Robust OFDM Diversity Receiver under Co-channel Narrowband Interference

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***Abstract*— The rapid increase in wireless devices and inherent limitation of RF spectrum is causing Co-Channel Interference (CCI). Effects of CCI are prevalent in Industrial Scientific Medical (ISM) bands which lack centralized control over devices operating on heterogeneous standards, a situation entirely different from cellular networks. In this study, we propose physical layer signal processing techniques for multi-antenna OFDM receivers in ISM band for mitigating narrowband CCI. Our work focuses only on receiver side modifications for interoperability with the existing infrastructure. We first analyze two such prominent multi-antenna interference mitigation methods: Optimal Combiner (OC) and Technology-Independent MIMO (TIMO). Optimal Combiner, although theoretically optimal, requires statistics of interferer which is difficult to obtain in practice. TIMO does not benefit from diversity gain despite having two antennas. We propose MLSC (Maximal Ratio Combiner with LLR Scaling) for multi-antenna OFDM receivers which mitigates CCI caused by narrowband interferers as well as benefits from diversity gain. For a given Packet Error Rate (PER), MLSC achieves comparable Transmit Power Gain (TPG) to OC without needing the statistics of the interferer. In addition, MLSC achieves significant TPG compared to TIMO. Further, we propose an improvement to TIMO: DC-TIMO (Diversity Combiner TIMO) which enables it to perform joint interference nulling and diversity combining.**

I. INTRODUCTION

The rapid increase in wireless devices and inherent limitation of RF spectrum is causing Co-Channel Interference (CCI). CCI is well addressed in cellular networks using centralized control over transmit power and transmit time scheduling [1]. In contrast, the Industrial, Scientific and Medical (ISM) bands where heterogeneous wireless standards share the same spectrum, application of methods used in cellular communication to mitigate CCI is not trivial due to lack of centralized control. We term such networks as *unmanaged networks*. An example of CCI in unmanaged networks can be found in 2.4 GHz ISM band where IEEE 802.11g, IEEE 802.15.1, and IEEE 802.15.4 operate without any mutual coordination. Consequently, all of them suffer significant throughput degradation even though they possess Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [2], [3]. The extent of the throughput degradation depends on received power levels (RXP) and the degree of time/frequency overlap of the interfering signals. In this work, we chose 2.4 GHz IEEE 802.11g (WiFi) [4] as desired signal and IEEE 802.15.4 (ZigBee) [5] as the co-channel interferer. In modern automated industries and smart homes, wireless ZigBee sensors are generously used and cause CCI to omnipresent WiFi devices [6].

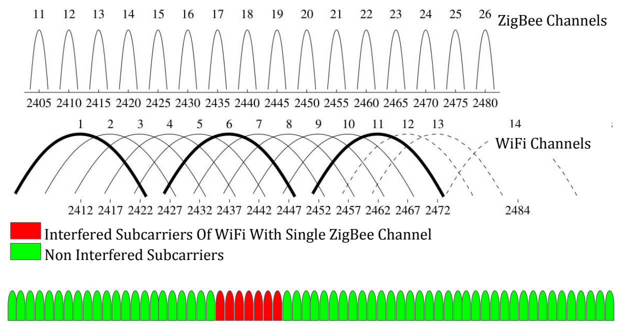

Fig. 1. WiFi-ZigBee subcarrier allocation in 2.4 GHz ISM band and overlap

2.4 GHz WiFi is an OFDM based wideband system. It is 20MHz wide and divided into 64 orthogonal subcarriers, each 312.5 kHz wide. In contrast, ZigBee operating in 2.4 GHz is a narrowband system with a bandwidth of 2 MHz and uses O-QPSK (Offset-Quadrature Phase Shift Keying) and DSSS (Direct Sequence Spread Spectrum). Fig. 1 shows single channel (20 MHz each) of WiFi and 4 channels of ZigBee (2 MHz each) overlapping each other. Both WiFi and ZigBee apply CSMA/CA as collision avoidance mechanism but still, the collision happens due to hidden node and differences in channel sensing/response time [7] . In case of CCI, 7 subcarriers of WiFi are overlapped with a single 2 MHz wide ZigBee channel. In Fig. 1, we refer to this set of 7 subcarriers as S_{interf} (marked red) and the set of rest of subcarriers as $S_{\text{non-interf}}$ (marked green) such that $S_{\text{interf}} \cup S_{\text{non-interf}} = S_{\text{WiFi}}$, where S_{WiFi} is the set of all used WiFi subcarriers. In the event of collision, noise variance on S_{interf} becomes higher than $S_{\text{non-interf}}$ and causes increased PER for both WiFi and ZigBee [2] [3], [8].

