Deliverable 2.1:
System Modeling and State of the Art

Christian Forsch, Zilu Zhao, Laura Cottatellucci, Dirk Slock

January 30, 2026

Abstract

The cell-free massive multiple-input multiple-output (CF-MaMIMO) network architecture is a promising candidate for beyond-5G communication systems. In this document, we briefly summarize the key concepts and challenges of CF-MaMIMO. Furthermore, we introduce relevant literature and show open problems. We present state-of-the-art algorithms for channel estimation and data detection and focus on the application of the expectation propagation (EP) algorithm on CF-MaMIMO systems.

This document is created as part of the "CellFree6G" project which focuses on reduced complexity techniques and performance analysis towards 6G cell-free massive MIMO. This project was funded by the DFG (German Research Foundation) for FAU and by the ANR for EURECOM – Project CellFree6G CO 1311/1-1, Project ID 491320625.

Contents

1 Introduction to Cell-Free Massive MIMO

The cell-free massive multiple-input multiple-output (CF-MaMIMO) network architecture is a promising candidate for next-generation mobile communication systems. There are several works which have studied this kind of system architecture. Some of them will be presented in this document. More details and further references on CF-MaMIMO can be found in the surveys [1–4] and the monograph from Demir et al. [5].

1.1 Motivation

Today's mobile networks are built as cellular networks. Here, a user is connected to one of many geographically distributed access points (APs) which provide the user with data. These APs are also denoted as base stations (BSs). The user equipment (UE) connects to the one BS which provides the strongest signal. Hence, each BS forms a cell within it supports data services to UEs.

One of the main figure of merits in communication systems is the achievable data rate which increases with increasing signal-to-interference-plus-noise ratio (SINR). One disadvantage of cellular networks is that the UEs at the cell edge have a much lower SINR than the UEs at the cell center. One reason for this is the small received signal power caused by the large distance between UE and BS. Another reason is the interference from neighboring BSs which is larger for cell-edge UEs than for UEs at the center of a cell. Thus, there are large data rate variations within a cell which violate the goal of ubiquitous high data rate wireless access of future mobile communication systems. A CF network architecture, which will be introduced in the following, can reach the goal of uniformly high data rates everywhere.

1.2 Cell-Free Massive MIMO

1.2.1 Concept

CF-MaMIMO can be seen as a combination of three existing technologies [5]: Ultra-dense networks [6, 7], coordinated multipoint (CoMP) transmission/ reception with joint processing [8–10], and massive MIMO [11–14]. The idea is to exploit the advantages of all three technologies by combining them into a single network and, thus, mitigate the detrimental effects of interference, high path loss, and fading.

Similar concepts for interference mitigation via distributed antenna systems have been considered in the past under the name of distributed wireless communication systems [15] and network MIMO [16]. The term "cell-free" was first mentioned in [17], while the combination with MaMIMO was introduced in [18]. The main advantages of CF-MaMIMO compared to cellular MaMIMO and small cells are the uniformly high data rates in the coverage area and the high energy efficiency [5, 19–22].

1.2.2 Network Architecture

A CF-MaMIMO network, illustrated in Fig. 1, consists of many geographically distributed APs which jointly serve a much smaller number of UEs. One AP can be equipped with one or multiple antennas. The joint processing is coordinated by central processing units (CPUs) which are connected to the APs via fronthaul links. This architecture reminds of the centralized radio access network (C-RAN) architecture of current cellular systems [23–25]. The fronthaul links in a CF network can be used for sharing physical-layer signals for downlink (DL), forwarding received uplink (UL) data, or sharing channel state information (CSI). Furthermore, they can be used for phase synchronization between APs. Besides, the CPUs are interconnected via backhaul links.

1.2.3 Clustering

In the first papers on CF systems, all users were served by all APs. The cooperation between all available APs can be beneficial in terms of performance, however, this system is not scalable [26].

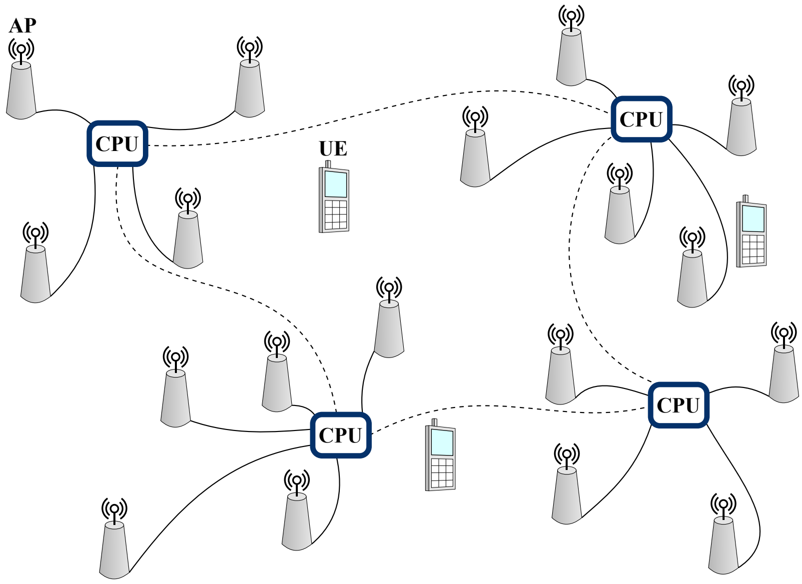


Figure 1: CF-MaMIMO network architecture.

