Improving Fairness by Cooperative Communications and Selection of Critical Users

Juan Awad, Mohammad A. Imran and Rahim Tafazolli
Centre for Communication Systems Research
Faculty of Engineering and Physical Sciences
University of Surrey, Guildford, UK, GU2 7XH
Email: {J.Awad, M.Imran, R.Tafazolli}@surrey.ac.uk

***Abstract*—Cooperative Transmission can be used in a multicell scenario where base stations are connected to a central processing unit. This cooperation can be used to improve the fairness for users with bad channel conditions–critical users. This paper will look into using cooperative transmission alongside the orthogonal OFDM scheme to improve fairness by careful selection of critical users and a resource allocation and resource division between the two schemes. A solution for power and subcarrier allocations is provided together with a solution for the selection of the critical users. Simulation results is provided to show the fairness achieved by the proposed critical users selection method, resource allocation and the resource division method applied under the stated assumptions.**

***Index Terms*—Cirtical Users, Cooperative Communications, Radio Resource Allocations, Fairness.**

I. Introduction

In recent years, interest in multimedia application, VoIP in and high-speed internet in mobile devices has lead to more demand on data rate thus rapid development in of wireless communications making it the fastest growing segment of the communications industry. With over two billion mobile users around the world, it has a very lucrative market.

Many transmission techniques have been created to best utilize the spectrum. OFDM (Orthogonal Frequency Division Multiplexing) is one of them. This multicarrier transmission technique has proven itself to be one of the most efficient techniques in wireless and wired transmissions and it has been employed in several standards such as IEEE 802.11a/g and HIPERLAN/2 due to its immunity to Inter-Symbol Interference (ISI). OFDM transmitter transmits a number of parallel low bandwidth subcarriers making the effect of frequency selective fading negligible. These subchannels are usually modulated using an M-ary QAM (Quadrature Amplitude Modulation) scheme. OFDMA (Orthogonal Frequency Division Multiple Access) is the multi-user variant of OFDM and it has been chosen for LTE downlink transmission for the 4th generation mobile communications.

Besides transmission techniques, resource utilization is an important tool to reach the best spectrum efficiency. Subcarrier allocation and power adaptation are two of these optimization methods. It has been shown that they provide a better spectrum utilization. Subcarriers are given to the users that show the best channels condition keeping in mind other factors like fairness. Power is distributed among users in a similar manner where good channels are assigned more power than worse channels and some are not assigned any power at all [1]–[3]. Both of those should be used for better results.

In this paper, we will be looking into a method of frequency reuse different from most frequency reuse techniques. Few frequncy reuse schemes has been mentioned in the literature like Fractional Frequency Reuse (FFR) [4] where all cell centres use all the available spectrum and cell-edges have spectrum allocations orthogonal to all other cell-edges. This scheme will allow interference to be caused by a high power transmission from one cell-centre to another cell-edge. Soft Frequency Reuse (SFR) [5] have also been proposed to reduce this problem where it's similar to FFR but it puts a limit on the transmit power to reduce interference this reducing the interference caused by cell-centre transmissions.

All the frequency reuse scheme aim to reduce and avoid the interference on the most vulnerable users at the cell edge. In this paper, we will propose a scheme that will benefit from the similar proximity of cell-edge users to all base stage by performing what is known as Distributed-MIMO [6] communications. We also use orthogonal spectrum at the cell centres thus eliminating interference at one cluster scenario and reducing it at the whole system stage. This technique will prove it self as fair to all users. And as for all fair systems, fairness comes at a price which is spectral efficiency.

The remainder of this paper will be organized as follows. In Section II we will be looking at the system model then formulate the resource allocation problem. In Section III, a solution is formulated for the subcarriers and power allocation problems in the cooperative case along with the method for selecting the critical users and their resources will explained. Simulation results to show fairness and system performance are provided in Section IV. And finally, Section V conclude this paper.