But why is the noise variance so important? A typical

WiFi receiver either uses Hard Decision Viterbi Decoder (HDVD) or Soft Decision Viterbi Decoder (SDVD). Performance of SDVD is significantly better than HDVD in an interference limited environment because SDVD takes into account the noise information [9],[10]. Hence, better the noise variance estimation, better the performance of SDVD. In the presence of CCI, conventional method of noise variance estimation in WiFi [11] fails to capture the Local Noise Variance (LNV) estimates of S_{interf} and $S_{\text{non-interf}}$ region, eventually causing increase in PER of WiFi. In our previous work [12], we propose to perform localized estimation of noise variances, i.e., estimation of LNV corresponding to S_{interf} and $S_{\text{non-interf}}$ separately.

In commercial WiFi systems, multi-antenna receivers are being widely applied such as IEEE 802.11g, IEEE 802.11n, IEEE 802.16, and IEEE 802.11af. The indoor channel, especially inside home and industries are rich in multipath [6]. With the appropriate spatial separation between receiver antennas, the extent of multipath fading on different antennas will be different [13]. Hence, for WiFi and ZigBee transmitters positioned at different locations, the extent of ZigBee interference to WiFi signal on different antennas of multi-antenna WiFi receiver will be different. In our work, we use this intuitive cause for applying multi-antenna diversity techniques on WiFi receivers to achieve additional gains while mitigating CCI.

We chose two prominent multi-antenna methods for comparing our work with. Optimal Combiner (OC [14] and Technology Independent MIMO (TIMO) [15]. Details of OC and TIMO are discussed in Section III-B and Section III-C respectively. Our major contributions in this work are summarized as follows:

1) We propose MLSC: Maximal Ratio Combiner with LLR Scaling (MLSC) for multi-antenna OFDM receivers, a joint interference mitigating and diversity combining scheme utilizing LNV based Log-Likelihood Ratio (LLR) scaling and Maximal Ratio Combining (MRC) to mitigate narrowband CCI on OFDM based multi-antenna receivers. Our method:
    a) Does not require statistics of interference.
    b) Achieves the same efficiency as OC for a given Packet Error Rate (PER).
    c) Achieves significant Transmit Power Gain (TPG) compared to TIMO for a given PER.
2) We propose an enhancement to TIMO receiver: DC-TIMO. DC-TIMO benefits from diversity in addition to interference nulling and achieves significant TPG compared to conventional TIMO for a given PER.

Both our methods propose modifications only at the receiver side making them easily inter-operable with existing infrastructure.

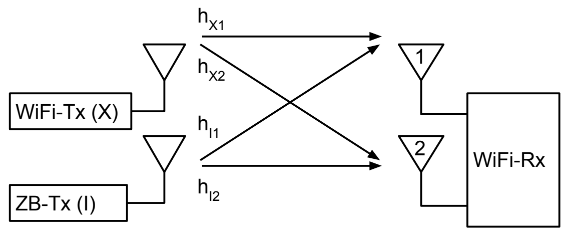

Fig. 2. Signal Model Single Antenna WiFi Transmitter, Single Antenna ZigBee Interferer and Two Antenna WiFi receiver

The remainder of this paper is organized as follows: Section II discusses the state-of-the-art. Section III provides a background of Signal model, MRC, OC, and TIMO. Section IV discusses the details of our proposed methods. Section V presents the experimental set-up and concludes with the discussion on the results of simulations.

II. Related Work

Several solutions have been proposed to mitigate CCI in unmanaged networks with multi-antenna receivers. Authors in [16] propose chain decoding of mutually interfering WiFi signals and modifications in MAC layer. Despite being effective, it requires changes in the WiFi standard and limited to CCI between WiFi only. Authors in [8] propose to precode the interfering signals on the transmitter side which again requires to change the WiFi standard. Such solutions are difficult to integrate into existing infrastructures. Authors in [17], propose an SINR (Signal to Interference Noise Ratio) based Maximal Ratio Combining (MRC) scheme to mitigate CCI, however, the accuracy of their solution depends on averaging over multiple OFDM symbols. Authors in [18], estimate noise variance per subcarrier in order to mitigate the colored nature of inter-carrier-interference in OFDM systems. However, they dont use SDVD and hence fail to utilize channel state information during channel decoding. Performance of SDVD along with channel state information is significantly better than HDVD in an interference limited environment [10]. In addition, OC and TIMO are two other prominent methods of interference nulling but, we discuss their benefits and demerits in Section III-B and Section III-C respectively.

