Matching Coalitions for Interference Classification in Large Heterogeneous Networks

Matthieu De Mari
Alcatel-Lucent Chaire, Supelec
and CEA LETI
Gif-sur-Yvette, France and Grenoble, France
Email: matthieu.demari@supelec.fr

Emilio Calvanese Strinati
CEA LETI
Grenoble, France
Email: emilio.calvanese-strinati@cea.fr

Merouane Debbah
Alcatel-Lucent Chaire, Supelec
Gif-sur-Yvette, France
Email: merouane.debbah@supelec.fr

***Abstract*—Due to large numbers of interferers, in-band interference is a bottleneck that future wireless heterogeneous networks have to deal with. Recent advances in information theory have shown that interference does not have to be avoided or strongly limited, so that reliable transmissions can occur. In this paper, we propose a novel Radio Resource Management (RRM) approach, capable to exploit those recent advances, by methodically coupling and processing in-band interferers. To do so, we first reuse the design of a previous two interference regime classifier. Then, we propose an algorithm which forms coalitions of interferers over the available spectral resources, in such a way that the spectral efficiency (SE) of the system is maximized. Simulations results show that our proposed RRM algorithm strongly limits the undesired effects of the traditional tradeoff between in-band interference and overall system performance (SE).**

I. Introduction

Future wireless networks will incorporate more relays, pico/femto-cells in their deployment. Such heterogeneous networks suffer from one fundamental bottleneck that strongly limits the network performance: in-band interference. The scarcity of spectral resources forces cells to overlap and operate in a common geographic area, causing in-band interference, which may drastically affect the reliability of transmissions between access points and their assigned UEs.

The common understanding is that interference, which is classically processed as additive noise, must be ideally avoided, or at least strongly limited. In that sense, Radio Resource Management and network planning are designed to limit undesired effects of cross-tier and co-tier in-band interference. Therefore, interference may be limited and even avoided by orthogonalizing transmissions [1]. However, orthogonalization of resources drives to a sub-optimal system spectral efficiency. A more spectral-efficient way to deal with interference are given by power control designs, where the system carefully balances power allocations among interfering sources [2]. However, interference-aware power balancing techniques often seek equilibria with iterative approaches. Each iteration adapts the transmissions powers, reset the overall network interference patterns and consequently the victims interference perceptions [3] [4]. As a direct consequence, power allocation techniques in autonomous systems suffer from high complexity, due to vicious circle effects [5].

Thanks to recent advances in interference management and classification, it appears that one does not necessarily have to treat interference as noise anymore. Intrinsic properties of the interfering signals may be exploited and can result in a spectral efficiency improvement. In that sense, interference was first classified into 5 regimes by Tse [6]. For each regime, it appears that there is an efficient way to process interference and reliably recover a message. The 5-regime classification from Tse was then simplified into a 3-regimes classification by Abgrall [7].

In this paper, we face the problem of organizing resource allocation among several users, assigned to different BSs, but sharing a common geographic area and sets of spectral resources. Our objective is to find a smart way to form coalitions of interferers from each BS, such that the total spectral efficiency of the system is maximized. Users from different BSs, belonging to a same coalition, suffer from in-band interference and may process it according to one of the 3 regimes, defined by Abgrall. We solve this RRM problem in two steps.

First, for a given coalition of users, one must find the most efficient way to process interference at each receiver, so that spectral efficiency is maximized. To do so, each transmitter may, at will, change the robustness of its transmission and its perception of incoming interference. By doing so, the receiver may switch from one interference regime to another, resulting in improved spectral efficiency. An analysis of this problem has been conducted for the 2 users case in [8], which led to a 2-regimes interference classifier. However, when the number of interferers becomes greater than two, finding the best way to process interference at each receiver becomes a lot more complex.