II. System Model and Problem Formulation

A. System Model

Consider three interfering sectors shown in Fig. 1 each sector has an independant base station sector antenna. The three base stations are connected together through a backhaul to a Central Processing Unit (CPU). This backhaul is assumed

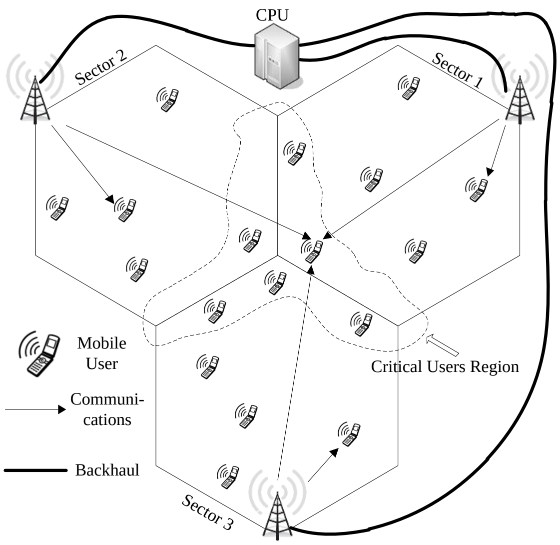

Fig. 1. System Model

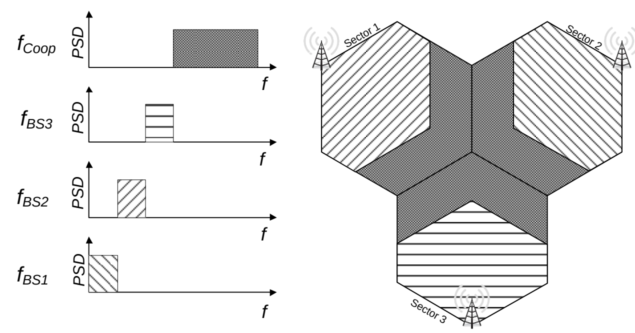

Fig. 2. Bandwidth Division

to be of an unlimited bandwidth. The closest practical representation to that is an optical fibre backhaul. The CPU is responsible for resource allocation and the choice of critical users and all the channel state information estimated at the base stations are passed to the CPU. As shown in Fig. 2 each sector is divided into a non-critical and a critical users regions. The choice of critical users is to be discussed further in details in Section III-C. The channel state information (CSI) is assumed to be estimated at the receiver and fed back to the transmitter fast enough for accurate knowledge at the base station for the current state.

We assume that the channel is frequency selective and the fading is slow enough for the channel to stay constant over one transmission. OFDM modulation technique is used to combat frequncy selectivity. It is assumed that perfect instantaneous channel state information are available at the receiver and the transmitter. The available spectrum is distributed between the critical users and non-critical users as shown in Fig. 1, where f_{BS_m} is the available spectrum for non-critical users in sectror m at the mth base station and f_{Coop} is the spectrum availabe for critical users at all the base stations. We will also assume that the power will be distributed between the two transmission schemes. Assuming P_{total} is the total power at each base station, P_m will be the power given for the orthogonal scheme equal at all base stations and P_{Coop} is the amount of power given for the cooperative scheme also equal at all base staions; $P_{total} = P_m + P_{Coop}$.

B. Problem Formulation

The objective is to maximise the sum rate while maintaining fairness for all users by dividing the system into two different schemes stated above. In the orthogonal part of the system dedicated for non-critical users the sum rate of user k in the mth sector is:

$$R_k = \sum_{n=1}^{N_m} B_N \log_2\left(1 + p_{k,n}\frac{|h_{k,n}|^2}{N_0 B_N}\right) \qquad \forall k = 1,\ldots,K, \tag{1}$$

where N_m is the total number of subcarriers for orthogonal scheme user k, K is the total number of orthogoanl users, B_N is the bandwidth per subcarrier (all subcarriers have the same bandwidth), $p_{k,n}$ and $h_{k,n}$ is the power and complex channel on the nth subcarrier for the kth user respectivly, N_0 is the noise power spectral density (PSD). The objective is to maximise the sum rate

$$\max_{\mathbf{p}} \sum_{k=1}^{K} R_k \tag{2}$$

$$\text{Subject to:} \quad p_{k,n} \geq 0 \qquad \forall n,k$$

$$\textstyle\sum_N \sum_K p_{k,n} = P_m,$$

where P_m is the total power available for the orthogoanl scheme at the respective base station m. Please note that the power allocation for the base stations are seperate problems. The solution to this porblem is the well known greedy subcarriers allocation [7] and single-user water-filling [8].

