Alexander von Humboldt Professorship Research Project:

Foundations and Architectures for the Next Generation of Wireless Networks

Progress Report (April 2014 – March 2015)

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1 Research

1.1 Publications

This is a list of publications during the first year of the AvH project:

1. Jiang, Z. ; Molisch, A. ; Caire, G. ; Niu, Z., “Achievable Rates of FDD Massive MIMO Systems with Spatial Channel Correlation,” *IEEE Transactions on Wireless Communications*, Volume: PP , Issue: 99, 2015.

2. Bethanabhotla, D. ; Caire, G. ; Neely, M.J., “Adaptive Video Streaming for Wireless Networks With Multiple Users and Helpers,” *IEEE Transactions on Communications*, Vol. 63, No. 1, pp. 268–285, 2015.

3. Ntranos, V. ; Maddah-Ali, M.A. ; Caire, G., “Cellular Interference Alignment,” *IEEE Transactions on Information Theory*, Vol. 61, No. 3, pp. 1194–1217, 2015.

4. Tchamkerten, A. ; Chandar, V. ; Caire, G, “Energy and Sampling Constrained Asynchronous Communication,” *IEEE Transactions on Information Theory*, Vol. 60, No. 12, pp. 7686–7697, 2014.

5. Rogalin, R. ; Bursalioglu, O.Y. ; Papadopoulos, H. ; Caire, G. ; Molisch, A.F. ; Michaloliakos, A. ; Balan, V. ; Psounis, K. “Scalable Synchronization and Reciprocity Calibration for Distributed Multiuser MIMO,” *IEEE Transactions on Wireless Communications,* Volume: 13 , Issue: 4 Page(s): 1815 - 1831, 2014.

6. Song-Nam Hong ; Caire, G. “On Interference Networks Over Finite Fields,” *IEEE Transactions on Information Theory,* Volume: 60 , Issue: 8, Page(s): 4902 - 4921, 2014.

7. Shanmugam, K. ; Papailiopoulos, D.S. ; Dimakis, A.G. ; Caire, G. “A Repair Framework for Scalar MDS Codes,” *IEEE Journal on Selected Areas in Communications,* Volume: 32 , Issue: 5, Page(s): 998 - 1007, 2014.

8. Junyoung Nam ; Adhikary, A. ; Jae-Young Ahn ; Caire, G. “Joint Spatial Division and Multiplexing: Opportunistic Beamforming, User Grouping and Simplified Downlink Scheduling,” *IEEE Journal of Selected Topics in Signal Processing,* Volume: 8 , Issue: 5, Page(s): 876 - 890, 2014.

9. Adhikary, A. ; Al Safadi, E. ; Samimi, M.K. ; Rui Wang ; Caire, G. ; Rappaport, T.S. ; Molisch, A.F. "Joint Spatial Division and Multiplexing for mm-Wave Channels," *IEEE Journal on Selected Areas in Communications,* Volume: 32 , Issue: 6, Page(s): 1239 - 1255, 2014.
10. Al-Naffouri, T.Y. ; Quadeer, A.A. ; Caire, G. "Impulse Noise Estimation and Removal for OFDM Systems," *IEEE Transactions on Communications,* Volume: 62 , Issue: 3, Page(s): 976 - 989, 2014.
11. Kurras, Martin and Thiele, Lars and Caire, Giuseppe, "Interference Mitigation and Multiuser Multiplexing with Beam-Steering Antennas," *19th International ITG Workshop on Smart Antennas WSA 2015*, Ilmenau, Germany, April 2015.
12. Song-Nam Hong ; Caire, G. "Demystifying the scaling laws of dense wireless networks: No linear scaling in practice," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 71 - 75
13. Bethanabhotla, D. ; Bursalioglu, O.Y. ; Papadopoulos, H.C. ; Caire, G. "User association and load balancing for cellular massive MIMO," Information Theory and Applications Workshop (ITA), 2014 Publication Year: 2014 , Page(s): 1 - 10
14. Dhillon, H.S. ; Caire, G. "Scalability of line-of-sight massive MIMO mesh networks for wireless backhaul," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 2709 - 2713
15. Ji, Mingyue ; Tulino, Antonia M. ; Llorca, Jaime ; Caire, Giuseppe "On the average performance of caching and coded multicasting with random demands," Wireless Communications Systems (ISWCS), 2014 11th International Symposium on Publication Year: 2014 , Page(s): 922 - 926
16. Adhikary, A. ; Al Safadi, E. ; Caire, G. "Massive MIMO and inter-tier interference coordination," Information Theory and Applications Workshop (ITA), 2014 Publication Year: 2014 , Page(s): 1 - 10
17. Dhillon, H.S. ; Caire, G. "Information theoretic upper bound on the capacity of wireless backhaul networks," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 251 - 255
18. Ntranos, V. ; Maddah-Ali, M.A. ; Caire, G. "Cellular interference alignment," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 1598 - 1602
19. Wei Yang ; Caire, G. ; Durisi, G. ; Polyanskiy, Y. "Finite-blocklength channel coding rate under a long-term power constraint," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 2067 - 2071
20. Tehrani, A.S. ; Caire, G. "ZigZag neighbor discovery in wireless networks," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 1386 - 1390
21. Tulino, A. ; Caire, G. ; Shamai, S. "Broadcast approach for the sparse-input random-sampled MIMO Gaussian channel," Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 621 - 625

1.2 Information theoretic study of caching wireless networks

Data traffic generated by wireless and mobile devices is predicted to increase by something between one and two orders of magnitude [1] in the next five years, mainly due to wireless video streaming. Traditional methods for increasing the area spectral efficiency, such as using more spectrum and/or deploying more base stations, are either insufficient to provide the necessary wireless throughput increase, or are too expensive. Thus, exploring alternative strategies that leverage different and cheaper network resources is of great practical and theoretical interest.

The bulk of wireless video traffic is due to asynchronous *video on demand*, where users request video files from some library (e.g., iTunes, Netflix, Hulu or Amazon Prime) at arbitrary times. This type of traffic differs significantly from *live streaming*. The latter is essentially a lossy multicasting problem, for which the broadcast nature of the wireless channel can be naturally exploited (see for example [2, 3, 4, 5, 6]). The theoretical foundation of schemes for live streaming relies on well-known information theoretic settings for one-to-many transmission of a common message with possible refinement information, such as successive refinement [7, 8, 9] or multiple description coding [10, 11, 12].