III. Background

A. Signal model

To illustrate our approach, we model a dual-antenna WiFi receiver (WiFi-Rx), a single antenna WiFi transmitter (WiFi-Tx), and a single antenna ZigBee transmitter (ZB-Tx) as illustrated in Fig. 2. After FFT, the received signal $\mathbf{y}$ on i-th subcarrier of j-th WiFi OFDM symbol with the desired WiFi and interfering ZigBee samples $X(i,j)$ and $I(i,j)$ respectively can be written as:

$$\mathbf{y}(i,j) = X(i,j)\mathbf{h}_X(i) + I(i,j)\mathbf{h}_I(i) + \mathbf{n}(i,j), \quad (1)$$

$$\mathbf{n}(i,j) = [n_1(i,j),\, n_2(i,j)]^T, \quad (2)$$

$$\mathbf{h}_X(i) = [h_{X_1}(i),\, h_{X_2}(i)]^T, \quad (3)$$

$$\mathbf{h}_I(i) = \begin{cases} [h_{I_1}(i),\, h_{I_2}(i)]^T & \forall i \in S_{\text{interf}}, \\ \text{Not defined} & \forall i \in S_{\text{non-interf}}; \end{cases} \quad (4)$$

$$i = 1, 2, \ldots, U_{\text{sub}}.$$

Here U_{sub} is the number of used subcarriers in WiFi and equals 52 according to the standard [4]. Channel estimation and all further signal processing is done in frequency domain, channels $\mathbf{h}_X(i)$ and $\mathbf{h}_I(i)$ are assumed uncorrelated, while correlation ρ_X between channels of WiFi $h_{X_1}(i)$ and $h_{X_2}(i)$ and correlation ρ_I between channels of ZigBee $h_{I_1}(i)$ and $h_{I_2}(i)$ is non-zero. Note that for the interference-free WiFi subcarriers, ZigBee channels are not defined. Entries of the thermal noise vector $\mathbf{n}(i,j)$ are Gaussian distributed with zero mean and variance σ^2. The thermal noise variance is assumed to be constant for a given OFDM frame. Without loss of generality, we omit subcarrier and OFDM symbol indexes (i,j) from notations of the received vector $\mathbf{y}$, samples X and I and noise vector $\mathbf{n}$ and use them only when required.

B. Maximal Ratio Combining and Optimal Combining

In OFDM systems, MRC is performed on per-subcarrier basis as follows [20]:

$$y_{\text{MRC}} = \widehat{\mathbf{h}}_X^H \mathbf{y}. \quad (5)$$

Where y_{MRC} is the complex sample after MRC and $\widehat{\mathbf{h}_X}$ denotes the estimated channel. However, the performance of MRC degrades in the presence of colored noise [14]. In context of OFDM, a colored noise is a narrowband interference. The OC technique is a superset of MRC which, in the presence of colored noise (interference), additionally computes Interference-plus-Noise (IPN) correlation matrix across all the receive antennas and nullifies the interference [14],[20]. The optimally combined signal for two antenna system for subcarriers experiencing interference (S_{interf}) can be written as:

$$y_{\text{OC}} = \widehat{\mathbf{h}}_X^H \boldsymbol{\phi}_{RR}^{-1} \mathbf{y}. \quad (6)$$

$$\text{Where} \quad \boldsymbol{\phi}_{RR} = \mathbb{E}\left\{[\tilde{y}_1, \tilde{y}_2]\,[\tilde{y}_1, \tilde{y}_2]^H\right\} \quad (7)$$

is the IPN correlation matrix, and $\tilde{y}_1$ and $\tilde{y}_2$ are received signals on first and second WiFi-Rx antenna respectively when only ZB-Tx transmits and WiFi-Tx is silent. For the interference-free subcarriers, $\boldsymbol{\phi}_{RR} = \sigma^2\mathbf{I}$ where $\mathbf{I}$ is $M \times M$ identity matrix and σ^2 is the noise variance. Thus, in the absence of interference, OC acts as MRC [20, Eq-6.92]. The drawback of OC is that computation of $\boldsymbol{\phi}_{RR}$ needs to be performed for all the interfered subcarriers when only ZB-Tx transmits. In addition, $\boldsymbol{\phi}_{RR}$ needs to be updated with the period of coherence time of $\mathbf{h}_I$ as it varies with channel fading rate. Both of these conditions are difficult to meet in practice. Moreover, since $\boldsymbol{\phi}_{RR}$ is a matrix of order M, the computational complexity of matrix inversion grows with the number of antennas M.

C. Technology Independent MIMO

Technology Independent MIMO (TIMO) [15] applies Zero Forcing (ZF) receive beamforming using two antennas to null the interference. Conventionally ZF receive beamforming requires exact channel estimates of the interferer [8], [16], [18]. In contrast, TIMO uses Channel Estimation Ratio (CER) $\beta = \widehat{h}_{I_1}/\widehat{h}_{I_2}$ instead of using the exact channel estimates of interferer, i.e., $\widehat{\mathbf{h}}_I$. Such property of TIMO makes it suitable for unmanaged networks as obtaining the channel estimates of the interferer in unmanaged networks is impossible or very costly due to the unknown structure of the interfering signals. The early work of TIMO in [15] ignores noise [15, Eq-5,6] during computation of CER β. Hence, we refer to recent work on TIMO in [21] where authors consider the noise and use an MMSE estimator in order to compute CER β for the interfered subcarriers as follows:

$$\beta = \frac{\mathbb{E}\{(Ih_{I_1} + n_1)\left(Ih_{I_2} + n_2\right)^H\}}{\mathbb{E}\left\{|y_2|^2\right\}}. \quad (8)$$