As for the cooperative part of the system (for critical users), where MRC is used, the rate of user k can be written as in [9]

$$R_k = \sum_{n=1}^{N} B_N \log_2\left(1 + \sum_{m=1}^{M} p_{k,n,m}\frac{|h_{k,n,m}|^2}{N_0 B_N}\right), \quad \forall n = 1,\ldots,N \tag{3}$$

where $p_{k,n,m}$ is the transmit power from the mth antenna (base station) to the kth user on the nth subcarrier, and $h_{k,n,m}$ is the channel from the mth antenna (base station) to the kth user on the nth subcarrier.

$$\max_{\mathbf{p}} \sum_{k=1}^{K} R_k \tag{4}$$

$$\text{Subject to :} \quad p_{k,n,m} \geq 0 \qquad \forall k,n,m$$

$$\textstyle\sum_K \sum_N p_{k,n,m} = P_{Coop} \qquad \forall m,$$

where P_{Coop} is the total power available for the cooperative scheme which is equal at all base stations.

The objective is to maximize both equations (2) and (4) subject to their coressponding constraints while maintaining fairness between users. fairness can be considered by carefully selecting critical users.

III. Resource Allocation for the Cooperative Scheme

We will split the problem of subcarriers and power allocation into two seperate problems. Firstly the subcarriers allocations and secondly the power allocation. The subcarrier and power allocation should be done simultaneously but we will relax the problem to reduce computational complexity at the base stations [10].

A. Subcarriers Allocation

In the cooperative case, the subcarriers assignement for each user is done in a greedy approach giving priority to the users with the worst channel condition. The choice of subcarriers is done from the frequency band assigned to the cooperative scheme f_{Coop}. In addition to that, because of maximal ratio combining method, each user has to take the same subcarrier frequancy from all base base stations at the same instance. In other words, the user with the worst channel condition choses first the subcarrier that has the best mean SNR from all base stations. Algorithm 1 shows the subcarrier allocation method used in this paper.

Algorithm 1 Subcarrier Allocation for the Cooperative Scheme

```
Initialization U = sort({w_k}_{k=1}^K)    A = {1, ..., N_Coop}
for k = U repeat until A = φ do
    for n = A do
        G_{k,n} ⇐ {mean(|h_{k,1,1}|^2, ..., |h_{k,N,M}|^2)}
    end for
    K_n = max_n G_{k,n}
    A ⇐ A − n
end for
```

B. Power Allocation

The problem of power allocation is to solve the Equation (4), Eq (4) is convex and its constraint are linear. Its Lagrangian dual function is

$$\begin{aligned}\mathcal{L}(\mathbf{p}, \boldsymbol{\lambda}, \boldsymbol{\nu}) = &-\sum_{N} w_n R_n - \sum_{m=1}^{M} \lambda_m p_{k,n,m} \\ &+ \sum_{m=1}^{M} \nu_m \left(\sum_{K} \sum_{N} p_{k,n,m} - P_{m_{total}} \right),\end{aligned} \tag{5}$$

where $\boldsymbol{\lambda} = \{\lambda_1, \ldots, \lambda_M\}$ and $\boldsymbol{\nu} = \{\nu_1, \ldots, \nu_M\}$ are the Largange multipliers and because of the convexity of the original problem in (4) the Karush-Kuhn-Tucker (KKT) Conditions are necessery and sufficient [11], that leads to

$$p_{k,n,m} = \left[\gamma - \frac{1}{H_{k,n,m}} \right]^+ \qquad \forall k,n,m, \tag{6}$$

where $H_{k,n,m} = \frac{|h_{k,n,m}|^2}{N_0 B/N}$ is the unit power SNR, $\gamma = \frac{1}{\lambda_1 + \ldots + \lambda_M}$ is the water level and $[x]^+ = \max(x, 0)$.

Equation (6) is equivalent to a single user water-filling at each base stations. We can benefit from that to reduce the computational complexity at the central processing unit.

