A low-complexity distributed Inter-Cell Interference Coordination (ICIC) Scheme for emerging multi-cell HetNets

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***Abstract*—In this paper, we propose a low-complexity distributed Inter-Cell Interference Coordination (ICIC) for emerging multi-cell HetNets (Heterogeneous Networks). The proposed scheme is quickly solved using linear programming tools and aims to maximize both the critical and the overall performance of the multi-cell system. Additionally, a utility measure is used to provide a varying level of user fairness to satisfy the most demanding network providers. Simulation results confirm the low-complexity of the proposed algorithm and its increased effectiveness over a number of state-of-art interference avoidance schemes.**

Keywords-component; Dynamic Interference Avoidance; Dynamic ICIC; Binary Linear Optimization; Inter-Cell Interference Coordination

I. INTRODUCTION

The exponential growth in the number of communications devices over the past decade has set out new ambitious targets to meet the ever-increasing demand for user capacity in emerging wireless systems. However, the inherent impairments of communication channels in cellular systems pose constant challenges to meet the envisioned targets. In order to deal with the high cost and scarcity of wireless spectrum, higher spectral reuse efficiency is required across the cells, inevitably leading to higher levels of inter-cell interference.

In the future, a mass deployment of overlaid networks i.e. remote radio heads (relays) and low-power nodes (e.g. femtocells, picocells) is expected to extend the radio coverage in licensed bands and to provide a large number of bandwidth-hungry multimedia services. However, their heterogeneity will cause higher inter-cell interference if their operation is not coordinated. Thus, investigation of inter-cell interference mitigation techniques is urgently required.

Interference avoidance through Inter-Cell Interference Coordination (ICIC) is a promising inter-cell radio resource management (RRM) technique which, by applying radio resource restrictions, provides favorable radio conditions across subsets of users that are severely impacted by the inter-cell interference; and thus attains high spectral efficiency. This coordinated resource management can be achieved through fixed, adaptive or real-time coordination with the help of additional inter-cell signaling in which the signaling rate can vary accordingly [1]. In general, inter-cell signaling refers to the communication interface among neighboring cells and the received measurements from user equipments (UEs). Figure 1 illustrates this concept showing an example of interference avoidance between UE1 and UE2 due to unfavorable interference conditions that existed.

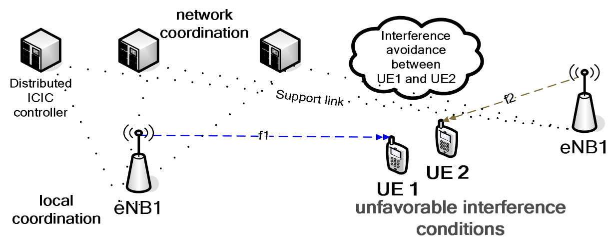

Fig. 1. Example of interference avoidance through ICIC

The current demand in inter-cell RRM is a low-complexity distributed approach, which can have a near optimal performance [2]. This paper continues the on-going research effort in providing an efficient and effective RRM for ICIC in multi-cell networks. We investigate low-complexity approaches which can be solved via either binary linear programming or linear programming relaxation. In [3], the authors proposed a formulation on ICIC that achieves a global optimum for OFDMA-based networks; however, no comparison is given with the state-of-art interference avoidance schemes. In addition, the global ICIC is not suitable for large-scale multi-cell networks, such as heterogeneous network (HetNets), since it is overly complex and difficult to solve considering the large number of parameters involved. Recently, a distributed version of the global optimal solution is proposed in [4]. However, a number of iterations are needed to minimize the optimality gap, which can result in excessive inter-cell signaling. In this paper, we propose a near-optimal low-complexity distributed ICIC for downlink transmissions. We show through simulation results that the near-optimal proposed scheme improves both the overall and critical performance of the system compared with a number of state-of-the-art reference schemes found in the literature.

This paper is organized as follows: In Section II a general description about the radio interface based on OFDMA technology is given. The centralized ICIC problem in OFDMA environments is formulated in Section III. In Section IV, we give our low-complexity distributed solution of the global optimum. Simulation results of the proposed scheme are provided in Section V. We then conclude this paper with Section VI.

II. System Model

Next generation mobile systems such as 3GPP LTE, LTE-Advanced (LTE-A), and WiMax have adopted a radio interface based on OFDMA (Orthogonal Frequency Division Multiple Access) technology, which is a multi-user version of OFDM (Orthogonal Frequency Division Multiplexing). The radio resource unit in LTE downlink OFDMA is a radio frame consisting of 10 sub-frames (or blocks), where each one is one ms long in duration. However, two sub-frames (or slots) are considered in scheduling, also commonly known as a transmission time interval (TTI). This scheduling block can be seen as two consecutive resource blocks (RBs), which are in turn sub-divided (in the frequency domain) into 12 subcarriers keeping 15 kHz sub-carrier spacing (thus occupying a total of 180 KHz). In the time domain, the RB can be divided into 6 or 7 OFDM symbols depending on which extension of cyclic prefix (normal or extended) is chosen. In the case when normal cyclic prefix is employed, a grid of 84 resource elements (REs) is formed per RB [5].