In contrast, the *asynchronous* nature of video on demand prevents from taking advantage of multicasting, despite the significant overlap of the requests (people wish to watch a few very popular files). Hence, even though users keep requesting the same few popular files, the asynchronism of their requests is large with respect to the duration of the video itself, such that the probability that a single transmission from the base station is useful for more than one user is *essentially zero*. Due to this reason, current practical implementation of video on demand over wireless networks is handled at the application layer, requiring a dedicated data connection (typically TCP/IP) between each client (user) and the server (base station), for each streaming user, as if users were requesting independent information.

One of the most promising approaches to take advantage of the inherent *asynchronous content reuse* is *caching*, widely used in content distribution networks over the (wired) Internet [13]. In [14, 15], the idea of deploying dedicated "helper nodes" with large caches, that can be refreshed via wireless at the cellular network off-peak time, was proposed as a cost-effective alternative to providing large capacity wired backhaul to a network of densely deployed small cells. An even more radical view considers caching directly at the wireless users, exploiting the fact that modern devices have tens and even hundreds of GBytes of largely under-utilized storage space, which represents an enormous, cheap and yet untapped network resource.

Recently, a *coded multicasting* scheme exploiting caching at the user nodes was proposed in [16]. In this scheme, the files in the library are divided in blocks (packets) and users cache carefully designed subsets of such packets. Then, for given set of user demands, the base station sends to all users (multicasting) a common codeword formed by a sequence of packets obtained as linear combinations of the original file packets. As noticed in [16], coded multicasting can handle any form of asynchronism by suitable sub-packetization. Hence, the scheme is able to create multicasting opportunities through coding, exploiting the overlap of demands while eliminating the asynchronism problem. For the case of arbitrary (adversarial) demands, the coded multicasting scheme of [16] is shown to perform within a small gap, independent of the number of users, of the cache size and of the library size, from the cut-set bound of the underlying compound channel.[1] However, the scheme has some significant drawbacks that makes it not easy to be implemented in practice: 1) the construction of the caches is combinatorial and the sub-packetization explodes exponentially with the library size and number of users; 2) changing even a single file in the library requires a significant reconfiguration of the user caches, making the cache update difficult. In [17], similar near-optimal performance of coded caching is shown to be achieved also through a *random caching scheme*, where each user caches a random selection of bits from each file in the library. In this case, though, the combinatorial complexity of the coded caching scheme is transferred from the caching phase to the (coded) delivery phase, where the construction of the multicast codeword requires solving multiple clique cover problems with fixed clique size (known to be NP-complete), for which a greedy algorithm is shown to be efficient.

Our contributions: We have focused on an alternative approach that involves random independent caching at the user nodes and device-to-device (D2D) communication. Instead of creating multicasting opportunities by coding, we exploit the spatial reuse provided by concurrent multiple short-range D2D

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[1] The compound nature of this model is due to the fact that the scheme handles adversarial demands.

transmissions. Inspired by the current standardization of a D2D mode for LTE (the 4-th generation of cellular systems) [18], we restrict to one-hop communication. Under such assumption, requiring that all users mustbe served for any request configuration is too constraining. Therefore, we introduce the possibility of outages, i.e., that some requests are not served, because of some network admission control policy (to be discussed in details later on). We defined the throughput-outage region and obtain achievability and converses that are sufficiently tight to characterize the throughput-outage scaling laws within a small gap of the *constants of the leading term*. Furthermore, our analysis shows very good agreement with with finite-dimensional simulation results.

In the relevant regime of small outage probability, the throughput of the D2D one-hop caching network behaves in the same near-optimal way as the throughput of coded multicasting [16, 17], while the system architecture is significantly more straightforward for a practical implementation. In particular, for fixed cache size M, as the number of users n and the number of files m become large with $nM \gg m$, the throughput of the D2D one-hop caching network grows linearly with M, and it is inversely proportional to m, but it is independent of n. Hence, D2D one-hop caching networks are very attractive to handle situations where a relatively small library of popular files (e.g., the 500 most popular movies and TV shows of the week) is requested by a large number of users (e.g., 10,000 users per km^2 in a typical urban environment). In this regime, the proposed system is able to efficiently **turn memory into bandwidth, in the sense that the per-user throughput increases proportionally to the cache capacity of the user devices.** We believe that this conclusion is important for the design of future wireless systems, since bandwidth is a much more scarce and expensive resource than storage capacity.

Main results:

- The throughput-vs-outage tradeoff of a D2D caching network has been characterized in our recent work:

  Mingyue Ji, Giuseppe Caire, Andreas F. Molisch “The Throughput-Outage Tradeoff of Wireless One-Hop Caching Networks,” *Submitted to IEEE Transaction on Information Theory*, Preprint available at `http://arxiv.org/abs/1312.2637`

- A network-coding version of the D2D delivery scheme, based on multicasting linear combinations of subpackets, has been presented in our recent work:

  Mingyue Ji, Giuseppe Caire, Andreas F. Molisch, “Fundamental Limits of Caching in Wireless D2D Networks,” *Submitted to IEEE Transaction on Information Theory*, Preprint available at `http://arxiv.org/abs/`

- The extension of the analysis of the throughput scaling laws for a network with caching at the user nodes and a single server, in the presence of random user demands, has been recently given in our work:

  Mingyue Ji, Antonia M. Tulino, Jaime Llorca, Giuseppe Caire, “Order-Optimal Rate of Caching and Coded Multicasting with Random Demands,” *Submitted to IEEE Transaction on Information Theory*, Preprint available at `http://arxiv.org/abs/1502.03124`.

- A very recent result (published in May 2015) consists of the extension of the D2D caching network to the case of multi-hop transmission. In this case, we showed that the per-user throughput scales as $\sqrt{M/m}$, which is significantly better than M/m as for the one-hop case. This recent result is presented in the paper:

  Sang-Woon Jeon, Song-Nam Hong, Mingyue Ji, and Giuseppe Caire, “On the Capacity of Multihop Device-to-Device Caching Networks,” *IEEE Information Theory Workshop*, Jerusalem, Israel, April 26 - Mary 1, 2015.

