Hybrid Multi Beamforming and Multi-User Detection Technique for MU MIMO System

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Abstract
Multi User—Multiple-input multiple-output based wireless communication system has several advantages over conventional MIMO systems such as high data rate and channel capacity which has drawn great attention recently and is prominently preferred for 5G systems. The other side interferences due to the Multi-User mobile environment such as co-channel interference and multiple access interference the overall system performance will be degraded. Highly reliable techniques need to be incorporated to improve the Quality of services. Moreover, the energy efficiency and compactness requirement of 5G systems present new challenges to investigate techniques for reliable communications. Introducing a novel low-complexity radix factorization based Fast Fourier transform multi beam former and maximal likelihood –multi-user detection techniques. As signal detector tailored with optimal sub-detector systems which results in considerable complexity reduction with intolerable error rate performance. The proposed radix factorized Fast Fourier transform—multi-beam forming architectures have the potential to reduce both hardware complexity and energy consumptions as compared to its state-of-the-art methods while meeting the throughput requirements of emerging 5G devices. Here through simulation results, the efficiency of the scaled ML sub-detector system at the downlink side is compared with the conventional ML detectors. Through experimental results, it is well proved that the proposed detector offers significant hardware and energy efficiency with the least possible error rate performance overhead.

Keywords MU-MIMO · Fast Fourier transform · Index mapping modulation · Multi-user detection · Bit error rate · ML sub-detector · FPGA
1 Introduction

In recent years’ Multi User—Multiple-input multiple-output (MU-MIMO) system has been emerged as one of the prominent techniques to achieve performance metrics such as quality of services and improved data rate with the limited spectrum availability [1, 2]. Since the 5G telecommunication system is expected to support prominently many high data rate applications such as IP based mobile broadband applications, IP telephony, live multimedia gaming services etc. The demands over maximizing spectral efficiency and channel capacity keep on increasing. On the other side, the energy level and compactness requirements of 5G devices present new challenges such as fully integrated transceivers with the least complexity and energy consumption overhead.

However major challenges are involved in the MU-MIMO system over interference caused by multi-user channel environment. An efficient MU-MIMO system should provide better performance in reducing the semantic gap between channel capacity enhancement and the attainable quality of services. Several methodologies have been investigated to overcome this co-channel interference at the receiver side. In most cases, multi beam forming is applied at the transmitter side (uplink MU-MIMO system) and accurate multiuser detection (MUD) is incorporated at the downlink side. Zero-forcing joint beam forming technique to maximize the energy level at the receiver side to satisfy the SINR constraints for each user in MU-MIMO systems [3]. However, it requires channel state information to steer the signals into an optimal direction since formulating CSI knowledge for each antenna is difficult which results in poor link budget beam forming. Conventional beam forming techniques are not applicable for multi-user MIMO interference channels where multiple decentralized users are transmitting too many receivers which are always involved with many challenging and complicated optimization problems compared to many-to-one or one-to-many systems since there is no coordination among the signal transmissions in MU-MIMO systems. Thus, multi-beam forming is essential to increase channel capacity, data rate, as well as the multi-user environments which grow explosively in wireless applications which are accomplished using an array of multiple antennas. Virtual multi-beam forming for multipoint-to-multipoint transmission system and optimal pre-coding theory is incorporated to nullify the multiple-access interference each among users in MU-MIMO systems [4]. On the other side, the Fast Fourier transform is investigated prominently in recent times which can produce an orthogonal set of RF beams over the multi-direction. But due to its computationally intense computations and complex natures, complexity reduction and energy-efficiency techniques are incorporated to support 5G device requirements. In [5] multiple independent radio frequency (RF) beams are generated using FFT transform and the multiplier-less approximation model is used for low-complexity and power efficiency. Developed approximate-FFT algorithms with sparse factorizations to accomplish multi-beam forming for 5G Transceivers [6].