The second step consists of finding the most appropriate coalition formation, such that all users from each BS are assigned to a one and only one coalition, and the total spectral efficiency of the system is maximized. The optimal coalition formation appears to be a multidimensional assignment problem (MAP), which is NP-Hard [12]. Fortunately, there exists heuristic algorithms, such that the Kuhn-Munkres algorithm [9][10], that are able to compute the optimal assignment in polynomial time. However, when the number of BSs M

becomes greater than 2, solving the problem becomes more complicated, since there does not exist an algorithm, both time polynomial and optimal.

Without modifying the short-term power allocation strategy, the system can deal with in-band interference by smartly coupling interferers assigned to different BSs and by telling them how to process interference. The RRM algorithm we obtain benefits from a low complexity and is able to exploit recent advances in interference management and classification. Numerical simulations show that such an RRM approach offers significant spectral efficiency improvements compared to classical resource allocation algorithms.

In Section II, we define the system model and optimization problem to be solved. In Section III, we address the optimization problem for the particular case where the number of BSs M is two and explore the admissible interference regimes. System performance is numerically evaluated for several scenarios in Section IV. For a larger number of BSs M ($M \geq 3$), we discuss our interference classifier and propose suboptimal approaches to solve the NP-hard optimization problem in Section V.

II. System model and optimization problem

In this paper, the system consists of a set of M base stations (BS) and M and MN UEs (N UEs assigned to each BS), sharing the same geographical area. We denote UE (k,i), where $k \in \{1,...,M\}$ and $i \in \{1,...,N\}$, the UE i assigned to BS k. We consider a downlink transmission from each BS k to all its assigned UEs $(k,.)$. In the following, "interferer (k,i)" refers to the combination BS k - UE (k,i).

We denote h_i^{kl} the channel between BS k and UE (l,i). Transmission powers are fixed: p_i^k denotes the transmission power from BS k to its assigned UE (k,i). If interferers $[(1,i_1),...,(M,i_M)]$ share the same spectral resources, they suffer from interference: as depicted in Figure 1, $\forall(i_1,...,i_M) \in \{1,...,N\}^M$, an interference channel is considered for the coalition of interferers $[(1,i_1),...,(M,i_M)]$.

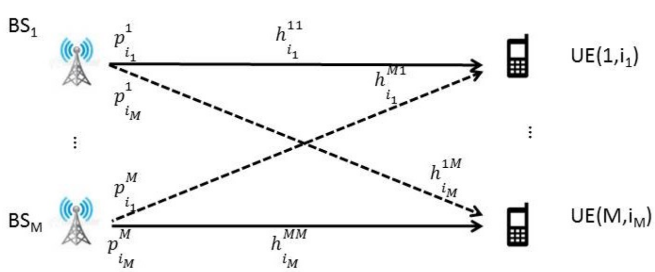

Fig. 1. A simple interference channel scheme with M APs and UEs.

Based on the previous definitions, we can define $\gamma(k,i)$, the SNR perceived by UE (k,i), due to an incoming transmission from its associated BS k. In a similar way, $\delta(k,l,i,j)$ denotes the INR perceived by UE (k,i) due to interference, related to the incoming transmission from BS l to its UE (l,j). Note that the INR criterion only makes sense, when $l \neq k$. Finally, we denote σ_n^2 the noise variance.

$$\gamma(k,i) = \frac{p_i^k |h_i^{kk}|^2}{\sigma_n^2} \text{ and } \delta(k,l,i,j) = \frac{p_j^l |h_i^{lk}|^2}{\sigma_n^2} \quad (1)$$

Finally, we denote $\omega(i_1,i_2,...i_M)$ the set of SNRs/INRs related to a coalition of interferers $[(1,i_1),(2,i_2),...,(M,i_M)]$, where:

$$\omega(i_1,i_2,...i_M) = [\Gamma(i_1,i_2,...i_M), \Delta(i_1,i_2,...i_M)]$$
$$\Gamma(i_1,i_2,...i_M) = [\gamma(1,i_1),...,\gamma(M,i_M)]$$
$$\Delta(i_1,i_2,...i_M) = [\delta(j,k,i_j,i_k) \mid j,k \in \{1,...,M\} \text{ and } j \neq k]$$

In this paper, we assume that the spectral resources are split in N equal parts, $(S_1,...,S_N)$. Our objective is to smartly couple interferers from each cluster into N coalitions of interferers with exactly one interferer belonging to each cluster, in such a way that the total spectral efficiency of the system is maximized. We assume that all the SNRs/INRs can be accurately estimated.

