Exploring pilot assignment methods for pilot contamination mitigation in massive MIMO systems

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Abstract: In massive multi-input multi-output (MIMO) antenna system, the performance is restricted by inter-cell interference called pilot contamination. However, acquisition of channel state information for channel estimation introduces overheads of pilots required to estimate the channel, a disadvantage that causes inefficient use of bandwidth. A tradeoff thus exists between the number of pilots required to estimate the channel versus the spectral efficiency. Studies on pilot decontamination using pilot assignment lack consideration of the comparative analysis to determine superior approaches. Limited literature exists on the analysis of the existing pilot assignment techniques. Different techniques exhibit varied performances and influence on resource utilization. The purpose of this study is to analyze various methods of pilot assignment schemes for mitigation of pilot contamination in massive MIMO systems. A systematic review approach is adopted to examine different related works and the adopted methodologies, outcomes, and restrictions to determine the most suitable approaches. This study further demonstrates the impact of coherence interval distribution between the pilots for channel estimation and data transmission. An analysis of a tradeoff between FDD and TDD

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PUBLIC INTEREST STATEMENT
Recent advances in Massive MIMO technology have provided different approaches to reduce pilot contamination in Massive MIMO multi-cell environment based on pilot assignment. The acquisition of the channel state information introduces overheads of pilots that are required to frequently study the channel; a disadvantage that causes inefficient use of bandwidth. The challenge is extracting the channel state information using pilots at limited coherence interval while trying to eliminate pilot contamination. Spectral efficiency decreases as more resources within the coherence interval are assigned for pilots for estimation compared to payload for transmission, hence the need for optimization. It is thus important to leverage the scarce resources for improved spectral efficiency so that more pilots are assigned for data transmission than channel estimation. This research examined the most recent pilot assignment methods for pilot contamination mitigation in massive MIMO systems.
modes is presented to determine the most suitable for massive MIMO antennas. In addition, the study provides recommendations for future research.

Subjects: Communications & Information Processing; Communication Networks & Systems; Communications System Design; Digital & Wireless Communication; Telecommunications

Keywords: massive MIMO; pilot allocation; pilot assignment; pilot contamination

1. Introduction

Massive multi-input multi-output (MIMO) consists of a large number of antenna arrays at the base station, typically hundreds, serving a large number of users in the same time-frequency resources (Larsson et al., 2014; Medbo et al., 2014). Having a large number of base station antennas than the number of user terminals improves the throughput and channel estimation quality for each antenna (Hassan, 2017). Nevertheless, massive MIMO system performance is constrained by pilot contamination that restricts the capacity of massive MIMO systems (Ngo, 2015; L. Zhao et al., 2018). Regardless of the rise in the number of antennas at the base station, the capacity reaches a saturation point.

Recent studies have shown that pilot assignment can reduce pilot contamination (Nie & Zhao, 2020; Omid, 2019; Shahabi, 2019; Yang & Chen, 2020). However, one major challenge in pilot decontamination is the inefficient use of frequency resources. The challenge is attributed to a compromise between the number of frequency resources required to estimate the channel (pilots) and the system performance in terms of spectral efficiency. When the number of pilots increases, more frequency resources are required, hence escalating the transmission overhead. Different pilot assignment schemes demonstrate diverse performances and the leverage on resource utilization. However, limited literature exists on the comparative analysis of the various pilot assignment techniques. Consequently, a detailed analysis is required to compare and enumerate the performance of pilot assignment schemes.

This research uses a systematic review approach to examine different works of massive MIMO literature that explore pilot decontamination using pilot allocation and assignment approaches. Specifically, this research 1) analyzes related works and respective methodologies, performance metrics, results, and limitations on the reduction of pilot contamination; 2) compares various pilot assignment schemes based on achieved results using duplexing modes and spectral efficiency; and 3) presents recommendations for future research.

Other sections of the paper are organized as follows: Section II provides a literature review on massive MIMO system, pilot assignment, and pilot contamination. Section III covers a systematic review approach used in this study to elaborate on the selection of works in the literature. Section IV provides a review of related works on pilot assignment approaches. Section V presents a comparative analysis of related works by examining the most recent pilot assignment schemes for pilot decontamination and the achieved results. Section VI presents the recommendations for future research directions. Finally, section VII concludes the paper.

2. Massive MIMO system overview

Massive MIMO exploits the multipath effect to its advantage to obtain the diversity and multiplexing gain, hence the improvement of the link rate and the reduction in bit error rate (Zheng et al., 2015). Massive MIMO antennas evolved from the MIMO antenna system whereby the base station consists of many antennas compared to the user terminal antennas (Marzetta et al., 2016). Researchers perform experiments on massive MIMO with a different number of antennas. For example, Lund University has a massive MIMO testbed with 100 base station antennas at 3.7 GHz; while that at KU Leuven has 64 base station antennas between 2.4 and 2.62 GHz, and between 3.4 and 3.6 GHz bands (Björnson et al., 2019).
Massive MIMO antenna system enhances both spectral efficiency and energy efficiency (Badr et al., 2017). The large array gain in massive MIMO increases the spectral efficiency (Jing & Zheng, 2014). The energy efficiency in massive MIMO is a result of the deployment of many antennas that focus energy into a narrow beam on small areas in the location of the user equipment (Zheng et al., 2014).

