Downlink Cell-Free Fixed Wireless Access: Architectures, Physical Realities and Research Opportunities

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***Abstract*—Recently a new paradigm of wireless access, termed as cell-free massive multiple-input multiple-output (MIMO), has drawn significant research interest. Its primary distinction from conventional massive MIMO aided cellular networks is the ability to eliminate the detrimental inter-cell interference (ICI), or to convert ICI into extra power for the intended signal via a multi-cell cooperation approach originated from *network MIMO*. However, the information-theoretical limit of cell-free access is achieved at the expense of large network configuration overhead and high MIMO processing complexity. Because of the dynamic nature of wireless channels, the global channel state information (CSI) invoked for network MIMO quickly becomes outdated, leading to performance degradation. This paper focuses on the cell-free implementation of fixed wireless access (FWA), a complementary solution to fibre-to-the-premise (FTTP) where the latter is prohibitively expensive. In particular, we discuss the centralisation architectures and channel characteristics of cell-free FWA, as well as their joint implications on imperfect CSI performance. Moreover, measurement-based offline simulations show that the long coherence time ('quasi-static') assumption of real-world FWA channels is only valid against a completely motionless background, and thus it should not be used in FWA system design or performance analysis. Finally, we present new research opportunities for cell-free FWA in terms of physical infrastructure, data processing as well as machine learning.**

I. Introduction

WORLDWIDE 5G rollout provides a robust hardware infrastructure for a new generation of fixed wireless access (FWA), complementing the fibre-to-the-premise (FTTP) wireline access paradigm. FWA is attracting escalating interest from the academia, major network operators, network device manufacturers and standardisation bodies due to its high flexibility, low cost and the 5G breakthroughs. 5G FWA targets a peak rate of Gigabit per second (Gbps) at the customer end while offering ubiquitous connectivity, hence it may be perceived as an expanded use case of enhanced mobile broadband (eMBB). As a complement of massive multiple-input-multiple-output (MIMO) [1], cell-free cooperation [2] between base station (BSs) can further optimise the spectral efficiency (SE), coverage and power consumption of FWA systems. With the ambition of ubiquitous broadband connectivity, enhanced FWA solutions may have a significant role for use cases such as remote rural/mountain side areas, where fibre deployment is too expensive. While recent studies [3] discussed the potential of millimetre wave (mmWave) techniques in 5G FWA as a standardised use case in IEEE 802.11ay, the higher path loss compared to sub-6 GHz band signalling restricts the feasibility of mmWave to ultra dense networks. Due to this limitation, the potential of mmWave in certain major FWA scenarios (e.g., rural) is compromised. In this paper, we instead focus on the architecture and fundamental characteristics of cell-free FWA on the sub-6 GHz band as a complementary FWA solution.

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Conventional cellular communication networks rely on a system of BSs with each one covering a certain geographic area termed a cell. At any given location, a user equipment (UE) is exclusively served by a single BS. If the signals from adjacent BSs are not perfectly orthogonalized, they will cause interference, thereby reducing the achievable spectral efficiency of the UE. Moreover, the presence of multiple active UEs belonging to different cells also causes mutual interference. In contrast, cell-free cooperation unlocks diversity gain beyond cellular scenario when concurrently-arriving signals of overlapping frequencies from all adjacent BSs are relatively strong at a given UE's location, in which case the multi-user interference as well as the inter-cell interference (ICI) becomes beneficial. This scenario favours small cells at high user densities, and in a low-path-loss environment. Additionally, cell-free cooperation can also improve the reliability of FWA services, since an outage of service becomes less likely with an increasing number of cooperating BSs.

Cell-free massive MIMO is perceived as the evolution and consolidation of multiple cooperative MIMO technologies from the past two decades, which were mainly known as coordinated multi-point (CoMP) [4] where a BS is termed as a transmission point. Given that the downlink (DL) data intended for a UE are available at multiple BSs, we consider two specific CoMP modes (Fig. 1) depending on how the BS cluster schedules and allocates its pool of physical resources. In 4G Long Term Evolution (LTE), dynamic point selection (DPS) [5] specified systematic management of interference and radio resources across multiple sectors and cells. DPS aims to utilise the limited radio frequency (RF) spectrum resources and radio network infrastructure as efficiently as possible. Under moderate traffic demands, DPS can reduce interference levels, but under high traffic demands, the limited pool of radio resource becomes insufficient. However, the more powerful type of BS cooperation known as joint-transmission (JT) [4] is less susceptible to such limitations, because the size of the radio resource pool is increased per extra cooperating BS. In JT, more specifically coherent JT, multiple BSs cooperatively perform DL transmit precoding (TPC) by exploiting global channel state information (CSI). Hence, the signals from adjacent BSs will constructively combine at the UEs, leading to improved SE performance.