Let us define the following matching parameter m, as a N^M tensor, whose general term $m(i_1,i_2,...i_M)$ is defined $\forall(i_1,i_2,...,i_M) \in \{1,...,N\}^M$, as:

$$m(i_1,i_2,...,i_M) = \begin{cases} 1 & \text{if interferers } (1,i_1),...(M,i_M) \\ & \text{are matched together, share the} \\ & \text{same spectral resources and interfere} \\ 0 & \text{else} \end{cases}$$

Our objective is to define the optimal matching m^* such that $U(m)$, defined as follows, is maximized:

$$U(m) = \sum_{i_1=1}^{N} ... \sum_{i_M=1}^{N} m(i_1,...,i_M) C(i_1,...,i_M)$$

where C is the performance N^M tensor, whose general term $C(i_1,i_2,...i_M)$ refers to the total spectral efficiency a coalition of interferers $[(1,i_1),(2,i_2),...,(M,i_M)]$ can enjoy. The value of the general term $C(i_1,i_2,...i_M)$ is assumed to be strictly positive and depends on $\Delta(i_1,i_2,...i_M)$ and the way each interferer processes interference. We detail the admissible interference regimes and their performances in both Sections III-A and V. Matching m must also guarantee that there is exactly one user from each cluster assigned to each spectral resource. This means that the following constraints have to be verified, $\forall(i_1,i_2,...i_M) \in \{1,...,N\}^M$:

$$\begin{cases} \sum_{j_2=1}^{N} ... \sum_{j_M=1}^{N} m(i_1,j_2,...,j_M) = 1 \\ \vdots \\ \sum_{j_2=1}^{N} ... \sum_{j_{k-1}=1}^{N} \sum_{j_{k+1}=1}^{N} ... \sum_{j_M=1}^{N} m(j_1,...,j_{k-1},i_k,j_{k+1},...,j_M) = 1 \\ \vdots \\ \sum_{j_1=1}^{N} ... \sum_{j_{M-1}=1}^{N} m(k_1,...,k_{M-1},i_M) = 1 \end{cases}$$

III. Study of the case $M = 2$

In this section, we detail the optimization problem defined in Section II, when there are $M = 2$ sets of N users that have to be matched together. We focus on finding the optimal combination $(m^*, \mathcal{O}^*)$ of i) a bijective matching m between the N users of the two clusters, where $\forall (i_1, i_2) \in \{1, ..., N\}^2$, $m(i_1, i_2) = 1$ if the interferers $(1, i_1)$ and $(2, i_2)$ are matched together (otherwise, $m(i_1, i_2) = 0$.) ; and ii) interference regimes $\mathcal{O}$ for every couple $[(1, i_1), ..., (M, i_M)]$, defined by m with admissible values in Table I:

$$\mathcal{O} = \{(O_1(i_1, i_2), O_2(i_2, i_1)) \mid i_1, i_2 \in \{1, ..., N\}, m(i_1, i_2) = 1\} \quad (2)$$

Such that the total spectral efficiency $U(m, \mathcal{O})$, defined hereafter, is maximized.

$$U(m, \mathcal{O}) = \sum_{i_1=1}^{N} \sum_{i_2=1}^{N} m(i_1, i_2) C(i_1, i_2)) \quad (3)$$

$$(m^*, \mathcal{O}^*) = \arg\max_{(m, \mathcal{O})} [U(m, \mathcal{O})]$$

The matrix values $C(i_1, i_2)$ depend on the interference channel configuration $\omega(i_1, i_2)$ and the interference regimes $[O_1(i_1, i_2), O_2(i_2, i_1)]$ of any couple of interferers $[(1, i_1), (2, i_2)]$. We provide details in the following section.

