Decentralized Joint Beamforming, User Scheduling and QoS Management in 5G and Beyond Systems

Roberto P. Antonioli, Gábor Fodor, Pablo Soldati and Tarcisio F. Maciel

Abstract—Fifth generation cellular systems support a broad range of services, including mobile broadband, critical and massive Internet of Things and are used in a variety of scenarios. In many of these scenarios, the main challenge is maintaining high throughput and ensuring proper quality of service (QoS) in irregular topologies. In multiple input multiple output systems, this challenge translates to designing linear transmit and receive beamformers that maximize the system throughput and manage QoS constraints. In this paper, we argue that this basic design task in 5G and beyond systems must be extended such that beamforming design and user scheduling are managed jointly. Specifically, we propose a fully decentralized joint beamforming design and user scheduling algorithm that manages QoS. A novel feature of this scheme is its ability to reduce the initial rate requirements in case of infeasibility. By means of simulations that model contemporary 5G scenarios, we show that the proposed decentralized scheme outperforms benchmarking algorithms that do not support minimum rate requirements and previously proposed algorithms that support QoS requirements.

Index Terms—Resource allocation, decentralized algorithms, transceiver design, QoS management, MIMO.

I. INTRODUCTION

Current and emerging wireless communications technologies support a wide variety of applications and services, ranging from mobile broadband to ultra-reliable low-latency, broadband Internet of Things, including vehicular communications, advanced driver assistance systems, communication between unmanned aerial vehicles (UAVs), factory automation, high-resolution gaming etc. [1], [2]. Such a broad range of application scenarios and services poses an equally broad set of design requirements and quality of service (QoS) demands in terms of latency, reliability, energy and spectral efficiency. For example, remote driving – supported by the fifth generation (5G) of wireless networks – requires less than 10 msec latency and 99.999% reliability over the radio interface, while advanced driving assistance systems employing augmented vehicular reality technology require several 100 Mb/s in the downlink [3]–[5].

Addressing all these design challenges necessitates a variety of solutions in terms of enhanced deployment scenarios and more advanced transmission and reception technologies.

This work was supported by Ericsson Research, Technical Cooperation contract UFC.46 (EDB/NAIVE). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, CNPq and FUNCAP. The authors acknowledge the assistance of Iran M. Braga Jr. for drawing Figure 1.

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Network deployments are becoming increasingly dense and heterogeneous, with enhanced cellular base stations being co-deployed with wireless relay nodes, remote radio heads, wireless roadside units, drone-mounted base stations, multiple transmit and reception points and cell-free configurations [6]. These solutions will support an ever-growing number of connections to a large variety of user equipment, ranging from typical mobile handsets to connected vehicles, UAVs, low-power wireless sensors and actuators, etc., as illustrated in Fig. 1. The resulting system is typically interference-limited [7]. On the other hand, starting from the fourth-generation (4G) LTE systems, communication networks are featuring an increasing number of antennas, both at network nodes and user equipments. Such systems exploit advanced multiple input multiple output (MIMO) transmission and reception (transceiver) algorithms to capitalize on multi-path propagation diversity and spatial multiplexing and increase spectral efficiency. Such deployment environments can be characterized as systems operating using a MIMO interference broadcast channel (IBC).

To address the needs of emerging communication technologies operating in MIMO IBC scenarios, we argue that two design features are of paramount importance: (a) joint procedures of transceiver beamforming design and link scheduling for QoS management capable of ensuring that the links either meet the respective QoS requirements or suffer only a minor QoS degradation; and (b) decentralized solutions to suit the distributed nature of modern communication systems. These
two features are of high interest in several MIMO IBC systems being currently investigated by 3rd Generation Partnership Project (3GPP) and illustrated in Fig. 1, such as New Radio (NR) vehicle-to-everything (V2X) [5], UAV [8] as well as general Internet of Things (IoT) scenarios [9].