C. Selection of Critical Users

Critical users are those with bad channel conditions these users are usually, but not necessarly, on the cell edge they also can be users in the cell centre. The cooperative scheme provides better rates because of the use, if feasable, of the three base stations. Firstly, we indroduce a performance measure called here users weights $W = \{w_1, \ldots w_{K_{Coop}}\}$ for the sole reason to grade the users performance or rates. The weights are normalized where $\sum_{K_{Coop}} w_k = K_{Coop}$. As for the selection of critical users and their resources, we introduce a parameter $\alpha \in [0,1]$ where as $\alpha \to 0$ more users become in the cooperative scheme and more resources (i.e. subcarriers and power) goes to that scheme and as $\alpha \to 1$ more users and resources goes to the orthogonal scheme. α is related to the users' weights where $((1-\alpha) \times 100)\%$ of the users with the highest weights are under the cooperative scheme and the rest of users are under the orthogonal scheme in their corresponding sectors. As for the resource allocation, each scheme gets resource proportional to α and the weights W favouring the cooperative scheme. In other words, the cooperative scheme gets more resources (i.e. subcarriers and power) because its users have higher weights.

IV. Simulation Results

In this section, we simulate the system model depicted in Fig. 1. Resources are allocated according to Eqs. (2) and (4) for the orthogonal and the cooperative schemes, respectively. All simulations presented in this paper correspond to a frequency-selective fading channel according to the ITU Pedestrian B model [12]. Simulation parameters are shown in Table I. The 54 users are distributed deterministically and equally on all sectors and the users distribution is constant over all iterations.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Number of subcarriers	288
Number of users in each sector	18
Max power at each base station antenna	50W
Bandwidth	5MHz
Noise Power Spectral Density	-139dBm
Path Loss Exponent	3.5
Multipath channel model	ITU Pedestrian B
Inter-Site Distance	3km
Users' distribution	deterministic

In Figs. 3 – 6, the Cumulative Distribution Function (CDF) of the average users data rate over all iterations is shown for different α values, Jain's Fairness Index J [13] and the Gini Coefficient G [14] is also shown. Results showed that in this specific scenario where the intersite distance is 3km That the best α value is 0.6 meaning 40% of users with the worst condition are under the cooperative scheme and 60% are under the orthogonal scheme. Fig. 4 also shows that this is only true for those conditions, for a bigger or small (ISD) α's best values differ.

Because of the greedy water-filling of power of the cooperative scheme, for a higher number of users in a large ISD the cooperative scheme reduces to an orthogonal scheme. That is because the users near base stations m have a good channel from that base stations relative to other base stations and it will be an feasible to give power to those users from the other base stations. In that case, the users will only get power from one base station.

Fig. 7 shows the overall average spectrall efficiency over all simulated α. The spectral efficiency goes down while α goes to the orthogonal scheme. That is because, the amount of subcarriers and power given to the orthogonal scheme is *relatively* less than those given to the cooperative scheme. It's also worth noting that the spectral efficiency is not at it's peak when the fairness is. The spectral efficiency is at it best when α is 0.3 and where the spectral efficiency is 25% hight than at $\alpha = 0.6$ and the fairness figure and numbers from 4 shows that to gain that amoung of spectral efficiency is justified because the loss in fairness is not severe.

V. CONCLUSION

In this paper, a method for frequncy reuse is proposed. Using cooperative communications and maximal ratio combining. We also looked at allocating power a subcarriers to the cooperative scheme. alongside, a method to choose the most vulnerable users at the cell edge to provide the fairest system.