Even though massive MIMO promises spectral efficiency to support next-generation wireless systems, massive MIMO has the following challenges, which provide an opportunity for further research: instantaneous reciprocity, channel state information acquisition, hardware impairments, channel feedback, architecture, and reciprocity (Araújo et al., 2016). The use of many antennas in massive MIMO increases signal processing complexity and computations in channel estimation, detection, and precoding (L. Zhao et al., 2018). Massive MIMO research includes channel estimation, channel modeling, antenna deployment, practical applications, resource management (frequency, time, and spatial resources), precoding, and massively distributed antennas (L. Zhao et al., 2018). This research focuses on channel estimation, which influences the accurate detection of a transmitted signal, at the receiver. Figure 1 shows various research areas in massive MIMO.

### 2.1. Pilot contamination

Pilot contamination is a condition that occurs when the precoding matrix adopted at a base station is correlated with the channel of users in other cells because of non-orthogonal pilots allocated to users (Fatema et al., 2018). For the duration of the channel estimation process, the coherence time is limited. (Coherence time defines a time interval within which a system can acquire CSI in an attempt to estimate the channel.) CSI is computed based on the pilots used during transmission and then matched with the received pilot signals.

During the coherence time, orthogonal pilot training sequences are finite, thus non-orthogonal pilots can be re-used in adjacent cells. Consequently, the base station estimates the channel of user equipment in its cell while user equipment in another cell communicates the same pilot signal (interference). The channel estimate acquired from such cells is corrupted by estimates from nearby cells, thus reducing the estimation quality, subsequently leading to pilot contamination (Hoydis et al., 2011; Jing & Zheng, 2014).

Since pilot contamination gives rise to coherent interference, it influences the capacity in terms of values of spectral efficiency and Bit Error Rate (BER). Consider a base station with m base station antenna terminals, l cells, and k is user terminals, where $H$ is the channel matrix between the $k$ users and the $M$ antennas, $n$ is the noise matrix, $\rho$ is the signal-to-noise ratio. If $x$ is the transmitted signal matrix and $y$ is the received signal matrix, then the respective equations for uplink and downlink channel are given by Equations (1) and (2) respectively (Marzetta et al., 2016).

$$y = \sqrt{\rho} \sum_{k=1}^{K} h_{lk}^{lm} x_k w_l + \sqrt{\rho} \sum_{l=1}^{L} \sum_{k=1}^{K} h_{lk}^{lm} x_l w_l + n$$  \hspace{1cm} (1)$$

and 

$$y = \sqrt{\rho} \sum_{k=1}^{K} \bar{h}_{lk}^{lm} x_k + \sqrt{\rho} \sum_{k=1}^{K} \sum_{l=1}^{L} h_{lk}^{lm} x_l + n$$ \hspace{1cm} (2)$$

These equations represent a received signal “tainted” by interference and noise. $h_{lk}^{lm}$ is the channel or CSI and is represented by

$$h_{lk}^{lm} = \sqrt{\rho_{lk}} g_{lk}^{lm}$$ \hspace{1cm} (3)$$
where $\theta$ is a large-scale fading coefficient, $h_{kl}^m$ is the channel for users $k$ in cell $l$ and $g$ is the small-scale fading coefficient. The channel matrix of $h$ is given by (Marzetta et al., 2016; Ngo, 2015)

$$
H = \begin{bmatrix}
    h_{11}^1 & \ldots & h_{1k}^1 \\
    \vdots & \ddots & \vdots \\
    h_{11}^M & \ldots & h_{1k}^M \\
    h_{M1}^1 & \ldots & h_{Mk}^1 \\
    \vdots & \ddots & \vdots \\
    h_{M1}^M & \ldots & h_{Mk}^M 
\end{bmatrix}
$$

(4)

2.2. Pilot assignment

A challenge exists in determining the number of pilots to assign to users in a massive MIMO network (Björnson, 2016). The time-frequency resources are shared among the data and pilot sequences. Hence, the more the number of resources utilized for channel estimation, the fewer the resources available to transmit data; hence, the need to balance to realize spectral efficiency in massive MIMO. In some studies, the words “pilot assignment” and “pilot allocation” are used interchangeably to explain the arrangement or distribution of pilot signals during channel estimation. Several pilot assignment approaches exist that present various ways of allocating pilots (L. Zhao et al., 2018).