After TIMO based nulling for all the interfered subcarriers, SOI on the interfered subcarriers is obtained as follows:

$$y_{\text{TIMO}}^{\text{interf}} = \frac{y_1 - \beta y_2}{\widehat{h}_{X_1} - \beta \widehat{h}_{X_2}}. \quad (9)$$

To compute SOI on the interference-free subcarriers, we first obtain CER β for the interference-free subcarriers. We set $I = 0$ in (8) and since, n_1 and n_2 are uncorrelated, it can be shown that $\beta = 0$ for all the interference-free subcarriers. Hence, SOI for all the interference-free subcarriers $y_{\text{TIMO}}^{\text{non-interf}}$ can be written as:

$$y_{\text{TIMO}}^{\text{non-interf}} = \frac{y_1}{\widehat{h}_{X_1}}. \quad (10)$$

Expression (10) is a well known Zero-Forcing Equalization (ZFE) over a single antenna [20, Sec-7.3.1.1]. We observe that TIMO fails to exploit the diversity gain for all the interference-free subcarriers which potentially could be achieved using the already available two antennas of the TIMO receiver. Additionally, CER β varies with fading rate of $\mathbf{h}_I$ and hence needs continuous update. This requirement is difficult to guarantee in practice.

IV. Proposed Methods

A. Maximal ratio combining with LLR SCaling (MLSC)

We propose to jointly perform MRC over signals from the M antennas, and further scale the obtained LLRs from MRC combined signal using a vector of Localized Noise Variance (LNV) estimates aggregated over the M antennas. We term our method as Maximal ratio combining with LLR Scaling (MLSC). It enables a multi-antenna receiver to simultaneously benefit from diversity gain and interference mitigation without knowing the statistics of the interferer. MLSC is performed in following two steps:

1) Localized Noise Variance estimation: First, we present a brief account of our previous work on LNV estimation in OFDM systems for K single antenna narrowband interferers. Based on Section I, the overall effect of narrowband CCI is adding additional noise to the interfered subcarriers. Thus we model the combined thermal noise and interference for the interfered subcarriers as zero mean Gaussian noise $\widetilde{\mathbf{n}}$, as both these variables are zero-mean. We then may write (1) for the interfered subcarriers as follows:

$$\mathbf{y} = X(i,j)\widehat{\mathbf{h}}_X + \widetilde{\mathbf{n}}. \tag{11}$$

Variance of $\widetilde{\mathbf{n}}$, localized to the interfered subcarriers and variance of thermal noise $\mathbf{n}$, localized to the interference-free subcarriers are estimated using our method of LNV estimation which uses Long Training Sequence (LTS) of WiFi [4].

We start with a generalized case of K single antenna uncorrelated narrowband interferers (K single antenna ZB-Tx) and a WiFi receiver with M antennas ($K < M$). In our settings, S_k is the set of WiFi subcarriers affected by the k-th interferer ($k = 1, \ldots, K$) and S_0 is the set of all the subcarriers unaffected by any of the k interferers such that $S_0 \cup S_1 \cup .... \cup\ S_K = S_{\text{WiFi}}$. An exemplary illustration of our WiFi subcarrier setting for the case of 4 ZigBee interferers to a single WiFi channel is shown in Fig. 3 for clarity. As the center frequencies of different wireless standards are fixed and their bandwidths are predefined, the knowledge of various S_k and S_0 sets can be obtained apriori. For example, when a WiFi channel centered at 2.437 GHz gets interference from two ZigBee channels centered at 2.435 and 2.440 GHz: $S_1 = \{17 \ldots 23\}$ and $S_2 = \{32 \ldots 38\}$, $S_0 = S_{\text{WiFi}} - S_1 - S_2$. Thus, $|S_1| = |S_2| = 7$ and $|S_0| = 38$ where $|B|$ means the cardinality of the set B.