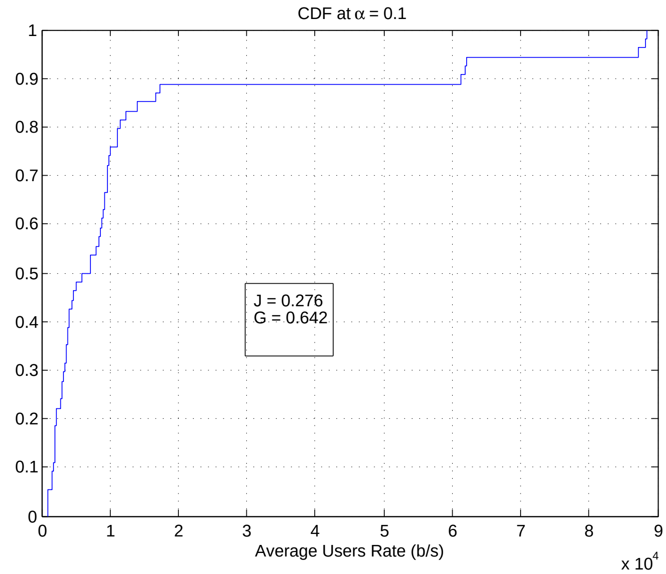

Fig. 3. Distribution of the data rates at $\alpha = 0.1$

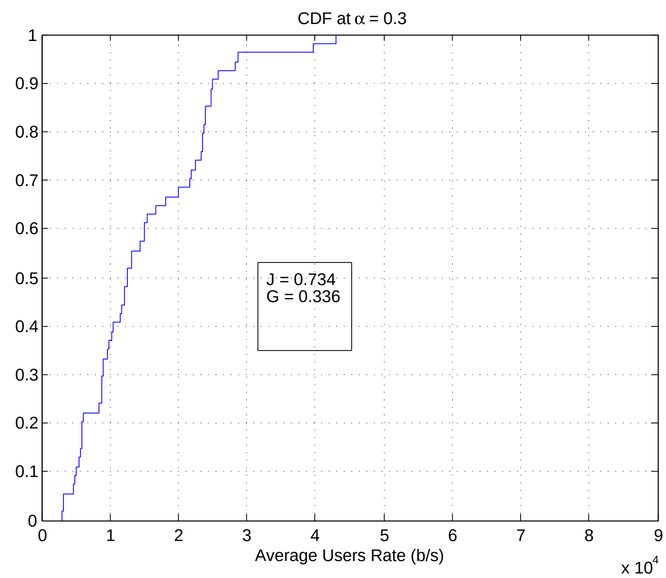

Fig. 4. Distribution of the data rates at $\alpha = 0.3$

Fairness for all cell-edge and cell-centre users is achieved when the 70% of the critical users are cooperating with the base stations and the rest have orthgonal frequency. $\Re$

REFERENCES

[1] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *IEEE Transactions on Wireless Communications*, vol. 4, no. 6, pp. 2726–2737, November 2005.

[2] H.-W. Lee and S. Chong, "Downlink resource allocation in multi-carrier systems: frequency-selective vs. equal power allocation," *IEEE Transactions on Wireless Communications*, vol. 7, no. 10, pp. 3738 – 3747, Oct 2008.

[3] S. Sadr, A. Anpalagan, and K. Raahemifar, "Radio resource allocation algorithms for the downlink of multiuser ofdm communication systems,"