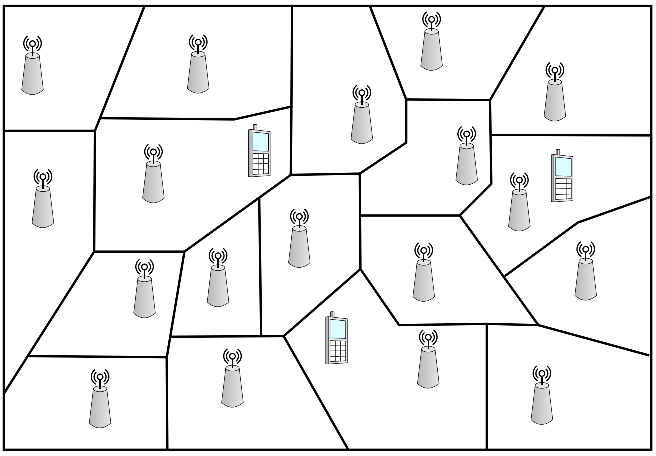
Hence, a clustering of APs [27] is necessary which can be roughly divided into user-centric and network-centric clustering, illustrated in Fig. 2. Different clustering schemes were already studied in the CoMP framework of LTE-Advanced [9,28]. In order to arrive at a real CF network architecture, the clustering has to be user-centric, shown in Fig. 2c. Each user is served by a subset of all available APs which depends on the location of the user and, hence, has to change dynamically in a mobile scenario. User-centric clustering for CF networks has been considered in [29, 30]. Another way to find the user-centric AP clusters in a scalable way was proposed by Björnson in the dynamic cooperation clustering (DCC) framework [26, 31].

1.3 Challenges and Open Problems

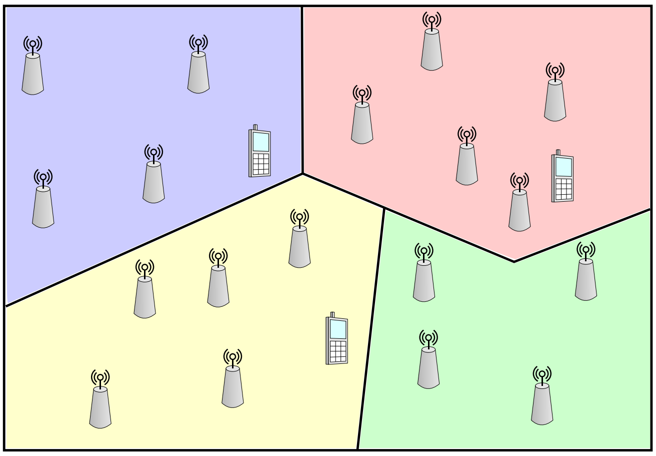
There are several challenges and open problems in CF-MaMIMO. In general, the main challenge is to achieve the benefits of CF systems in a practically feasible way, with computational complexity and fronthaul requirements that are scalable to enable massively large networks with many mobile devices [5]. In the following, we present some specific challenges. Further challenges and corresponding references can be found in the surveys [1–4].

1.3.1 Fronthaul Topology and Limitations

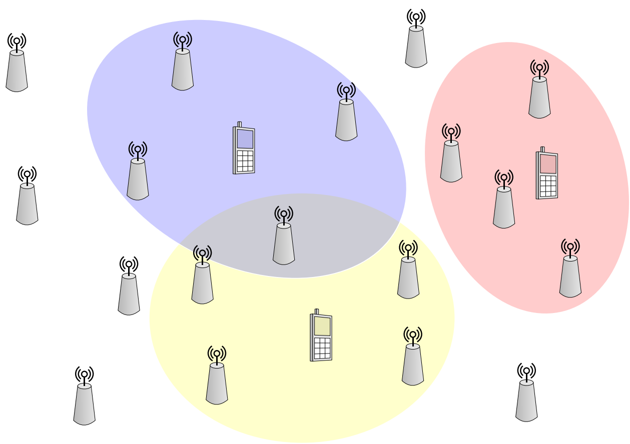
A practical implementation of a CF system has to consider the cabling cost caused by the fronhaul links. Connecting all APs to a single CPU in a star topology is too costly in that regard. Hence, multiple CPUs are necessary. If two APs which belong to different CPUs are cooperating, the respective signals have to be exchanged between CPUs. Besides, radio-stripes [32] can be used to further reduce the cabling cost. Here, APs are deployed in a sequential way along a fronthaul cable. Therefore, signal processing schemes which can be distributed over multiple CPUs and support a sequential connection of APs to the CPU are needed. Another challenge is the capacity-limited fronthaul. One way to reduce the fronthaul load is quantization [33]. Thus, it matters whether the information is processed at full precision at the AP or with reduced precision at the CPU.