1.3 Information theoretic characterization of base-station cooperation in cellular systems

Interference is the dominant limiting factor in the performance of today's wireless networks. Recent theoretical results [19, 20, 21] have shown that transmission schemes based on *interference alignment* [22, 19] are able to provide half of the Degrees of Freedom (DoFs) to each user in the network. In our context, degrees of freedom are defined as the equivalent number of parallel interference-free Gaussian channels over which users can communicate. While these results promise significant gains compared to conventional interference mitigation techniques, the extent to which such gains can be realized in practice has been so far limited.

The crucial observation is that the topology of the network can significantly affect the deployment of interference alignment. For example, interference alignment can be easily deployed for a three-user interference channel, where each transmitter and receiver are equipped with two antennas. However, adding just one more user radically changes the nature of the problem. The known solutions for four-user interference channels, rely on asymptotic expansion of the signaling and forming exponentially-many data streams, each carrying a vanishingly-small data rate [22, 19, 20, 23]. This *asymptotic interference alignment* approach requires exponentially-large delay or exponentially-accurate channel estimation, which makes it unfavorable in practice. On the other hand, there are some results showing that without such exponential expansion in fully connected networks, the the DoF gain of any linear interference alignment scheme vanishes [24, 25, 26]. This is one of the main fundamental challenges of implementing interference alignment in practical scenarios, particularly in cellular systems. There are several approaches that try to resolve this problem:

- *Clustering:* In this approach, the networks are split into smaller sub-networks, where non-asymptotic interference alignment is feasible within each cluster (see for example [27]). The problem with this approach is that the remaining interference, between the clusters, will eliminate the potential gain of interference alignment in large networks.
- *Relaying:* It is shown that in some scenarios, using relays in the network can help us align interference without expansion [28, 29]. However, the major bottleneck in the proposed solutions is that the number of antennas in each relay is required to grow with the size of the network.
- *Feedback:* Using output feedback is another approach that can help us achieve the full degrees of freedom without asymptotic expansion [30, 31, 32]. However, the current solutions do not scale with the number of users and therefore cannot be used in large networks.

While all of the above approaches deserve more exploration and are currently the subject of extensive research, in this paper, we are pursuing an alternative solution which is particularly suitable for wireless cellular systems. Our approach relies on backhaul collaboration and exploits the locality of interference which are both very important features of cellular networks. The main contribution of this paper is to use backhaul collaboration in order to change the effective interference pattern in the network, such that practical interference alignment is possible. The proposed scheme can be applied in large cellular networks and is able to achieve the optimal degrees of freedom without asymptotic symbol expansion.

Cooperation among base stations, enabled though backhaul connections, is one of the major approaches of interference management. In the uplink, all base stations can share their (quantized) received signal samples over the backhaul of the network and then jointly decode the corresponding user messages. Similarly, in the downlink, all user messages can be shared across the entire network, so that base stations can cooperatively transmit the messages to the corresponding users and manage the interference. This technique, which often relies on *full cooperation* of the base stations and referred to as ”Network MIMO” in the literature [33, 34, 35, 36], effectively reduces the system to a (network-wide) multiple-antenna multiaccess channel for the uplink, or a multiple-antenna broadcast channel [37, 38] for the downlink. In an effort to reduce the significant backhaul load requirements of the above technique, *clustered cooperation* has been proposed, where for the downlink [39, 40, 41, 42, 43] the message of each base station has been shared with a cluster of base stations, and for the uplink [44, 45, 46, 47, 48, 49] the sampled (or quantized) received signal of each base station is shared within a cluster of users. Another important form of collaboration among base stations is what we call *process and share*. In this class of cooperation for the uplink, base stations process all the signals that they have collected so far, including, (i) the signal sampled from its receiver antennas, and (ii) the signals it received from other base stations through the backhaul, and then form a "backhaul message" that can be shared with other base stations in a cluster. Similarly, for the downlink, each base station shares over the backhaul, a signal which is the result of jointly processing (i) its own signal, and (ii) what it received from other base stations over backhaul. In other words, under this class of backhaul collaboration schemes, base stations collaborate by sharing a function of all the information they have gathered up to that point, instead of simply forwarding raw data. The choice of this function is a design parameter and the corresponding signal processing can be either linear or non-linear. In [50, 51, 52, 53] this approach has been used to approximately characterize the capacity of two-user interference channels with limited transmitter (or receiver) collaboration. This approach has also been used for cellular systems [46].

In our work – in order to implement interference alignment without expansion in the uplink of cellular systems – we have considered a non-linear process-and-share cooperation framework, motivated by schemes embraced in practice (see [54] for an example). In our framework, each base station processes the signal sampled from its receive antennas, as well as the signals it received through the backhaul links, in order to decode its own message. That message is then shared locally, over the backhaul, in order to help in the decoding process of neighboring base stations. In this paper, we show that this *local* and *one directional* data exchange — restricted only to decoded messages — is enough to reduce the uplink of a sectored cellular network to a topology in which half of degrees of freedom per transmit-receive antenna can be achieved by linear interference alignment schemes without requiring time-frequency expansion or lattice alignment. The proposed algorithm takes advantage of the *partial connectivity* of extended cellular networks[2] and has several desired properties that are necessary in practical applications:

- *Scalability:* The overall performance of the scheme materializes irrespectively of the size of the cellular network, i.e., when the number of transmit-receive pairs becomes arbitrarily large.
- *Locality:* The transmission scheme operates under local information exchange, and exploits the distributed nature of the cellular network.
- *Spectral Efficiency:* The scheme achieves high spectral-efficiency by allowing more (interference-free) parallel transmissions to take place within the same spectrum.

The idea of combining interference alignment with decoded message sharing has been studied in [58] for small network configurations (e.g, with three active receivers in the uplink). In contrast, here we focus on large cellular networks in which interference alignment without asymptotic symbol expansion is not known to be feasible. We emphasize that locally sharing decoded information messages over the backhaul and restricting to single-user decoding can be easily implemented within the current technology.

