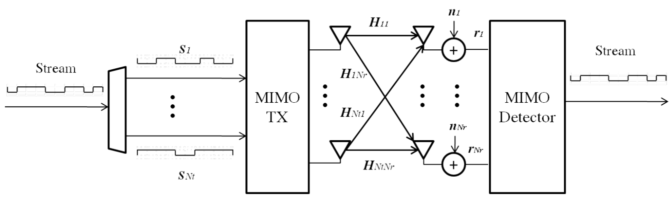

Fig.1. MIMO system with N_t transmit antenna and N_r receive antenna.

Where $\boldsymbol{H}$ is an $N_t \times N_r$ channel gain matrix whose elements are independent zero-mean complex Gaussian random variables with a unity variance. The N_r elements of vector $\boldsymbol{n}$ are samples of independent complex additive white Gaussian noise (AWGN) processes with single-sided power spectral density N_o [6]. In this paper, the performance of different MIMO detectors will be examined as follow:

A. Maximum Likelihood Detector

Maximum Likelihood detector (MLD) is the optimal detector for MIMO multiplexing systems. It gives the best BER performance but with the highest complexity load. In ML detector, decision is taken according to the minimum Euclidean distance [7]:

$$\hat{c} = arg\ \ min\|\boldsymbol{y} - \boldsymbol{Hs}\|^2$$

Computational steps that are followed within the ML detector are demonstrated in Fig.2.

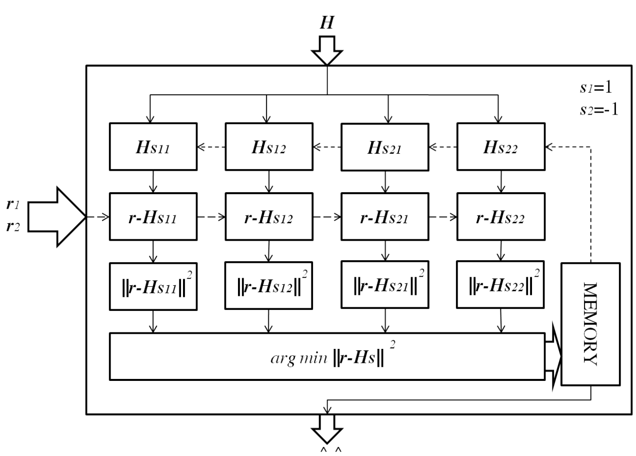

Fig.2. Operations stages inside the ML detector for BPSK 2×2 linear MIMO spatial multiplexing system.

The operational complexity load of such detector can be developed in general formulas summarized in Table I where M is the number of constellation vectors and k is the number of bits per symbol.

B. Zero Forcing Detector

In a zero forcing (ZF) detector, the inverse of the channel matrix is multiplied directly by the received signal vector $\boldsymbol{y}$ which leads into interference suppression. However, noise will be amplified [8] as demonstrated in the following equation:

$$\boldsymbol{s_{ZF}} = \boldsymbol{H^{-1}}\ \boldsymbol{y}$$
$$\rightarrow\ \boldsymbol{s_{ZF}} = \boldsymbol{s} + \boldsymbol{H^{-1}}\ \boldsymbol{n}$$

Decision here is also taken according to the minimum Euclidean distance:

$$\hat{c} = arg\ \ min\|\boldsymbol{s_{ZF}} - \boldsymbol{s}\|^2$$

The complexity analysis for 2×2 MIMO-ZF system is summarized in Table II.

C. Minimum Mean Square Error Detector

Minimum Mean Square Error detector (MMSE) minimizes the noise power between the received and desired signal by generating a weight matrix $\boldsymbol{G}$:

$$\boldsymbol{G} = \boldsymbol{H^H}(\boldsymbol{HH^H} + \sigma^2\boldsymbol{I})^{-1}$$

Received signal $\boldsymbol{y}$ is multiplied by the weight matrix $\boldsymbol{G}$. Decision is again taken according to the minimum Euclidean distance [9]:

$$\hat{c} = arg\ \ min\|\boldsymbol{s} - \boldsymbol{Gy}\|^2$$

Complexity computational load are summarized in Table III for 2×2 MIMO system.