LNV estimates for $k = 0, \ldots, K$ on the m-th WiFi-Rx antenna for i-th OFDM subcarrier are computed as:

$$\widehat{\sigma}^2_{S_{k_m}} = \frac{1}{2|S_k|} \sum_{i \in S_k} |y_m^{\text{LTS}}(i,1) - y_m^{\text{LTS}}(i,2)|^2, \quad m = 1, \ldots, M \tag{12}$$

where $y_m^{\text{LTS}}(i,1)$ and $y_m^{\text{LTS}}(i,2)$ are the first and second LTS symbols of WiFi on the m-th antenna and $|S_k|$ denotes the cardinality of S_k. We further define index vectors $\boldsymbol{V}_{S_{k_m}}$ for m-th antenna as:

$$\left[\boldsymbol{V}_{S_{k_m}}\right]_i = \begin{cases} 1, i \in S_k \\ 0, i \notin S_k \end{cases} \qquad i = 1, 2, \ldots, U_{\text{sub}}. \tag{13}$$

Using (12) and (13), we create a vector of LNV estimates $\widehat{\boldsymbol{\sigma}}^2_m$ corresponding to U_{sub} on the m-th antenna as follows:

$$\widehat{\boldsymbol{\sigma}}^2_m = \sum_{k=0}^{K} \boldsymbol{V}_{S_{k_m}} \widehat{\sigma}^2_{S_{k_m}}. \tag{14}$$

Corresponding to Fig. 3, a typical plot of $\widehat{\boldsymbol{\sigma}}^2_m$ is illustrated in Fig. 4 where a single WiFi channel faces interference from 4 ZigBee interferers. In Fig. 4, we observe that conventional method of noise variance estimation [12, Eq-2] does not preserve the information of local noise variances cause by co-channel narrowband interferers while our method, i.e., (12) does. In (12) distinguish lobes appear due to the increased noise variances caused by narrowband interferers. Our method to estimate LNV using LTS requires an overlap between LTS of WiFi and an ongoing ZigBee transmission. This is a fair assumption as typical frame lengths of WiFi ($194\,\mu\text{s} - 542\,\mu\text{s}$) is shorter than that of ZigBee ($352\,\mu\text{s} - 4256\,\mu\text{s}$) [7].

2) LLR scaling per subcarrier using LNV Estimates: For LLR scaling per subcarrier, we first obtain the LLRs corresponding to every MRC combined signal of i-th subcarrier, i.e., $y_{\text{MRC}}(i)$. We follow the maxlog approximation of the maximum likelihood approach for obtaining LLRs $\Lambda_{i,l}$ of i-th subcarrier and l-th bit as follows [9, Eq-2]:

$$\Lambda_{i,l} = \frac{\min\limits_{z \in Z_0^l} \left(|y_{\text{MRC}}(i) - z|^2\right) - \min\limits_{z \in Z_1^l} \left(|y_{\text{MRC}}(i) - z|^2\right)}{\widehat{\sigma}^2} \tag{15}$$

where $Z_q^{(l)} = \{z | b_l(z) = q\}$ and b_l denotes the l-th bit in the gray mapping of z and $\widehat{\sigma}^2$ is the conventional noise estimate. We observe that $\widehat{\sigma}^2$ acts as a scaling factor which scales the LLRs according to the extent of noise variance on that subcarrier. However, conventional $\widehat{\sigma}^2$ does not contain local information of noise variance caused by narrowband interferers and hence scales all the LLRs by the same amount. We solve this problem by first averaging the LNV vectors obtained from (14) over all the M antennas as follows:

$$\widehat{\boldsymbol{\sigma}}^2_{\text{Avg}} = \frac{1}{M} \sum_{m=1}^{M} \widehat{\boldsymbol{\sigma}}^2_m. \tag{16}$$

And then we use $\widehat{\boldsymbol{\sigma}}^2_{\text{Avg}}$ to scale the LLRs obtained from (15) as follows:

$$\Lambda_{i,l} = \frac{\min\limits_{z \in Z_0^l} \left(|y_{\text{MRC}}(i) - z|^2\right) - \min\limits_{z \in Z_1^l} \left(|y_{\text{MRC}}(i) - z|^2\right)}{\widehat{\sigma}^2_{\text{Avg}}(i)} \tag{17}$$

where $\widehat{\sigma}^2_{\text{Avg}}(i)$ is the i-th element of the vector $\widehat{\boldsymbol{\sigma}}^2_{\text{Avg}}$. In summary, MLSC is performed in the following steps:

- Perform MRC over received signals from M antennas as in (5) to obtain $y_{\text{MRC}}(i)$.

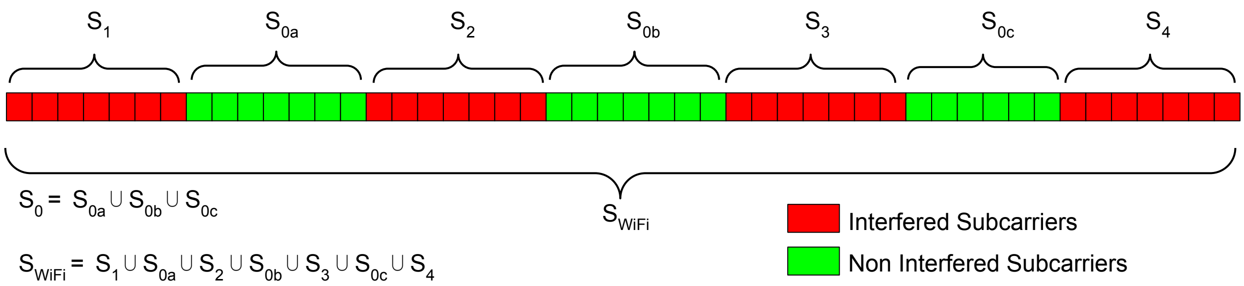

Fig. 3. Set of interfered and interference-free WiFi Subcarriers by 4 Co-Channel ZigBee Interferers