In general, in coordinated cell processing strategies, there is always the risk that the signaling scheme relies on the strength of interference in order to achieve reliable communication. However, practical systems are not designed to guarantee that strength. On the contrary, current system deployment is geared to making interfering links as weak as possible. Hence, a scheme that relies on "strong interference" links would fail if applied to a system which was designed according to the current guidelines. In order to address this issue, we introduce the concept of *topological robustness*, where the goal is to design communication schemes that can maintain a minimum rate (or degrees of freedom) no matter if the interference links are strong or

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[2] Following [55, 56, 57] we refer to an "extended" network as a network with a fixed spatial density of cells and increasing total coverage area, in contrast to a "dense" network where the total coverage area is fixed and the cell density increases.

weak. In particular, we show that such schemes exists in our framework and prove their optimality using a compound network formulation.

Main results:

- The fundamental characterization of degrees of freedom achieved by one-shot interference alignment and base station cooperation, in the form of decoded message passing (for the uplink) and forwarding of quantized versions of the precoded signals (downlink), for the case of sectorized cellular networks, is provided in:

  Ntranos, V. ; Maddah-Ali, M.A. ; Caire, G., "Cellular Interference Alignment," *IEEE Transactions on Information Theory*, Vol. 61, No. 3, pp. 1194–1217, 2015.

- An extension of these results to non-sectorized cellular networks, for which the connectivity of the interference graph is higher, is given in:

  Vasilis Ntranos, Mohammad Ali Maddah-Ali, Giuseppe Caire, "Cellular Interference Alignment: Omni-Directional Antennas and Asymmetric Configurations," *Submitted to IEEE Transaction on Information Theory*, Preprint available at `http://arxiv.org/abs/1404.6512`.

- A recent result on the fundamental limits of base station cooperation without the restriction of decoded message passing will be presented at ISIT 2015:

  Vasilis Ntranos, Mohammad Ali Maddah-Ali, Giuseppe Caire, "Cooperation Alignment for Distributed Interference Management," to be presented at *IEEE Int. Symposium on Inform. Theory, ISIT*, Hong-Kong, Republic of China, June 2015.

1.4 Network optimization, dynamic scheduling and video quality control for video streaming over wireless networks

With the proliferation of mobile devices and services, industry predicts that the wireless data traffic is going to increase by two to three orders of magnitude within a decade [59]. Although the definition of the next generation of systems and standards is at its initial phase, it is widely agreed that the next generation of wireless networks, generally referred to as "5G", will involve a combination of multiuser MIMO technology, cell densification, and heterogeneous architectures based on nested tiers of smaller and smaller cells operating at higher and higher frequencies, in order to target traffic hot-spots [60]. These trends have motivated the recent surge of research on massive and dense deployment of base station antennas, both in the form of *Massive MIMO* schemes, with hundreds of antennas at each cell site [61, 62, 63], and in the form of multi-tier networks of densely deployed small-cells [64, 65].

Massive MIMO promises dramatic increases in spectral efficiency by transmitting independent data streams simultaneously to multiple users sharing the same transmission resource (time-frequency slot). The massive MIMO regime [61, 62, 63] distinguishes itself from classical multiuser MIMO [66, 67] by the fact that the number of served users is significantly less than the (very large) number of base station antennas. Operating in *Time-Division Duplexing* (TDD) mode, massive MIMO can provide very large spectral efficiencies, simple per-cell processing, and very attractive power efficiency due to the large array gain [61]. Thanks to the higher and higher carrier frequencies [68], it is possible to implement massive MIMO even in relatively small base stations within a reasonable form factor. Hence, it is envisaged that massive MIMO will not just be applied to large tower-mounted base stations, but also used in conjunction with small cells [69].

The heterogeneous wireless network framework mentioned above may include some of the following features: 1) base stations that may differ significantly by transmit power, number of antennas, and multiplexing gain (e.g., see [70] and references therein); 2) non-homogeneous user spatial distribution, characterized by high-density hot-spots separated by less dense regions [71]; 3) Due to the large beamforming gain of massive MIMO, a user may be in good SINR conditions with respect to several base stations. As a consequence, the rationale that has driven for decades the conventional cellular system design and optimization, based on symmetric lattice-deployed cells (see for example [61, 62, 63]) and/or (roughly) uniform number of users per cell (e.g., see [72] and references therein), must be abandoned in favor of more efficient schemes that include user-cell association into the optimization problem.

In conventional technologies, the user-cell association is decided on the basis of the so-called *Reference Signal Received Power* (RSRP), possibly in combination with *Reference Signal Received Quality* (RSRQ) (see [71] for details). In short, these are measures of the signal strength measured on a load-independent reference beacon signal sent by each base station [73]. Such association does not take into account the actual load of base stations, i.e., the number of associated users per downlink data stream, and may be arbitrarily suboptimal in a heterogeneous scenario. "Biasing" is a commonly proposed method to cope with cell or user density asymmetries, where the RSRP is artificially scaled by a bias term that depends on the type of base station [74, 73] in order to inherently steer users to associate with close small-cell base stations, thereby "off-loading" congested macro-cells. Nevertheless, biasing methods are either heuristic or are based on some *average* performance metrics, where averaging is over the random placement of users and base station according to stochastic geometry models [72, 73, 74, 75]. Furthermore, biasing attempts to balance user traffic across tiers, but not within each tier. In contrast, here we seek *pointwise optimal user-cell association*, i.e., for any given placement of users and base stations.

In our work, we have focused on the problem of optimal user-cell association for the downlink of a heterogeneous wireless network (including the features said above) with massive MIMO base stations. Our problem formulation captures the fact that, in modern data-oriented systems with OFDMA/TDMA scheduling, not all users are simultaneously served on all the transmission resources (time-frequency slots). Hence, what matters is not the user *instantaneous* rate or SINR level, achieved at any given time-frequency slot, rather the long-term average rate, referred to hereafter as per-user *throughput*. It is also important to notice that, in realistic network topologies, users have different distances and propagation conditions (path-loss) with respect to the base stations. Hence, maximizing the network spectral efficiency (user sum rate) typically yields unacceptable per-user performance, since this may lead to a large number of users located in unfavorable positions (e.g., at the cell edges) with near-zero throughput (see [63, 76, 77]). Motivated by the above observations, we formulate the system optimization problem as a rigorous Network Utility Maximization (NUM), where the fairness criterion is reflected by the choice of the network utility function. Instead of focusing on the per-slot instantaneous user rates, our network utility is a function of the user throughputs. It should be noticed that fairness across the users is often *implicitly* assumed by considering equal user air-time, as for example in [61, 62]. Since equal air-time is *just one of the many possible fairness criteria*, here we take a more systematic approach, which includes equal air-time as a special case.

