Matching-Based Resource Allocation for Multi-User URLLC in Unlicensed Frequency Bands

(Invited Paper)

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***Abstract*—One of the key services of the upcoming fifth generation (5G) of wireless communications systems and beyond is considered to be ultra-reliable low latency communications (URLLC). However, enabling URLLC is challenging due to the strict requirements in terms of latency and reliability. Focusing on the demands of wireless factory automation, the scope of this work is to discuss conflicting priorities of resource allocation for URLLC networks such as matching stability, fairness between multiple users, and maximum throughput. Since wireless factory automation requires also cost-efficiency and global applicability, the unlicensed 5 GHz ISM band is modelled as an interference-limited multi-connectivity system. In the context of stable matching the influence of the parameter quota is studied, characterizing the maximum number of channels for any user. In order to link stable matching with minimum rate requirements, a new resource allocation algorithm is proposed. Selected approaches are applied to an exemplary scenario and their performance is comparatively evaluated to analyze the trade-offs between achieved maximum sum rates and fairness, i.e., minimum per user rate.**

***Index Terms*—5G, multi-connectivity, reliability, wireless systems, stable matching**

I. Introduction

The fifth generation (5G) of mobile communications systems is expected to address three main use cases: 1) enhanced mobile broadband will be an evolution of traditional mobile communication services with a focus on high throughput, 2) massive machine type communication implies that an enormous number of devices will be connected to the network, e.g. to provide sensor data, and 3) ultra-reliable low latency communications (URLLC) will enable new applications where objects are remotely controlled in real time [1]. The broad range of targeted 5G capabilities will be a basic prerequisite for realizing the vision of Tactile Internet aiming to deliver real-time control and physical tactile experiences remotely. In this regard, especially ultra-reliable and ultra-responsive network connectivity will be indispensable [2]. However, due to the limited available resources in wireless networks, research on allocation problems will remain an important part on the journey towards URLLC in 5G and beyond.

Since resource allocation deals with assigning channels to users, these problems are closely related to matchings which are defined as a mapping from the elements of one set to the elements of another set. One of the most popular matching problems is the stable marriage problem, i.e., if a set of men and a set of women decide on who to get married with based on their preferences. In this regard, the stability of the matching is important, because enduring marriages are desirable [3]. These one-to-one stable matchings can be extended to many-to-one stable matchings, which are applied to college admissions, where students are assigned to colleges based on preference relations. It is known that there exists at least one stable matching which can be determined by a constructive algorithm, the deferred acceptance algorithm [4]. Applying stable matching to resource allocation in wireless networks has shown that the resource proposing stable matching gives the maximum utility stable matching. However, three common channel aware schedulers (maximum throughput scheduler, score-based scheduler, and the proportional fair scheduler) do not result necessarily in a stable matching [3]. Recently, stable matching approaches for achieving reliability requirements of URLLC for multi-user settings gained attention [5].

Besides the matching stability, further important but opposing objectives of resource allocation are maximizing fairness and maximizing throughput. This work focuses on a trade-off analysis of resource allocation approaches for URLLC which is expected to guarantee every user a certain minimum rate besides aiming to maximize the throughput. One related application is factory automation with the aim to enable wireless closed-loop control with maximum acceptable outage probabilities in the order of 10^{-9} [6]. At the same time, industrial automation requires multi-user, low-cost, and worldwide applicability. Thus, the $5\,\mathrm{GHz}$ ISM bands are a promising candidate for wireless automation applications. However, since everybody is allowed to use these unlicensed frequencies, co-channel interference is a major challenge. In this regard, we derive a model for the outage capacity of selection-combined channels for interference-limited Rician/Rayleigh environments. We evaluate the performance of existing matching approaches which we apply to the resource allocation problem in wireless networks. In addition, we propose a combination approach to target the conflicting priorities of maximizing throughput, maximizing fairness and stability of the resource allocation.

II. System Model

We consider the downlink of a wireless network scenario for wireless factory automation with a set of users, denoted as $\mathcal{K} = \{1, 2, \ldots, K\}$, and a set of indivisible resources

$\mathcal{N} = \{1, 2, \ldots, N\}$. The resources are channels of a bandwidth B lying within the 5 GHz ISM band. These frequency bands are selected in order to meet the requirements of industrial automation with regard to low-cost and worldwide applicability. A major challenge in utilizing ISM bands is interference between neighbouring wireless systems. Thus, the system is assumed to be interference-limited.