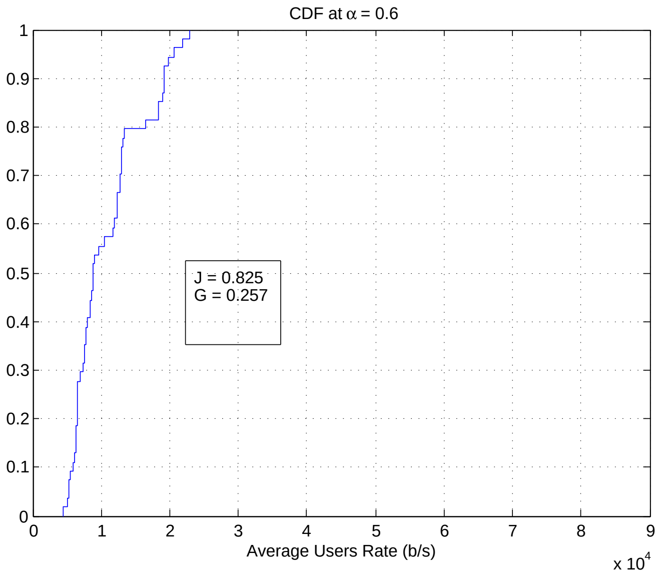

Fig. 5. Distribution of the data rates at $\alpha = 0.6$

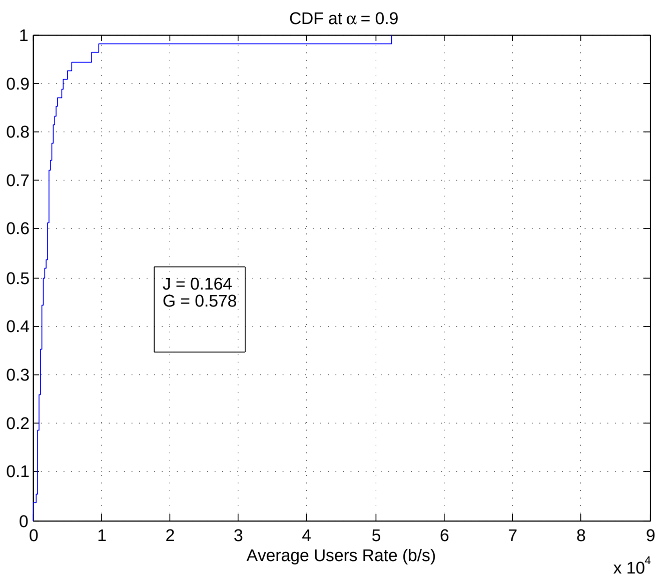

Fig. 6. Distribution of the data rates at $\alpha = 0.9$

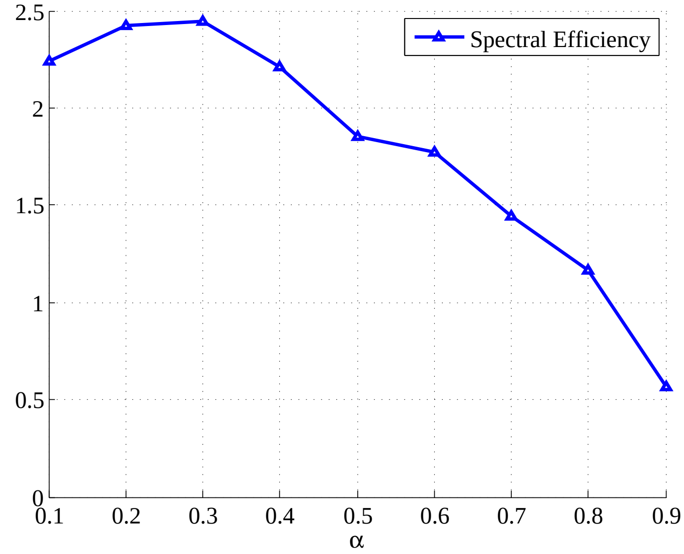

Fig. 7. Spectral efficiency in bps/Hz against different α

IEEE Communications Surveys Tutorials, vol. 11, no. 3, pp. 92 –106, Third Quarter 2009.

[4] M. Sternad, T. Ottosson, A. Ahlen, and A. Svensson, "Attaining both coverage and spectral efficiency with adaptive OFDM downlinks," in *Proceedings of The 58th IEEE Semiannua Vehicular Technology Conference, 2003. VTC 2003-Fall.*, October 2003.

[5] Huawei, *Soft Frequency Reuse Scheme*. UTRAN LTE, 3GPP R1-050507, TSG RAN WG1 Meeting 41, Athens, Greece, May 2007.

[6] J. Wang, F. Adachi, and X. Xia, "Coordinated and distributed mimo [guest editorial]," *IEEE Wireless Communications*, vol. 17, no. 3, pp. 24 – 25, June 2010.

[7] W. Rhee and J. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation," in *IEEE 51st Vehicular Technology Conference Proceedings*, vol. 2, 2000, pp. 1085–1089.

[8] J. Jang and K. Bok Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE Journal on Slected Areas in Communications*, vol. 21, no. 2, pp. 171–178, February 2003.

[9] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[10] Z. Shen, J. G. Andrews, and B. L. Evans, "Optimal power allocation in multiuser OFDM systems," in *IEEE Global Communications Conference Proceedings*, December 2003, pp. 337–341.

[11] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[12] "Recommendation ITU-R M.1225: Guidelines for evaluation of radio transmission technologies for IMT-2000," Tech. Rep., 1997.

[13] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," DEC Research, Tech. Rep. TR-301, September 1984.

[14] C. W. Gini, "Variabilitè e mutabilitè," *Studi Econornico-Giuridici della R. Universita de Cagliari*, 1912.