2.2.1. Fractional frequency reuse

Pilot reuse with a reuse factor can be utilized to diminish pilot contamination and is grouped into two categories (Su & Yang, 2015). To mitigate pilot contamination, the first category is when cells in the similar group are allocated similar pilot sequences whilst cells in different groups are allocated orthogonal pilot sequences. The second category of fractional frequency reuse separates users into cell-center users and cell-edge users. Pilot contamination severely affects cell-edge users. A cell-center pilot group is reused for all cell-center users. A cell-edge pilot group is adopted in the neighboring cells for the edge users (Su & Yang, 2015; Wu et al., 2018). However, a drawback of the fractional pilot reuse method is the introduction of additional pilot overhead (Wu et al., 2018).

2.2.2. Superimposed pilots

To reduce pilot overheads, pilot sequences can be superimposed on the data sequences to provide more orthogonal pilot sequences as the length of the uplink block (Kudathanthirige & Amarasuriya, 2018). This results in the reduction of PC. However, there exists interference between pilot and data transmissions. Cell-edge users are most affected by pilot contamination compared with cell-center users. Thus, scholars recommend allocation of the right proportion of power to data and pilots.

2.2.3. Time-shifted pilots

A time-shifted frame structure can be deployed to mitigate pilot contamination. All cells are distributed into separate groups that transmit their uplink (UL) pilots in different time slots. While grouping users to share pilots, users with large path loss differences and different spatial channel correlation must be grouped since they cause less contamination to each other. At the instance, a specific group sends UL pilots, other groups send downlink (DL) data. To efficiently suppress the inter-channel interference received from the inner group, optimal power allocation is deployed based on the received Signal to Interference plus Noise Ratio (SINR) for both UL and DL (L. Zhao et al., 2018).

2.3. Duplexing modes

Pilot signals are used to characterize the channel for estimation. Each terminal synchronously sends pilot sequences uplink data to the base stations, which use the pilots for channel estimation and perform precoding. Subsequently, the base stations send downlink data to users making use of the channel estimations as beamforming vectors (Fernandes et al., 2013). Due to the nature of mobile networks, the channels require estimation for every coherence interval. Mobility only
supports shorter coherence times (Jose et al., 2011). Massive MIMO can accommodate both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes (Hassan, 2017).

In TDD, the acquired CSI is used to estimate the channel in downlink using the principle of reciprocity, hence it does not require feedback (Fiordelis et al., 2018; Jose et al., 2011). Reciprocity means that the impulse response is the same in both directions. In TDD uplink and downlink, transmissions use the same frequency spectrum, but different time slots and the base station estimates the CSI.

For FDD, the number of pilot samples per coherence interval should be at least greater or equal to the number of transmit antenna orthogonal pilots in the forward link (Marzetta et al., 2016). Each antenna in the FDD system at the base station transmits an orthogonal pilot sequence compared with pilot sequences transmitted by the other antennas (Upadhyay et al., 2017). FDD Massive MIMO uses different frequency bands for uplink and downlink. FDD has increased overhead compared with TDD, thus massive MIMO performance is reduced (P. Zhao et al., 2017). Moreover, as a result of non-reciprocity, the FDD mode time is longer (Araújo et al., 2016). Table 1 shows a comparison between TDD and FDD in terms of the number of pilots used for channel estimation.

### 2.4. Distribution of pilot sequences and spectral efficiency

CSI acquisition is influenced by how fast the channel conditions are changing (Hoydis et al., 2011). CSI is estimated using pilot sequences (Ashikhmin & Marzetta, 2012). To avoid pilot contamination, the same pilot sequence is utilized in the same cell but a different orthogonal sequence is used in other cells such that if \( \psi_i \) and \( \psi_j \) are pilot sequences from different cells \( i \) and \( j \) thus,

\[
\psi_i \times \psi_j = 1 \text{if} i = j \text{and} \psi_i \times \psi_j = 0 \text{if} i \neq j
\]  

(5)

The coherence interval, \( \tau_c \) should be selected such that it accommodates mobility. Since Massive MIMO employs Orthogonal Frequency Division Multiplexing, accounting for cyclic prefix then the useful samples per coherence interval become \( \frac{14}{15} \times \tau_c \). The net spectral efficiency (Marzetta et al., 2016) is thus

\[
C_{\text{net}} = C_{\text{inst}} \times f \times \frac{14}{15} \times \left(1 - \left(\frac{\tau_p}{\frac{14}{15} \times \tau_c}\right)\right)
\]  

(6)

where \( C_{\text{net}} \) is the instantaneous spectral efficiency and \( f \) is the split of transmission time of data shared between uplink and downlink. For a multi-cell massive MIMO system with \( K \) user terminals per cell and a reuse factor of \( \eta_{\text{reuse}} \) in the network, the pilots will thus occupy \( K \times \frac{\eta_{\text{reuse}}}{\tau_c} \) samples from the total \( \tau_c \) samples. The pilot overhead thus becomes the fraction, \( \frac{K \times \eta_{\text{reuse}}}{\tau_c} \). Hence, as the number of users increases per cell, the number of pilot sequences will increase but the spectral efficiency will decrease.

