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Dual–Adaptive Redundancy Minimisation-Based Channel Estimation Method for MIMO OFDM Systems

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Abstract— Filtered Orthogonal Frequency Division Multiplexing (FOFDM) is one of the key candidates for harvesting the features that millimetre wave cellular communication is to offer for the 5G and beyond cellular generation. Its chief robust features are increased throughput, efficient spectral utilisation, and interference immunity. Some strict methodologies must be considered to fully utilise these inherent features, especially those allowing guard tones, accurate CSI management and other filter design parameters. This paper proposes a technique to exploit the added redundancies in pilot-based estimators. Here, the authors present an extension idea of an adaptive weight estimator with dual adaptive weights instead of one unique weight factor. We show that these redundancies are insignificant when considering the massive amount of data to be processed and thus can be eliminated to expedite the estimation process efficiently. We implement a weight-based estimator with the necessary accuracy threshold but faster converging to achieve this goal. Simulations follow to demonstrate the advantages of the proposed method.

Keywords: *Millimeter wave, FOFDM, Channel estimation, Massive MIMO, Pilot signals*

1. INTRODUCTION

Filtered OFDM is popular in communication because of its flexibility in cyclic prefix (CP) length, immunity from noise, custom-size sub-bands, etc. [1]. Its backwards compatibility with OFDM means any network structure compatible with OFDM is also compatible [2],[3]. One of the key points in building a MIMO or Massive MIMO network is to determine which type of filtering is to be used. And how it should be implemented, as nowadays it's normal to use some filter bank in modern 5G and 5G plus cellular networks [4]. The need that gave rise to the conception of F-OFDM was the various interference problem caused by the inexistence of any band separation [5],[6]. Because of this operation in separate bandwidth in separate filter banks, networks can take full advantage of unique CP lengths. It allows the network to carry various data payloads for different services within the same subframe [7]. Especially nowadays, when technologies like the IoT, Machine learning are getting popular, this technology can be enabled to achieve the full benefits. For instance, the data for different interconnected IoT devices can be carried out simultaneously if the system uses the F-OFDM structures, not to mention the numerous user data classification described by the 15 and beyond releases by the 3GPP [8]. Using cellular data for IoT devices is commonplace nowadays since today's bandwidth is sufficient to carry small amounts of IoT data with other significant shares of essential cellular data [9]. Owing to this segregated bandwidth allocation, which is fixed considering the operating waveform parameters and the actual traffic scenario, the ability of the transmitter and the receiver to efficiently separate the data traffic from the interference is crucial, especially during the reception. A slight offset in reception can fail to capture whole data blocks. This is one of the moot points of the research that has been integrating the FOFDM into 5G scenarios. These divided subbands are then aggregated at the receiver to complete the transmission process. To enable the network to use dynamic soft parameter setup for the aerial interface considering various traffic loads [3].

The extra padding for the sub-band filters at the beginning of the payload is compensated at the receiver, so it doesn't affect the transmission mode. It can be easily implemented in OFDM systems. Although because of the use of these sub-bands, the length of the guard tones has to be adjusted to allow for the extra padding required for these filters. But since the bands are separated, FOFDM also allows asynchronous inter-band transmissions, which can be a handy feature in the modern era of cellular communications [10]. So it can be inferred from the above that some significant problems in OFDM are nonadjustable CP and subcarrier spacing length, spectrum localisation, time domain adjustments, etc. On the other hand, and as mentioned before, F-OFDM is backwards compatible, meaning that all the networking terminology and techniques related to OFDM can also be applied to it. Moreover, adding distinctive F-OFDM properties like strong out-of-band rejection and custom sub-band settings are favourable for the new generation cellular structure [11].

In practice, though, some problems limit the proper use of this technology with a 5G cell structure. It requires some additional components and maintenance to reap all of the benefits. For instance, we need a minimally truncated filter with a fixed window [12]. Localising accurately in both the time and frequency domains is impossible as a tradeoff. Usually, frequency domain analysis is applied for filter operation since it's much more straightforward and renders the whole process a little easier.