It is well-known that solving the general joint user-cell association, precoding vectors design, and power allocation problem is NP-hard [78, 79]. Instead, in this paper we heavily exploit the specific system simplification occurring in the massive MIMO regime [61, 62, 63]. While in general the user instantaneous rates are functions of the multiuser MIMO precoding scheme, of the base station power allocation, and of the MIMO channel matrix realization (e.g., see [80]), in a massive MIMO system the instantaneous rates converge to easily computable *deterministic limits* $R_{k,j}$ that depend only on the overall system topology (path gains between base stations user k) and system configuration (pilot signal allocation, transmit power, number of antennas and number of downlink data streams of the base stations), but are independent of the other users' cell association. It follows that the massive MIMO regime induces *decoupling* and *symmetrization* of the user instantaneous rates, yielding a dramatic simplification of the NUM problem, which turns out to be convex with respect to the user activity fractions, i.e., the fractions $\alpha_{k,j}$ of transmission resources over which user k is served by base station j. Furthermore, we prove that the solution to this convex problem is *physically realizable* in the following sense: there exists a feasible schedule consisting of a sequence of *integer scheduling configurations* such that, by time-sharing these configurations, the time-averaged user rates converge to the globally optimal throughput vector.

While our NUM solution is optimal, its implementation as an on-line protocol requires centralized computation and coordination across the base stations. This may be undesirable in practice. Then, we also consider a fully decentralized user-centric scheme similar to [81], where each user has a positive probability to switch cell association if the utility expected from a different base station is higher than the utility achieved from the currently associated one. In particular, we formulate a related non-cooperative association game where the users are the players, and the base stations operate according to a local resource allocation rule that determines the users' utility. By studying the KKT conditions of the global optimization problem and comparing them with the conditions under which the best-response strategy of the game makes all users keep their current association, we prove that the pure-strategy Nash equilibria of such a game must be very close to the global optimum of the centralized problem. Furthermore, we prove that, under certain technical conditions that we refer to as *heavy-loaded network*, if the centralized global optimum consists of a unique association (i.e., no user has positive activity fraction to more than one base station), then this association is a pure-strategy Nash equilibrium of the corresponding user-centric association game. Based on [81], we also have that the proposed user-centric decentralized scheme converges to a Nash equilibrium with probability 1, for the practically relevant cases of proportional fairness (PF) and hard fairness (HF). Hence, our user-centric algorithm is attractive not only for its simplicity and fully decentralized implementation, but also because its operates near the system *social* optimum.

Our problem formulation is to some extent related to that of [74]. However, [74] assumes that each base station applies a local PF criterion, and the optimization is given in terms of integer (binary 0-1) association variables. The resulting integer-programming problem is relaxed, and a subgradient method, which can also be seen as an on-line iterative protocol, is proposed. The same problem is considered in [82], where Lagrangian duality is used in order to circumvent the integer programming problem, and the dual problem is solved via a coordinate descent method, without the need for relaxation. Notice that the problem formulation in [74, 82] applies only to base stations serving a single user per slot (no multiuser MIMO), and uniquely to the case where each base station applies, independently of the others, a local PF policy giving equal air-time to its associated users. In contrast, our problem is formulated for a global network utility function (which includes PF at the whole network level) and our NUM problem is convex in nature, not requiring any convex relaxation.

On a separate thread, [81] proposes a user-centric game-theoretic approach to the association problem, which is completely decentralized. The associated randomized algorithm (which can be turned into an on-line protocol) is shown to converge to a Nash equilibrium under certain conditions on the per-user utility function. The Pareto efficiency of the Nash equilibria is studied, but it is not a priori clear whether such operating points are close to any well-defined global system optimality (social welfare). Our user-centric scheme is closely related to the scheme of [81]. However, we consider a more general class of user-centric utility functions reflecting a desired notion of local (per-cell) fairness, and we show the non-trivial fact that the corresponding user-centric schemes operate near the system social optimum of the corresponding network-wide utility function.

Main results:

- The solution of optimal user-cell association in a massive MIMO heterogeneous network is presented in

Dilip Bethanabhotla, Ozgun Bursalioglu, Haralabos Papadopoulos, Giuseppe Caire "Optimal User-Cell Association for Massive MIMO Wireless Networks," *Submitted to IEEE Transaction on Wireless Communications*, Preprint available at `http://arxiv.org/abs/1407.6731`.

Wireless data traffic is predicted to increase dramatically in the next few years, up to two orders of magnitude by 2020 [1]. This increase is mainly due to streaming of Video on Demand (VoD), enabled by multimedia devices such as tablets and smartphones. It is well understood that the current trend of cellular technology (e.g., LTE [83]) cannot cope with such traffic increase, unless the density of the deployed wireless infrastructure is increased correspondingly. This motivates the recent flurry of research on massive and dense deployment of base station antennas, either in the form of "massive MIMO" solutions (hundreds of antennas at each cell site [84, 63, 62]) or in the form of very dense small-cell networks (multiple nested tiers of smaller and smaller cells, possibly operating at higher and higher carrier frequencies [65, 64]). While discussing the relative merits of these approaches is out of the scope of this paper, we mention here that the small-cell solution appears to be particularly attractive to handle a high density of nomadic (low mobility) users demanding high data rates, as for typical VoD streaming users.

Motivated by these considerations, in this paper we envisage a network formed by densely deployed fixed nodes (hereafter denoted as *helpers*), serving multiple stationary or low-mobility (nomadic) video-streaming users. We focus on VoD streaming, where users start their streaming sessions at random times, and demand different video files. Hence, the approach of having all users overhearing a common multicasting data stream, as in live streaming, is not applicable. In contrast, each streaming user requests sequentially a number of video segments (referred to as *chunks*) and starts its playback after some *pre-buferring* delay, typically much smaller than the duration of the whole streaming session. In order to guarantee continuous playback in the streaming session, the system has to ensure that each video chunk is delivered before its playback deadline. This fundamentally differentiates *VoD streaming* from both *live streaming* and *file downloading*.