### Table 1. Comparison of TDD versus FDD

|                | Uplink                              | Downlink                           |
|----------------|-------------------------------------|------------------------------------|
| TDD            | User Equipment (K) pilots           | None                               |
| FDD            | User Equipment (K) pilots + Base Station Antennas (M) CSI coefficients | Base Station Antennas (M) pilots |
3. Methodology
This research adopts a systematic review approach for analysis of recently published research. The filtering criteria are based on the methodology used in the published research and the resulting performance of the proposed approach. The following databases were used to search for relevant literature: Scopus, IEEE Xplore, Science Direct, and arXiv. The search included the most recent journal and conference articles published in the English language only. The following keywords were used to search for appropriate literature relevant to this study: massive MIMO, pilot decontamination, pilot assignment, pilot allocation, and pilot contamination; and three hundred and twenty-one (321) papers were found.

The screening was performed based on the relevance, and quality of titles and abstracts; then, one hundred and thirty-eight (138) papers were included in the study and one hundred and eighty-three (183) papers were discarded. The papers were further filtered to obtain papers focused on the state-of-the-art pilot assignment schemes published between the years 2015 and 2020, whereby twenty-six (26) papers were considered.

A further detailed analysis was performed based on the significance of the results obtained and limitations, whereby seventeen (17) papers remained for comprehensive analysis. The comprehensive analysis included analysis of the papers based on the duplexing mode and the pilot assignment method used. This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart to describe how the selection of previous researches for inclusion in this study was conducted (Liberati et al., 2009). Figure 2 presents a PRISMA flow chart that was used for literature screening.

Recognizing the impact of pilot assignment and the duplexing modes selection for massive MIMO and pilot assignment methods, a detailed analysis of both was conducted. The impact of coherence interval distribution between the transmission of data and pilots, and the spectral efficiency was demonstrated. MATLAB was used to analyze the variation of spectral efficiency and the coherence interval allocations. Moreover, the tradeoff between FDD and TDD modes was analyzed, to determine the most suitable for massive MIMO antennas.

4. Related works in pilot decontamination
To assess the performance of pilot assignment schemes, 26 works of literature were examined. The qualitative analysis explored related studies on pilot assignment depicting the methodology
applied, results, and limitations. The literature discussed has adopted either TDD or FDD modes. The literature has been arranged in ascending order of the year published.

Recent advances in Massive MIMO technology have provided different approaches to reduce pilot contamination in Massive MIMO multi-cell environment based on pilot assignment. The authors in (Z. Zhao et al., 2015) proposed a pilot assignment scheme based on novel cell sectorization-based (CS-PA) which operates by using orthogonal pilots between adjacent sectors. The proposed method was compared with the typical pilot contamination mitigation methods (conventional synchronized pilot scheme and time-shifted scheme). The results showed that the proposed CS-PA scheme was able to effectively suppress PC and achieve higher system throughput when the number of base station antennas increases to infinity. However, the sum-rate was observed to be low when the number of antennas is less than 40 since the system throughput in CS-PA was controlled by the impact of degrees of freedom per user.

Research by Zhu et al. (2015) examined a smart pilot assignment scheme to reduce pilot contamination. Unlike conventional methods that perform random assignments, the proposed smart pilot assignment sequentially allocates a pilot sequence with the smallest inter-cell interference to the user with the most severely degraded channel quality. Results showed that the proposed SPA scheme provided a better SINR compared with that of conventional schemes by approximately 0.6bps/Hz with performance close to optimal, as the number of base station antennas increases.

Furthermore, research by Su & Yang (2015) explored advanced-fractional frequency reuse scheme using Zadoff-Chu sequences. The study achieved a throughput of 60bps/Hz for 300 antennas. Nevertheless, utilizing different Zadoff-Chu sequences in adjacent cells leads to pilot contamination, hence reducing the performance of the cell-edge users.
A novel scheme based on time-shift to alleviate pilot contamination was introduced in (Luo et al., 2016). In the proposed scheme, a similar pilot sequence was used in the cell but mutually orthogonal pilots are used in different cells. Time-shift was implemented by users within a cell to transmit the same pilot sequence within the channel estimation stage. The results demonstrated that the proposed approach mitigated pilot contamination and improved the performance compared with the popular orthogonal pilots.

Research by Jin et al. (2016) adopted the principle of Time-Shifted Pilots. The study achieved sum-rates greater than 41bps/Hz for 150 users. However, the research assumes perfect channel state information. A study by Akbar et al. (2016) proposed a pilot assignment using the location information of users to compute the line of sight (LOS) interference between the transmitted signal and the interfering signal. The approach allocates the same pilot sequences for users with the least LOS interference. The scheme outperforms the random pilot assignment with higher uplink sum-rate and provides nearly 20% improvement in uplink sum-rate as the number of base station antennas increases.

Research by Ma et al. (2017) applied superimposed Pilot Schemes to reduce pilot contamination. The research assumed partial CSI and considered the BER and sum-rates as performance parameters. The results indicate that at SNR =8 dB, the BER was as low as 10^{-5}.