In most cases, switchback filtering is used in practice so that when the switch is turned off, the system will return to regular OFDM operation. This is useful when reduced power is suddenly required to shed some load. All of these are treated as separate components. It includes subcarrier spacing, Time to initiate (TTI) duration and CP durations. There's a slight difference in the degree of utilisation as the dual links more often utilise near-frequency sub-bands. In addition, the guard tones are often treated as reserved to save some bandwidth.

Since the new cellular structure for the 5th generation facilitates more diverse traffic situations [13], it's intuitive to exploit this characteristic to make the waveform parameters dynamic. However, it means we still can drawback using the legacy OFDM features.

This paper proposes a weight-based channel estimation method based on legacy pilot estimation methods like least squares and minimum mean square error. But we make our estimator adaptive and devoid of redundancies to balance performance and accuracy compared to some recent works [14],[15]. We analyse both uplink and downlink traffic. We use conventional pilot-based methods compared to the trend of using semi-blind or compressed sensing techniques which is a novel approach. The simulations show the difference between a non-adaptive fixed and an adaptive weight-based estimator.

Hence, we can divide the contribution of this paper into three parts-

- An intuitive algorithm that uses adaptive weight factors to estimate the channel parameters.
- A method with reduced redundancy that balances complexity and performance.
- A vital candidate for the 5G plus era, which requires enormous amounts of user data to be processed in a short time.

The rest of the paper is divided into four sections. The following section discusses the methodology of the scheme and the algorithm. It also describes the underlying techniques of our proposed structure. Then it's the results section demonstrating the simulation results of the scheme. The discussion and conclusion section follows discussing the findings and features of our proposal. Lastly, we have the references used for this work.

2. METHODOLOGY

For this work, we assumed a block-fading system with t transmitting antennas and r receiving antennas. In a block fading system, the fading is considered uniform throughout the transmission of each symbol. The inherent characteristic of the F-OFDM system makes it more system specific but also requires dedicated phase and amplitude compensations [16]. Therefore, it considered separate waveform parameters set according to the traffic scenario. As a result, it offsets the high blockage and path loss in the millimetre wave to a certain degree. It also helps the transmitter and the receiver to separate the user data from the interference [17]. This allows the scheme to incorporate a very flexible subframe structure, carrying various service data within the same subframe. Combined with the sub-frame-specific waveform parameters, we can exploit more flexibility than what is offered by the conventional OFDM systems.

To develop our model, we start by calculating the cyclic prefix length. Here we wish to augment the CP length by n_g, so in our system, if the no of subcarriers is n, we will be able to represent each of the transmitted symbols as follows-

$$f(n) = \sum_{l=0}^{L-1} f_l\Big(n - l\big(n - n_g\big)\Big) \tag{1}$$

Where, L is the no of OFDM symbols.

Now, if we want a subset from the symbols described in Eq. (1), we can write as-

$$f_l(n) = \sum_{m=0}^{m+M-1} d_{l,m} e^{\frac{2\pi jmn_a}{n}}, \quad n_g \le n_a \le n \tag{2}$$

In Eq. (2) $d_{l,m}$ is the parameters from the debut l – mapped OFDM symbols. These are mapped with the subcarriers of m number symbol in the effective subcarrier mapping range. Since before the filtering operation, each sub-band can be regarded as a conventional OFDM symbol [18], then to express symbols in the k^{th} sub-band, we can write-

$$x_k(n) = f_k(n) \circledast j_k(n) \quad k = 1, 2, 3 \ldots K \tag{3}$$

Where $f_k(n)$ is unfiltered and from the i^{th} sub-band; on the other hand, $j_k(n)$ is the impulse signal from that subband's transmission filter. The symbols generated from Eq. (3) expression are then passed through the noisy channel and face attenuation. This effect is shown in the time domain as follows-

$$x(n) = \sum_{k=0}^{K-1} x_k(n) \tag{4}$$

Now applying convolution theory, we can write-

$$r(n) = x(n) \circledast h(n) + z(n) \tag{4a}$$

$$= \sum_{k=0}^{K-1} x_k(n) \circledast h(n) + z(n) \tag{4b}$$

$$= \sum_{k=0}^{K-1} \Big\{ f_k(n) \circledast f_k^1(n) \circledast h(n) + z(n) \Big\} \tag{5a}$$