Our work focuses on the design of a scheduling policy for VoD streaming in a wireless network formed by many users and helpers, deployed over a localized geographic area and sharing the same channel bandwidth. We focus on the wireless segment of the network, assuming that the video files are already present at the helper nodes. This condition holds when the backhaul connecting the helper nodes to some video server in the core network is fast enough, such that we can neglect the delays introduced by the backhaul. In the case where such fast backhaul is not present, the recently proposed approach of caching at the wireless edge (see [85, 86, 87, 88, 89, 90, 91, 17, 92, 93, 94, 95]) was shown to be able to exploit the inherent asynchronous content reuse of VoD in order to predict and proactively store the popular video files such that, with high probability, the demanded files are effectively already present in the helpers caches. This justifies our assumption of neglecting the effects of the wired backhaul and focusing only on the wireless segment of the system.

In order to obtain a tractable formulation, we follow a "divide and conquer" approach, conceptually organized in the following steps:

i) We formulate a Network Utility Maximization (NUM) problem [96, 97, 98] where the network utility function is a concave and componentwise non-decreasing function of the time-averaged users' *requested* video quality index and the maximization is subject to the stability of all queues in the system. The shape of the network utility function can be chosen in order to enforce some desired notion of fairness across the users [99].

ii) We solve the NUM problem in the framework of Lyapunov Optimization [100], using the *drift plus penalty* (DPP) approach [100]. The obtained solution is provably asymptotically optimal (with respect to the defined NUM problem) on a per-sample path sense (i.e., without assuming stationarity and ergodicity of the underlying network state process [100, 101]). Furthermore, it naturally decomposes into sub-policies that can be implemented in a distributed way, by functions performed at the users and the helpers, requiring only *local* information. The function implemented at the user nodes is referred to as *congestion control,* since it consists of the adaptive selection of the video quality and the serving helper. The function implemented at the helpers is referred to as *transmission scheduling,* since it corresponds to the adaptive selection of the user to be served on the downlink of each helper station.

iii) We observe that, since all queues in the system are stable, all *requested* video chunks shall be eventually *delivered.*

iv) As a consequence, in order to ensure that all the video chunks are delivered within their playback deadline, it is sufficient to ensure that the largest delay among all queues at the helpers serving any given user is not larger than the pre-buffering time allowed for that user at its streaming session startup phase. We refer to the event that a chunk is not delivered within its playback deadline as a *buffer underrun* event. Since such events are perceived as very harmful for the overall quality of the streaming session, the system must operate in the regime where the relative fraction of such chunks (referred to as *buffer underrun rate*) is small. We refer to such desirable regime as the *smooth streaming regime*. In particular, when the maximum delay of each queue in the system admits a deterministic upper bound (e.g., see [102]), setting the pre-buffering time larger than such bound makes the underrun rate equal to zero. However, for a system with arbitrary user mobility, arbitrary per-chunk fluctuations of the video coding rate (as in typical Variable Bit-Rate (VBR) coding [103]), and users joining or leaving the system at arbitrary times, such deterministic delay upper bounds do not exist. Hence, in order to make the system operate in the smooth streaming regime, we propose a method to locally estimate the delays with which the video packets are delivered, such that each user can calculate its pre-buffering and re-buffering time to be larger than the locally estimated maximum queue delay. Through simulations, we demonstrate that the combination of our scheduling policy and adaptive pre-buffering scheme is able to achieve the desired fairness across the users and, at the same time, very small playback buffer underrun rate.

Since the proposed policy achieves NUM optimality on a per-sample path basis and, thanks to the adaptive dimensioning of the users' pre-buffering time, the system operates in the regime of small buffer underrun rate (i.e., in the smooth streaming regime), the resulting system performance is near-optimal in the following sense: for any *bounded* penalty weight assigned to the buffer underrun events, the system network utility (including such penalty) is just a small perturbation away from the optimal NUM value obtained by our DPP policy.

Main results:

- Our first work on NUM-based joint transmission scheduling and dynamic video quality selection in a multicell multiuser environment has been published in the paper:

  Bethanabhotla, D. ; Caire, G. ; Neely, M.J., "Adaptive Video Streaming for Wireless Networks With Multiple Users and Helpers," *IEEE Transactions on Communications*, Vol. 63, No. 1, pp. 268–285, 2015.

- Successively, we have investigated a different setting where the wireless network is formed by a device-to-device system with direct transmission between the user nodes, and where the video files are cached inside the user devices. These results are the subject of the paper:

  Joongheon Kim, Andreas F. Molisch, Giuseppe Caire, "Max-Weight Scheduling and Quality-Aware Streaming for Device-to-Device Video Delivery," *submitted to the IEEE/ACM Transactions on Networking*, preprint available at `http://arxiv.org/abs/1406.4917`.

- Finally, through the collaboration with prof. Adam Wolisz and his PhD student, Kostantin Miller, we have tackled the same problem using a different approach based on control theory, where the goal is to schedule video packets in order to maintain a certain desired equilibrium level in the users' playback buffer. This topic is treated in the paper:

Konstantin Miller, Dilip Bethanabhotla, Giuseppe Caire, Adam Wolisz, “A Control-Theoretic Approach to Adaptive Video Streaming in Dense Wireless Networks,” *submitted to the IEEE Transactions on Multimedia*, preprint available at `http://arxiv.org/abs/1502.02943`.

1.5 Optimization and implementation of massive MIMO schemes

Massive MIMO (multiple-input multiple-output) systems are equipped with a large number (dozens or hundreds) of antenna elements at the base station (BS) [61, 104]. They are intended to be employed in a multi-user MIMO (MU-MIMO) setting, such that the number of BS antenna elements is much larger than the number of users. Such an arrangement leads not only to very high spectral efficiency, but also to an important simplification of the signal processing: in the idealized regime of independent and isotropically distributed channel vectors, in the limit of an infinite number of BS antennas, single-user beamforming, specifically conjugate beamforming (i.e., maximum ratio combining in the receive mode, and maximum ratio transmission for the transmit mode) eliminates inter-user interference. Furthermore, the transmit power can be drastically reduced, leading to less interference and a lower energy consumption of the BS. For all these reasons, massive MIMO has received tremendous attention in the last years [105, 106, 107, 108, 109].