While the literature on MIMO IBC systems provides an abundance of solutions for the transceiver design, only a handful of works have addressed link scheduling in MIMO IBC and even fewer have considered QoS requirements (for example, in terms of signal to interference-plus-noise ratio (SINR), date rate, tolerable latency, and energy efficiency). This niche of works, however, either focuses entirely on the transceiver design (assuming feasible QoS requirements) or relies on centralized solutions to handle link scheduling and QoS management. Nevertheless, the MIMO IBC arises in many broadband Internet of Things scenarios for which the existing centralized solutions might not be applicable. Concerning massive MIMO deployments, it could be argued that when perfect or high-quality channel state information (CSI) is available, the links become orthogonal, rendering the joint transceiver design and link scheduling superfluous. However, many real-life deployments are subject to CSI errors and have limited number of antennas [5], [9]. Therefore, it is often necessary to develop solutions for decentralized transceiver beamforming design and link scheduling for QoS management in MIMO IBC deployments.

To fill this gap, this work presents a novel concept that jointly tackles the beamforming design, user scheduling and QoS management for QoS-constrained MIMO IBC systems. Jointly addressing these three problems is novel and highly relevant to fifth generation (5G) and beyond MIMO systems. Moreover, the proposed concept is highly different from previous works, which have addressed the problems of beamforming design, user scheduling and QoS management separately or by proposing complex and centralized solutions to address some combination of the above three problems. The key feature of our approach is an optimization mechanism for QoS management that, unlike related works in the literature, manages QoS in a decentralized fashion and handles infeasible instances of QoS requirements by allowing (and optimizing) a QoS degradation for some links, which eventually results in some link deactivation when inevitable. We discuss the algorithmic and signaling aspects of implementing the proposed solution in practical systems, which are aspects often ignored in previous works. Finally, simulations show the advantages of the proposed joint transceiver beamforming design and link scheduling compared to existing solutions.

II. CURRENT BEAMFORMING DESIGN, USER SCHEDULING AND QoS MANAGEMENT IN MIMO SYSTEMS

The importance of transceiver beamforming design and link scheduling for the MIMO IBC has been recognized for long and a rich literature of solution approaches exists. We highlight the main lines of research and discuss outstanding issues related to implementing some of the proposed solutions in contemporary MIMO IBC scenarios.

Considering single-antenna systems, the problem of link scheduling with QoS constraints has been widely studied in the literature and several approaches have been implemented in practice [10]. In such single-antenna systems, the link scheduling task is mainly conducted by selecting appropriate power levels depending on the targeted objective. These solutions are not applicable in today’s MIMO systems, because when the transmitters and receivers are equipped with multiple antennas, proper transmit and receive vectors that facilitate beamforming and spatial-division multiplexing must be designed.

Transceiver beamforming design and optimization, on the other hand, has been extensively studied for MIMO IBC systems, some of which might be of interest for application in 5G and beyond emerging radio technologies. To this end, a widely pursued performance metric is the maximization of the total system weighted sum-rate. Such metric is of high interest for network operators as the simple choice of its weights allows to steer the allocation of radio resources towards different goals, e.g., from maximizing the overall system throughput to ensuring some form of fairness among users. With this objective in mind, the authors in Shi et al. [11] proposed an iterative and decentralized transceiver design mechanism based on the weighted minimum mean squared error (WMMSE) approach. While Shi et al. [11] has stimulated more research in this area, this approach is limited to transceiver design for unconstrained sum-rate maximization, i.e., the authors ignored QoS management aspects.

In 5G and beyond wireless communications systems, however, many services will demand certain QoS from the underlying communication links. From an optimization prospective, adding QoS constraints may lead to feasibility issues in interference-limited systems, which per se is a non-trivial challenge. Transceiver design considering QoS demands for the weighted sum-rate maximization was considered in [12]. This work, however, only addresses the transceiver design aspect requiring that a feasible set of links was previously selected prior to executing the transceiver optimization, meaning that the authors ignored user scheduling aspects.