D. Nonlinear Phase Detector

The proposed MIMO system in [5] has a nonlinear operator $g()$ set before the detector as shown in Fig.3.

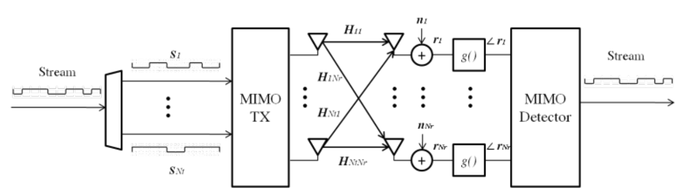

Fig.3. Nonlinear MIMO system with N_t transmit antenna and N_r receive antenna.

The nonlinear operator captures only the phase of received signal in the RF stage and then feeds it into the detector:

$$g(r_i) = y_{i,phase} = \angle(r_i) = \tan^{-1}\left(\frac{\Im(y_i)}{\Re(y_i)}\right)$$

Then, ML detection of MIMO system based in extracted phase information is conducted. The internal parts of the ML detector should be modified to perform simpler one-dimensional operations as demonstrated in Fig.4 block B2.

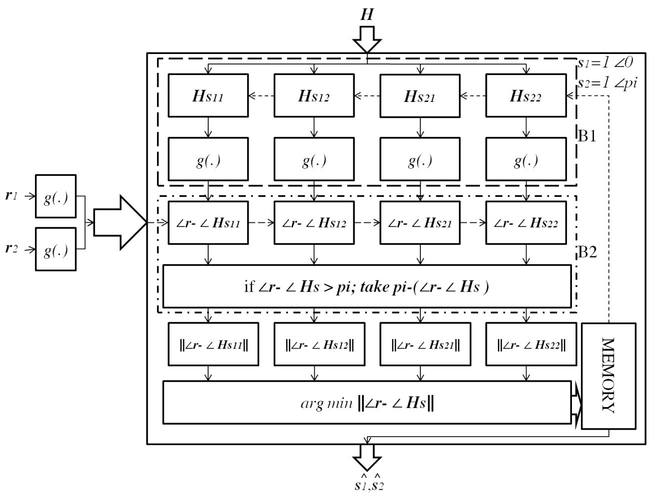

Fig.4. Operations stages inside the phase detector (nonlinear MIMO detector) in BPSK 2×2 MIMO spatial multiplexing system.

Decision is then taken according to the one-dimensional Euclidean distance between phases:

$$\hat{c} = arg\ \ min\|\angle \boldsymbol{r} - \angle \boldsymbol{Hs}\|$$

Complexity is assumed to be reduced and computational formulas are listed in Table IV.

To achieve higher complexity reduction, operations in Fig.4 block B1 might be done on the RF stage as delay elements instead of complex logical multiplication. After that, we would have complex logical additions to simulate the performance of regular matrix multiplication. This is explained in Fig.5. Computational complexity in this case is presented in Table V.

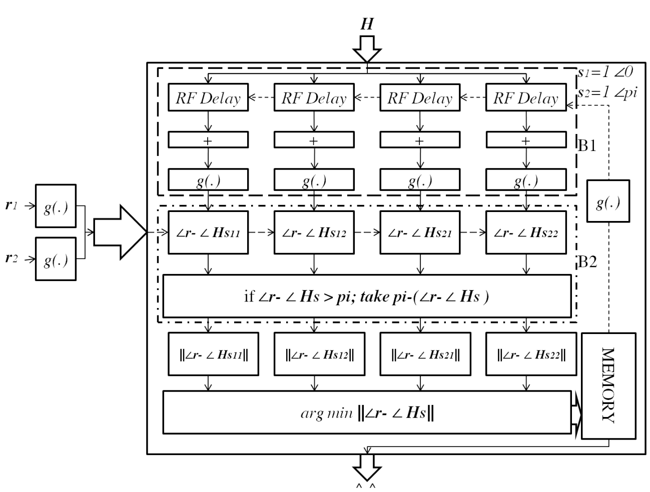

Fig.5. Operations stages inside the phase detector (nonlinear MIMO detector) in BPSK 2×2 MIMO spatial multiplexing system with extended RF stage.