On the other hand, receivers should be equipped with soft interference canceller (for Multiple accuses and co-channel interferences) and an appropriate decoder (to detect each user data over a multiple-access system). In general by producing the extrinsic log-likelihood ratio (LLR) for each symbol an efficient implementation of the signal detector was carried out. It is impossible to accommodate multiuser data with output with well approximated Gaussian distribution and this linear MMSE will deteriorate over a multi-user environment [7]. In most cases, ML has been used as a prominent MUD model which can reduce the performance gap that arises due to lack of coordination among users over MU-MIMO systems. However, this nonlinear ML model always emerges with a considerable
trade-off between performance and computational complexity since the ML detector is a computationally complex and power-hungry model. In [8] non-coherent maximum likelihood (ML) detector is used which exploits the channel orthogonally approximation to improve the error rate performance with minimized iterative complexity. Though the conventional purpose of using the MUD technique is to regulate the co-channel interference it is always preferred at the receiver side. Moreover, measures are to be taken to optimize these signal detection techniques signal detection to meet the complexity reduction at the receiver side with the least possible performance degradation overhead [9]. Though optimization technique has been used as a powerful technique to accomplish the complexity reduction where it considers only inherent bounds and constraints that arise at the receiver side [10].

In this paper, we combine hardware efficient FFT based multi beam forming with a highly optimized maximum likelihood detector which explores the following advantages.

- Finite approximation with radix factorization model is used to incorporate critical path reduction due to complex twiddle factor computation and accomplished multi-directional beam forming which minimizes light to moderate interferences among users.
- A hierarchical sub-detector based signal detector is used at the receiver side which will minimize the complexity trade-off over higher-order modulations such as 16-QAM and 64-QAM.

In addition, to optimize the complexity level multi beam forming and multi-user signal detection the proposed framework can offer complete robustness channel variations during multipath propagations.

2 Multi-User MIMO

Though MIMO systems are having numerous advantages such as improved reliability over fading environment, channel capacity enhancement and spectral efficiency metrics still it has several limitations since it is impractical to equip more antennas into mobile devices. The inclusion of additional antennas into the wireless devices may reduce battery life and increase hardware costs as well. In most cases, it suffers from limited diversity which is directly related to the number of antennas where it results in poor performance when the channel experience the Doppler effect or if it is affected by the channel delay spread. For complete robustness of MU-MIMO system over frequency-selective fading channels, CCI are widely preferred.

3 FFT Based Multi Beamforming Architecture

The availability of high-end bandwidth (> 6 GHz) for improved channel capacity tends to motivate Millimetre-wave (mmW) wireless communication. At mmW communication Radio signal transmission should be more directional and it is essential to accomplish radio propagations using sharp beams. On the other side for multiple access points the transmission needs to be done with a wide range of sharp beams and also it should result in the least power consumption and maximizing system efficiency. For
Highly-directional multi-beam radio signal propagation in mmW multi-directional beam forming techniques, FFT transforms were used. Here FFT is used to generate orthogonal bins driven directional beam forming from uniformly spaced linear antenna array signals. Multiple broad bands transmits/receive beams that are orthogonal to each other in space are a critical need for emerging wireless systems as well as defense applications in radar and electronic warfare as achieve greater capacity by enabling spatial diversity for MIMO.

A. Radix factorization model

The various issues discussed above in FFT computation tends to invent FFT computation using radix factorizations with improved hardware utilization rate which, in turn, help to improve system performance and energy level as well. The other aspect related to overall latency and energy level assisted transceiver designs is additional performance metrics that can be obtained.

In the proposed radix factorization, the non-trivial twiddle factors are converted into trivial twiddle factors which can be easily modeled using simple logical swapping and 2’s complemented operations in different stages of FFT computation. Hierarchical index mapping rule is used to decompose the radix-2 DIF FFT into multiple region model and twiddle factors features are extracted using linear index mapping process. This will give reduce the number of complex twiddle factor multiplication at a different level with the order of magnitude of the index map. As stated above, this approach of the configuration of the twiddle factors that better adapt to any architectural level changes as like conventional high radix indices.

By integrating decomposition levels in radix-2 DIF FFT through a 3-dimensional linear index map number of complex multipliers used for FFT computation is reduces as follows from Eqs. 1.1–1.6.

\[
\begin{align*}
n &= N/2n_1 + N/4n_2 + n_3 \{ n_1, n_2 &= 0, 1n_3 = 0 \sim N/4 - 1 \} \\
k &= k_1 + 2k_2 + 4k_3 \{ k_1, k_2 &= 0, 1k_3 = 0 \sim N/4 - 1 \}
\end{align*}
\]

(1.1)