The feasibility issues brought by per-user QoS requirements can naturally be seen as part of a scheduling problem, i.e., finding a subset of users that can be co-scheduled in the same radio resource so as to optimize the desired performance metric while satisfying the users’ respective QoS demands. In the context of MIMO IBC systems with per-user QoS requirements, joint transceiver design and link scheduling with QoS management consists of optimizing the transceiver beamforming vectors while selecting a set of users for which the respective QoS demands can be simultaneously fulfilled or suffer only a minor QoS degradation. These two scheduling approaches are referred in the literature as the user set reduction approach and the relaxation of QoS constraints approach, respectively, which are illustrated in Fig. 2.

Fig. 2a depicts an example of user set reduction with QoS demands in terms of minimum rate requirements. User-2 in this example is deactivated so that the QoS demands of the remaining subset of users can be simultaneously fulfilled. Fig. 2b, illustrates an example of relaxation of QoS constraints in terms of minimum rate requirement. This approach relaxes the QoS requirements to find a common minimum QoS requirement that can be met by the users simultaneously.
III. DECENTRALIZING JOINT Beamforming, USER SCHEDULING AND QoS MANAGEMENT IN 5G AND BEYOND MIMO SYSTEMS

Meeting the requirements imposed by the stringent and heterogeneous demands of new communication services requires advanced QoS management solutions. To this end, we propose a novel concept to address QoS management in MIMO IBC systems based on jointly computing the transceiver beamforming vectors and link scheduling. The proposed solution has two main advantages: (i) the computations are executed in a decentralized fashion, making it suitable in 5G and beyond systems, conveniently modelled as MIMO IBC, and (ii) the solution employs an optimization framework that generalizes and combines existing scheduling approaches for QoS management. Specifically, it combines user set reduction and relaxation of QoS requirements into a single mechanism that handles infeasible QoS instances by either scheduling links with reduced QoS requirements or deactivating some links.

The first aspect to be highlighted is that – as opposed to alternative methods – our solution is fully distributed, thus it does not require a centralized unit. This characteristic is extremely important in 5G and beyond wireless communications systems that are inherently distributed and cannot rely on a centralized unit. Nevertheless, the proposed solution requires some communication between transmitters and receivers using backhaul links (when available) or using over-the-air signaling schemes, as for instance [16], which will be described in the next section. It is worth highlighting that - as opposed to existing solutions - the proposed solution jointly handles the beamforming design, user scheduling and QoS management problems, which are relevant aspects need by 5G and beyond MIMO systems.

A. System Model and High-Level Description of the Proposed Optimization Problem

We consider a general setup of 5G and beyond systems, conveniently modeled as a MIMO IBC system, in which $B$ transmitting nodes equipped with $N_T$ antennas serve in total $U$ multi-antenna receivers each equipped with $N_R$ antennas. All transmitting nodes operate over a common frequency channel and serve the respective users with linear transmit beamforming. $S_u$ denotes a fixed number of spatial streams allocated to receiver $u$ and we indicate the $s$th stream of receiver $u$ by the pair $(u, s)$.

The downlink signal received by receiver $u$ over spatial stream $s$ is expressed as

$$y_{u, s} = \mathbf{H}_{b_{u, t}} \mathbf{m}_{u, s} x_{u, s} + \sum_{i=1}^{U} \sum_{j=1, (i,j)\notin(u,s)}^{S_u} \mathbf{H}_{b_{i, t}} \mathbf{m}_{u, j} x_{i, j} + \mathbf{n}_u,$$  \hspace{1cm} (1)