TABLE I

COMPLEXITY COMPUTATIONS FORMULAS FOR ML DETECTOR

Operation	Formula
Complex Multiplication	$N_tN_rM^{N_t}$
Scalar Multiplication	$2N_rM^{N_t}$
Complex Addition	$((N_r-1)N_t)M^{N_t}$
Scalar Addition	$(2N_r-1)M^{N_t}$
Complex subtraction	$N_rM^{N_t}$
Comparison	$M^{N_t}-1$

TABLE II

COMPLEXITY COMPUTATIONS FORMULAS FOR 2×2 MIMO-ZF DETECTOR

Operation	Formula
Complex Multiplication	N_rN_t+8
Scalar Multiplication	$2N_rM^{N_t}$
Complex Addition	N_r-1
Scalar Addition	$(2N_r-1)M^{N_t}$
Complex subtraction	$N_rM^{N_t}+1$
Comparison	$M^{N_t}-1$

TABLE III

COMPLEXITY COMPUTATIONS FORMULAS FOR 2×2 MIMO-MMSE DETECTOR

Operation	Formula
Complex Multiplication	$2N_t^2N_r+N_tN_r+8$
Scalar Multiplication	$2N_rM^{N_t}+N_r+1$
Complex Addition	$2(N_r-1)N_t^2+N_rN_t+N_r-1$
Scalar Addition	$(2N_r-1)M^{N_t}$
Complex subtraction	$N_rM^{N_t}+1$
Comparison	$M^{N_t}-1$

TABLE IV

COMPLEXITY COMPUTATIONS FORMULAS FOR NONLINEAR MIMO DETECTOR

Operation	Formula
Complex Multiplication	$N_tN_rM^{N_t}$
Scalar Multiplication	$N_rM^{N_t}$
Complex Addition	$(N_r-1)N_tM^{N_t}$
Scalar Addition	$(N_r-1)M^{N_t}$
Scalar subtraction	$N_rM^{N_t}$
Comparison	$M^{N_t}-1$

TABLE V

COMPLEXITY COMPUTATIONS FORMULAS FOR NONLINEAR MIMO DETECTOR WITH EXTENDED RF STAGE.

Operation	Formula
Complex Multiplication	0
Scalar Multiplication	$N_rM^{N_t}$
Complex Addition	$(N_r-1)N_tM^{N_t}$
Scalar Addition	$(N_r-1)M^{N_t}$
Scalar subtraction	$N_rM^{N_t}$
Comparison	$M^{N_t}-1$

III. SIMULATION RESULTS

Next, we examine the error rate performance of NL MMO system. We started by testing the BER performance of NL MIMO for different constellations and compare them with the counterpart MLD detector performance. In Fig.6, results are presented for 2×2 MIMO-MLD system in a Rayleigh fading channel. The same results of conventional nonlinear phase detection MIMO are in Fig.7 with the same constellations. For nonlinear MIMO with extended RF stage, results are shown in Fig.8. It is observed from these results that:

- NL MIMO with BPSK and QPSK modulations are having very good error rate performance.
- NL MIMO with higher order constellations such as 16PSK and 16QAM comprise BER performance too much and not be advisable.
- The case of 16QAM (and this is true for any other constellation having two or more signal pairs with the same phase) leads to error floor that cannot be resolved by increasing the SNR making error free application of NL MIMO not possible even at infinite SNR. Thus, the major practically advisable scenario for the utilization of NL MIMO in sensor networks would be with BPSK and QPSK modulations, when error rate performance are considerable. This is similar to what exists now in the 3G cellular system where almost all 3G networks deploy only BPSK or QPSK (and their variants). 16QAM or 16PSK were not deployed due to large BER degradation. The deployment of 16QAM is only practically achieved in WIMAX (4G systems).