A. Admissible interference regimes

Let us denote two arbitrary values $i_1, i_2 \in \{1, ..., N\}$. If interferer $(1, i_1)$ is coupled to interferer $(2, i_2)$, we assume that they share spectral resources and suffer from interference. We consider an interference channel, between BS 1, BS 2, UE $(1, i_1)$ and UE $(2, i_2)$.

We denote $\mathcal{O}(i_1, i_2) = (O_1(i_1, i_2), O_2(i_2, i_1))$ the coupled interference regime. The notation $O_1(i_1, i_2)$ refers to the way $(1, i_1)$ processes interference due to interferer $(2, i_2)$. The proposed admissible regimes rely on a simplified 3-regimes interference classification developed by Abgrall [7], based on Etkin & Tse 5-regimes classification [6], which has been extensively studied in [8]. The acceptable regimes are listed below:

- Noisy & Noisy - $\mathcal{O} = (1, 1)$: the interference is processed as additive noise by both interferers.
- Orth. & Orth. - $\mathcal{O} = (2, 2)$: splitting available spectral resources, allows transmissions to occur without any interference, at the cost of a halved spectral efficiency for both interferers.
- Noisy & SIC - $\mathcal{O} = (1, 3)$: UE $(2, i_2)$ successfully decodes the interference coming from BS 1 and cancels it out of the received signal via Successive Interference Cancellation. UE $(1, i_1)$ treats the interference as noise.
- SIC & Noisy - $\mathcal{O} = (3, 1)$: same concept as $(1, 3)$, but roles are inverted.
- SIC & SIC - $\mathcal{O} = (3, 3)$: both users can successfully decode the interference and cancel it out of their received signal via SIC techniques.

For any couple $(1, i_1) - (2, i_2)$, each interference regime $(O_1(i_1, i_2), O_2(i_2, i_1))$ allows a total spectral efficiency for the couple $(1, i_1) - (2, i_2)$, denoted $R(i_1, i_2, O_1(i_1, i_2), O_2(i_2, i_1), \omega(i_1, i_2)) = R_1 + R_2$ Details are listed in Table I. Note that $\omega(i_1, i_2)$ refers to the SNRs/INRs related to the couple $[(1, i_1), (2, i_2)]$, i.e. $\omega(i_1, i_2) = (\gamma(1, i_1), \gamma(2, i_2), \delta(1, 2, i_1, i_2), \delta(2, 1, i_2, i_1))$.

Interf. Reg.	$R = R_1 + R_2$
(1,1)	$\log_2\left(1 + \frac{\gamma(1,i_1)}{1+\delta(1,2,i_1,i_2)}\right) + \log_2\left(1 + \frac{\gamma(2,i_2)}{1+\delta(2,1,i_2,i_1)}\right)$
(2,2)	$\frac{1}{2}\log_2\left(1 + \gamma(1,i_1)\right) + \frac{1}{2}\log_2\left(1 + \gamma(2,i_2)\right)$
(1,3)	$\log_2\left(1 + \min\left[\frac{\gamma(1,i_1)}{1+\delta(1,2,i_1,i_2)}, \frac{\delta(2,1,i_2,i_1)}{1+\gamma(2,i_2)}\right]\right)$ $+ \log_2\left(1 + \gamma(2,i_2)\right)$
(3,1)	$\log_2\left(1 + \gamma(1,i_1)\right)$ $+ \log_2\left(1 + \min\left[\frac{\gamma(2,i_2)}{1+\delta(2,1,i_2,i_1)}, \frac{\delta(1,2,i_1,i_2)}{1+\gamma(1,i_1)}\right]\right)$
(3,3)	$\log_2\left(1 + \min\left[\gamma(1,i), \frac{\delta(2,1,i_2,i_1)}{1+\gamma(2,i_2)}\right]\right)$ $+ \log_2\left(1 + \min\left[\gamma(2,i_2), \frac{\delta(1,2,i_1,i_2)}{1+\gamma(1,i_1)}\right]\right)$