The channel quality of user k on channel n is represented by the local mean signal-to-interference ratio (SIR) $\bar{\gamma}_{(n,k)}$ and determined based on local information, i.e. user k's position, log-distance path loss (PL), and log-normal shadowing according to the industrial indoor channel in [7]. In addition, we take the exponential spatial autocorrelation with decorrelation distance d_{corr} into account. The the local mean SIR in dB of user k operating on channel n is defined as

$$\bar{\gamma}_{(n,k)} = P^{\mathrm{R}}_{(n,k)} - P^{\mathrm{I}}_{n} \tag{1}$$

with cochannel interference power P^{I}_{n} and received power

$$P^{\mathrm{R}}_{(n,k)} = P^{\mathrm{T}}_{n} - PL(d) \tag{2}$$

assuming the distance d between user k and the access point, which transmits at power P^{T}_{n}.

Each user $k \in K$ can be assigned to a maximum of $q \geq 1$ channels whereas each channel $n \in N$ can be assigned to not more than one user. Thus, this scenario leads to a channel to user matching problem also known as the many-to-one matching problem [3]. We assume that the low-complexity combining scheme selection combining is performed if more than one channel is matched to a user to meet the strict latency requirements of URLLC. The assignment of channels to users corresponds to the matching μ. We assume that control information, e.g. preference lists and resource allocation, is exchanged between each user and the access point over one dedicated channel.

III. Outage Capacity

In order to design URLLC systems, a typical specification is the maximum rate a user can exploit without exceeding a required outage probability. This metric corresponds to the outage capacity. In this section, we derive a mathematical expression for the outage capacity of selection-combined channels for interference-limited environments in the case of a single interferer. We assume that the desired signal experiences Rician fading while the cochannel interferer's signal is Rayleigh-faded based on [8], which are reasonable assumptions for wireless communications system in factory automation operating in unlicensed frequency bands. Due to strict latency restrictions in URLLC, the channel capacity cannot be expressed as the average of the capacities for all possible channel realizations. Instead, the channel capacity

$$C = B \cdot \mathrm{ld}(1 + \gamma) \tag{3}$$

is a random variable with instantaneous SIR γ and bandwidth B. In order to improve readability, the indices (n, k) are waived in this section. Outages occur if the rate r exceeds capacity [9]. The outage probability of a channel is

$$P_{\mathrm{out}} = \Pr[C < r] = \Pr[\gamma < \gamma_{\mathrm{th}}]\,, \tag{4}$$

characterizing the probability that the instantaneous SIR γ falls below a threshold γ_{th}. The outage capacity

$$C_{\epsilon} = \max\{r : P_{\mathrm{out}} \leq \epsilon\}\,, \tag{5}$$

is the highest transmission rate that keeps the outage probability below a threshold ϵ.

We focus on a Rician/Rayleigh fading environment with a single interferer. The corresponding outage probability of a channel i is given by [8]

$$P_{\mathrm{out},i} = \frac{\gamma_{\mathrm{th}}}{\gamma_{\mathrm{th}} + \bar{\gamma}_i} \exp\left(-\frac{K\bar{\gamma}_i}{\gamma_{\mathrm{th}} + \bar{\gamma}_i}\right), \tag{6}$$

where the local mean SIR in channel i is denoted by $\bar{\gamma}_i$ and the Rician K factor characterizes the ratio between the power in the dominant path of the desired signal and the power in the scattered paths of the interferer.