Even though the concept of CoMP-based BS cooperation already appeared in 3GPP case studies, cell-free architectures have not been standardised for commercial FWA or mobile networks. This is mainly because of the high processing delay

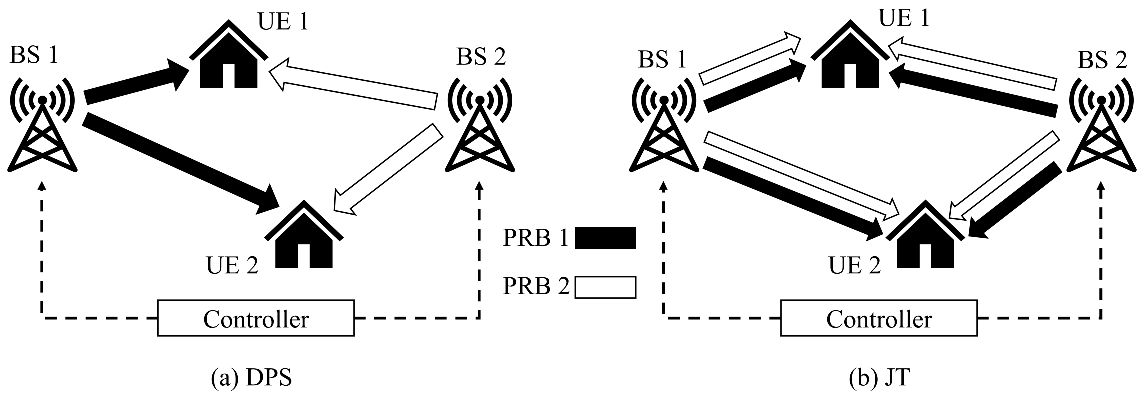


Fig. 1. Cell-free FWA coordination modes. (a) DPS prohibits simultaneous use of the same physical resource block (PRB) by different BSs; (b) JT allows PRB sharing across coordinated BSs.

incurred by essential MIMO TPC related operations and by BS-side information exchange via non-ideal fronthaul, as well as of the fact that the transfer characteristics of a wireless channel remain almost constant only for a short period. Practically, if the DL channel from a BS to a UE changes significantly between *the point of CSI acquisition at BS* and *the point of DL data reception at UE*, then a performance degradation is inevitable as a result of CSI estimation error. Therefore, the channel needs to be stable and the signal processing delay needs to be low for cell-free cooperation to provide practical gains. Due to the stationary UEs, FWA channels are widely assumed to change more slowly than mobile ones, even though the assertion that FWA exhibits quasi-static channel states requires practical validation. In stark contrast to previous CoMP case studies such as [4] which addressed the design trade-off between performance gain and network configuration overhead for multiple CoMP modes, this paper focuses on the fundamental challenge of wireless channel variability, how it affects the cooperation gain of CoMP, and what implications it has on the performance limit of FWA.

II. Cell-Free FWA

In comparison to the network-centric CoMP, cell-free networks are user-centric by design. Due to MIMO processing complexity, synchronisation requirement and fronthaul constraints, only a few selected BSs having the strongest signal contributions at the UE can cooperate in a meaningful way, while the inclusion of redundant BSs leads to diminishing performance gain and a waste of radio resources. Comparing to mobile services, where the user-centric nature of cell-free architecture requires dynamic BS clustering around each moving UE as a result of the time-varying path loss, FWA as a complementary broadband service to FTTP only needs static clustering unless the user traffic demand changes dramatically. As a result, the main challenge for user-centric cell-free FWA design arises from the on-off switching and the resulting fluctuating traffic demand of UEs. Therefore, despite of their differences in dynamic clustering design, CoMP and cell-free architectures are principally equivalent in the context of FWA. In the remainder of this paper, we will consider the various modes readily defined for CoMP as specific FWA realisations of the cell-free concept.

A. BS Coordination Strategies

In cell-free FWA, ICI exploitation can have a constructive impact on the target UE's received signal-to-noise ratio (SNR), and it is therefore more powerful than ICI reduction or avoidance. However, optimal cell-free FWA incurs considerable network configuration overhead due to the need for global CSI aggregation and sometimes even user data sharing at a CoMP controller via fronthaul. In addition, the global CSI matrix naturally has a higher rank than those associated with a single BS or UE, which also increases the complexity of channel estimation and TPC-related matrix operations. To mitigate these predicaments, time division duplexing (TDD) has been widely accepted as the more realistic duplexing option over frequency division duplexing (FDD) since it facilitates channel reciprocity exploitation between uplink (UL) and DL. UL/DL channel reciprocity in general frees up the radio resource budget reserved for CSI sample feedback as well as reducing the associated processing delay. In this section, we present an overview of the main architecture of the ICI-avoiding and the ICI-exploiting BS coordination strategies.