Research by P. Zhao et al. (2017) exploited the reduction of training overhead which was a dominant challenge with FDD. The authors developed an angular domain pilot design and channel estimation scheme for reduction of the required overhead by manipulating the angle-domain channel sparsity. Results depicted that the proposed method delivers a good mean square error (MSE) performance with a great reduction of pilot overhead, and achieves an improved downlink throughput.

In a study by Upadhya et al. (2017), the method of superimposed pilots was adopted. The results revealed that the proposed method achieved SINR of 6 dB for 100 antennas and 22 dB for 600 antennas compared with conventional methods. The proposed method achieves BER as low as 10^{-4}. At smaller values of user radius, the self-interference in superimposed pilots reduces the performance.

A Pilot Allocation Protocol (PAP) scheme was proposed in (Tekanyi et al., 2018) to alleviate the effect of pilot contamination. The proposed method was based on sectional pilot sequence initialization and sharing which operates by assigning more than one user to share the same orthogonal pilot sequence within a cell. The results indicated a throughput improvement over the conventional scheme of 20.5b/s/Hz for uplink, at 250 base station antennas with ZF detector. The MF detector had a throughput improvement of 8.1b/s/Hz for UL at 250 base station antennas. Moreover, MF provided a BER of 10^{-1.25} at SNR of 8 dB while ZF provided a BER of 10^{-3} at SNR of 8 dB. However, the PAP scheme creates intra-cell interference.

Research by Dao & Kim (2018) proposed a Worst Cell-Based Pilot Allocation algorithm by considering a cell with the poorest channel quality, to increase the uplink achievable sum-rate of the system. The algorithm selected users with the highest inter-cell interfering to assign a unique pilot sequence if the number of pilot sequences was greater than the number of users in a cell. The Worst Cell-Based Pilot Allocation algorithm outperforms the conventional pilot allocation schemes.

Wu et al. (2018) suggested a pilot scheduling scheme based on performance degradation. The proposed scheme outperforms the conventional approaches and achieves approximately 3.3 bps/Hz, with 512 base station antennas and 10 user terminals. However, the user-grouping scheme outperforms the proposed scheme based on degradation while the number of edge users was less than five.
A novel pilot assignment for Novel Non-Orthogonal Multiple Access (NOMA) users was proposed by Kudathanthinige & Amarasuriya (2018) to counter the effects of intra-cluster pilot contamination. Users in the system, are grouped into clusters by using their spatial signatures. Moreover, to guarantee user-fairness, a max-min fairness optimal transmit power allocation algorithm was proposed. The results revealed that the proposed approach could support massive access while the achievable sum-rate gains remain unaffected.

The authors in (Al-hubaishi et al., 2019) developed an efficient pilot assignment scheme by maximizing the minimum uplink rate of the specified users in the cell. The approach minimizes the outgoing inter-cell interference at the target cell. The simulation results show that the proposed scheme outperforms both the smart pilot assignment and the conventional by mitigating the effect of inter-cell interference.

An efficient pilot allocation based on asynchronous scheduling which was based on the fractional pilot reuse was proposed by the authors (Zhou et al., 2018). The different sets of pilots are allocated to the different groups of users on the cell edge and the cell-center. The results indicated that the performance of the recommended scheme outperformed the conventional integer reuse approach.

A deep learning approach for a pilot assignment was developed by Wen et al. (2018). The novel CSI sensing and recovery approach learns to use channel structure from training samples to determine the CSI. The results show considerably improved signal reconstruction quality and reduced time complexity compared with existing compressive sensing approaches.

Furthermore, another deep learning-based pilot allocation scheme was presented by Kim et al. (2018). The proposed method can improve the performance in cellular networks with pilot contamination by understanding the connection between pilot assignment and the user locations. The proposed method delivers 99.38% theoretical upper-bound performance with low complexity.

The authors in (Ullah et al., 2019) also explored the use of cell splitting and sectorization-based pilot assignment strategy to alleviate pilot contamination, whereby the users are categorized into cell-center and cell-edge zones. The results showed that, compared with traditional pilot allocation strategy, the proposed method reduces pilot contamination and achieved higher system throughput, low Mean Square Error, and Normalized MSE. The MSE was reduced from −29 dB to −36 dB for SNR of 15 dB.

Research by Shahabi (2019) devised a low-overhead iterative pilot assignment strategy to reduce overhead and complexity. Numerical results revealed that the proposed approach achieves reduced complexity and overhead compared with the exhaustive search algorithm. However, the system experienced a slight performance loss.

A study by Jiang & Wang (2019) suggested a dynamic pilot assignment method based on the interference extent of cells within the same group. The approach was able to improve the center cell’s minimum uplink SIR and improve the center cell’s average uplink signal to interference ratio by considering the overall user interference. The proposed scheme improved the uplink and downlink signal to interference ratio and average uplink user capacity of the cell-center.