In Eq.(4a), $r(n)$ is the symbol received as the antenna at the receiver after passing through the sub-band filter. The signal subset is one that we get from Eq. (4). Also, $h(n)$ here is the channel impulse, and the AWGN is represented by $z(n)$. The F-OFDM system we're using uses matched filters. So we can assume such a filter $f_k^{2\cdot}(-n)$ at the receiver has a pairing filter at the transmitter, which decouples the signals in each sub-band. We can represent this as-

$$r_k(n) = r(n) \circledast f_k^{1\cdot}(-n) \tag{5b}$$

$$= f_k^{1\cdot}(-n) \circledast \sum_{k=0}^{K-1} f_k(n) \circledast f_k^{1\cdot}(n) \circledast h(n) + f_k^{1\cdot}(-n) \circledast z(n) \tag{6}$$

As mentioned above, rk(n) here in Eq. (5b) is the received symbol after filtering by the k^{th} sub-band filter. After that, each sub-band goes through an identical process demonstrated by Eq. (6). This filtering scheme differs from

OFDM before any symbol reaches the receiving terminal. The goal of applying dedicated filter blocks is not to lose synchronisation by adding any phase or amplitude offset [19]. It should be mentioned that it's still possible in F-OFDM to have non-ideal synchronisation in the uplink and receive an accurate phase and amplitude representation at the receiver [20]. Still, for this work, we're considering synchronised uplink for simplicity.

2.1 *Proposed Algorithm*

Here we present now the algorithm for the proposed estimation scheme:

Input: $\bar{x}$, $\bar{y}$, $\bar{z}$
Output: $\hat{h}$ for k attempts
Setup: set *residual* $r_0 = \hat{y}$; $\hat{h} = 0$; $i=s$; $k = 1$; $attempt = 1$
while $\neq$ *(stopping condition)*
Step 1: Start; select $f_k = max\left(\left| h \cdot r_{k-1}, i \right| \right)$
Step 2: Create test vector- $L_k = \varnothing \cup f_k$
Step 3: Finalise test vector $L - max\left(\left| h_{L_k}^{\cdot} \right|, i \right)$
Step 4: Residual $\boldsymbol{r_a} = \bar{y} - h_L h_L^* \bar{y}$; *Resudual* $\boldsymbol{r_b} = \bar{y} - h_L h_L^* \bar{y}^*$
Step 5: Check $\boldsymbol{r_a} \sim \boldsymbol{r_b}$; $\boldsymbol{r_a} > \boldsymbol{r_b} \rightarrow$ step 6 *else* $\rightarrow$ step 2 : $\hat{h} = \hat{h} * f_k(\hat{h})$
Step 6: If $\|r\|_2 < \|r_{k-1}\|_2$ $\rightarrow$ *step 7* ***else*** $\rightarrow$ *step* 4: $i = i + 1$
Step 7: Update $L = i \times f$ ***or*** $L_k = L$; $r_k = r$; $k = k+1$
Step 8: $\hat{\mathrm{h}} = \dfrac{h^*{}_L}{r_a{}^* \, r_b}$; ***end loop***
Stop

We can see in step 5 that instead of going on with a single weight factor, it opted for two. It makes the scheme more robust to added noise and interference since the next iteration is based on the difference between the weight factors instead of just one. Hence, sudden changes depicted as outliers in the estimation theory are automatically cut out. We'll see in the results section that this aide to also the asynchronous nature of the sub-bands, which eventually fastens the convergence [21]. A schematic approach to the whole process is given below in Fig. 1.