(a) Classical cellular network.



(b) Network-centric clustering.



(c) User-centric clustering.

Figure 2: Comparison between a classical cellular network, network-centric clustering, and user-centric clustering.

1.3.2 Synchronization and Hardware Impairments

For multiple APs to jointly serve a UE via coherent transmission, an accurate time and phase synchronization among the APs is necessary. Furthermore, reciprocity calibration is important when the DL channel is estimated from UL pilots. AP synchronization and reciprocity can be done over the air [34,35]. This kind of synchronization is necessary if the wired fronthaul cannot provide a sufficiently accurate common time and frequency reference. Furthermore, the effect of hardware impairments must be considered in CF-MaMIMO networks for a more practical analysis [36–38].

1.3.3 High-Mobility Scenarios

The challenge in a high-mobility scenario is the quickly changing channel between the user and the APs which leads to channel aging, i.e., the channel estimation is outdated and differs from the actual channel [39, 40]. User mobility also leads to a phase shift of the line-of-sight (LoS) path which has to be considered [41,42]. Furthermore, in a user-centric CF-MaMIMO system, a quickly moving UE requires to update the serving cluster very often. Hence, signal processing schemes which can cope with these challenges are needed.

1.3.4 Pilot Contamination

In CF-MaMIMO, similar as in centralized MaMIMO, the number of AP antennas is much larger than the number of UEs. However, not all properties of the centralized MaMIMO channel can be transferred to the CF scenario. Channel hardening and favorable propagation do not necessarily hold in CF-MaMIMO [5,43–47]. Hence, the results from the MaMIMO literature cannot be simply applied to CF-MaMIMO. Especially, the solutions on pilot decontamination [48–52] cannot be readily transferred to CF systems.Pilot contamination originates from users sharing the same pilot sequence during channel estimation. One approach to mitigate pilot contamination is via careful pilot assignment [53–56] or using superimposed pilots [57]. Another approach is through joint channel estimation and data detection (JCD) [58]. Despite these initial works, pilot contamination is still an open problem in CF-MaMIMO.

2 Expectation Propagation

2.1 The Expectation Propagation Algorithm

The expectation propagation (EP) algorithm, proposed by Minka [59, 60], is an approximate inference technique extending the idea of assumed density filtering (ADF). EP iteratively finds an approximation of factorized distributions in a tractable way by projecting the approximate factors onto an exponential family. The projection aims at minimizing the Kullback-Leibler (KL) divergence which results in the so-called *moment matching* criterion. The EP algorithm can be implemented as a message-passing scheme [61] which facilitates developing distributed algorithms.

2.2 Application of Expectation Propagation

2.2.1 General Wireless Communications

Céspedes [62] proposed a low-complexity EP-based MIMO detector while assuming perfect CSI. Here, a Gaussian approximation was used for the posterior distribution of the data symbols. The EP-based detector was shown to outperform the minimum mean square error (MMSE) detector as well as the Gaussian tree approximation (GTA) algorithm with successive interference cancellation (SIC). Besides, the detector produces soft-decision information which yields good performance in combination with a low-density parity-check (LDPC)-decoder [63]. The extension of [62] to imperfect CSI was presented by Ghavami in [64]. Here, the channel estimation error is incorporated in the EP formulation which enhances the performance under imperfect CSI. Furthermore, new factor graph representations for EP-based message-passing algorithms are introduced in [65, 66] to reduce the computational complexity and enhance the performance. The new factor graphs are generated by preprocessing based on matrix decompositions.

In [67], EP was used to develop a smoothing algorithm for symbol detection in a fading channel which is modelled as complex autoregressive moving-average (ARMA) process. The symbol and channel information are jointly estimated without pilot symbols, and the resulting algorithm performs close to a pilot-assisted classical detection scheme in terms of bit error rate (BER). Other blind or noncoherent schemes have been considered in [68–70]. Ghavami proposed a noncoherent single-input multiple-output (SIMO) detector [68] and a blind channel estimation and symbol detection scheme for multi-cell MaMIMO systems [69]. In both schemes, the approximations for channel and symbol distribution are chosen to be a multivariate Gaussian distribution and a discrete distribution, respectively. Even though the algorithm yields an EP-based estimate of the transmitted symbols, a linear detection scheme is finally used for MIMO detection [69] since the complexity of the EP-based solution is too high. Hence, at first, the channel is estimated in a blind or semi-blind fashion using the EP framework and, then, the transmitted symbols are detected using linear detection schemes like zero forcing (ZF) or MMSE detection. The EP-based schemes outperform the coherent MMSE detector with MMSE- and eigenvalue decomposition (EVD)-based channel estimation. In [70], a noncoherent multi-user detector was proposed for the SIMO multiple access channel (MAC). Here, the detector was derived by applying message-passing rules for EP on a factor graph with a discrete distribution approximation for the data symbols.. The resulting algorithm can be applied for pilot-assisted communications as well and shows good performance. However, the complexity of the detector is too high for long data sequences. In [71], the EP algorithm was used to develop a joint active user and channel estimation scheme for massive machine-type communications. Here, the sparse effective channel of the machine-type devices, which incorporates the activity of the devices and the channel coefficients, is approximated by a Gaussian distribution and estimated via pilot symbols. The resulting algorithm outperforms conventional sparse recovery algorithms.