1) Dynamic Point Selection: Generally, DPS does not permit the sharing of a single physical resource block (PRB) across multiple BSs due to the lack of essential ICI-exploiting operations such as global TPC [5]. In TDD DPS (Fig. 2a), the UL signal (pilot/reference signals included) received at each BS undergoes the typical analogue-to-digital conversion (ADC), bit timing and multi-user synchronisation, as well as demodulation (e.g., a discrete Fourier transform (DFT) for the orthogonal frequency division multiplexing (OFDM) scheme). After demodulation, while the UL user data is passed to error correction decoders and backhaul transmission protocols (which have been neglected in Fig. 2 for simplicity), UL channel estimation is performed locally at the BSs. With local UL CSI available, each BS can perform independent CSI preprocessing, including UL-DL conversion as well as other mandatory TPC initialisation steps (e.g., matrix inversion). Given the availability of PRB instructions obtained via fronthaul and the locally available TPC weights, BS can precode the requested DL user data fetched via backhaul. The precoded DL data are modulated (e.g., by inverse DFT) and converted to analogue signals before finally being sent to the UEs via

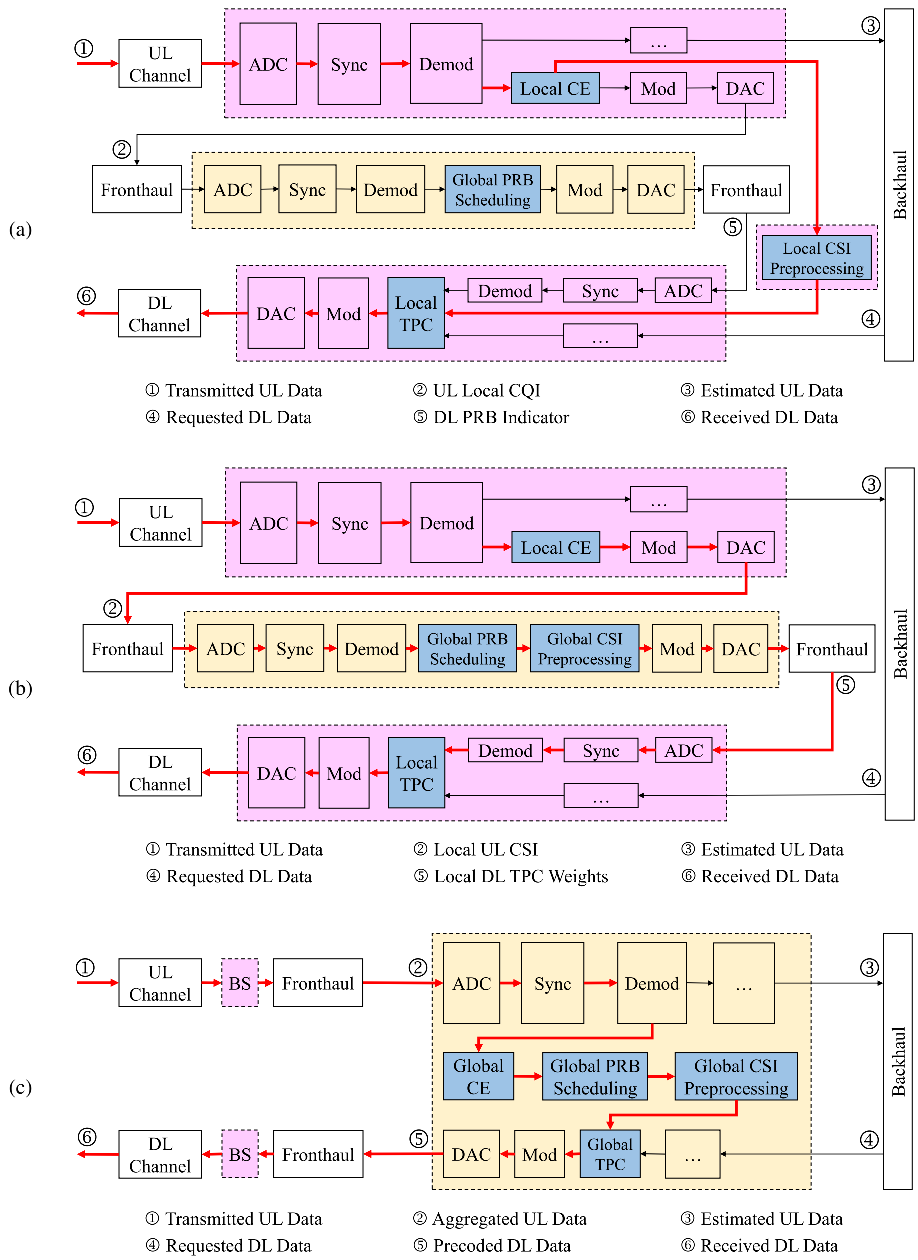


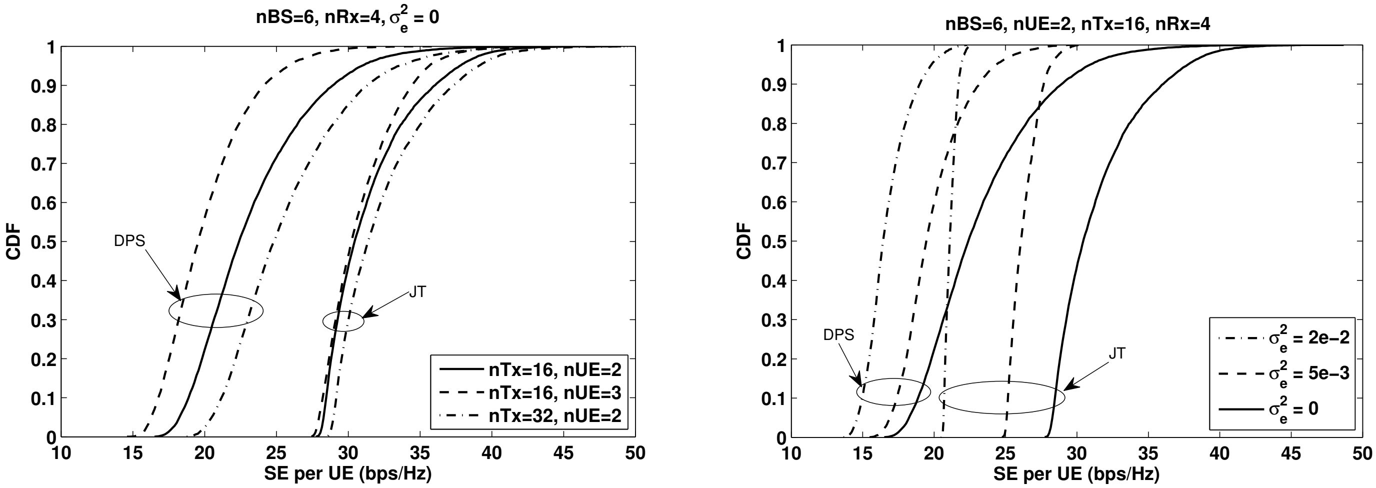
Fig. 2. TDD cell-free FWA architectures. The red chains signify critical CSI processing paths associated with channel stability requirement. Pink blocks are the BSs while the yellow blocks represent the CoMP controllers. A controller can be deployed remotely or within a master BS. (a) Only PRB scheduling is performed at the controller; (b) CSI processing is performed at the controller but TPC is performed locally at each BS; (c) Both CSI processing and TPC are performed at the controller.

the DL FWA channel.