TABLE I
5 Admissible regimes and their performance

B. Two steps definition of the optimization problem

The optimization problem can then be solved in two steps. First, we solve, for any couple $(1, i_1) - (2, i_2)$, the optimization problem which consists of finding the optimal interference regime $(O_1^*(i_1, i_2), O_2^*(i_2, i_1))$ that maximizes $R(i_1, i_2, \omega(i_1, i_2))$, among all the admissible regimes listed in Section III-A. This problem has been previously studied and led to a low-complexity classification algorithm, described in [8]. The classification algorithm that we recall in Proposition III.1, returns, for any interference channel configuration $\omega(i_1, i_2)$, the one interference regime $(O_1^*(i_1, i_2), O_2^*(i_2, i_1))$ that maximizes the total spectral efficiency $R(i_1, i_2, O_1(i_1, i_2), O_2(i_2, i_1), \omega(i_1, i_2))$.

Proposition III.1 (Recall from 2 Regimes Interf. Classif. [8]**).** $(1, 1)$ *is the best interference regime if and only if* $\omega(i_1, i_2)$ *verifies the two following statements:*

- $\gamma(1, i_1) \geq (1 + \delta(1, 2, i_1, i_2))\delta(2, 1, i_2, i_1)$
- $\gamma(2, i_2) \geq (1 + \delta(2, 1, i_2, i_1))\delta(1, 2, i_1, i_2)$

$(3, 3)$ *is the best interference regime if and only if* $\omega(i_1, i_2)$ *verifies the four following statements:*

- $\gamma(1, i_1) \leq \delta(2, 1, i_2, i_1)$
- $\gamma(2, i_2) \leq \delta(1, 2, i_1, i_2)$
- $(1 + \gamma(1, i_1))(1 + \gamma(2, i_2))$ $\leq (1 + \delta(1, 2, i_1, i_2))\left(1 + \frac{\delta(2,1,i_2,i_1)}{1+\gamma(2,i_2)}\right)$
- $(1 + \gamma(1, i_1))(1 + \gamma(2, i_2))$ $\leq (1 + \delta(2, 1, i_2, i_1))\left(1 + \frac{\delta(1,2,i_1,i_2)}{1+\gamma(1,i_1)}\right)$

When $\omega(i_1, i_2)$ *does not satisfy any of the previous conditions, then the best regime is either (1,3) or (3,1).*
In such a configuration, (1,3) outperforms (3,1) if and only if

- $[\gamma(2, i_2) \geq \delta(1, 2, 2, i_1, i_2)$
  and $\gamma(2, i_2) \geq \gamma(1, i_1) + (\delta(1, 2, i_1, i_2) - \delta(2, 1, i_2, i_1))]$
- *or* $[\gamma(2, i_2) \leq \delta(1, 2, i_1, i_2)$
  and $(1 + \gamma(1, i_1)\delta(1, 2, i_1, i_2))\gamma(2, i_2)\delta(2, 1i_2, i_1)$

$$\geq (1 + \gamma(2, i_2) + \delta(2, 1, i_2, i_1))\gamma(1, i_1)\delta(1, 2, i_1, i_2)]$$

We can now define the following $N \times N$ matrix C, whose general term is:

$$C(i_1, i_2) = R\left(i_1, i_2, O_1^*(i_1, i_2), O_2^*(i_2, i_1), \omega(i_1, i_2)\right) \quad (4)$$