In [72], an iterative MIMO receiver was developed in the EP message-passing framework. The resulting turbo-like receiver exchanges extrinsic information between equalizer, demapper, and decoder, and constitutes a low-complexity alternative to the well-known bit-interleaved coded modulation (BICM) receiver with iterative decoding. The EP-based scheme with Gaussian data symbol beliefs performs better than iterative linear MMSE receivers and close to the conventional BICM receiver. An EP-based equalization scheme for channels with memory was proposed in [73]. Here, performance gains were achieved by replacing the uniform symbol prior during moment matching by a non-uniform prior based on the information from the decoder. This equalizer scheme can be modified by adding an outer EP loop to arrive at a turbo double EP-based receiver [74]. A similar approach as in [72], however, with a serial scheduling of the EP-based update rules was investigated in [75] for channels with memory and yields a decision feedback equalization (DFE) receiver. In [76], the double EP structure was combined with the DFE approach. This scheme outperforms the previously mentioned equalization techniques. The turbo double EP-based receiver from [74] has been also applied to the MIMO case [77]. A low-complexity EP detector for iterative detection and decoding for MIMO systems was proposed in [78] with Gaussian symbol approximations. Here, the computation of an inverse in the EP formulation is simplified by a diagonal matrix approximation which is enabled by the channel decoder feedback. Furthermore, EP has been used for channel decoding. The tree-structure EP algorithm [79–81] was shown to outperform the belief propagation solution for LDPC decoding.

Finally, we present some works which developed decentralized detection schemes based on EP. In [82], EP message passing was applied to extra-large scale MaMIMO systems in order develop a distributed detector with subarray-based processing. The distribution of the data symbols in the EP formulation was constrained to be a multivariate Gaussian distribution with a scaled identity matrix as covariance matrix in order to save computational resources. The proposed detector with perfect CSI knowledge performs close to the centralized EP detector from [62]. In [83], another decentralized subarray-based MaMIMO receiver was developed which considered extrinsic information from the decoder as a priori information for the EP-based detector with Gaussian approximations for the data symbols. Under certain conditions, the resulting decentralized receiver with iterative detection and decoding outperforms the centralized MMSE receiver. The scheduling here is different compared to [82]. At first, local iterations within each subarray are performed which produce a local estimate. Then, these local estimates are combined at the CPU, and the resulting log-likelihood ratios (LLRs) are send to the decoder. In [84], the performance of the decentralized detector in [83] was enhanced by some preprocessing based on the QR-factorization and a variance compensation scheme. The preprocessing leads to less loops in the underlying factor graph and suppresses interference. In [85], a decentralized EP detector is developed based on user grouping and and groupwise joint detection with a multivariate Gaussian approximation. Furthermore, a daisy-chain architecture was proposed as an alternative decentralized scheme. The resulting scheme outperforms the detector without user grouping [83] at the expense of a higher computational complexity. Without any feedback from the CPU to the subarrays, the daisy-chain architecture also yields a performance gain since information is shared between the distributed units.

2.2.2 Cell-Free Massive MIMO

EP-based receivers have been also proposed for CF-MaMIMO systems. The authors in [86] utilized a centralized EP-based detector with Gaussian data approximations which incorporates channel estimation errors as in [64]. The channel estimation error accounts for pilot contamination and general estimation errors due to noise. The resulting detector outperforms the MMSE-SIC detector. In [87], He et al. proposed a distributed EP detector for CF-MaMIMO based on the decentralized subarray-based detector in [82]. The distributed EP-based detector outperforms the centralized MMSE detector under perfect CSI. The aforementioned approach was extended to an iterative channel estimation and data detection (ICD) scheme in [88]. Here, the data detection is based on EP which incorporates channel estimation errors, and the channel estimation is based on MMSE estimation with detected data symbols as additional pilots. The distributed ICD approach outperforms again the centralized MMSE receiver and performs close to the centralized EP detector in [86]. In [89], an EP algorithm is proposed for semi-blind channel estimation with Gaussian data symbols. Here, a Gaussian approximation was used in the EP framework. The resulting EP-based channel estimation scheme outperforms the channel maximum a posteriori (MAP) estimator and the JCD scheme from [58].