DPS facilitates more relaxed BS coordination and generally incurs less configuration overhead than JT. More specifically, since the role of the controller is to schedule PRB allocation to the BSs, it only needs to know qualitatively an abstraction of each BS's local CSI, namely a channel quality indicator (CQI). In comparison to sharing full size channel matrices, CQI sharing significantly reduces the amount of information that needs to be exchanged via the fronthaul. An immediate benefit of it is the reduction of processing delay and quantisation loss happening in both directions of the fronthaul. Moreover, since the centrally managed PRB allocation information does not have to be updated in line with the instantaneous CSI, the role of the controller is not part of the critical signal processing timeline (i.e., the red paths in Fig. 2).

2) Joint Transmission: In a nutshell, JT based cell-free access may be perceived as the ultimate form of network MIMO [6]. Similar to distributed antenna systems, JT can utilise geographically separated transmit antennas belonging to different cooperating BSs. Therefore, it is capable of achieving the optimal multiplexing or diversity gain. Despite the existence of other CoMP modes such as coordinated beamforming (CB) or scheduling (CS) [4], the information-theoretical performance limit of network MIMO can only be truly achieved by coherent JT.

Coherent JT relies on the availability of instantaneous global



(a) (b)

Fig. 3. Cell-free FWA performance and CSI error tolerance for a densely packed BS cluster arranged in a hexagonal lattice shape. Simulation assumes a path loss exponent of 2.8 and correlated Rayleigh fading, with an antenna correlation of 0.5 between closest elements. The comparisons show that (a) the low spatial channel correlation leads to negligible JT gain when MIMO arrays become larger and (b) high temporal channel correlation is required for achieving theoretical performance upper bounds.