where $\mathbf{H}_{b_{u, t}} \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix between receiver $u$ and transmitter $b$ serving receiver $i$, $\mathbf{m}_{u, s} \in \mathbb{C}^{N_T}$ is the transmit beamforming vector of the corresponding data stream, $x_{u, s}$ is the mutually independent transmitted data symbol with $\mathbb{E}[|x_{u, s}|^2] = 1$ and $\mathbf{n}_u \in \mathbb{C}^{N_R} \sim \mathcal{CN}(0, \sigma_u^2)$ is the noise at user $u$. User $u$ decodes the signal $y_{u, s}$ via a unit norm receive
beamformer $w_{u,s} \in \mathbb{C}^{N_r}$. The SINR for stream $s$ of user $u$ is given by
\begin{equation}
\Gamma_{u,s} = \frac{|w_{u,s}^H H_{u,b,u} m_{u,s}|^2}{\sum_{i=1}^U \sum_{j=1}^{S_i} |w_{u,s}^H H_{b_i,u} m_{i,j}|^2 + \sigma_i^2 \|w_{u,s}\|^2}.
\end{equation}

The proposed concept relies on formulating an optimization problem wherein the individual QoS requirements are modeled as constraints to which an optimization variable is added to enable the optimization of QoS management in case of infeasible instances of the problem. Such an additional optimization variable is used to control the QoS degradation incurred to the users in infeasible scenarios, while a penalty function of this variable is subtracted in the objective function to diminish the suffered QoS degradation. Mathematically, the proposed optimization problem can be formulated as:

\begin{equation}
\begin{array}{ll}
\text{maximize} & \sum_{u=1}^U \beta_u \left( g(\Gamma_{u,s}) - f(d_u) \right) \\
\text{subject to} & \sum_{u \in \mathcal{U}} \sum_{s=1}^{S_u} \|m_{u,s}\|^2 \leq P_b, \quad \forall b, \\
& \text{QoS requirement constraint, } \forall u,
\end{array}
\end{equation}

where $\beta_u > 0$ models the priority weight and QoS requirement of receiver $u$ and $P_b$ is the power budget of transmitter $b$. The QoS requirements constraints can be modeled as $g(\Gamma_{u,s}) \geq \text{QoS}_{u} - d_u$, in case there is a minimum per-receiver QoS requirement (e.g., rate or SINR) or as $g(\Gamma_{u,s}) \leq \text{QoS}_u + d_u$, in case there is a maximum per-receiver QoS requirement (e.g., packet latency or outage probability), where $\text{QoS}_u$ models the QoS requirement of receiver $u$. Thus, besides the transmit-receive beamforming variables $\{m_{u,s}, w_{u,s}\}_{\forall (u,s)}$, the optimization is conducted over the variables $\{d_u\}_{\forall u}$, which allows the QoS constraints to be relaxed. Therefore, $d_u$ is a QoS relaxation variable. Finally, one should have constraints restricting the domain of $d_u$, where the formulation of such constraints varies depending on the considered QoS constraints. For instance, one could have $d_u (d_u - \text{QoS}_u) \leq 0$ in case there are minimum per-receiver QoS requirements. These additional optimization variables $d_u$ are used to control the QoS degradation incurred to the users in infeasible scenarios, while a penalty function of this variable is subtracted in the objective function to diminish the suffered QoS degradation.

One example of the application of problem (3) is to consider a penalized sum-rate maximization problem subject to minimum rate constraints, in which $g(\Gamma_{u,s})$ models the rate of receiver $u$, the QoS constraints are expressed in terms of minimum rate constraints, and, thus, the $d_u$ variables are rate relaxation variables. Nevertheless, it is worth noting that our concept is applicable to a broad range of QoS requirements, such as minimum rate or SINR requirements as well as maximum packet latency. Moreover, our concept supports many types of optimization of a key performance indicator, such as maximizing the total system sum-rate or minimizing the power expenditure in the system.