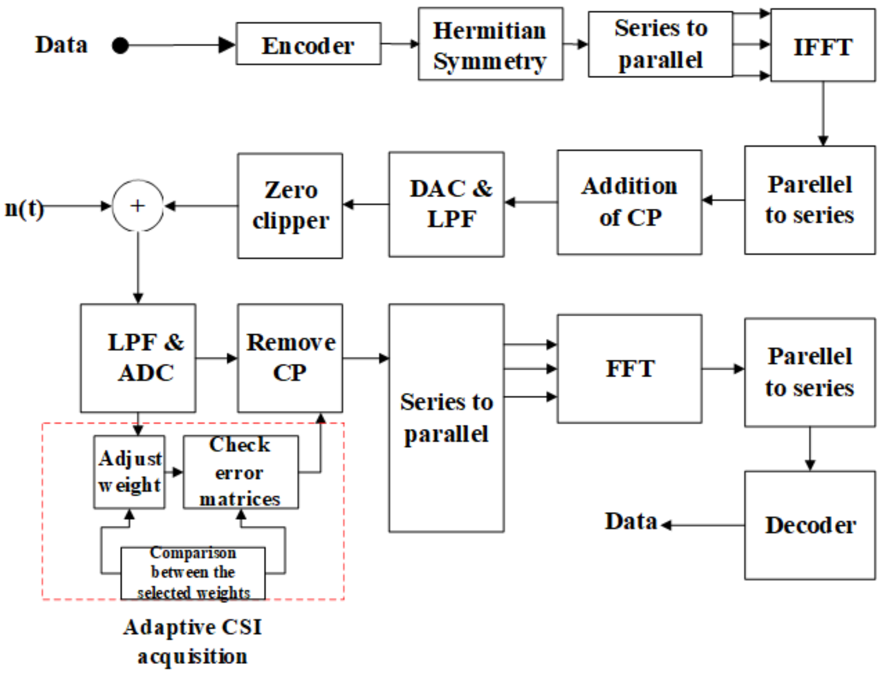

Fig. 1: Schematic diagram for the adaptive CSI acquisition process.

To ease the estimation process, we modelled the channel as a narrowband. It prevents the out-of-bound leakage problem in the OFDM systems [22]. Moreover, robust synchronisation is required in conventional OFDM systems to achieve minimal Inter signal interference (ISI). Here the proposed scheme gets the added immunity thanks to the sub-band division and the intelligent weight selection method. Custom CP length also helps in this regard.

3. RESULTS & DISCUSSION

We used Matlab® for our simulation purposes. For this setup, we simulated 1500 subcarriers. Each subcarrier is considered free of ISI and ICI, i.e. they're deemed ideal. Since we have considered an orthogonal subcarrier, it can also assume zero adjacent channels (ACI) and co-channel interference (CCI). We used the one factor at a time or OFAT method, meaning the number of subcarriers or taps was changed in each simulation. As mentioned at the beginning, the assumption of a block fading scenario allows us to model any impairment caused by the atmosphere as constant for one signal block.