CSI at the controller. Depending on the level of centralisation, the controller can operate in one of the following two ways. If the controller has no access to DL user data (Fig. 2b), it will simply aggregate, synchronise the local UL CSI and perform global CSI preprocessing in order to derive the global DL TPC matrix, which will be distributed alongside the global PRB allocation instructions to the BSs for local TPC. On the other hand, if the controller has direct access to all of the DL data fetched via backhaul in addition to global CSI (Fig. 2c), it will perform centralised global TPC before distributing the precoded DL data to the BSs. In both cases, the CSI has to be shared in full, which imposes much more stringent requirements upon the latency and capacity of fronthaul networks than DPS does. Furthermore, in comparison to Fig. 2c, the additional ADC, bit timing synchronisation and modems occurring in both directions of the fronthaul in Fig. 2b lead to more quantisation loss and processing delay. This is also different from DPS in Fig. 2a because fronthaul is used much more frequently in 2b due to mandatory CSI and TPC matrix updates. Therefore, fronthaul uses constitutes a part of the critical path of 2b but not for 2a. Strategic BS clustering considerably relaxes the various constraints associated with multi-BS joint signal processing in the DL as well as UL [7]. Meanwhile, because FWA facilitates fixed clustering, the performance gap between clustered and full BS cooperation may be trivial to analyse.

B. Channel Characteristics

Cell-free FWA exhibits different channel characteristics than cellular massive MIMO or mobile services, due to the stationary and geographically distributed nature of UE terminals. In a nutshell, Cell-free FWA channels do not usually behave like independent and identically distributed (i.i.d.) random variables, because the path losses from different serving BSs to the same UE tend to be exceptionally different due to the varying distances. Moreover, cell-free FWA channels are also expected to have low spatial correlation but high temporal correlation, with the former being more likely in JT types of implementations. We discuss the soundness of these common expectations in further details in the following sections.

1) Spatial Correlation: A simulated scenario is considered for quantifying the spatial correlation characteristics of cell-free FWA, with particular respect to the effect of UE distribution and of antenna correlation. Specifically, we consider a cluster of six cooperating BSs arranged in a hexagonal lattice pattern in the shape of an equilateral triangle, deployed in a sub-urban environment. The fixed UEs are assumed to be uniformly distributed (at fixed locations) within a circle centred at the joint of three hexagonal cells. Due to the path loss, out-of-cluster signals, detrimental or beneficial, are heavily attenuated in this area. Hence, the generality of this assessment is not affected even if more BSs are introduced. The simulation considered a path loss exponent of 2.8 and an antenna correlation factor of 0.5 between adjacent elements of the same array. Spacing between the closest pair of BSs is 346 m. Considering the limited availability of line of sight (LOS) paths in the sub-urban environment, we selected the Rayleigh model for multi-path fading.

Overall, it is shown in Fig. 3a that the SE performance of JT scales better than DPS with an increasing number of active UEs. This result aligns with the fact that DPS cannot exploit diversity gain from the UE-side channels associated with other cooperating BSs while JT can. On the other hand, the addition of transmit antenna elements in the array yields less gain for JT. Due to the proximity, conventional (massive MIMO) arrays deployed over a single BS have densely packed antenna elements which inevitably spawn spatially correlated channels. This is circumvented in JT, which jointly utilises antenna elements from distributed BS locations, but not in DPS. Hence, increasing the number of (correlated) antenna elements has more explicit benefits for DPS. In order to exploit spatial diversity/multiplexing gain, it may be more beneficial to deploy smaller arrays of fewer antenna elements over a larger number of cooperative BSs, even though it might weaken the desirable 'channel hardening' property of massive MIMO [8].

2) Temporal Correlation: The most prominent challenge associated with cell-free FWA (as well as mobile access) is the variability of wireless channels. In most of the information theoretical analysis of network MIMO systems, the controller is required to have perfect and non-causal knowledge of the global DL CSI matrix. However, as a result of signal processing delay, such an assumption is never valid in practice. A typical wireless channel remains constant only for a limited duration as a result of Doppler effect, arising from the relative motion between transceiver terminals. This characteristic time interval is termed as coherence time, which shows the temporal correlation of the propagation environment.

Longer coherence time relative to computational time is key for BS coordination. The coherence time will determine how much cyclic prefix or suffix is needed for OFDM-based transmissions, as well as the pilot length requirement for channel estimation purposes. Those cyclic extensions of message-carrying data consume extra radio resources. Consequently, their length has a pivotal effect on the SE capacity limit. It should be mentioned that the minimum coherence requirements for field trials and commercial deployment are hardware-specific variables which also depend on signal processing designs. Generally, the minimum coherence time needs to be longer than the total transmitter-side data processing delay (as portrayed in Fig. 2 from ① to ⑥ for all sub categories).