The authors in (Omid, 2019) proposed a pilot assignment strategy that integrates a low-complexity optimization problem compared with conventional algorithms. In the proposed scheme, the problem of the pilot assignment was organized by discrete optimization variables. The results demonstrated that the proposed scheme converges in very few iterations in comparison with the exhaustive search method in terms of complexity, at a slight cost of a reduction in the signal-to-interference-plus-noise ratio.
An efficient pilot assignment scheme based on Tabu Search (TS) was proposed in (Liu et al., 2019) to reduce the severe pilot contamination effect. TS was applied to determine the suboptimal pilot assignment outcome with low complexity. Results indicate that the proposed TS-based pilot assignment scheme improves the 95% per-user net throughput with the same complexity compared with the greedy schemes and conventional random.

One of the most recent works in the year 2020 is by Yang & Chen (2020), which proposes a pilot reuse scheme based on the location-aware approach to reduce pilot contamination. The approach makes use of the locations of mobile devices to estimate channel statistics between the base stations and mobile devices. Simulation results indicated that the location-aware approach enhanced the channel estimation quality for all users. Moreover, the approach improved fairness for different cells.

The authors in (Nie & Zhao, 2020) recommended a joint pilot allocation and pilot sequences optimization scheme to mitigate pilot contamination and maximize the spectral efficiency. The approach uses the location information to compute the distance between users in different cells to determine the interference among users. Orthogonal pilots are assigned to users with a shorter distance and higher similarity. The results showed that the combination of pilot sequence optimization and pilot allocation considerably improved the spectral efficiency.

In the study by Shahabi et al. (2020), exploited a pilot assignment scheme with low-complexity optimization problems. To address the non-convex optimization, the problem was solved iteratively and sequential convex programming was exploited. The results showed that the proposed scheme outperformed the conventional methods in terms of complexity (fast convergence), however, experienced a decline in the uplink sum-rate.

In the research by Salh et al. (2020), the achievable rate was improved by reducing pilot contamination. The research adopted a TDD mode and implemented MMSE precoding. The study suggested that the number of pilot sequence within a cell might be less than or equal to the number of user equipment, considering the different number of user equipment that transmitted similar pilot sequence in the same cell. However, increasing the number of coherence interval delivered a small data rate because of increased interference and noise at a higher number of transmitting pilot sequence.

From the literature analyzed, initial research on pilot assignment methods was based on frequency re-use, super-imposed pilots and time-shifted pilots approach. However, recent trends of pilot assignment include the application of deep learning, which entail training of the system with large volumes of training samples to estimate the channel as presented in (Kim et al., 2018; Wen et al., 2018). The deep learning approach is used for CSI sensing and recovery based on the channel structure from training samples, thus the CSI is recovered. Furthermore, angle of arrival (AoA) approach has been used to acquire location information of users to estimate and monitor the distance between users in different cells (Nie & Zhao, 2020; Shahabi et al., 2020), thus facilitate to determine the possible transit power interference among users.

Table 2 presents a comparative analysis of studies based on the type of duplexing mode and pilot assignment adopted. The table further examines different types of studies on pilot assignment to depict the trends of the adopted methods. The studies have been arranged based on the publication year, starting with the most recent work.

From the analysis, many researchers have opted to use TDD mode during channel estimation. TDD is highly recommended in a practical massive MIMO system, as the most feasible alternative compared with FDD for efficient use of resources (Ali et al., 2017; Flordelis et al., 2018; Marzetta et al., 2016). In FDD, the users’ terminals need to estimate the CSI for each antenna and then the CSI has to be shared from the user terminals to the base station, a process that significantly consumes bandwidth (Upadhya et al., 2017).
| S/N | Literature | Method | Duplexing Mode | Frequency Re-use | Super-imposed Pilots | Time Shifted Pilots | Other Pilot Assignment Methods |
|-----|------------|--------|----------------|------------------|----------------------|---------------------|--------------------------------|
| 1   | Shahabi et al. (2020) | The angle of arrival (AoA)-exploited pilot assignment scheme with low complexity optimization problems | Not specified | Not specified | AoA-driven pilot assignment |
| 2   | Nie and Zhao (2020) | Joint pilot allocation and pilot sequences optimization (JPA-PSO) scheme | TDD | Not specified | AoA positioning method |
| 3   | Al-hubaishi et al. (2019) | Efficient pilot assignment by maximizing the minimum uplink rate | TDD | Not specified | Smart Pilot Assignment |
| 4   | Qian et al. (2018) | A Novel pilot allocation scheme utilizing the asymptotically orthogonal property of the channel | TDD | Not specified | Downlink training and orthogonal pilot allocation |
| 5   | Zhou et al. (2018) | Asynchronous scheduling based on the fractional pilot reuse | TDD | √ | |
| 6   | Kudathanthirige and Amarasuriya (2018) | Novel Non-Orthogonal Multiple Access (NOMA) | TDD | √ | |
| 7   | Kim et al. (2018) | Deep Learning-Based Pilot Allocation Scheme | Not specified | Not specified | Deep Learning-Based Pilot Allocation Scheme based on location |
| S/N | Literature | Method | Duplexing Mode | Frequency Re-use | Super-imposed Pilots | Time Shifted Pilots | Other Pilot Assignment Methods |
|-----|------------|--------|----------------|------------------|----------------------|---------------------|--------------------------------|
| 8   | Dao and Kim (2018) | Worst Cell-Based Pilot Allocation (WCPA) algorithm | TDD             |                  |                      |                     | Pilot assignment algorithm based on a target cell and user grouping |
| 9   | Wu et al. (2018) | Performance degradation-based Pilot scheduling scheme | Not Specified   |                  |                      |                     | User grouping and degradation |
| 10  | Tekanyi and Waziri (2018) | Pilot Allocation Protocol (PAP) scheme | TDD             | ✓                |                      |                     | A novel Deep Learning-based CSI sensing and recovery mechanism |
| 11  | Wen et al. (2018) | Deep Learning | FDD             |                  |                      |                     |                                  |
| 12  | Upadhye et al. (2017) | Superimposed pilots | TDD             |                  | ✓                    |                     |                                  |
| 13  | Ma et al. (2017) | Superimposed Pilot Schemes (compared with Orthogonal Pilot Scheme) | Not Specified   |                  | ✓                    |                     |                                  |
| 14  | Akbar et al. (2016) | Location-Aware Pilot Assignment | Not specified |                  |                      | Location-Aware Pilot Assignment |                                  |
| 15  | Luo, Wang, and Lv (2016) | A novel time-shift pilot scheme | TDD             |                  |                      | ✓                    |                                  |