From the matrix point-of-view, the second step of the original optimization problem we defined in Section III-B, is then strictly equivalent to a planar assignment problem, on matrix C. Indeed, we need to find the combinations of N terms in matrix C, such that i) there is one and only one selected term on each row and column (This condition is sufficient for the assignment being bijective) and ii) the sum of the N terms is maximal, which is strictly equivalent to the assignment maximizing U. Such an assignment problem can be solved, by either brute-forcing over the $N!$ possible combinations, or by a low-complexity algorithm, namely the Kuhn-Munkres algorithm [9] [10]. Using simple operations on matrix C, the Kuhn-Munkres algorithm returns, in polynomial time, the maximal bijective combination of N terms in matrix C, from which we extract the maximal bijective matching m^* to our optimization problem.

IV. Performance comparison when $M = 2$

A. Numerical parameters

In numerical simulations, we have considered two BSs, within a distance of d_{BS}. The N users of each cluster are uniformly distributed in the coverage area of each BS R_{BS}. In the following, we denote $d(i, j, k)$ the distance between BS i and UE (j, k). The channels h_k^{ij} include the antenna gain G, the path loss $L(d(i, j, k))$ and the shadowing ξ. All parameters are summarized in Table II, based on [11]. Figure 2 shows the network deployment under investigation: $M = 2$ BSs and $N = 20$ UEs per BS.

Parameter	Value
Distance between BS to BS d_{BS}	1km
Coverage Area R_{BS}	Users are unif. dist. ,s.t. dist. BS-UE $\in [r_{min}, r_{max}]$
$[r_{min}, r_{max}]$	$[35m, 750m]$
Transmission power p_k^i	Unif. Dist. between 20 and 46 dBm
Channels $h(i, j, k)$	$h(i, j, k) = \frac{G}{L(d(i,j,k))\xi}$
Antenna Gain G	10 dBi
Path Loss $L(d(i, j, k))$, [d in km]	$L = 131.1 + 42.8log_{10}(d(i, j, k))$
Shadowing ξ	Log-normal, $\sigma_{SH} = 10$ dB
Noise power σ_n	-104 dBm
Number of UEs per cluster N	20

TABLE II
SIMULATIONS PARAMETERS.

B. Performance comparison

Let us first define the total spectral efficiency performance U_{SC} (defined as in eq. (3)), related to the optimal strategy obtained when solving the optimization problem, defined in Section III-B. In this section, we compare the performance U_{SC} to those of two classical strategies, defined hereafter and two other scenarios of interest. The first one, is the best performance strategy one can access, when the interferers are only allowed to treat the interference as additive noise and a smart coupling is made. To do so, we force the interference regime to be $(1, 1)$ and solve the assignment problem whose performance matrix is R_{11} with general term $R_{11}(i_1, i_2)$:

$$R_{11}(i_1, i_2) = \log_2\left(1 + \frac{\gamma(1,i_1)}{1+\delta(1,2,i_1,i_2)}\right) + \log_2\left(1 + \frac{\gamma(2,i_2)}{1+\delta(2,1,i_2,i_1)}\right)$$

We denote U_{11}, the global spectral efficiency performance, of such a strategy. The same way, we define U_{F11} the performance of the system, in a scenario where interference is treated as noise and random coupling is considered, i.e. interferer $(1, i)$ is coupled to interferer $(2, i)$. Using the same coupling strategy, couples of interferers may also select the most appropriate interference regime among the four regimes of interest we have defined before, instead of (1,1). In such a scenario, we denote the global spectral efficiency performance as U_{BR}. Finally, we also consider the case where users avoid the interference, by forcing orthogonalization to happen between transmissions, i.e., the interference regime is always $(2, 2)$. In this scenario, any matching returns the same performance U_{F22}.