The DFT has the form of

\[
X(k_1 + 2k_2 + 4k_3) = \sum_{n_3=0}^{N-1} \sum_{n_2=0}^{N/4-1} \sum_{n_1=0}^{N/2-1} x\left(\frac{N}{2}n_1 + \frac{N}{4}n_2 + n_3\right)W_N^{nk}
\]

(1.2)

\[
= \sum_{n_3=0}^{N-1} \sum_{n_2=0}^{N/4-1} \left\{ B_{k_1}^{k_3}\left(\frac{N}{4}n_2 + n_3\right)\right\} W_N^{\frac{N}{2}n_2 + n_3 (k_1 + 2k_2 + 4k_3)}
\]

where the FFT stage one has the form of

\[
B_{k_1}^{k_3}\left(\frac{N}{4}n_2 + n_3\right) = x\left(\frac{N}{4}n_2 + n_3\right) + (-1)^{k_1}x\left(\frac{N}{4}n_2 + n_3 + \frac{N}{2}\right)
\]

(1.3)

The decomposition of radix-2 DIF FFT is represented as follows.
Substituting the Eq. (1.4) into Eq. (1.2) and expanding the summation concerning index $n_2$, have a set of 4 DFTs of length $N/4$.

$$W_N^{\left( n_2, n_3, (k_1 + 2k_2 + 4k_3) \right)} = (-j)^{n_2 (k_1 + 2k_2)} W_N^{n_3 (k_1 + 2k_2)} W_N^{n_3 k_3}$$  \hspace{1cm} (1.4)$$

Then the second stage of FFT $H_{N/4}^{k_1 k_2} (n_3)$ is described as

$$X(k_1 + 2k_2 + 4k_3) = \sum_{n_3=0}^{N-1} [H_{N/4}^{k_1 k_2} (n_3)] W_N^{n_2 k_2} W_N^{n_3 k_3}$$  \hspace{1cm} (1.5)$$

Decomposition of each radix-2 FFT stage is achieved recursively to the remaining length Eq. 1.6 will get the radix $-2^2$ FFT algorithms. Here at stage 1, 50% of non-trivial twiddle factors are transformed into trivial factors $(1, -1, j, -j)$ where only swapping and sign inversions are required. The algorithm is characterized here has all the merit as that of radix-4 but its structures same as a radix-2 butterfly.

4 Multi-User Detection Technique

The conventional purpose of using the MUD method is to reduce co-channel interference. However, in recent years several methodologies are invented to develop a MUD that can perform signal detection with the least complexity overhead. Ishihara, Koichi, et al. (2009) developed the MUD technique using fast Fourier transforms (FFT) by converting received symbols into frequency domain as overlapping the blocks and suppress the interference by deriving weights for each symbol from the minimum mean square error (MMSE) criterion which retains at low complexity irrespective of user rate. In general, linear MMSE MUD cannot perform well over a multi-user environment which is highly sensitive to co-channel interferences since inter-user interference has no degrees of freedom.

A. Sub detector optimization model

In general, linear MMSE MUD cannot perform well over a multi-user environment which is highly sensitive to co-channel interferences. Since ML detector is a computationally complex and power-hungry model, while linear MMSE is limited in its inter-user interference cancellation capability over multi-user environment several nonlinear models have emerged with the considerable tradeoff between performance and computational complexity. Here we present an optimized ML-based multi-user detector model for discriminating the user’s data streams with unique channel parameters to reduce the inter-user interference.
5 Performance Results

In this section, both MATLAB simulations and digital architecture implementations are carried out to demonstrate the error performance and design complexity respectively, of the proposed multi beam former and signal detector. The following facts can be observed: (1) All beams formulated with equal gain using FFT transforms are orthogonal to each other and complexity is decreased exponentially as N (FFT point) increases. (2) Optimized ML matches with the analytical ML BER very well in moderate and low SNR regimes and end with the least discrimination when BER is below $10^{-3}$ and explored that our optimal ML has major advantages in terms of complexity and data rate efficiency. In addition, FPGA hardware synthesis results can exploit the finite beneficiary measurements of our radix factorized FFT and optimized ML detectors Fig. 1.