III. Implications of Channel Coherence

A. CSI Error Considerations

Nearly four decades ago, the seminal work of Costa on dirty paper coding showed that, the optimal interference-free SE capacity of an interference-contaminated system can be fully recovered if the interference is perfectly and non-causally known at the transmitter. Unfortunately, it is impossible to fulfil such conditions in practice. Despite the performance promises, cell-free systems are in fact very vulnerable to CSI errors. Fig. 3b portrays the collective influence of additive CSI errors on the performance of cell-free FWA with varying CSI error variances σ_e^2. While JT always outperforms DPS at the same level of σ_e^2, its performance degrades much faster than DPS when σ_e^2 increases. More importantly, given the fact that JT needs to share critical information (CSI and/or user data) via unreliable fronthaul whilst DPS does not, the actual value of σ_e^2 may appear larger for JT even when their overall signal processing frameworks, channel estimation procedures and TPC designs are equivalent (particularly Fig. 2a and 2b).

Aside from the theoretical limitations of random variable estimators, imperfect channel estimation is also the collective result of short coherence time, imperfect BS coordination and hardware impairment. Among these factors, coherence time is regarded as the least influential for FWA. In fact, the so-called 'quasi-static' assumption is frequently employed for characterising FWA channels in the literature. The following sections will be dedicated to a series of channel measurements that identifies the extent to which the 'quasi-static' assumption is valid.

B. Fixed Terminal Coherence Time

Preliminary analysis of coherence time in the literature mostly relies on an autocorrelation-based statistical definition. However, statistical modelling of wireless channels is mostly for characterising an ensemble of channels rather than a particular deployment environment. Therefore channel coherence evaluation based on statistical models, such as a Rayleigh distribution, does not necessarily match the real-world observations. Such discrepancies in channel characterisation are likely to result in unrealistic performance expectations. Even though FWA does not experience Doppler shifts, nevertheless the environment between the transmitter and the receiver is not necessarily static, and this may have a significant role in determining the multi-path profile. The coherence time of fixed terminal 2×2 MIMO channels is characterised for indoor and outdoor scenarios, respectively.

During CSI collection, balanced power output from each antenna port is required such that the measurement data faithfully reflect the radio environment itself. For a quantitative measure, we calculated offline the SE capacity limit of *MIMO channel contaminated by interference unknown to the transmitter* as the key performance indicator (KPI) for characterising channel coherence. We note that, while transmit power and its imbalance over antenna ports are fundamental optimisation variables when evaluating the practical SE performance of cell-free implementations, uniform power allocation is sufficient for channel coherence evaluation.

1) Indoor Measurement: Three indoor measurements were taken at the Communications Lab, Loughborough University. The first test scenario involves a completely static room environment without any moving scatterers or reflectors, while the second scenario includes a person moving near the LOS path in the static background. Both sets of CSI are measured with a 0.8264 ms time resolution at a carrier frequency of 900 MHz, while the antenna spacing is 1 m between each other. Additionally, a third measurement in a different static room environment was also performed at a carrier frequency of 3.56 GHz. These carrier frequencies were chosen to represent typical 4G and 5G local area networks (LANs). The coherence time of indoor environment is portrayed in Fig. 4a, 4b and 4c by means of simulated SE limit. More particularly, the simulation depicts the effect of outdated CSI via an offline time-sliding methodology, where we gradually increase the delay between two hypothetical points in time, namely the point of CSI acquisition and the point of data transmission. A total transmit SNR of 60 dB was assumed for the indoor simulation scenarios. The 'time' axis in Fig. 4 represents the point when precoded data is transmitted, while the difference between the two channel states is treated as CSI error.

The immediate observation is that FWA channel is only 'quasi-static' when there are no moving scatterers or reflectors in the background, regardless of carrier frequency. In the presence of only one moving background obstacle, the quasi-static property of FWA channel is lost despite the preserved