3 Conclusion

CF-MaMIMO is a promising network architecture for next generation mobile communication systems. It enables uniformly high data rates in the coverage are and high energy efficiency. However, there are still open problems which have to be solved for a practically feasible CF-MaMIMO system.

In the CellFree6G project, we focus on a solution for pilot contamination based on joint pilot-based channel estimation and data detection. Furthermore, we aim at developing low-complexity decentralized receivers and channel estimation techniques with performance comparable to centralized techniques. Finally, we are interested in a large system analysis based on random matrix theory to characterize compactly the resulting performance and evaluate, guide, and compare various design options.

A References

[1] S. Chen, J. Zhang, J. Zhang, E. Björnson, and B. Ai, "A survey on user-centric cell-free massive MIMO systems," *Digit. Commun. Netw.*, vol. 8, no. 5, pp. 695–719, 2022.

[2] H. A. Ammar, R. Adve, S. Shahbazpanahi, G. Boudreau, and K. V. Srinivas, "User-centric cell-free massive MIMO networks: A survey of opportunities, challenges and solutions," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 611–652, 2022.

[3] S. Elhoushy, M. Ibrahim, and W. Hamouda, "Cell-free massive MIMO: A survey," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 492–523, 2022.

[4] J. Zhang, S. Chen, Y. Lin, J. Zheng, B. Ai, and L. Hanzo, "Cell-free massive MIMO: A new next-generation paradigm," *IEEE Access*, vol. 7, pp. 99878–99888, 2019.

[5] Ö. T. Demir, E. Björnson, and L. Sanguinetti, "Foundations of user-centric cell-free massive MIMO," *Found. Trends® Signal Process.*, vol. 14, no. 3-4, pp. 162–472, 2021.

[6] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-dense networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2522–2545, 2016.

[7] H. Zhang, J. Lee, T. Q. S. Quek, and C.-L. I, eds., *Ultra-dense Networks.* Cambridge University Press, 2020.

[8] S. Parkvall, E. Dahlman, A. Furuskar, Y. Jading, M. Olsson, S. Wanstedt, and K. Zangi, "LTE-advanced - evolving LTE towards IMT-advanced," in *Proc. IEEE 68th Veh. Technol. Conf. (VTC-Fall)*, pp. 1–5, 2008.

[9] M. Boldi, A. Tölli, M. Olsson, E. Hardouin, T. Svensson, F. Boccardi, L. Thiele, and V. Jungnickel, "Coordinated multipoint (CoMP) systems," in *Mobile and Wireless Communications for IMT-Advanced and Beyond* (A. Osseiran, J. F. Monserrat, and W. Mohr, eds.), ch. 6, pp. 121–155, Wiley, 2011.

[10] P. Marsch and G. P. Fettweis, eds., *Coordinated Multi-Point in Mobile Communications.* Cambridge University Press, 2011.

[11] T. L. Marzetta, "How much training is required for multiuser MIMO?," in *Proc. 40th Asilomar Conf. Signals, Syst., Comput.*, pp. 359–363, 2006.

[12] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, 2010.

[13] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO.* Cambridge University Press, 2016.

[14] E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO networks: Spectral, energy, and hardware efficiency," *Found. Trends® Signal Process.*, vol. 11, no. 3-4, pp. 154–655, 2017.

[15] S. Zhou, M. Zhao, X. Xu, J. Wang, and Y. Yao, "Distributed wireless communication system: a new architecture for future public wireless access," *IEEE Commun. Mag.*, vol. 41, no. 3, pp. 108–113, 2003.

[16] S. Venkatesan, A. Lozano, and R. Valenzuela, "Network MIMO: Overcoming intercell interference in indoor wireless systems," in *Proc. 41st Asilomar Conf. Signals, Syst., Comput.*, pp. 83–87, 2007.

[17] H. Yang and T. L. Marzetta, "Capacity performance of multicell large-scale antenna systems," in *Proc. 51st Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, pp. 668–675, 2013.

[18] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO: Uniformly great service for everyone," in *Proc. IEEE 16th Int. Workshop Signal Process. Advances in Wireless Commun. (SPAWC)*, pp. 201–205, 2015.

[19] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1834–1850, 2017.

[20] E. Nayebi, A. Ashikhmin, T. L. Marzetta, H. Yang, and B. D. Rao, "Precoding and power optimization in cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4445–4459, 2017.

[21] H. Q. Ngo, L.-N. Tran, T. Q. Duong, M. Matthaiou, and E. G. Larsson, "On the total energy efficiency of cell-free massive MIMO," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 1, pp. 25–39, 2018.

[22] H. Yang and T. L. Marzetta, "Energy efficiency of massive MIMO: Cell-free vs. cellular," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC-Spring)*, pp. 1–5, 2018.