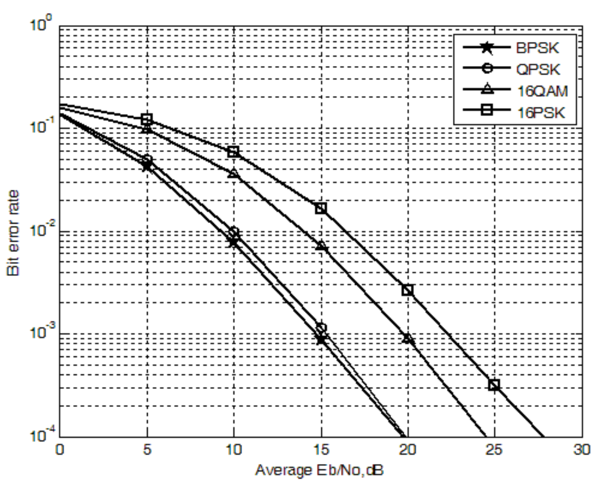

Fig.6. BER Simulation for different constellations with 2×2 MIMO-MLD in a Rayleigh fading channel.

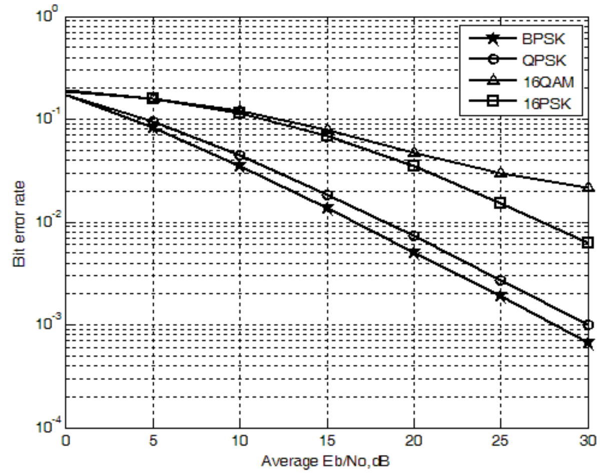

Fig.7. BER Simulation for different constellations for conventional nonlinear phase detection 2×2 MIMO detector in a Rayleigh fading channel.

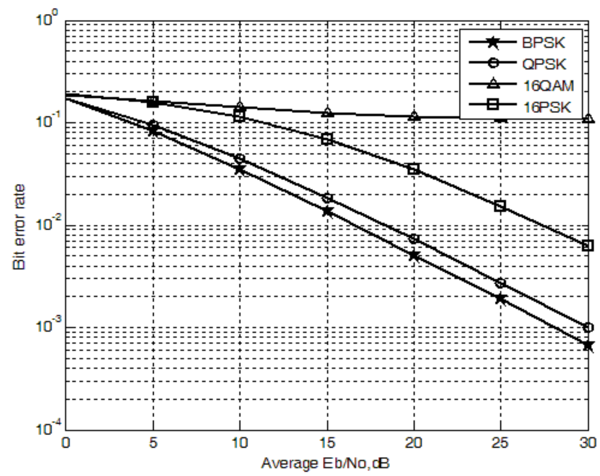

Fig.8. BER Simulation for different constellations with nonlinear phase detection 2×2 MIMO detector with RF delays in a Rayleigh fading channel.

Next, the performance of nonlinear MIMO is compared with other linear reduced complexity MIMO techniques for 2×2 BPSK, 2×2 QPSK and 4×4 BPSK MIMO systems in Fig.9, Fig.10 and Fig.11. Due to the phase detection nonlinearity nature, BER performance curves of this scheme will not follow the same waterfall behavior of linear MIMO detection schemes. In Fig.10, nonlinear 2×2MIMO detector gave worse performance than other cited MIMO detectors for QPSK. Moreover, it is observed that in Fig.11 a crossover occurs for 4×4 BPSK MIMO system between phase detection and MMSE at 12 dB. Here we can conclude that nonlinear MIMO is inefficient for higher order modulations and it is a highly power sensitive system. At higher SNR, it could give superior performance against some reduced complexity linear schemes while the opposite happens at low SNR.