**B. Illustrative Examples of the Proposed Concept**

Fig. 3 exemplifies the main features of the proposed solution considering a cellular MIMO IBC scenario with QoS requirements in terms of per-user minimum rate requirements. Even though we use a traditional cellular MIMO IBC scenario as example in Fig. 3, the proposed solution is applicable to any 5G scenario that operates in a MIMO IBC, such as the ones illustrated in Fig. 1. The first feature, showed in Fig. 3a, is the ability of optimizing the degradation of the QoS requirements of individual users in case of infeasible instances of QoS requirements. As such, our approach generalizes the relaxation of QoS constraints concept (cf. Section II). In particular, Fig. 3a shows an example wherein it is not possible to design a set of transmit and receiver beamforming vectors while meeting the minimum QoS requirement for all users. By allowing to optimize the QoS demands of individual users, the proposed mechanism returns a solution where only the QoS requirement of user-2 is reduced, while meeting the QoS demands of the remaining users. This is different from existing solutions based on relaxation of QoS constraints (e.g., [15]) which strive to find a minimum common QoS requirement that can be supported by all users (as shown, e.g. in Fig. 2b). On the other hand, this solution is also different from existing mechanisms that adopt the user set reduction approach, which would allocate zero rate to one user (possibly user-2) to meet the QoS demands of the remaining users, thus not fully optimizing the QoS management for that scenario. Therefore,

(a) Proposed solution only relaxes the QoS requirement of user-2 while meeting the rate requirements of the remaining users. In this case, it is not necessary to not schedule (i.e. deactivate) any user.

(b) Proposed solution performs a joint relaxation of QoS constraints and user set reduction, where user-1 is not scheduled and the QoS requirement of user-2 is relaxed.

Fig. 3: Rate allocation of proposed solution for joint link scheduling and transceiver design with QoS management considering cellular MIMO IBC scenarios.
our solution, in fact, allows some controlled QoS degradation aiming at degrading as little as possible the per-user QoS provisioning in infeasible scenarios.

Even though the rate provided to user-2 is below its minimum rate requirement, it can still be useful in many services consumed by that user. For example, consider the situation where all users demand minimum rates for streaming a 4K video, but it is not possible to support all the demands simultaneously. In this situation, the proposed solution computes a rate allocation that allows some users to watch the video in a lower resolution (e.g., 1080p), such as user-2 in Fig. 3a, while the remaining users watch the video in 4K. Besides that, since our solution is executed considering a single time-frequency resource, user-2 can still be served in other time-frequency resources to meet its minimum rate.

The second feature, depicted in Fig. 3b, is the ability to combine the relaxation of QoS constraints concept and the user set reduction approach (cf. Section II) into a single QoS management mechanism. In this example, it is only possible to satisfy the minimum QoS requirement of four out of the six users in the system. The solution found by the proposed mechanism is a combination of the QoS relaxation and user set reduction approaches, where the QoS requirement of user-2 is relaxed while user-1 is not scheduled. Such a result illustrates a situation where allocating some rate to user-1 would damage the QoS of most remaining users, thus it is more efficient to not schedule user-1 and satisfy the QoS demands of most remaining users. Existing user set reduction-based solutions would deactivate two users (possibly user-1 and user-2) to meet the QoS demands of the four remaining users, while existing mechanisms based on the relaxation of QoS requirements would need to dramatically reduce the QoS requirements of all users. Therefore, the rate allocation in Fig. 3b illustrates the capabilities of the proposed solution of managing QoS in an effective way to minimize the QoS degradation suffered by the users.

IV. ALGORITHMIC AND SIGNALING ASPECTS FOR 5G AND BEYOND DEPLOYMENTS

This section discusses how the proposed decentralized solution can be realized in practical 5G and beyond systems that operate as MIMO IBC systems. Specifically, we discuss the tasks that must be executed by transmitters and receivers so that a decentralized QoS control is achieved. Moreover, we discuss the signaling aspects involved in a practical deployment of the proposed solution, which enables our solution to use only local CSI and run in a completely decentralized fashion.

Fig. 4a illustrates a contemporary 5G scenario. Such a scenario is suitably modelled as a MIMO IBC since it incorporates a variety of multi-antenna transmitters (TXs) and receivers (RXs). The arrows indicate the RX to which each TX intends to send some data, where each TX can communicate with one or multiple RXs. Considering that the TX-RX links impose some QoS requirement, Fig. 4a shows a typical interference-limited MIMO IBC scenario where a decentralized QoS degradation control is required. In this general setting, the proposed solution can be deployed by means of each TX and RX executing the iterative algorithm presented in Fig. 4b and Fig. 4c, respectively. Those algorithms can be realized in practice using the frame structure depicted in Fig. 4d, which is based on [16], and extended to support the proposed solution. It is worth highlighting that the proposed frame structure is compatible with the 3GPP NR specification, as detailed in [16].