[23] CMRI, "C-RAN: The road towards green RAN," White Paper, China Mobile Research Institute (CMRI), 2010. Version 1.0.0.

[24] C.-L. I, J. Huang, R. Duan, C. Cui, J. Jiang, and L. Li, "Recent progress on C-RAN centralization and cloudification," *IEEE Access*, vol. 2, pp. 1030–1039, 2014.

[25] 3GPP, "Study on new radio access technology: Radio access architecture and interfaces," Technical Report (TR) 38.801, 3rd Generation Partnership Project (3GPP), 2017. Version 14.0.0.

[26] E. Björnson and L. Sanguinetti, "Scalable cell-free massive MIMO systems," *IEEE Trans. Commun.*, vol. 68, no. 7, pp. 4247–4261, 2020.

[27] S. Bassoy, H. Farooq, M. A. Imran, and A. Imran, "Coordinated multi-point clustering schemes: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 743–764, 2017.

[28] P. Marsch, S. Brück, A. Garavaglia, M. Schulist, R. Weber, and A. Dekorsy, "Clustering," in *Coordinated Multi-Point in Mobile Communications* (P. Marsch and G. P. Fettweis, eds.), ch. 7, pp. 139–160, Cambridge University Press, 2011.

[29] S. Buzzi and C. D'Andrea, "Cell-free massive MIMO: User-centric approach," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 706–709, 2017.

[30] G. Interdonato, P. Frenger, and E. G. Larsson, "Scalability aspects of cell-free massive MIMO," in *Proc. IEEE Int. Conf. Commun. (ICC)*, pp. 1–6, 2019.

[31] E. Björnson, N. Jalden, M. Bengtsson, and B. Ottersten, "Optimality properties, distributed strategies, and measurement-based evaluation of coordinated multicell OFDMA transmission," *IEEE Trans. Signal Process.*, vol. 59, no. 12, pp. 6086–6101, 2011.

[32] G. Interdonato, E. Björnson, H. Q. Ngo, P. Frenger, and E. G. Larsson, "Ubiquitous cell-free massive MIMO communications," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, 2019.

[33] G. Femenias and F. Riera-Palou, "Fronthaul-constrained cell-free massive MIMO with low resolution ADCs," *IEEE Access*, vol. 8, pp. 116195–116215, 2020.

[34] H. V. Balan, R. Rogalin, A. Michaloliakos, K. Psounis, and G. Caire, "AirSync: Enabling distributed multiuser MIMO with full spatial multiplexing," *IEEE/ACM Trans. Netw.*, vol. 21, no. 6, pp. 1681–1695, 2013.

[35] R. Rogalin, O. Y. Bursalioglu, H. Papadopoulos, G. Caire, A. F. Molisch, A. Michaloliakos, V. Balan, and K. Psounis, "Scalable synchronization and reciprocity calibration for distributed multiuser MIMO," *IEEE Trans. Wireless Commun.*, vol. 13, no. 4, pp. 1815–1831, 2014.

[36] J. Zhang, Y. Wei, E. Björnson, Y. Han, and S. Jin, "Performance analysis and power control of cell-free massive MIMO systems with hardware impairments," *IEEE Access*, vol. 6, pp. 55302–55314, 2018.

[37] J. Zheng, J. Zhang, L. Zhang, X. Zhang, and B. Ai, "Efficient receiver design for uplink cell-free massive MIMO with hardware impairments," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4537–4541, 2020.

[38] Y. Zhang, M. Zhou, Y. Cheng, L. Yang, and H. Zhu, "RF impairments and low-resolution ADCs for nonideal uplink cell-free massive MIMO systems," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2519–2530, 2021.

[39] J. Zheng, J. Zhang, E. Björnson, and B. Ai, "Cell-free massive MIMO with channel aging and pilot contamination," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1–6, 2020.

[40] S. Elhoushy and W. Hamouda, "Limiting doppler shift effect on cell-free massive MIMO systems: A stochastic geometry approach," *IEEE Trans. Wireless Commun.*, vol. 20, no. 9, pp. 5656–5671, 2021.

[41] Ö. Özdogan, E. Björnson, and J. Zhang, "Performance of cell-free massive MIMO with rician fading and phase shifts," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5299–5315, 2019.

[42] Z. Wang, J. Zhang, E. Björnson, and B. Ai, "Uplink performance of cell-free massive MIMO over spatially correlated rician fading channels," *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1348–1352, 2021.

[43] H. Yin, D. Gesbert, and L. Cottatellucci, "Dealing with interference in distributed large-scale MIMO systems: A statistical approach," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 942–953, 2014.

[44] Z. Chen and E. Björnson, "Channel hardening and favorable propagation in cell-free massive MIMO with stochastic geometry," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5205–5219, 2018.