Finally, we examine the performance of NL MIMO system in hardware by conducting on FPGA implementation using Xilinx tools. Xilinx blocks for the 2×2 MIMO detectors were generated in AccelDSP and run through Simulink using similar setup as in previous parts. We employ a software-hardware co-simulation set up to test the BPSK-based MIMO-MLD, MIMO-ZF, MIMO-MMSE and the NL MIMO subsystems. The BER performances from the Xilinx hardware blocks were then compared with MATLAB floating-point simulation as shown in Fig.12 and good match between the hardware and software simulation results were observed. Thus, from Fig.12 we deduce that hardware implementation of NL MIMO in sensor networks will have BER performance similar to those presented in Fig.9-Fig.11, providing useful guide for practical implementation of NL MIMO system in sensor networks.

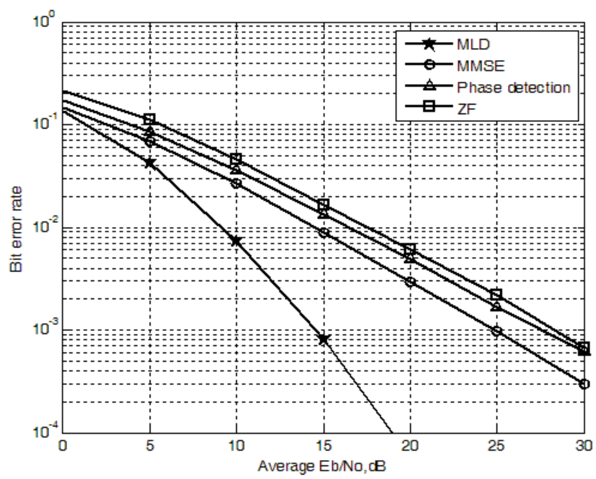

Fig.9. BER Simulation for different 2×2 MIMO detectors with BPSK constellation in a Rayleigh fading channel.

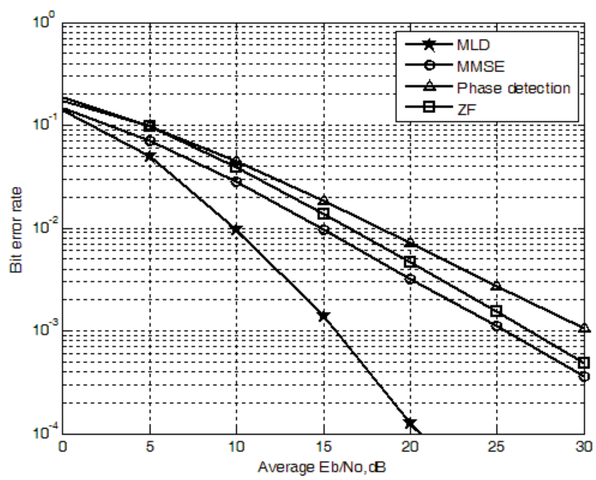

Fig.10. BER Simulation for different 2×2 MIMO detectors with QPSK constellation in a Rayleigh fading channel.

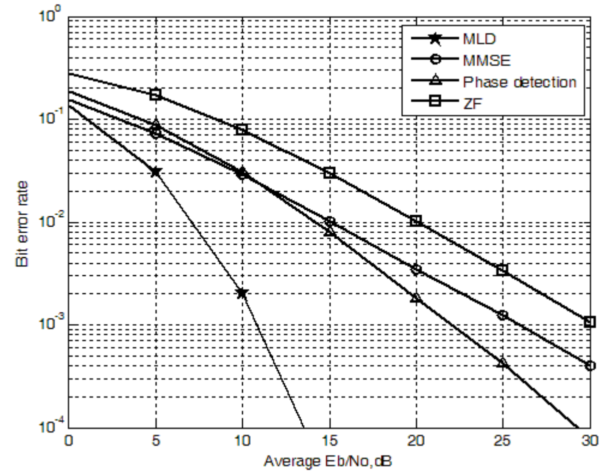

Fig.11. BER Simulation for different 4×4 MIMO detectors with BPSK constellation in a Rayleigh fading channel.