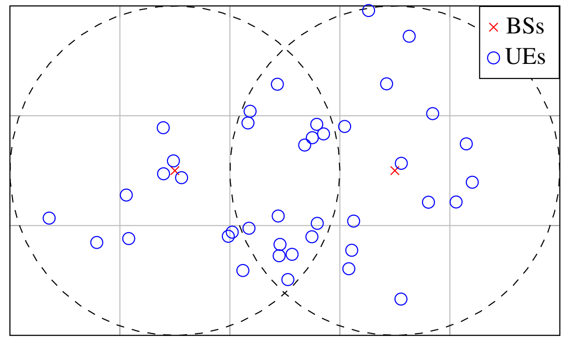

Fig. 2. One realization of the network under investigation - $M = 2$ APs and $N = 20$ UEs/AP.

We have run Monte-Carlo simulations, with $N_{MC} = 1000$ independent realizations and have compared the performances $U_{SC}, U_{F22}, U_{11}, U_{BR}$. Figure 3 represents the histogram plot of the performance realizations of each scenario.

It immediately appears, as expected, that the orthogonalization strategy is highly inefficient, compared to the 4 other scenarios. Allowing the system to select the best regime among the 4 regimes of interest we have detailed, allows an enhancement of the average performance by 8.5%, compared to the *Forced (1,1) + Random Association* scenario. Moreover, combining both improvements, i.e. smartly selecting the best interference regime and smartly coupling interferers grants the system an average performance improvement of 18.5% compared to the *Forced (1,1) + Random Association* scenario.

V. Optimization problem with $M \geq 3$

In this section, we take a glance at the matching problem defined in Section I, when $M \geq 3$.

When the number of interferers coupled together is $M = 2$, we can define, according to our previous study in [8], the

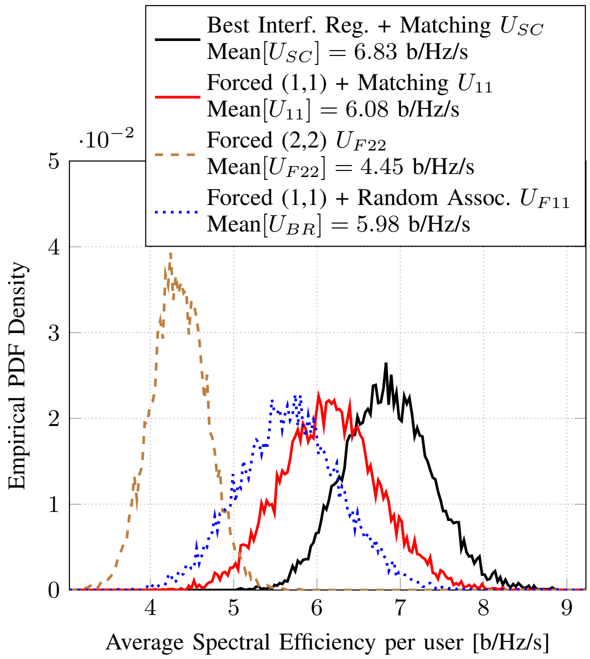

Fig. 3. Empirical PDF of the average user spectral efficiency, over $N_{MC} = 1000$ realizations, for 4 scenarios of interest.

best way to process the interference, so that the total spectral efficiency for the couple of interferers is maximized. However, when the number of interferers coupled together becomes larger than 2 ($M \geq 3$), defining the best interference regime and its performance for each user becomes a lot more complex. Group SIC, iterative k-SIC or k-Joint Decoding approaches might be considered, leading to multiple new regimes. Moreover, it appears complicated to define the spectral efficiencies for these new regimes. The matching approach can still be considered in simple scenarios where interference is treated as noise or where orthogonalization is considered. More details on this topic can be found in [15].

When $M \geq 3$, the Multidimensional Assignment Problem (MAP), defined in Section II, becomes NP-Hard [12]. The number of combinations a brute-force algorithm needs to try out before finding the maximum matching is $(N!)^{(M-1)}$. Integer Linear Programming approaches can be considered, but the computation time grows fast when M or N grows large [15]. However, heuristics can be considered, e.g. a memetic algorithm ,based on [13], can be used to find a suboptimal solution to the assignment problem, in acceptable computation times.