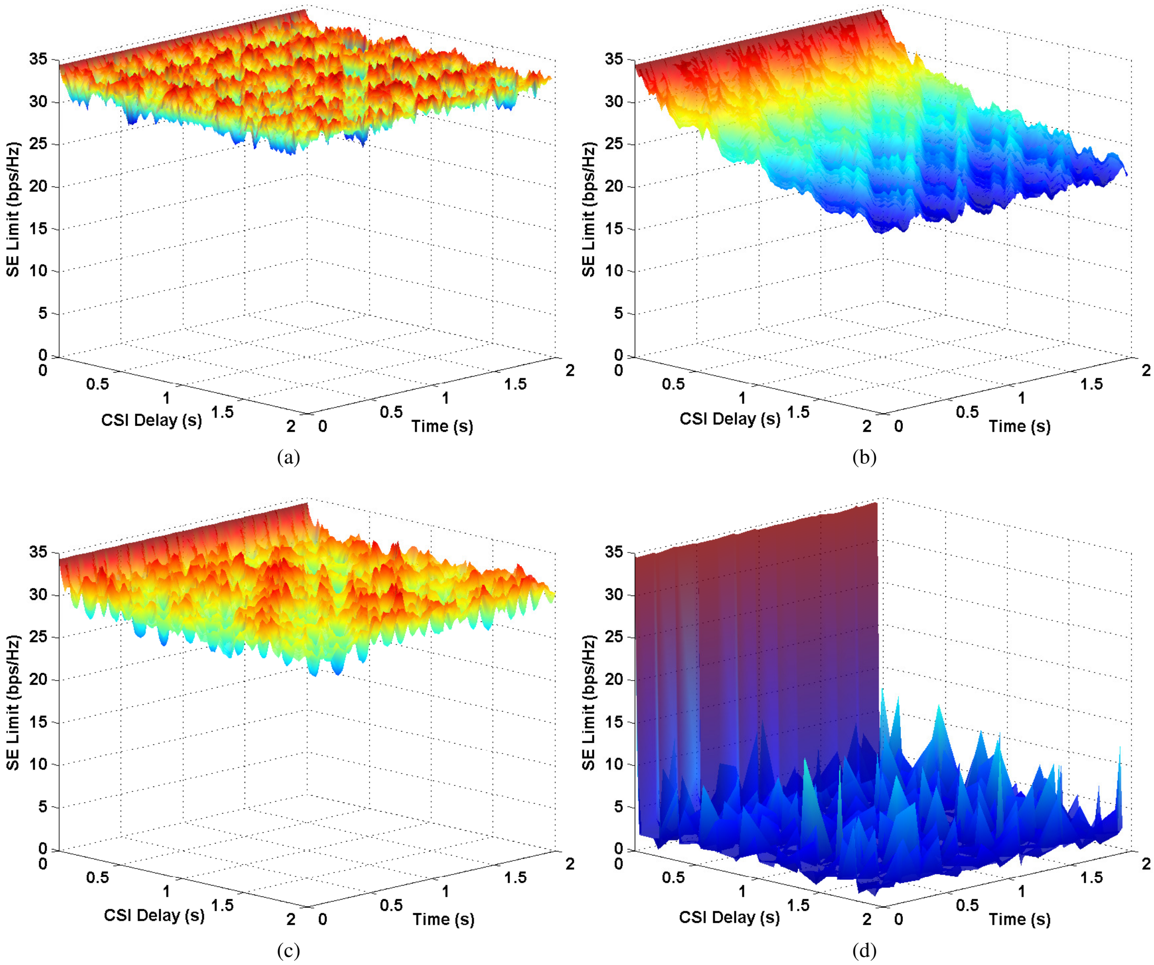


Fig. 4. Channel coherence time measurements for fixed 2×2 MIMO terminals in (a) a static indoor environment at 900 MHz, (b) a dynamic indoor environment at 900 MHz, (c) a static indoor environment at 3.56 GHz, and (d) an outdoor environment at 3.56 GHz. Offline time-sliding simulations were performed to obtain the SE results, where we slide the time axis associated with CSI collection against that associated with precoded DL data transmission.

LOS path. Moreover, the 'block-fading' assumption, where the CSI remains constant for a time block and changes in an i.i.d. manner between blocks, is not true for FWA, either. Instead, the dynamic environment CSI shows a continuous, gradual channel variation. Due to hardware limitations, our measurements only considered one BS-UE pair per scenario. However, the antennas of the transceiver terminals were deployed in a distributed way rather than on an array, leading to spatially uncorrelated channels for the given carrier frequency. Hence, the channel characteristics portrayed by these measurements already represent those of miniature multi-BS cell-free systems. The scalability of our fundamental conclusions about cell-free FWA channel coherence to larger scale networks should be trivial, but its experimental validation will be a subject for future work.

2) Outdoor Measurement: In order to evaluate the coherence time of a more realistic 5G FWA scenario, an outdoor channel measurement was taken at Adastral Park, Ipswich. The fixed 2×2 MIMO channel was measured from a building-top transmitting array to a ground-level receiving terminal with a LOS distance of approximately 60 m. The full measurement was taken with an average time resolution of 15 ms at a carrier frequency of 3.56 GHz. Given that the time-sliding SE calculation relies on a transmit SNR of 120 dB, we may observe from Fig. 4d that the SE variation over time is negligible for the error-free case (where CSI delay= 0) despite the non-constant CSI, which was also true for indoor scenarios. Comparing to the static indoor measurement of Fig. 4c, Fig. 4d further shows that FWA channel coherence time is severely affected by background motions.

The consistent 'SE capacity stability' of both indoor and outdoor scenarios implies that, at reasonably high SNRs, the SE capacity of FWA becomes insensitive to the relative channel variations, thus exhibiting a 'quasi-hardening' effect at the performance level. In comparison to prior outdoor massive MIMO mobile channel measurements reported in [9], an outdoor FWA channel exhibits strong channel hardening even for 2×2 MIMO. In the presence of more antenna elements and distributed arrays, the physical arrangement of arrays and layout of antenna elements may impact channel variations. However, experimentally quantifying how these form factors affect channel coherence or hardening effect is beyond the scope of this paper due to hardware limitations. If rich scattering is a faithful characterisation of outdoor radio environments, the Rayleigh channel model would indeed become physically realistic. In this special case, cell-free FWA exhibits the well-known channel hardening by having a large number of antenna elements per array [8]. Hence, the 'SE capacity stability' may be achieved without requiring high SNR.