Massive MIMO is especially promising for systems operating at millimeter (mm-) Wave frequencies. Due to the short wavelength, very large arrays can be created with a reasonable form factor - a 100-element linear array is only about 50 cm long at a carrier frequency of 30 GHz. In light of the extremely large bandwidths that are available for commercial use (up to 7 GHz bandwidth in the 60 GHz band, and around 1 GHz at 28 and 38 GHz carrier frequency), massive MIMO systems in the mm-Wave range are ideally suited for high-capacity transmission and thus anticipated to form an important part of 5G systems. While the first commercial mm-Wave products are intended for in-home, short-range communications (e.g., for transmission of uncompressed video) [110], the potential of mm-Waves for *cellular outdoor* has recently been investigated [111, 112, 113]. Experiments have shown a coverage range of more than 200 m even in non line of sight (NLOS) situations [113]. Such long-range transmissions require high-gain adaptive antennas - something that massive MIMO implicitly provides.

For the downlink, massive MIMO systems at mm-Wave (or, for that matter, any other) frequencies require channel state information at the transmitter (CSIT), for conjugate beamforming as well as for other, more advanced, forms of MU-MIMO precoding (see [80] and references therein). In most existing papers, it has been assumed that this CSIT can be obtained from the uplink sounding signals, based on the principle of channel reciprocity [61]. However, reciprocity only holds (approximately) in Time Division Duplexing (TDD) systems, where the duplexing time is much shorter than the coherence time of the channel. In Frequency Division Duplexing (FDD) systems, which are widely used in cellular communications, the spacing between uplink and downlink frequency is - for all practical systems - much larger than the coherence bandwidth of the channel [114]. Consequently, CSIT has to be provided through feedback - i.e., each user measures its channel vector in the downlink, and sends it to the BS in (quantized) form. Due to the large number of BS antenna elements, the overhead for this feedback can become overwhelming, and methods have to be devised for reducing this load.[3]

Joint Spatial Division and Multiplexing (JSDM) is a recent technique proposed in [115] to achieve massive-MIMO like gains for FDD systems (or, more generally, for systems that do not make explicit use of channel reciprocity), with the added advantage of a reduced requirement for CSIT[4]. The idea is to partition the user space into groups of users with *approximately similar* covariances,[5] and split the beamforming into

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[3] TDD might also require feedback because accurate TDD calibration is difficult to achieve in practical hardware implementations. This is the reason why the only existing commercial standard that considers MU-MIMO downlink, IEEE 802.11ac, also prescribes explicit downlink training and quantized CSIT feedback, even though it uses TDD.

[4] An approach that exploits the same directional structure of the channel covariance matrix used by JSDM, in order to eliminate pilot contamination in a multi-cell massive MIMO setting, was proposed concurrently and independently in [116].

[5] Usually caused by the fact that the multi-path components of such users have similar angles at the BS

two stages: a first stage consisting of a pre-beamformer that depends only on the second order statistics, i.e., the covariances of the user channels, and a second stage comprising a standard MU-MIMO precoder for spatial multiplexing on the effective channel obtained after pre-beamforming. The instantaneous CSIT of such an effective channel is easier to acquire thanks to the considerable dimensionality reduction produced by the pre-beamforming stage. Also, JSDM lends itself to a *hybrid beamforming* implementation, where pre-beamforming (which changes slowly in time) may be implemented in the analog RF domain, while the MU-MIMO precoding stage is implemented by standard baseband processing. This approach allows the use of a very large number of antennas with a limited number of baseband-to-RF chains; the latter depends on the number of independent data streams that we wish to send simultaneously to the users. A major challenge for massive MIMO in the mm-Wave region is the fact that the Doppler shift scales linearly with frequency, and thus the coherence time is an order of magnitude lower than that of comparable microwave systems. Thus, massive MIMO systems at mm-Wave frequencies need to be restricted to low-mobility scenarios. For comparable speeds of motion, for example, at pedestrian speeds (1 m/s), coherence times are of the order of a few ms at mm-Wave frequencies. Since (outdoor) coherence bandwidths of mm-Wave channels are similar to those of microwave channels [111, 117], the overall challenges of CSI feedback overhead are then comparable to those of higher-mobility (vehicular) microwave massive-MIMO systems. For example, a 30 GHz channel for a user moving at 1 m/s has the same coherence time and bandwidth of a 3 GHz channel for a user moving at 10 m/s. In this work, we explicitly assume the availability of perfect channel state information for simplicity (wherever required). In reality, devoting a certain amount of resource to the training phase would discount the achievable throughput by a certain factor [115].

The performance of JSDM depends on the type of channel statistics. Previous analysis was based on the one-cluster (local scattering) model, which means that the BS "sees" the incoming multi-path components (MPCs) under a very constrained angular range. This allows for an easy division of the users into sets, whose associated MPCs are disjoint in the angular domain, and can thus be separated by the pre-beamformers. However, this model does not represent many important scenarios. For example, in urban environments, high-rise buildings or street canyons can act as important "common clusters" that create spatially correlated MPCs for many users [118], [119], [120]. Another important effect, which becomes particularly relevant at mm-Wave frequencies, is *channel sparsity* - in other words, the number of significant MPCs is much lower than that for a microwave system operating in a similar environment. The low number of MPCs enables a further reduction of the CSIT that has to be fed back, and enables a new "degenerate" variant of JSDM, proposed in this paper and referred to as *Covariance-based JSDM*, that depends on the channel covariance information only. In fact, it is well known that, as long as the scattering geometry relative to a given user remains unchanged, the fading channel statistics are wide-sense stationary (WSS). In particular, this means that the channel covariance matrix is time-invariant. In a typical scattering scenario, even if a user changes its position by several meters, the channel second order statistics remain unchanged [121, Chapter 4]. Hence, for a user moving at walking speed (1 m/s), the channel fading process is "locally" WSS over a time horizon of several seconds, spanning a very large number of symbol time slots (for example, a 20 MHz OFDM channel has symbol duration of 4 μs, corresponding to 10^6 symbols over an interval of 4s, corresponding to a user position displacement of 4m). We conclude that it is effectively possible to learn very accurately the channel covariance matrix at the transmitter side, even without requiring very fast CSIT feedback. This makes our scheme particularly interesting for mm-Waves.