The proposed decentralized scheme is initiated by each TX computing the respective initial TX beamforming vectors (step 1 in Fig. 4b) using the maximum ratio transmission approach, for example. Next, each TX transmits precoded...
pilots using the initial values of TX beamforming vectors (step 2 in Fig. 4b). These precoded pilots are used by each RX to estimate their local CSI and mean squared error (MSE) as well as to compute the respective RX beamforming vectors, which are steps 2 and 3 in Fig. 4c. The next steps performed by each RX are the computation of the QoS degradation control factors and the transmission of those values via precoded pilots to the respective TXs, which encompasses steps 4 and 5 in Fig. 4c. Then, each TX receives the information transmitted by its intended RXs in step 4 of Fig. 4b. After that, each TX exchanges dynamic stream weights with its neighboring TXs in step 4 of Fig. 4b, which are used to control how much rate should be allocated to each RX in order to meet or minimally degrade the QoS demands. Finally, each TX updates its respective TX beamforming vectors and use them to transmit precoded pilots in steps 6 and 7 in Fig. 4b, respectively. All the described steps comprise one iteration of the proposed iterative solution.

The proposed frame structure is divided into two main parts: one used for the transceiver beamforming vectors configuration, while the second comprises the actual data transmission. In the beamforming configuration phase, the over-the-air signaling is split into two parts: the letter $F$ denotes the forward pilot transmission, which occurs from the TXs to the RXs and corresponds to steps 2 and 7 in Fig. 4b, while the letter $B$ denotes the backward pilot transmission, which happens from each RX to its serving TX and corresponds to step 5 in Fig. 4c. Finally, $I_{TX}$ denotes the signaling that occurs between TXs, which is used to share the dynamic stream weights in step 5 in Fig. 4b. When available, a backhaul link can be used in the $I_{TX}$, otherwise over-the-air signaling should be employed.

The computational complexity of algorithms derived from problem (3) when using a successive convex approximation (SCA) approach to solve the problem of penalized sum-rate maximization with minimum rate constraints is in the order of $O(U^2 N_T N_R^2 + U^2 N_T^2 N_R + U^2 N_T^3 + U N_R^3)$. Such a computational complexity comes from the computation of the transmit beamforming vector, the minimum mean squared error (MSE) receivers and MSE values. For different objective functions and types of QoS requirement, the computational complexity of the derived algorithms need to be further analyzed, which is out of the scope of this work.

V. PERFORMANCE EVALUATION

This section analyses the performance of the proposed solution considering the MIMO IBC scenarios shown in Fig. 1 and Fig. 4a. These scenarios are more challenging than existing cellular MIMO IBC systems due to the random positioning of both transmitters and receivers, which creates complicated interference patterns.

The simulated scenarios consider that 10 transmitters and the respective 2 intended receivers of each transmitter are randomly dropped within a 400 m radius region. Transmitters and receivers are equipped with 8 and 4 antennas each, respectively, which represents a possible contemporary MIMO IBC scenario where the devices do not employ massive MIMO, such as the scenarios in [5] and [9]. The channel matrices are computed using the Wireless World Initiative New Radio (WINNER) II B1 channel model. The per-transmitter power budget is 35 dBm. The results are averaged over 400 Monte-Carlo simulations. The objective of the proposed solution is maximizing the total system rate subject to per-link minimum rate constraints. For performance comparison, we use the WMMSE algorithm [11] and the algorithm in [12], which are also decentralized algorithms and have similar computational complexity as the proposed solution.