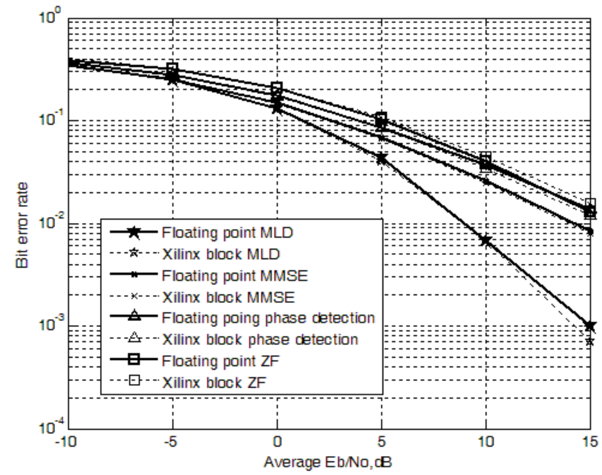

Fig.12. BER Simulation for different 2×2 MIMO detectors Xilinx blocks with BPSK constellation in a Rayleigh fading channel.

In the following Table VI-VIII, we compare the computational complexity of different MIMO schemes calculated in Tables I-V, with the complexity reported by AccelDSP "Generate RTL report". As an approximation, we assumed in our calculation that complex operations consume double the complexity of scalar operations. It should be noted that complexity reported AccelDSP in the RTL report is usually based in the specific implementation of the logic and flows in the hardware design. This will be high for a highly complex system and low for a reduced complexity system, but the number of operation reported in the AccelDSP RTL report would not be exactly same as the calculated operations in Table I-V above, and in most cases higher depending on the hardware design perfection employed. Thus, what we can observe from Table VII is only a guide on the relatively low complexity of NL MIMO compared to other MIMO detection schemes as illustrated in Table VII.

Thus, from hardware complexity in Table VII, we can still argue that NL MIMO complexity is affordable based on information from Ref […] on affordable complexity in sensors.

TABLE VI

COMPARISON BETWEEN COMPLEXITY COMPUTATION OF ML DETECTOR AND PHASE DETECTION IN 2×2 MIMO SYSTEM.

Constellation	MLD	Phase detection	Reduction [%]
BPSK	95	71	25.06
QPSK	383	287	25.06
16QAM	6143	4607	25.00
16PSK	6143	4607	25.00

TABLE VII

CALCULATED AND REPORTED BY AccelDSP COMPLEXITY COMPUTATIONS FOR DIFFERENT MIMO DETECTORS FOR BPSK 2×2 MIMO.

Detection Scheme	Calculated	AccelDSP
MLD	95	196
Phase Detection	71	139
ZF	75	272
MMSE	132	323

TABLE VIII

COMPLEXITY REDUCTION FOR BPSK 2×2 MIMO SYSTEM REPORTED BY AccelDSP.

Constellation	Full complexity	Phase detection	Reduction [%]
BPSK	196	139	29.28

IV. CONCLUSION

MIMO systems are very useful in enhancing the BER level. However, applying them directly on sensors is not possible as sensors have got limited abilities. Utilizing nonlinear MIMO showed some improvements toward bringing the MIMO into sensors networks. If sensors were able to satisfy the computational load in these methods, the loss in BER will be a small price compared to the simplicity we get in implying MIMO systems and achieving their benefits. All in all, to get the aimed outcomes, MIMO techniques must be designed carefully, part by part with a deep knowledge in sensors internal components. Otherwise design might not be applicable for real implementation.

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