III. General Problem Formulation

By the geometric nature of a typical homogeneous cellular system, cell-edge UEs are the most disadvantaged members of the network as in addition to the higher path loss experienced by the attached sector, significant interference is received from close-by cells. Any optimal or suboptimal inter-cell RRM with a throughput maximization objective will avoid scheduling these disadvantaged UEs, since their contribution to the overall throughput is negligible [3]. Therefore, by employing interference avoidance on such UEs, the network can effectively extend their minimum required data rates.

Table I. List Of Symbols

k	index of UE
n	index of RB
i / j	index of serving/interfering eNB
g^i	index of in-eNB interfering group of eNB i
$\mathbb{S}$	the set of eNBs ($\{i, j, \ldots, k\}$)
S	total number of eNBs ($\lvert\mathbb{S}\rvert$)
N	total number of RBs
K	total number of UEs served in each eNB
P	power allocated per RB
N_w	thermal noise existed in each RB
$\rho_{k,n}$	indicator to show whether the RB n is allocated to user k or not
$H^i_{k,n}$	channel gain experienced by UE k on RB n in eNB i
$\gamma^j_{k,n}$	SINR estimated by UE k on RB n in eNB i
$r^i_{k,n}$	date rate achieved by UE k on RB n in eNB i
d^i_k	demand factor requested by UE k in eNB i
$U^i_{k,n}$	utility price constructed for UE k on RB n in eNB i

We consider a LTE system based on OFDMA technology with a set of inter-connected eNodeBs (eNBs) $\mathbb{S} = \{1, 2, \ldots, S\}$ with total S eNBs, K UEs and N RBs. It is been assumed that the transmit power on each RB is the same and fixed. For simplicity, if a specific RB termed as 'restricted' no power is allocated to this RB (P_w=0).

To define a possible set of in-group interfering eNBs we use the powerset expression $P(\,)$. For example, the powerset of $\{x, y\}$ is $\{\}$, $\{x\}$, $\{y\}$, $\{x, y\}$. Following this, we can construct all possible subsets of eNBs that can interfere with eNB i using the following notation $P(\mathbb{S}\setminus\{i\})$. Note that the powerset $|P(\mathbb{S}\setminus\{i\})|$ contains 2^{S-1} combinations.

It is been also assumed that the served users can measure the separate levels for different sources of interference by employing cell-specific orthogonal reference sequences. In DL LTE systems up to six pilot sequences (including the serving one) are expected to be identifiable and measurable [6]. With the help of g^i, i.e. an index to represent the subset of the $P(\mathbb{S}\setminus\{i\})$, the SINR is conveniently constructed with a list of non-restricted interferences as:

$$\gamma^{i,g^i}_{k,n} = \frac{P_w \cdot H^i_{k,n}}{P_w \cdot \sum_{\substack{j\neq i \\ j\notin g^i}} H^j_{k,n} + N_w}. \tag{1}$$

Here, $\gamma^{i,g^i}_{k,n}$ denotes the instantaneous SINR at UE k that is connected to eNB i excluding the g^i interfering eNB group. The $H_{k,n}$ denotes the channel gain which includes all key fading components (path loss, shadowing, multi-path) that UE k experiences on RB n. On the same notation, the super-indexes i and j represent the desired and interfering link, respectively. For convenience, Table I shows a list of symbols used in this paper. We define $f(\,)$ as a mapping function where the instantaneous SINR is converted through achievable data rate as:

$$r^{i,g_i}_{k,n} = f\left(\gamma^{i,g_i}_{k,n}\right). \tag{2}$$

The general problem of using interference avoidance through ICIC in an interference-limited multi-cell system is formulated below:

$$\text{maximize} \quad \sum_i \sum_{g^i} \left(\sum_{k=1}^{K} \sum_{n=1}^{N} U^{i,g^i}_{k,n} \cdot \rho^{i,g^i}_{k,n} \right); \tag{3a}$$

$$U^{i,g^i}_{k,n} = (r^{i,g^i}_{k,n})^x \cdot (d^i_k)^y; \quad x,\ y \in \mathrm{N}^+,$$

$$\text{subject to} \quad \underbrace{\sum_{g^i} \sum_{k=1}^{K} \overbrace{\rho^{i,g^i}_{k,n}}^{\mathrm{V1}}}_{\mathrm{X1}} + \underbrace{\sum_{j\in g^i} \sum_{g^j} \sum_{k=1}^{K} \overbrace{\rho^{j,g^j}_{k,n}}^{\mathrm{V2}}}_{\mathrm{X2}} \in \{0, 1\};\ \forall n \tag{3b}$$

The optimization problem in (3) is used with the multi-option utility measure in order to favor a varying degree of emphasis on user throughput and fairness; x and y exponents are defined, respectively. For instance, the x=1 and y=0 option or other non-zero x options, aim to maximize the aggregate sector throughput as the utility shows minimal benefit to the deprived users [3]. Therefore, other non-zero y options of the utility can give more gain to these users.