(Continued)
Table 2. (Continued)

| S/N | Literature          | Method                              | Duplexing Mode | Frequency Re-use | Super-imposed Pilots | Time Shifted Pilots | Other Pilot Assignment Methods |
|-----|---------------------|-------------------------------------|----------------|------------------|----------------------|---------------------|---------------------------------|
| 16  | Zhu et al. (2015)   | Smart Pilot Assignment (SPA)        | TDD            |                  |                      |                     | SPA method whereby a user with the worst channel quality sequentially is assigned a pilot sequence with the smallest interell interference. |
| 17  | Su and Yang (2015)  | Advanced-fractional frequency reuse scheme using Zadoff-Chu sequences | TDD            |                  | √                    |                     |                                 |
Correct channel estimation to reduce pilot contamination (PC) depends on the accuracy of the CSI. However, the acquisition of CSI introduces overheads of pilots required to estimate the channel frequently (Upadhyay et al., 2017). Learning the channel by sending pilots consumes frequency resources that could otherwise be used for data transmission. Moreover, the time required to acquire CSI for channel estimation is limited by the coherence time. Therefore, for pilot assignment, the challenge is extracting the CSI, at limited coherence interval while trying to eliminate PC.

5. Performance analysis

5.1. Efficient pilot assignment
Pilot contamination is an inter-cell interference affecting the performance of massive MIMO in terms of the capacity of the system. To correctly estimate the channel and avoid interference, the channel needs to be estimated frequently. However, estimation requires time-frequency resources. However, a trade-off exists between the sizes of pilots required to estimate the channel versus the spectral efficiency. The sum-spectral efficiency bounds (Ngo et al., 2013) show that the Sum spectral efficiency ($R$) can be defined by the following formulas:

$$R = \begin{cases} 
(1 - \frac{1}{\tau_p}) \times K \log_2 \left( 1 + \frac{\sigma_p (M-1)^2}{\sigma_p (K-1)^2 + (1 + K) M^2} \right) & \text{for MRT}, \\
(1 - \frac{1}{\tau_p}) \times K \log_2 \left( 1 + \frac{\sigma_p (M-1)^2}{(1 + K) M^2} \right) & \text{for ZF}. 
\end{cases}$$

(7)

where $\tau_p$ is the coherence interval assigned to pilots and $\tau_c$ is the overall coherence interval, with power $P$, $M$ antennas at the base station and $K$ user terminals. To reduce pilot contamination, it would be apparent to increase the number of orthogonal pilot sequences, since each pilot can be assigned to fewer users in the network. However, resulting in a larger pilot overhead. Figure 3 depicts the relationship between spectral efficiency and the proportion of coherence interval allocated for data, $(\tau_c - \tau_p)$. The Figure is plotted at 128 base station antennas, 16 user terminals, coherence interval of 200 samples and 0 dB power. The Figure shows how spectral efficiency increases as more resources are assigned to data transmission, whilst fewer resources within the coherence interval are provided to pilots signals for estimations. The comparison is provided when using Zero Forcing (ZF) and Maximum Ratio Transmit (MRT) precoders.
5.2. Duplexing mode analysis

From literature, FDD provides better SNR than TDD for noise-limited and peak power constraint and noise-limited operation (Marzetta et al., 2016). Nevertheless, for interference-limited condition, the advantage diminishes since the interference power for TDD is the same as for FDD (Marzetta et al., 2016). Research has thus shown that FDD systems are considered impractical for channel estimation in massive MIMO. Moreover, in FDD, users estimate CSI for each antenna and the CSI has to be shared from the users to the base station, a process which further utilizes bandwidth (Upadhyya et al., 2017).