A. Simulation results

The resultant ML detector is capable of achieving a flexible tradeoff in terms of the achievable BER, least possible design complexity and tolerable error protection. Moreover, by exploiting the benefits of multi beam forming at the transmitter side which can minimize inter-channel interference among users the receiver side can able to detect the signal received using the proposed optimal maximum-likelihood (ML) detector. This signal detector can able to jointly detect the signals from beneficiary diversity enabled MIMO channels. Though the ML detector complexity is exponentially increased with modulation order and as well as the diversity gain employed at the transmitter side the proposed detector results with least possible design complexity overhead since simpler mathematical models were used at each sub-detectors with the least possible iterations and each considers only minimal constellations analytically which is statistically obtained for every modulation order.

As shown in Fig. 1 BER Vs Eb/No performance of optimal and ML detectors with 16-QAM MU-MIMO system. These comparison results proved the performance level of optimal ML detector has nearly matched to conventional ML detectors with metrics over maximized complexity reduction.

![Fig. 1 Performance comparison over QoS trade-off measure of optimal ML detector over the conventional detector](image)
Fig. 2 Multi beam forming

(a) Beam pattern

(b) Gain over Beam angle

(c) Array gain over the degree of freedom

(d) Multi-beam patterns using FFT
In general, the overall performance measure of the proposed optimal ML Detector is directly related to the probability of error that can be minimized by using both diverted orthogonal sharp beams and diversified signal transmission using the MIMO system. The efficiency of FFT multi beam forming over conventional beam forming is also validated using various beam and array gain plots separately in Fig. 2a–d. Based on evaluation results simple finite FFT core model is structured. The results indicated that our FFT model can able to support high speed computation quite efficiently and also add reliability to accurate FFT computation.

B. Experimental Results Here systematic approach of scaling the index of radix with twiddle factor optimized FFT computation is validated over conventional stage optimized FFT radix indices in Table 1. The area efficiency, power dissipation and speed of radix factorization are analyzed. The benefits of critical path delay reduction due to reduced bit-level accumulation over precise high radix FFT computation is also proved through delay metrics analyzes.

The performance of the proposed radix factorized FFT over conventional high radix regimes and metrics of optimized ML sub-detector over using single compound ML as a MUD benchmark scheme which is explored in Table 2 with improved hardware

| Table 1 | Performance comparison of 8-point radix factorized FFT model |
|---------|-------------------------------------------------------------|
|         | FFT model used | Logic element used | Fmax report | Power dissipation report(mW) |
| Radix-2 | 3405           | 71.41 MHz          | 178.12 mW   |
| Radix-2^2 methodology | 2253 | 75.18 MHz          | 160.11 mW   |

| Table 2 | Comparison of proposed optimized ML sub-detector model |
|---------|---------------------------------------------------------|
| Detector model used | Logic cells | Logic registers | DSP elements(9 bit embedded multiplier) | DSP 18 x 18 elements | LUT’s | Fmax report summary(MHz) |
| ML      | 2826 | 1112 | 112 | 56 | 1714 | 56.59 |
| Optimized ML sub-detector | 1584 | 1024 | 64 | 32 | 570 | 117.9 |

Fig. 3 Hardware register transfer level view
efficiency. Using Verilog HDL implementation and the hardware efficiency was proved using Cyclone III (EP3C16F484C6) ALTERA FPGA implementation. The hardware synthesis was carried to prove the complexity reduction of the aforementioned optimal ML detector designs. Architectural level modifications were incorporated as shown in hardware report in Fig. 3 which achieved the highest achievable complexity reduction and delay optimization in terms of improved operating frequency.

6 Conclusion

The methodologies discussed in this work can provide highly reliable Multi-user MIMO radio signal transmission at mm-Wave. Here the attenuations caused by multi-user dynamic mobile environments are compensated by using directional sharp beams at the transmitter side and an appropriate multi-user detector at the receiver side. A comprehensive study of the MU-MIMO performance degradation implemented based on the IEEE 802.15.3c standard for high data-rate applications has been presented for the first time. In particular, radix twiddle factors are normalized by trivial conversion and more realistic signal detectors are embedded at the receiver side. The performance assessment of both factorized FFT multi beam former and optimal ML detector was conducted through FPGA hardware synthesis, array gain analyzes over various beam angles and simulated BER analysis over an ITU channel. Moreover, the demands over compactness and high data rate for future 5G devices which employing MU-MIMO radio signal transmission with appropriate methodologies for improved QoS services such as multi beam forming (at the uplink side) and multi-user detection (at the downlink side), respectively, have been proposed and analyzed.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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