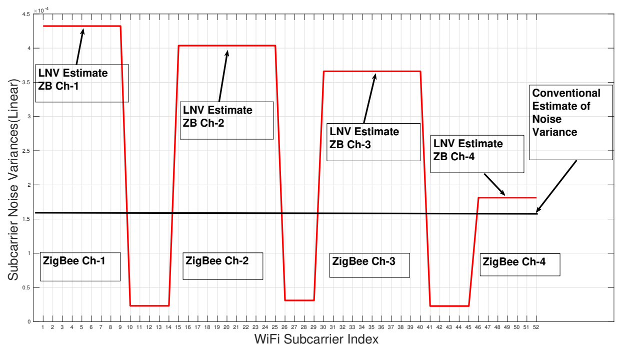

Fig. 4. Conventional Noise variance and Proposed LNV Estimates for 4 Ch-Channel ZigBee Interferers on Single WiFi Channel

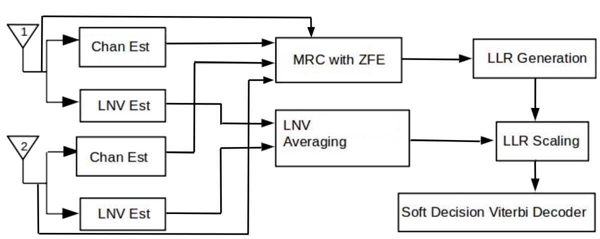

Fig. 5. Schematic of Proposed MLSC for 2 Antenna WiFi Receiver

- Estimate LNV $\widehat{\boldsymbol{\sigma}}^2_{\text{m}}$ as in (12), (13), (14)
- Average LNVs from M receive antennas as in (16) to obtain average LNV vector $\widehat{\boldsymbol{\sigma}}^2_{\text{Avg}}$.
- Scale the LLRs obtained from $y_{\text{MRC}}(i)$ with $\widehat{\boldsymbol{\sigma}}^2_{\text{Avg}}$ on per subcarrier basis as in (17).

For a dual antenna WiFi receiver, the entire process is illustrated in Fig. 5.

B. Diversity Combiner TIMO (DC-TIMO)

We have observed in Section III-C that TIMO does not exploit the potential diversity gain for all the interference-free subcarriers in an OFDM system. We propose to solve this issue by performing MRC on all the interference-free subcarriers. Our method is very simple and enables a TIMO receiver to benefit from interference nulling on the interfered subcarriers as well as from diversity gain on the interference-free subcarriers simultaneously. We term the proposed method as Diversity Combiner TIMO (DC-TIMO). SOI with DC-TIMO for the interfered subcarriers $y^{\text{interf}}_{\text{DC-TIMO}}$ and the interference-free subcarriers $y^{\text{non-interf}}_{\text{DC-TIMO}}$ is obtained as follows:

$$y^{\text{interf}}_{\text{DC-TIMO}} = \frac{y_1 - \beta y_2}{\widehat{h}_{X_1} - \beta \widehat{h}_{X_2}} \tag{18}$$

$$y^{\text{non-interf}}_{\text{DC-TIMO}} = \widehat{\mathbf{h}}^H_X \mathbf{y}. \tag{19}$$

Finally, the signals are sent for rest of the signal processing.

V. Performance Evaluation

A. Simulation Setup

To validate our methods, we perform Monte Carlo simulations using the standard compliant IEEE 802.11g and IEEE 802.15.4 libraries available in release 2017b of MATLAB. Occasionally, interference between WiFi and ZigBee causes loss of WiFi frame synchronization [3], but in this work, we assume only the instances of perfect synchronization. Additionally, we simulated the worst case scenario, i.e., when lack of CSMA/CA creates a 100% chance of collision. For all the experiments, we iterated until statistical reliability was achieved (in our case, until 2000+ frames were erroneous). The simulation parameters are mentioned in Table I. For all the experiments, we choose Transmit Power level (TXP) required to achieve 10% PER as our performance metric as mentioned in [4, Sec-17.3.10.4].