Research shows that, in TDD, only uplink pilots are sufficient to estimate the channel (Marzetta et al., 2016). Thus, as shown in Figure 4,

\[ \tau_{ul} + \tau_{dl} + \tau_{ul,p} = \tau_c. \]

(8)

The channel estimation has to be within the channel coherence time, which is the time within which the channel is assumed static. Hence, \( \tau_{slot} \leq \tau_c \).

Therefore,

\[ \frac{Ts \times Ns \times Nsub}{Tu} \leq \tau_c. \]

(9)

where \( Ts \) is the Orthogonal Frequency Division Multiplexing (OFDM) symbol duration, \( Ns \) is the number of OFDM symbols within one slot, \( Nsub \) is the number of subcarriers within coherence bandwidth, and \( Tu \) is the duration of OFDM symbol containing data samples.

Research shows that TDD is highly preferred in massive MIMO as the best alternative for optimal performance (Ali et al., 2017; Forderl et al., 2018; Marzetta et al., 2016). Using TDD, the number of resources required for transmission of pilots only depends on the number of simultaneously served terminals, and only the base station acquires the CSI. TDD allows massive MIMO to be scalable even when the number of antennas at the base station increases. Within the coherence time, the user equipment directs pilots to the base station for estimation. The base station then directs beams towards the user terminals with a transposed version of the estimated uplink channel matrix (Araújo et al., 2016).

6. Recommendations for future research

Massive MIMO faces challenges in the estimation of CSI due to the existence of many antennas that result in high dimensional channels. The challenge causes large training overheads for the duration of channel estimation and data transmission thus increasing the computational complexity. The pilot overheads lead to the reduction of the spectral efficiency. Research has shown that Angle of Arrival and Deep learning methods are the most adopted approaches in recent years. More efficient pilot assignment schemes, expanding into a combination of several pilot decontamination approaches can be implemented for improved results. Future work includes research examining the impact of the combination of more than one pilot decontamination schemes. Researchers are exploring the combination of precoding and pilot assignment (Choi et al., 2018; M. Zhao et al., 2017; Zuo et al., 2016).

Apart from the pilot assignment strategy, other pilot contamination mitigation strategies in Massive MIMO include Pilot contamination precoding (Ashikhmin & Marzetta, 2012; Jose et al., 2011), Pilot allocation using MMSE (L. Zhao et al., 2018), and using semi-blind and blind estimation approaches.

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Figure 4. Coherence Interval during TDD Estimation.

| Length of Coherence Interval (symbols) |
|---------------------------------------|
| Uplink Data (\( \tau_{ul} \))       |
| Uplink Pilots (\( \tau_{ul,p} \))   |
| Downlink Data (\( \tau_{dl} \))     |
(Müller et al., 2014). Further research to improve the performance of the pilot contamination mitigation strategies by adopting multiple approaches can result in more efficient approaches.

Furthermore, although many existing 3rd Generation and 4th Generation telecommunications systems use FDD (Tekanyi et al., 2018), research has shown that TDD is highly recommended compared with FDD for use in massive MIMO systems since it reduces pilot overheads during channel estimation. A comparative study between TDD and FDD shows that FDD can achieve high sum-rates compared to TDD under LOS with high Rician factors. However, the performance loss is significant for non-reciprocity-based beamforming solutions. Therefore, reciprocity-based TDD beamforming is recommended (Flordelis et al., 2018).

7. Conclusions
This research examined the most recent pilot assignment methods for pilot contamination mitigation in massive MIMO systems. Moreover, the impact of pilot assignment on the spectral efficiency for massive MIMO systems was explored. The performances of different pilot assignment schemes were examined for comparative analysis. A systematic review approach was used to analyze the most recent literature published on a pilot assignment based on the respective methodologies, results, and limitations associated with pilot contamination. Furthermore, 17 studies were selected for further analysis based on the pilot assignment method and spectral efficiency. Furthermore, in this research MATLAB was used to demonstrate the performance analysis for pilot assignment on the allocation of resources during estimation. Results show that an effective pilot assignment to mitigate interference in the transmission channel. Although it is essential to assign more pilots for channel estimation to mitigate pilot contamination, spectral efficiency decreases as more resources within the coherence interval are assigned for pilots for estimation compared to when are assigned to the payload for transmission. Thus, when the number of users increases per cell, the number of pilot sequences increases causing a decline in the spectral efficiency. Optimization of the scarce resources is significant for improved spectral efficiency so that more pilots are assigned for data transmission rather than pilots for channel estimation. The trend showed that pilot assignment schemes that implement Angle of Arrival and Deep learning methods are the most adopted approaches recently. Moreover, TDD is highly commended in practical applications of massive MIMO systems compared with FDD. This study contributes to the analysis of a variety of state-of-the-art pilot assignment methods to determine the most efficient. Future research includes the adoption of multiple pilot decontamination approaches to improve efficiency.

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