We extend this outage analysis to multiple but independent channels because diversity is key in order to reduce the outage probability of a connection. Applying selection combining with L channels, outage occurs if all channels are in outage,

$$P_{\mathrm{out}} = \prod_{i}^{L} P_{\mathrm{out},i} = \prod_{i}^{L} \frac{\gamma_{\mathrm{th}}}{\gamma_{\mathrm{th}} + \bar{\gamma}_i} \exp\left(-\frac{K\bar{\gamma}_i}{\gamma_{\mathrm{th}} + \bar{\gamma}_i}\right) \tag{7}$$

under the assumption that the channels are separated in frequency at least by the coherence bandwidth. If all channels have equal local mean SIR $\bar{\gamma}$ and equal threshold γ_{th}, the outage probability of the diversity system simplifies to

$$P_{\mathrm{out}} = \left(\frac{\gamma_{\mathrm{th}}}{\gamma_{\mathrm{th}} + \bar{\gamma}} \exp\left(-\frac{K\bar{\gamma}}{\gamma_{\mathrm{th}} + \bar{\gamma}}\right)\right)^{L}. \tag{8}$$

Solving $P_{\mathrm{out}} = \epsilon$ for γ_{th} and inserting eq. (3) yields the outage capacity

$$C_{\epsilon} = r_k = B \cdot \mathrm{ld}\left(1 - \frac{\bar{\gamma} W_0\left(\exp(K) K \epsilon^{1/L}\right)}{W_0\left(\exp(K) K \epsilon^{1/L}\right) - K}\right), \tag{9}$$

where W_0 denotes the main branch of the Lambert W function. Focusing on a multi-user scenario, the outage capacity of a user k is referred to as user rate r_k because the local mean SIR $\bar{\gamma}$ and the number of channels L are user dependent. The user rate r_k corresponds to the maximum rate, a user k can exploit without exceeding an outage probability of ϵ, which is a suitable requirement specification for URLLC systems. We consider a system to be fair if the minimum user rate among all users is maximized. An overall performance measure is the system's sum rate resulting as

$$r_{\mathrm{S}} = \sum_{k \in \mathcal{K}} r_k. \tag{10}$$

IV. Resource Allocation Approaches

Resource allocation in wireless networks with multiple users requires an efficient algorithm to cope with the target

Algorithm 1 Many-to-one stable matching.

Input: user quota q, preference lists of all UEs ℓ_k^{pref} with $k \in \mathcal{K}$ and all channels ℓ_n^{pref} with $n \in \mathcal{N}$

Proposing and Matching:

Step $t = 0$*:*

Initialize the ordered set of user k's temporarily accepted channels $\mathcal{A}^t(k) = \emptyset$ for $k \in \mathcal{K}$.

Step t*:*

Proposals:

Every channel not yet assigned $n \in \mathcal{N} \setminus \bigcup_{k\in\mathcal{K}} \mathcal{A}^{t-1}(k)$ sends a proposal to its most preferred user $k \in \mathcal{K}$. This index is cleared from preference list ℓ_n^{pref} of channel n.

Decisions:

Denote channels which proposed to user k in step t as $\mathcal{P}^t(k)$. User k keeps the q best ranked channels from $\mathcal{A}^{t-1} \cup \mathcal{P}^t(k)$ with subject to its preference list ℓ_k^{pref} and updates $\mathcal{A}^t(k)$ accordingly.

Output: Stable matching μ

performance of the network and/or each user's service requirements and to guarantee fairness. Conflicting objectives of the considered resource allocation problem require various approaches. The following subsections introduce resource allocation algorithms with respect to a many-to-one stable matching with maximum sum utility in Section IV-A and maximizing fairness based on the weakest selects approach in Section IV-B, respectively. In addition, a combination of both approaches is proposed in Section IV-C.

A. Stable Matching

Stability is considered as the key property in matching because it ensures that the matches are satisfactory from the viewpoint of the individual users and channels. A matching μ is stable if no pair of channel and user prefers being matched to each other instead of matched to their current partner. A more detailed definition on stability of matchings can be found in [5]. In the context of this paper, the local mean SIR $\bar{\gamma}_{(n,k)}$ serves as a utility function. It is proven that the "resource proposing stable matching" yields the stable matching with maximum sum utility for a given user quota q [3] . This many-to-one matching approach is extended from one of the most popular matching problems, the stable marriage problem, and it is applied to college admissions [4]. The terminology can be translated to the resource allocation context: Users correspond to colleges and resources are identified with students since a student can only be assigned to one college. Every resource allocation problem has at least one stable matching which can be determined by the resource proposing deferred acceptance algorithm described in Algorithm 1, based on [4].

Each resource applies for the first user on its preference list and all users keep the first q resources which are best ranked on their preference lists. These steps are executed recurrently. The algorithm stops after a finite number of steps when all resources are matched to users or every unmatched resource has been rejected by every user on its preference list. In the following we refer to this approach as "stable matching" (SM).