TABLE I: Simulation Parameters

Channel Model WiFi	11 tap Rayleigh, Exponential Power Delay profile, RMS Delay Spread 49 ns
Channel Model ZigBee	1 tap Rayleigh
Noise Power	−100 dBm
WiFi PSDU	1000 bytes
ZigBee PSDU	120 bytes
Sampling Rate	WiFi 20 MHz, ZigBee oversampled to 20 MHz

B. Experiments

We performed the following three experiments:

1) OC vs MLSC: We simulated a dual antenna WiFi-Rx capable of performing OC and MLSC simultaneously. The WiFi-Rx decodes packets received from a single antenna WiFi-Tx under interference from a single antenna ZB-Tx as illustrated in Fig. 2. Three different ZigBee TXP levels $(-85, -80$, and $-75)$ dBm were used. The correlation coefficient ρ_X was fixed to 0.4 based on the measurements shown in [19]. Since, for both the OC and MRC, the performance is agnostic of ρ_I [22], we fixed it to 0.1. In order to obtain ϕ_{RR} for OC in (6), we computed it when only ZB-Tx was transmitting. The expectation was taken over approximately $80,000$ ZigBee samples collected from two receive antennas of WiFi-Rx prior to every iteration in order to guarantee the best performance of OC.

2) TIMO vs MLSC: We simulated the same scenario as in Section V-B1 with the difference that now the WiFi-Rx was able to perform TIMO and MLSC simultaneously. Three different ZigBee TXP $(-85, -80$, and $-75)$ dBm were used. Instead of estimating β for (9), we directly computed it from the channel realization of Zigbee to guarantee the best performance of TIMO.

3) TIMO vs DC-TIMO: We simulated the same scenario as in Section V-B2 except now the WiFi-Rx was able to perform TIMO and DC-TIMO simultaneously. Three different ZigBee TXP $(-85, -80$, and $-75)$ dBm were used. CER β was computed directly from the channel realization of ZigBee.

For all the three experiments, we also simulated WiFi PER in the absence of interference for WiFi MCS 0 in order to show the extent of PER degradation when interference appears at different TXP levels.

C. Results and Discussion

1) OC vs MLSC: The results for WiFi MCS0 are illustrated in Fig. 6. The curves for other MCS follow the same trend. We also plotted the performance of conventional MRC under the same setup. We observe that for all the mentioned ZigBee TXP, the performance of MLSC is close to the performance of OC. This result can be explained by the fact that OC nulls the interference on all the interfered OFDM subcarriers which effectively scales the LLR obtained from all the interfered subcarriers. MLSC performs the same action by directly scaling the LLRs obtained from all the interfered subcarriers in proportion to the LNV estimates. As a result, for a given WiFi TXP, MLSC can achieve PER performance very close to the OC but with a lower computational complexity and without the knowledge of the statistics of the interferers.

2) TIMO vs MLSC: The plots of WiFi TXP versus PER for WiFi MCS 0 are presented in Fig. 7. We term the difference between WiFi TXP required to achieve

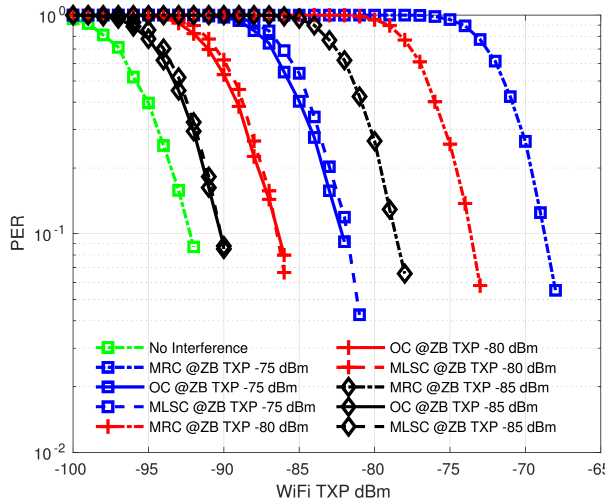

Fig. 6. TXP required by OC and MLSC to achieve 10% PER for WiFi MCS-0, $\rho_X = 0.4$ and $\rho_I = 0.1$. MLSC needs approximately same TXP as OC at all ZigBee TXP.

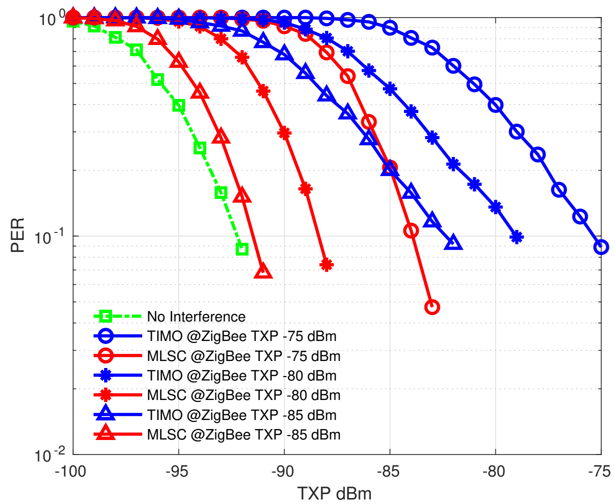

Fig. 7. TXP required by TIMO and MLSC to achieve 10% PER for WiFi MCS-0, $\rho_X = 0.4$ and $\rho_I = 0.1$. MLSC needs significantly lower TXP compared to TIMO at all ZigBee TXP.