IV. Research Opportunities

Channel variation has always been perceived as the ultimate challenge of wireless communications. Recently, due to the rise of a new vision known as smart radio environment [10], the demand for a crossover between the theory of communications and the theory of electromagnetism has been escalating. To this end, we present several research directions for cell-free FWA, aiming at the physical characteristics, data processing design and appropriate use cases for machine learning.

A. Orthogonal Time Frequency Space Modulation

OFDM, the standard multi-carrier modulation scheme in LTE, is robust against frequency domain channel variations by design. Recently, an expansion of OFDM, termed as orthogonal time frequency space modulation (OTFS) [11], was conceived for achieving robustness in both time and frequency domain simultaneously. In principle, OTFS converts a fast frequency-selective fading channel into multiple slow flat fading sub-channels via two-dimensional sub-carrier mapping, negating both the multi-path delay and the Doppler spread. The practical implementation as well as performance analysis for a generalisation of OTFS in real-world cell-free FWA scenarios presents an open challenge for future research, given our new insight where Doppler spread is shown to be insufficient for characterising channel coherence time.

B. Edge Computing

Edge computing is an appealing technique for alleviating the pressure of fronthaul and backhaul of cell-free/CoMP networks [12] without sacrificing significant cooperation gain. The need to exchange channel, control and user information via both the backhaul and fronthaul significantly increases the total processing delay, as well as the coordination overhead of cell-free MIMO TPC. To this end, edge computing, which is capable of remote caching by design, may dispense with excessive information sharing by caching popular user content locally at the BS. Meanwhile, its distributed computing capability implies that a cell-free cluster may execute time-consuming user requests more efficiently with the aid of parallel processing across multiple BSs. These characteristics of edge computing favourably match the operational requirements of cell-free FWA. With further integration of edge computing, how to design fully distributed cell-free FWA while preserving the cooperation gain of centralised JT presents exciting and promising research opportunities.

C. Reconfigurable Intelligent Surface

The vision of smart radio environment states that we will eventually be able to modify the fundamental properties of wireless channels to our own will with the aid of reconfigurable intelligent surfaces (RISs). While RIS has stimulated expansive research for disruptive physical layer technologies focusing on relay-style applications such as spectral or energy efficiency optimisation, physical layer security, wireless power transfer, etc. [10], how to enhance the intrinsic quality of wireless channels remains as a scarcity. In general, although urban and bustling indoor locations have the highest demand for intelligent channel control because of their complex and hostile natural radio environment, rural FWA may also harness SNR gain from RIS where the LOS path between a BS and a UE is blocked.

Recently, the concept of coherence extension was systematically studied in [13]. Relying on a network of ideal RISs, it was shown that the channel coherence can be extended indefinitely for a single moving receiver with predictable mobility. However, for more complex real-world FWA scenarios and/or imperfect RISs, coherence extension remains as an open challenge. Indeed, the purely statistical channel models extensively used in the wireless communications literature are not suitable for characterising environment-specific behaviours. As a result, coherence extension will have to rely on analysing the physical realities behind the particular propagation environment of interest, which facilitate new research opportunities for full-wave, electromagnetic channel characterisation [14].

D. Machine Learning and Network Intelligence

Besides the aforementioned use cases, machine learning also has a critical role in dynamically optimising various network functions in the face of time-varying CSI. In particular, it can exploit hidden features/patterns embedded in channel and control information which model-based analysis is unable to extract. Thus machine learning may naturally act as a data-driven calibration tool for mitigating practical error sources such as outdated CSI [15]. Moreover, due to the series of sophisticated information processing and sharing steps associated with cell-free cooperation, an end-to-end machine learning framework, e.g., autoencoder, may potentially serve as a low-latency substitute to the conventional network configurations. Such a paradigm shift may affect the cell-free performance-complexity trade-offs in a fundamental way.

V. Conclusions

CoMP-JT based cell-free massive MIMO constitutes a promising solution for next-gen FWA that can be readily deployed over the existing 4G and 5G infrastructure with low capital expenditure. The performance of JT based BS coordination is shown for a theoretical network topology to be considerably improved compared with the state-of-the-art BS coordination strategy DPS, as long as the severity of CSI error is comparable in both cases. It is also shown by measurements that the 'quasi-static' assumption for FWA holds valid only for a completely static environment, while the coherence of a typical outdoor environment is expected to be much weaker. To this end, several emerging research opportunities are identified for mitigating the problem of outdated CSI in practical cell-free FWA networks.

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