B. Maximizing Fairness – Weakest Selects

In max-min fairness, it is aimed to maximize the minimum user rate among the users. The corresponding optimization problem is given by

$$\max \min r_k. \tag{11}$$

A resource allocation method working close to the optimum solution of this combinatorial problem is "weakest selects" (WS) [10]. This algorithm with very low computational complexity aims at assigning equal rates to all users. Therefore, in each iteration the user with the smallest accumulated rate selects its best channel out of the remaining ones. In case of several possibilities, it decides randomly. In this approach, the weakest user is matched to its potentially best remaining resource, i.e. WS is a matching approach yielding fairness and preventing starvation without stability guarantee.

C. Minimum Rate Matching

Within the context of 5G and especially URLLC, one important requirement is a guaranteed minimum throughput for each user. Hence, certain scenarios are conceivable where it is sufficient to satisfy only minimum throughput requirements of users instead of maximizing fairness, e.g. for periodic URLLC traffic [11] . In this regard, we propose a two-step resource allocation algorithm denoted as "minimum rate matching" (MRM) in order to avoid starvation by, at the same time, maximizing the total network throughput. MRM initially executes WS to satisfy a minimum rate

$$r_k \geq r_{\min} \, \forall k \in \mathcal{K} \tag{12}$$

assuming enough resources are available. Subsequently, SM is executed to maximize the remaining sum rate share regarding the resources which are not yet assigned. Finally, both matching results are combined. The value of the minimum rate $r_{\min}$ depends on the application and is considered as constant. The considered value $r_{\min} = 1.6\,\text{Mbps}$ corresponds to periodic URLLC traffic, which requires transmitting a file size of $200\,\text{bytes}$ within a latency budget of $1\,\text{ms}$ [5].

V. Simulation Scenario and Results

We consider a wireless network scenario in factory hall with one central access point communicating to K user nodes. The access point is responsible for the allocation of N available resources to the K users. The total number of channels is $N = 18$, which complies with the $5\,\text{GHz}$ ISM band assuming one dedicated channel for control information. The user nodes are assumed to be uniformly and independently distributed over a planar area of $50\,\text{m} \times 100\,\text{m}$. We assume one interferer in every channel, providing a constant interference power $P_n^{\text{I}} = -50\,\text{dBm}$. This relates to a interferer at a distance of $35\,\text{m}$ with a transmit power of $30\,\text{dBm}$, assuming $10\,\text{dB}$ loss through the factory wall. and equal quotas q for all users. Further simulation parameters are summarized in Table I.

Table I
SIMULATION PARAMETERS.

Parameter	**Value**
channel bandwidth B	20 MHz
carrier frequency f	5.2 GHz
reference distance d_0	15 m
PL reference $PL(d_0)$	70.28 dB
PL exponent δ	2.59
shadowing std σ_X	6.09 dB
shadowing decorrelation distance d_{corr}	2 m
Rician K factor	14.1 dB
outage probability threshold ϵ	10^{-9}
transmit power $P_n^{\mathrm{T}}\ \forall n \in \mathcal{N}$	20 dBm
interference power $P_n^{\mathrm{I}}\ \forall n \in \mathcal{N}$	−50 dBm

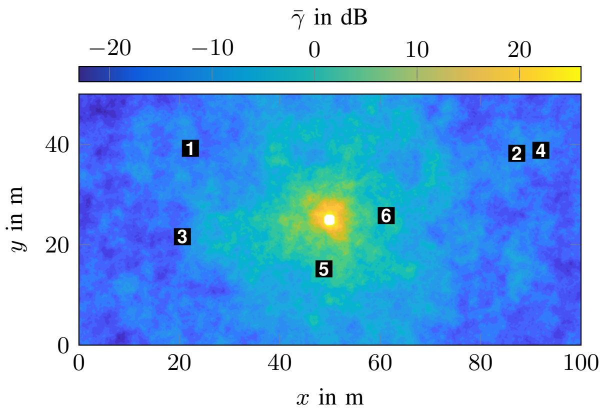

Figure 1. Local mean SIR distribution in factory hall with exemplary user locations.