The main goal of our work is to apply the JSDM approach to *realistic* propagation channels inspired, inter alia, by the recent experimental observations of mm-Wave channels in an urban outdoor environment [113]. Specifically, our contributions are:

- We identify a new optimization problem related to the application of JSDM to user groups that are coupled by the presence of common scatterers. In this case, nulling the common MPCs by pre-beamforming creates linearly independent user groups which can be served simultaneously, on the same transmission resource (Spatial Multiplexing approach). In contrast, allocating the user groups on orthogonal transmission resources allows to use all the MPCs to convey signal energy to the users (Orthogonalization approach). The ranking of these two approaches in terms of total system throughput depends on the operating SNR.

- We generalize the common scatterer problem to the case of many users (or user groups) with partial overlapping of their channel angular spectra (rigorously defined as the Fourier transform of the antenna correlation function). For this case, we develop two new algorithms for user grouping and pre-beamforming design. The first algorithm chooses users that fill many angular directions (i.e., it tends to serve less users with higher beamforming gain). The second algorithm maximizes the number of users with at least one mutually non-overlapping set of directions (i.e., it tends to serve more users with lower beamforming gain).

- We propose a new degenerate version of JSDM (Covariance-based JSDM) that provides orthogonalization of the users based only on the channel second-order statistics, and thus does not need feedback of the instantaneous CSIT. We discuss for which type of channels such reduced complexity scheme would perform well with respect to full JSDM, and show through numerical experiments that, as intuition suggest, covariance-based JSDM works well when the number of users is small with respect to the number of BS antennas and the channels are formed by a few MPCs with small angular spread. Remarkably, this is the case expected in a 5G small-cell system operating at mm-Wave frequencies.

- We illustrate the performance of the proposed user selection and JSDM schemes through various numerical examples, based on multiple clusters of MPCs, and discrete isolated MPCs, obtained from ray tracing in an outdoor campus environment.

- We also show sample performance results in *measured* propagation channels, from a 28 GHz measurement campaign recently carried out in New York City [113].

Overall, JSDM with appropriate user selection and, in some relevant cases, also the simple covariance-based JSDM, appears to be a very attractive approach for the implementation of multiuser MIMO downlink schemes in outdoor, small to medium range (10 to 200m) mm-Wave channels.

Main results:

- Our results on massive MIMO optimized in various relevant situations for TDD and FDD systems, including application to mm-Wave channels relevant to 5G systems, are included in the published papers:

  Jiang, Z. ; Molisch, A. ; Caire, G. ; Niu, Z., "Achievable Rates of FDD Massive MIMO Systems with Spatial Channel Correlation," *IEEE Transactions on Wireless Communications*, Volume: PP , Issue: 99, 2015.

  Rogalin, R. ; Bursalioglu, O.Y. ; Papadopoulos, H. ; Caire, G. ; Molisch, A.F. ; Michaloliakos, A. ; Balan, V. ; Psounis, K. "Scalable Synchronization and Reciprocity Calibration for Distributed Multiuser MIMO," *IEEE Transactions on Wireless Communications,* Volume: 13 , Issue: 4 Page(s): 1815 - 1831, 2014.

  Junyoung Nam ; Adhikary, A. ; Jae-Young Ahn ; Caire, G. "Joint Spatial Division and Multiplexing: Opportunistic Beamforming, User Grouping and Simplified Downlink Scheduling," *IEEE Journal of Selected Topics in Signal Processing,* Volume: 8 , Issue: 5, Page(s): 876 - 890, 2014.

  Adhikary, A. ; Al Safadi, E. ; Samimi, M.K. ; Rui Wang ; Caire, G. ; Rappaport, T.S. ; Molisch, A.F. "Joint Spatial Division and Multiplexing for mm-Wave Channels," *IEEE Journal on Selected Areas in Communications,* Volume: 32 , Issue: 6, Page(s): 1239 - 1255, 2014.

Kurras, Martin and Thiele, Lars and Caire, Giuseppe, “Interference Mitigation and Multiuser Multiplexing with Beam-Steering Antennas,” *19th International ITG Workshop on Smart Antennas WSA 2015*, Ilmenau, Germany, April 2015.

Dhillon, H.S. ; Caire, G. “Scalability of line-of-sight massive MIMO mesh networks for wireless backhaul,” Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 2709 - 2713

Adhikary, A. ; Al Safadi, E. ; Caire, G. “Massive MIMO and inter-tier interference coordination,” Information Theory and Applications Workshop (ITA), 2014 Publication Year: 2014 , Page(s): 1 - 10

Dhillon, H.S. ; Caire, G. “Information theoretic upper bound on the capacity of wireless backhaul networks,” Information Theory (ISIT), 2014 IEEE International Symposium on Publication Year: 2014 , Page(s): 251 - 255

In addition to the above theoretical studies, we have started the following two important research directions:

1. In collaboration with prof. Kutyniok (Mathematics Department, TUB), we have submitted a proposal to the DFG special focus program “Compressed Sensing in Information Processing” (CoSIP) SPP 1798, called:

   Compressed Sensing Algorithms for Structured Massive MIMO

   This proposal has received positive evaluation and will be funded in the second half of 2015. The goal of this project is to develop efficient signal processing techniques based on the principle of compressed sensing for the estimation of the high-dimensional massive MIMO channel, which can be modeled as a sparse signal in the angle of arrival and delay dimensions.

2. Using internal resources (AvH Professorship funds), we started to build up a wireless laboratory with the goal of designing and implementing an innovative massive MIMO platform, based on a flexible FPGA software defined radio architecture. Our platform will be able to handle hundreds of antennas through a very fast real-time data transfer from a number of massive MIMO interface boards (MMIB), designed by our team, to a high-performance FPGA acquisition card provided by Gidel, a small/medium enterprise based in Haifa, Israel, with which we have established an active collaboration. For the moment, initial steps towards the implementation of the lab, including hiring of key personnel (in particular, two PhD students with both hardware design and signal processing/communication theory background) have been made. We trust that by the end of the AvH project year 2, we will be able to report the first field trials of the new platform.

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