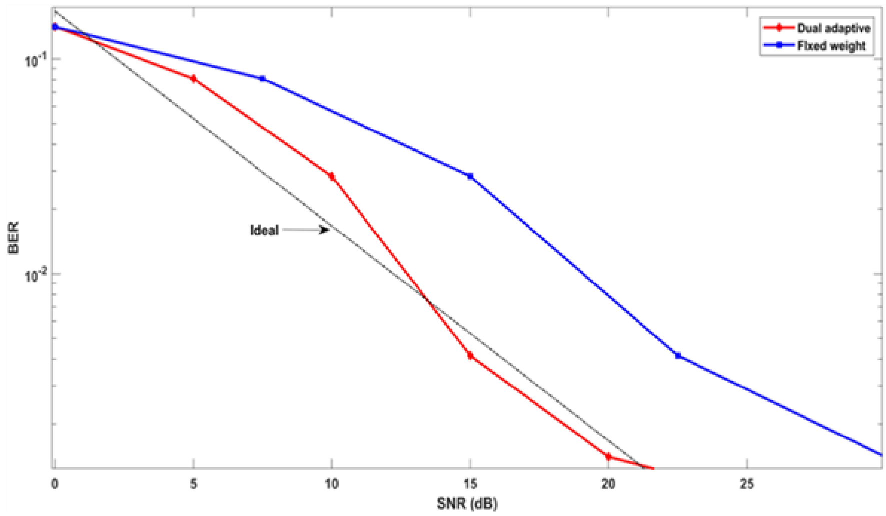

Fig. 2: BER analysis of the proposed method.

Fig. 2 shows that the receiver's response was much more efficient when using two adaptive weights compared to the single fixed weight method. The complexity added is minimal compared to the performance gain, so it is also preferable for the 5G scenario. The better response in the curve can also be characterised as the effect of the reduction of the emphasis on equalisation since, in F-OFDM, it's not essential, unlike OFDM. Fig. 2 shows the improvement in packet error rate, which is also lower than the one mentioned above. It should be noted that this result was obtained by keeping the no of taps up to 8 for the simplicity of the simulations. In other scenarios, it can be further facilitated.

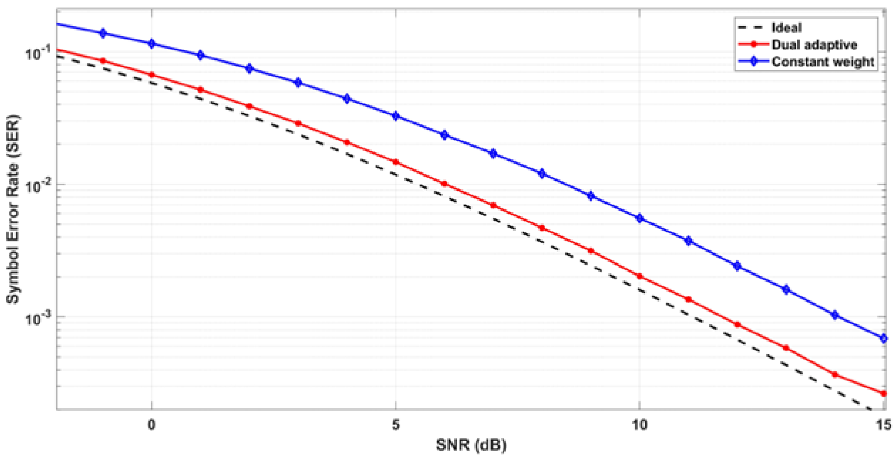

Fig. 3: Symbol error rate (SER) analysis of the estimator.

We also measure the SER analysis of the proposed estimator. It can be inferred from Fig. 3 that the proposed method has a near-ideal response to the question of adjacent symbol contamination. Symbol contamination is severe in modern 5G networks since additional user data has been specified to be sent during transmission per new standards. Therefore, minimising SER can lead to further smooth transmission and faster signal processing.

4. CONCLUSION

In this paper, an intelligent but modest method that exploits the redundancy of the pilot-based estimator was proposed, which adaptively can determine the channel coefficients. In this case, not only single but dual adaptive weight factors have been considered, which further improves the efficiency compared to unique adaptive weight. Simulations show that adaptive weight only needs a slight modification in the algorithm to get promising results. We get the near-ideal response for both BER and SER curves, which can be advantageous for Massive MIMO networks. This work can be judged as an extension of the idea developed by the author in his previous work. Because the terminology and standards are getting increasingly complex in next-gen communication, more straightforward methods with acknowledgeable results are welcomed. Finally, having adaptive weight does add some minor problems like slight to moderate modifications of the receiver, higher uplink traffic etc. However, these are not treated in this work, and the authors would like to leave them as a potential research interest.

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