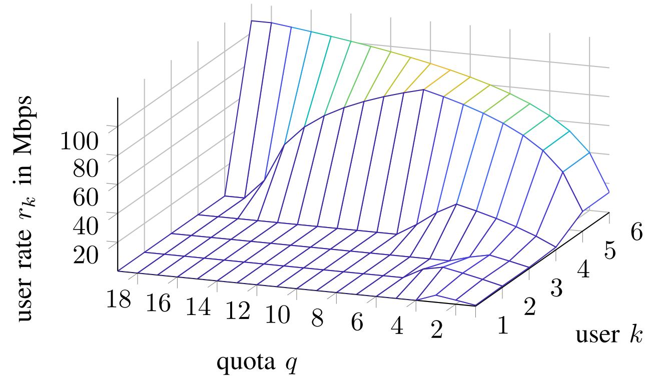

Figure 2. User rate r_k for one exemplary realization of $K = 6$ users obtained by stable matching based resource allocation for different quotas q.

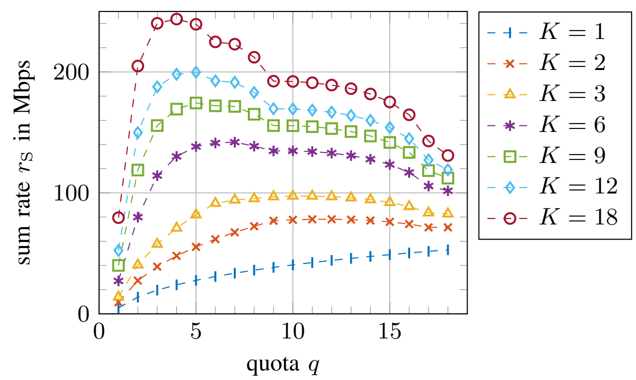

Figure 3. Sum rate r_{S} for different numbers of users obtained by stable matching based resource allocation for different quotas q.

Fig. 1 illustrates a realization of the local mean SIR in the factory hall. The effects of PL and the spatially correlated log-normal shadowing are clearly visible. The values vary between 25 dB near the central access point to −25 dB in the in the corner areas. We select the six marked exemplary user locations for the subsequent evaluation. Fig. 2 shows each user's rate r_k obtained by the SM approach for different quotas q. Obviously, the input parameter q significantly influences the user rates r_k and is hence a key parameter that has to be carefully selected for each scenario. The following three intervals for quotas can be derived:

- Interval 1: All user rates r_k increase in $1 \leq q \leq q' = 3$ because not all N available channels are yet assigned for small quotas. Some channels remain unused.
- Interval 2: At least one user rate r_k decreases for $q' \leq q \leq N$, i.e. starvation can be observed because one user takes channels from others.
- Interval 3: All user rates r_k do not change if $q > N$. If all N channels are assigned to the strongest user, further increasing the quota q cannot influence the resource allocation.

The effect of SM causing unfairness is presented in Fig. 2. The naive choice of high quota values causes starvation. We can formulate an optimization problem to choose q to prevent starvation according to $q' = \arg\max_q \min_k r_k$. The optimal quota for the scenario evaluated in this paper results as

$$q' = \begin{cases} \left\lfloor \dfrac{N}{K} \right\rfloor, & \text{if } N > K, \quad (13a) \\ 1, & \text{else.} \quad (13b) \end{cases}$$

The results of 1000 simulation runs with different user locations extend these findings to a more generalized evaluation. The sum rate r_{S} obtained by SM depending on the quota q is visualized in Fig. 3. The sum rate r_{S} increases at any quota q for higher number K of users. In order to achieve maximum sum rate r_{S} by SM, a higher value than the starvation threshold q' is recommendable. The quota value generating maximum sum rate r_{S} decreases with the number K of users because stronger users are assigned more channels at the expense of weaker users. Due to the selection combining scheme, this might reduce the overall sum rate r_{S}.