[45] R. Gholami, L. Cottatellucci, and D. Slock, "Favorable propagation and linear multiuser detection for distributed antenna systems," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process. (ICASSP)*, 2020.

[46] R. Gholami, L. Cottatellucci, and D. Slock, "Channel models, favorable propagation and MultiStage linear detection in cell-free massive MIMO," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, 2020.

[47] A. A. Polegre, F. Riera-Palou, G. Femenias, and A. G. Armada, "New insights on channel hardening in cell-free massive MIMO networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, 2020.

[48] H. Q. Ngo and E. G. Larsson, "EVD-based channel estimation in multicell multiuser MIMO systems with very large antenna arrays," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process. (ICASSP)*, 2012.

[49] H. Yin, D. Gesbert, M. Filippou, and Y. Liu, "A coordinated approach to channel estimation in large-scale multiple-antenna systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 264–273, 2013.

[50] L. Cottatellucci, R. R. Müller, and M. Vehkapera, "Analysis of pilot decontamination based on power control," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC-Spring)*, 2013.

[51] R. R. Müller, L. Cottatellucci, and M. Vehkapera, "Blind pilot decontamination," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 773–786, 2014.

[52] H. Yin, L. Cottatellucci, D. Gesbert, R. R. Müller, and G. He, "Robust pilot decontamination based on joint angle and power domain discrimination," *IEEE Trans. Signal Process.*, vol. 64, no. 11, pp. 2990–3003, 2016.

[53] Y. Zhang, H. Cao, P. Zhong, C. Qi, and L. Yang, "Location-based greedy pilot assignment for cell-free massive MIMO systems," in *Proc. IEEE 4th Int. Conf. Comput. Commun. (ICCC)*, 2018.

[54] M. Attarifar, A. Abbasfar, and A. Lozano, "Random vs structured pilot assignment in cell-free massive MIMO wireless networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, 2018.

[55] H. Liu, J. Zhang, S. Jin, and B. Ai, "Graph coloring based pilot assignment for cell-free massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 9180–9184, 2020.

[56] W. Zeng, Y. He, B. Li, and S. Wang, "Pilot assignment for cell free massive MIMO systems using a weighted graphic framework," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 6190–6194, 2021.

[57] Y. Zhang, X. Qiao, L. Yang, and H. Zhu, "Superimposed pilots are beneficial for mitigating pilot contamination in cell-free massive MIMO," *IEEE Commun. Lett.*, vol. 25, no. 1, pp. 279–283, 2021.

[58] R. Gholami, L. Cottatellucci, and D. Slock, "Tackling pilot contamination in cell-free massive MIMO by joint channel estimation and linear multi-user detection," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, 2021.

[59] T. P. Minka, *A family of algorithms for approximate Bayesian inference*. PhD thesis, Massachusetts Inst. Technol., Cambridge, 2001.

[60] T. P. Minka, "Expectation propagation for approximate Bayesian inference," in *Proc. 17th Conf. Uncertainty Artif. Intell. (UAI)*, pp. 362–369, 2001.

[61] T. Minka, "Divergence measures and message passing," Tech. Rep. MSR-TR-2005-173, Microsoft Research Ltd., 2005.

[62] J. Céspedes, P. M. Olmos, M. Sánchez-Fernández, and F. Perez-Cruz, "Expectation propagation detection for high-order high-dimensional MIMO systems," *IEEE Trans. Commun.*, vol. 62, no. 8, pp. 2840–2849, 2014.

[63] J. Céspedes, P. M. Olmos, M. Sánchez-Fernández, and F. Perez-Cruz, "Improved performance of LDPC-coded MIMO systems with EP-based soft-decisions," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, 2014.

[64] K. Ghavami and M. Naraghi-Pour, "MIMO detection with imperfect channel state information using expectation propagation," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8129–8138, 2017.

[65] Y. Dong, H. Li, Z. Zhang, X. Wang, and X. Dai, "Efficient EP detectors based on channel sparsification for massive MIMO systems," *IEEE Commun. Lett.*, vol. 24, no. 3, pp. 539–542, 2020.

[66] A. Mekhiche, A. M. Cipriano, and C. Poulliat, "Expectation propagation on factor graphs based on matrix decomposition," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process. (ICASSP)*, 2023.

[67] Y. Qi and T. P. Minka, "Window-based expectation propagation for adaptive signal detection in flat-fading channels," *IEEE Trans. Wireless Commun.*, vol. 6, no. 1, pp. 348–355, 2007.

[68] K. Ghavami and M. Naraghi-Pour, "Noncoherent SIMO detection by expectation propagation," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2017.

[69] K. Ghavami and M. Naraghi-Pour, "Blind channel estimation and symbol detection for multi-cell massive MIMO systems by expectation propagation," *IEEE Trans. Wireless Commun.*, vol. 17, no. 2, pp. 943–954, 2018.