VI. Conclusion

In this paper, we have defined a low-complexity optimization process, which re-arranges interferers over spectral resources and defines the best way for them to treat in-band interference. Compared to classical RRM scenarios, we observe that our optimization process offers significant gains, in terms of total spectral efficiency. Future work will further investigate the best interference regimes, when $M \geq 3$ interferers are coupled together. It may lead to a classifier, similar to the one we obtained in a previous paper for the case $M = 2$, which can then be reused in our matching optimization, in a scenario with $M \geq 3$ clusters of interferers.

Acknowledgment

This research has been supported by the ERC Starting Grant 305123 MORE (Advanced Mathematical Tools for Complex Network Engineering)

References

[1] Gesbert, D., Kiani, S. G., & Gjendemsj, A. (2007). “Adaptation, coordination, and distributed resource allocation in interference-limited wireless networks.” *Proceedings of the IEEE, 95(12), 2393-2409.*

[2] Shah, V., Mandayam, N. B., & Goodman, D. J. (1998, September). “Power control for wireless data based on utility and pricing.” *In Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on (Vol. 3, pp. 1427-1432). IEEE.*

[3] Sahin, O., Erkip, E., & Goodman, D. (2006, May). “Iterative Power Control for Multimedia Wireless Communications.” *In Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on (Vol. 4, pp. IV-IV). IEEE.*

[4] Holliday, T., Bambos, N., Glynn, P., & Goldsmith, A. (2003, October). “Distributed power control for time varying wireless networks: Optimality and convergence.” *In Proceedings of the annual ALLERTON Conference on Communication Control and Computing (Vol. 41, No. 2, pp. 1024-1033). The University; 1998.*

[5] Abgrall, C., Strinati, E. C., & Belfiore, J. C. (2010, September). “Distributed power allocation for interference limited networks.” *In Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on(pp. 1342-1347). IEEE.*

[6] Etkin, R. H., Tse, D. N., & Wang, H. (2008). “Gaussian interference channel capacity to within one bit.” *Information Theory, IEEE Transactions on, 54(12), 5534-5562.*

[7] Abgrall, C. (2009). “Resource allocation in dense wireless communication networks.” *Thesis Manuscript.*

[8] De Mari, M., Calvanese Strinati, E. & Debbah, M. , “Two-regimes interference classifier: an interference-aware resource allocation algorithm”, *WCNC 2014*

[9] Kuhn, H. W. (1955). ”The Hungarian method for the assignment problem”. *Naval research logistics quarterly’, 2(12), 83-97.*

[10] Munkres, J. (1957). ”Algorithms for the assignment and transportation problems.” *Journal of the Society for Industrial & Applied Mathematics, 5(1), 32-38.*

[11] 3GPP TSG RAN, 3GPP TR 36.814, Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9), *V9.0.0, March 2010.*

[12] Deb, S., Pattipati, K. R., Bar-Shalom, Y., & Tsaknakis, H. (1992, October). “A new algorithm for the generalized multidimensional assignment problem.” *In Systems, Man and Cybernetics, 1992., IEEE International Conference on (pp. 249-254). IEEE.*

[13] D. Karapetyan & G. Gutin, “A New Approach to Population Sizing for Memetic Algorithms: A Case Study for the Multidimensional Assignment Problem”, http://arxiv.org/ abs/1003.4314, *2010.*

[14] Blomer, J., & Jindal, N. (2009, June). ”‘Transmission capacity of wireless ad hoc networks: Successive interference cancellation vs. joint detection"’. *In Communications, 2009. ICC’09. IEEE International Conference on (pp. 1-5). IEEE.*

[15] De Mari, M., Calvanese Strinati, E. & Debbah, M. , “Interference Classification and Matching: Two Steps Optimization for Improving Spectral Efficiency” (Journal Version), *in processing.*