For the following comparative performance evaluation of the resource allocation algorithms SM, WS, and MRM, we focus on $K = 9$ users with quota $q = q' = N/K = 2$ avoiding starvation. The baseline approach of randomly assigning (Ran) channels to users is included as a reference. Fig. 4 shows boxplots of the system sum rate r_{S} for the different resource allocation algorithms. The bottom and top of a box are the first and third quartiles, respectively. The band inside the box is the median, outliers are depicted as "+" markers. In the considered

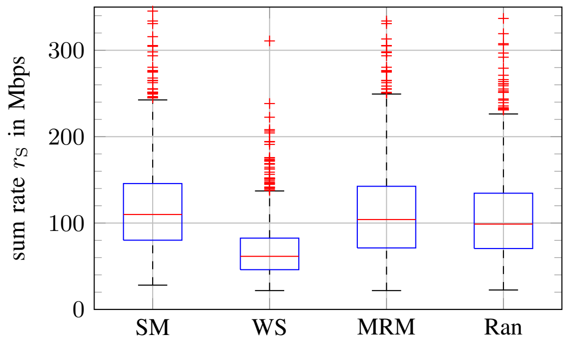

Figure 4. Sum rate for different resource allocation algorithms over realizations with $K = 9$ users.

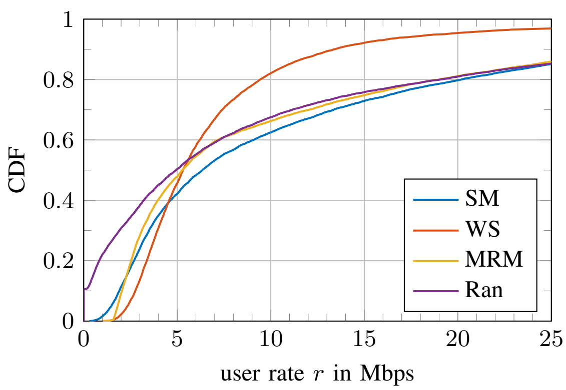

Figure 5. CDF of user rate for different resource allocation algorithms over realizations with $K = 9$ users.

scenario the highest median sum rate is achieved by SM. WS generates the smallest median sum rate because it aims to assign equal rates to all users and thus maximizes fairness. The minimum variance in sum rate r_S is achieved by WS which relates to a fair resource allocation. MRM and Ran achieve almost the same sum rate compared to SM. The combination approach MRM leads to a median of sum rate r_S which is higher than those of RA and WS and close to the median of sum rate r_S of SM. Please note that all but the SM matchings are not stable, i.e., there might be channels and users not matched which prefer each other to their partners. If the channels are administrated non-centrally, these channel-user pairs could destroy the outcome of the scheduling algorithm by swapping their allocated match with each other [3].

After evaluating the system sum rate r_S, the distribution of user rates r over different realizations presented in Fig. 5 provides valuable insights regarding fairness, i.e., trade-offs between weak and strong users. We consider the system to be fair if the minimum user rate is maximized. Especially in the context of wireless URLLC in factory automation with periodic traffic, each user should achieve a required minimum rate, which is $1.6\,\mathrm{Mbps}$ in the context of this paper. The reference approach Ran is not able to assign at least one channel to the weakest $10\,\%$ of users, the targeted minimum rate is not achieved by $27.6\,\%$ of the users. SM does not satisfy the minimum rate for $6.3\,\%$ of the users. On the other hand, WS and MRM provide the minimum rate to $99.6\,\%$ of all users. Thus, by utilizing MRM instead of SM, a $1600\,\%$ gain of satisfying the minimum rate requirement can be achieved, only marginally decreasing the system sum.

These results point out that for the considered scenario depending on the given requirements 1) SM can be selected to achieve maximized sum rates by disregarding the fairness, 2) WS can be selected if each user's rate is a critical performance parameter, or 3) the proposed MRM can be chosen as a trade-off between maximum sum rate and fairness.

VI. Conclusion

In this paper, we studied the resource allocation for multi-user URLLC, which can be modelled as a many-to-one matching problem. We presented advantages and limitations of different resource allocation algorithms, namely the many-to-one stable matching, the weakest selects, and a novel combination of both algorithms. In this context, we derived a mathematical expression for the outage capacity of selection combined channels in interference-limited systems. The importance of selecting a sufficient resource allocation approach and performance measures with respect to URLLC constraints and requirements was illustrated by simulation results. These investigations are basic steps to enable key challenges of future wireless networks, such as the Tactile Internet and wireless URLLC for factory automation operating in unlicensed frequency bands.

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