[70] K.-H. Ngo, M. Guillaud, A. Decurninge, S. Yang, and P. Schniter, "Multi-user detection based on expectation propagation for the non-coherent SIMO multiple access channel," *IEEE Trans. Wireless Commun.*, vol. 19, no. 9, pp. 6145–6161, 2020.

[71] J. Ahn, B. Shim, and K. B. Lee, "EP-based joint active user detection and channel estimation for massive machine-type communications," *IEEE Trans. Commun.*, vol. 67, no. 7, pp. 5178–5189, 2019.

[72] M. Senst and G. Ascheid, "How the framework of expectation propagation yields an iterative IC-LMMSE MIMO receiver," in *Proc. of IEEE Global Telecommun. Conf. (GLOBECOM)*, 2011.

[73] I. Santos, J. J. Murillo-Fuentes, E. A. de Reyna, and P. M. Olmos, "Turbo EP-based equalization: A filter-type implementation," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 4259–4270, 2018.

[74] I. Santos, J. J. Murillo-Fuentes, and E. A. de Reyna, "A double EP-based proposal for turbo equalization," *IEEE Signal Process. Lett.*, vol. 27, pp. 121–125, 2020.

[75] S. Şahin, A. M. Cipriano, C. Poulliat, and M.-L. Boucheret, "Iterative equalization with decision feedback based on expectation propagation," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4473–4487, 2018.

[76] C. Yin, W. Feng, J. Li, and G. Li, "Serially connected bidirectional double EP-based DFE for turbo equalization," *IEEE Commun. Lett.*, vol. 26, no. 10, pp. 2455–2459, 2022.

[77] J. J. Murillo-Fuentes, I. Santos, J. C. Aradillas, and M. Sánchez-Fernández, "A low-complexity double EP-based detector for iterative detection and decoding in MIMO," *IEEE Trans. Commun.*, vol. 69, no. 3, pp. 1538–1547, 2021.

[78] Y. Bian, C. Dong, and X. Xiong, "A low-complexity EP detector for IDD in massive-MIMO transmission," in *Proc. 5th Int. Conf. Commun., Inf. Syst., Comput. Eng. (CISCE)*, 2023.

[79] L. Salamanca, P. M. Olmos, J. J. Murillo-Fuentes, and F. Perez-Cruz, "Tree expectation propagation for ML decoding of LDPC codes over the BEC," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 465–473, 2013.

[80] P. M. Olmos, J. J. Murillo-Fuentes, and F. Perez-Cruz, "Tree-structure expectation propagation for LDPC decoding over the BEC," *IEEE Trans. Inf. Theory*, vol. 59, no. 6, pp. 3354–3377, 2013.

[81] L. Salamanca, P. M. Olmos, F. Perez-Cruz, and J. J. Murillo-Fuentes, "Tree-structured expectation propagation for LDPC decoding over BMS channels," *IEEE Trans. Commun.*, vol. 61, no. 10, pp. 4086–4095, 2013.

[82] H. Wang, A. Kosasih, C.-K. Wen, S. Jin, and W. Hardjawana, "Expectation propagation detector for extra-large scale massive MIMO," *IEEE Trans. Wireless Commun.*, vol. 19, no. 3, pp. 2036–2051, 2020.

[83] Z. Zhang, H. Li, Y. Dong, X. Wang, and X. Dai, "Decentralized signal detection via expectation propagation algorithm for uplink massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11233–11240, 2020.

[84] Y. Dong, H. Li, C. Gong, X. Wang, and X. Dai, "An enhanced fully decentralized detector for the uplink M-MIMO system," *IEEE Trans. Veh. Technol.*, vol. 71, no. 12, pp. 13030–13042, 2022.

[85] H. Li, Y. Dong, C. Gong, X. Wang, and X. Dai, "Decentralized groupwise expectation propagation detector for uplink massive MU-MIMO systems," *IEEE Internet Things J.*, vol. 10, no. 6, pp. 5393–5405, 2023.

[86] A. Kosasih, V. Miloslavskaya, W. Hardjawana, V. Andrean, and B. Vucetic, "Improving cell-free massive MIMO detection performance via expectation propagation," in *Proc. IEEE 94th Veh. Technol. Conf. (VTC2021-Fall)*, pp. 1–5, 2021.

[87] H. He, H. Wang, X. Yu, J. Zhang, S. H. Song, and K. B. Letaief, "Distributed expectation propagation detection for cell-free massive MIMO," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2021.

[88] H. He, X. Yu, J. Zhang, S. H. Song, and K. B. Letaief, "Cell-free massive MIMO detection: A distributed expectation propagation approach," *arXiv*, 2023.

[89] R. Gholami, L. Cottatellucci, and D. Slock, "Message passing for a bayesian semi-blind approach to cell-free massive MIMO," in *Proc. 55th Asilomar Conf. Signals, Syst., Comput.*, 2021.