10% PER by MLSC and TIMO as *Transmit Power Gain* (TPG). For the rest of WiFi MCS, corresponding TPGs are tabulated in Table II. Based on Fig. 7 and Table II, we observe that MLSC enjoys significant TPG w.r.t to TIMO for all the ZigBee TXP. This result can be explained by the fact that for all non interfering OFDM subcarriers, MLSC performs MRC to enhance the SOI while TIMO performs ZFE and fails to benefit from diversity gain. As a result, MLSC can achieve 10% PER mark at a lower WiFi TXP compared to TIMO and that too without the knowledge of β.

3) TIMO vs DC-TIMO: We plot TXP vs PER results for WiFi MCS 0 in Fig. 8 and summarize TPGs for rest of the WiFi MCS in Table III. From Fig. 8 and Table III we observe that DC-TIMO provides significant TPG w.r.t

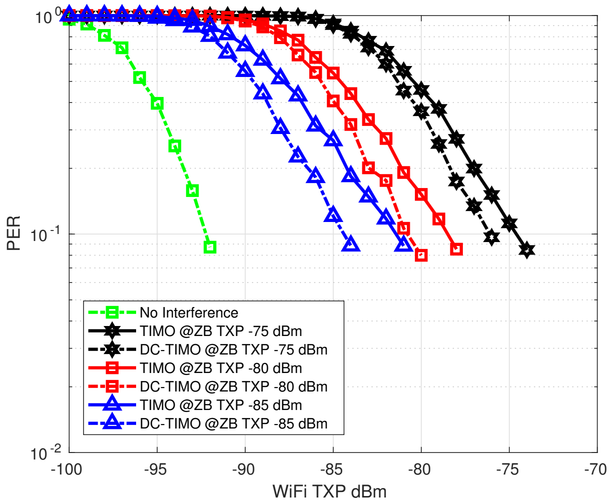

Fig. 8. TXP required by TIMO and DC-TIMO to achieve 10% PER for WiFi MCS-0, $\rho_X = 0.4$ and $\rho_I = 0.1$. DC-TIMO needs lower TXP compared to TIMO.

TABLE II: TPG of MLSC w.r.t TIMO in dB at $\rho_X = 0.4$ and $\rho_I = 0.1$. MLSC needs significantly lower TXP than TIMO in order to achieve 10% PER at all WiFi MCS.

WiFi MCS / ZigBee TXP(dBm)	0	2	4	6
-85	9.3	9.9	11.6	11
-80	9.5	10	11.7	10.4
-75	8.8	9.5	11.4	9.1

TABLE III: TPG of DC-TIMO w.r.t TIMO in dB at $\rho_X = 0.4$ and $\rho_I = 0.1$. DC-TIMO needs significantly lower TXP than TIMO in order to achieve 10% PER at all WiFi MCS.

WiFi MCS / ZigBee TXP(dBm)	0	2	4	6
-85	2.8	4.3	5.8	5.5
-80	2.5	3.5	5.1	4.8
-75	1.5	2.8	4.6	4.7

TIMO for all ZigBee TXP. This can be explained by the fact that DC-TIMO performs MRC on the interference-free OFDM subcarriers while TIMO performs ZFE on the same. As a result, DC-TIMO can achieve 10% PER at a lower WiFi TXP compared to TIMO.

VI. Conclusion

The CCI significantly degrades the throughput of wireless systems operating in overlapped frequency bands. In this paper, we analyzed two prominent methods of mitigating CCI in multi-antenna OFDM receivers: OC and TIMO. We propose the MLSC, a simple yet effective method to perform joint interference mitigation and diversity combining for wideband OFDM systems facing narrowband CCI. Performance of our method is close to OC in terms of PER and significantly better than TIMO in terms of TPG for all WiFi MCS. Next, we propose DC-TIMO which is an improvement to existing TIMO receiver. DC-TIMO benefits from diversity gain in addition to interference nulling leading to significant improvement of TPG of TIMO for all WiFi MCS. Both our methods, i.e., MLSC and DC-TIMO are not restricted by the knowledge of statistical properties of the interferer or its channel estimates. Moreover, our methods do not add any significant signal processing overhead to the existing multi-antenna receivers and hence can be realized in SDR hardware with minimal efforts. Although the experimental tests were performed for unmanaged networks, the proposed methods can find potential application in cellular networks too.

Acknowledgment

This work was supported by Siemens AG, Corporate Technology, Munich and Eurecom, France.

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