Fig. 5a shows the average QoS degradation when increasing the minimum rate requirement, where we consider only the links that do not meet the original rate requirements. The QoS degradation is the difference between the rate achieved by each link and its minimum rate requirement, thus it is given in the unit of rate. For the rate-unconstrained scenario, i.e., for the rate requirement of 0 bits/s/Hz, all algorithms present the same performance. This occurs because, in this case, there is no need for any link scheduling, so the proposed algorithm and the algorithm in [12], which consider rate requirements in their formulations, reduce to the rate-unconstrained case dealt by the WMMSE algorithm. When the rate requirement increases, the proposed solution achieves gains up to 85% over both comparison algorithms, while presenting a very small performance loss up to 5% in terms of total system rate. On the other hand, the algorithm in [12] and the WMMSE algorithm present very similar performances. This shows that,
in terms of average QoS degradation, algorithms that consider minimum QoS requirements but do not take into account any link scheduling mechanism (e.g., the solution in [12]) perform as poorly as algorithms that do not handle QoS demands (e.g., the WMMS algorithm) in MIMO IBC scenarios. This shows the importance of a complete solution that jointly handles transceiver design, link scheduling and QoS management, such as the proposed solution.

Fig. 5b shows the cumulative distribution function (CDF) of the QoS degradation values for the links that did not meet the respective rate requirements. This is shown for two values of minimum rate requirement, namely, 0.5 and 2.5 bits/s/Hz. Notice that in terms of user satisfaction, the algorithm in [12] performs similarly to the WMMS algorithm, which is designed for rate-unconstrained scenarios and, as such, does not deal with QoS demands. For the rate requirement of 0.5 bits/s/Hz, the proposed solution achieves higher user satisfaction in two ways: (a) unsatisfied links are consistently scheduled with rates closer to their minimum rate requirements, where the proposed solution achieves a gain of 138% considering unsatisfied links that get at least half of their rate requirement; and (b) the proposed solution provides a 90% gain in terms of deactivated links, i.e., links that are allocated with zero rate. For a higher value of minimum rate requirement, those gains are as high as 38% and 13%, respectively. This gain reduction occurs because in highly demanding scenarios, i.e., when the minimum rate requirement is further increased, the proposed solution has less freedom due to the reduced set of transceiver beamforming vectors that allow for a smaller QoS degradation with respect to the comparison algorithms. Nevertheless, the presented results show that designing a complete solution that jointly handles the transceiver design and link scheduling for QoS management provides significant gains in contemporary MIMO IBC scenarios.

VI. CONCLUSIONS AND OUTLOOK

Many current and emerging multi-antenna scenarios currently studied by the 3GPP community, including massive and broadband Internet of Things applications, can be characterized as MIMO IBC systems, which require decentralized mechanisms for transceiver design, link scheduling, and QoS management. Starting from a survey of the major works in this research field, this work proposed a solution concept for joint and distributed transceiver design and link scheduling with QoS management to fully harvest the potential gains in such systems. A key feature of our solution is the introduction of a QoS management mechanism that allows and optimizes, when necessary, a degradation of QoS per individual users while minimizing the overall users’ dissatisfaction in the system. Algorithmic and signaling aspects were also presented for practical implementations of the proposed solution. Numerical results demonstrated that our solution provides an enhanced QoS degradation control compared to existing solutions, proving that handling the user scheduling and transceiver design in a decentralized fashion in 5G and beyond wireless communications systems operating in the MIMO IBC is feasible and beneficial for managing QoS in a resource-efficient manner.

This work also provided a high-level description of the first steps toward a real implementation. Due to recent developments in 3GPP related to advanced QoS management, hybrid automatic repeat request (HARQ) mechanisms, channel state information acquisition, and resource allocation for both the cellular (Uu) and the sidelink (PCS) interfaces, including multihop sidelink relaying, and integrated access backhaul (IAB) signaling, the standardization community has already made the first steps toward decentralized MIMO IBC implementations supporting flexible topologies [4]. Therefore, this work connects the near-optimal theoretical solution to algorithmic and high-level implementation aspects.

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