The variables V1 & V2 in constraint (3b) are binary variables. Therefore, it is implied by 1 or 0 whether the RB n is assigned for UE k on eNB i excluding the interfering eNB group g^i or not. The term X1 makes certain that each RB cannot be assigned to more than one user and more than one interfering eNB group, which is restricted. In a similar way, the term X2 propagates this inter-relationship among all eNBs within interfering eNB group g_i. The equation X1 + X2 indicates that only to one UE can be allocated if the RB n is not restricted by g_i.

The complexity cost of the optimization problem in (3) increases significantly with the instances of variables i, k, n, g^i, ($O(n, k, i, g^i)$). Solving this global optimization problem on a network-wide scale and accounting for all variables can be a large computational burden.

IV. Proposed Algorithm

With some loss of optimality, this complex solution can be also decomposed into several sub-solutions at a time with a small set of interfering eNBs and RBs; thus reducing the computational run time significantly. The use of a predetermined dominant interference set with a small set of available RBs was investigated in [3]. While, only the mitigation of dominant interferences can contributed effectively to the overall cell throughput, the limitation of the small set of available RBs can degrade significantly the diversity gain stemming from channel variability. This limitation of available RBs led us to look into other ways of decomposing down the above problem without losing the optimality nor the performance yielded from the multi-user diversity.

With minimal loss of optimality, this complex solution can be simplified into two sub-problems i.e. the user allocation sub-problem and the inter-cell restriction sub-problem. The former can reside in the local processing unit in each eNB whereas the later should remain in the processing controller of the network. To describe with few words, the sub-problem which can reside in eNB issues a candidate list of best users for possible inter-cell restrictions for each RB (or groups of RBs). Afterwards, the sub-problem which stays in the network controller decides on each eNB which resource restrictions to be set. This simplification allows fast execution over the RBs, while keeping the optimality of the initial solution. By using effective linear optimization tools [7], the solution can be approximated quickly even for HetNet scenarios where numerous low-power eNBs can exist.

A. eNB-level procedure

The eNB-level procedure is to issue a candidate UE list for each possible inter-cell restriction. Let us then denote with indices '*j1*' and '*j2*' the IDs first and second interfering eNBs, respectively. This means that the possible interfering in-eNB scenarios are as follows: $\{\}$ $\{j1\}$ $\{j1, j2\}$ $\{j2\}$. For convenience in words, we refer to each possible interfering in-eNB scenario as a mode Therefore, four possible modes are indicated i.e. mode 1, mode 2, mode 3 and mode 4. In this paper, the latter mode is omitted since it provides insignificant performance improvement for the extra inter-cell signaling and computational complexity involved. For notational convenience, we use a generalized interference group i.e. $G^m_{k,n}$ to indicate these possible three modes in each RB: 1) $G^1_{k,n} = \{\}$, 2) $G^2_{k,n} = \{j1\}$, 3) $G^3_{k,n} = \{j1, j2\}$.

In each mode, a utility matrix is prepared at each eNB using a varying emphasis of fairness as follows:

$$U^m_{k,n} = (r^m_{k,n})^x / (d_k)^y; \qquad x, y \in \mathrm{N}^+ \quad . \tag{4}$$

Here, we define the user demand d_k as the average throughput of UE k divided with the average throughput across all UEs.

The max argument function can solve and determine the best user on each mode:

$$I^m_n = \arg\max_k \{ U^m_{k,n} \} \quad . \tag{5}$$

It is evident that in scenarios where channel variability may exist across the interference channel, the best user for each mode may not be the same in other modes. Based on the candidate UE list I^m_n, the refined utility A^m_n and interfering group G^m_n can be expressed as:

$$A^m_n = U^m_{k,n} \left(I^m_n \right) \quad , \tag{6a}$$

$$G^m_n = G^m_{k,n} \left(I^m_n \right) \quad . \tag{6b}$$

The problem of which mode is to be set in which eNB is send to the core network.

B. Network-level procedure

The central entity collects the refined lists A^m_n, G^m_n from each eNB and constructs the united list $A^{i,m}_n$, $G^{i,m}_n$, respectively. Each decision can be taken independently across all RBs. For each RB, an optimal solution on which mode an eNB should transmit can be given by a network controller. As each decision is independent, this centralized problem can be distributed between up to N different network processing entities.

The distributed optimization problem for each processing entity can be modeled as:

$$\text{maximize} \quad \sum_i \sum_{m=1}^{3} A^{i,m} \cdot \rho^{i,m}; \tag{7a}$$

$$\text{subject to} \quad \underbrace{\sum_{m=1}^{3} \overbrace{\rho^{i,m}}^{\mathrm{V1}}}_{\mathrm{X1}} + \underbrace{\sum_{j \in G^{i,m}} \sum_{m=1}^{3} \rho^{j,m}}_{\mathrm{X2}} \quad \begin{matrix} \in \{0, 1\} \\ or \\ \in [0, 1] \end{matrix} \quad . \tag{7b}$$

Based on eNB's candidate list and user's achieved utility, the network controller will decide in which mode an eNB will benefit more to the overall network. The constraint in (7b) can be solved via either binary linear programming or linear programming relaxation by rounding the solution to the nearest binary value.

Here, the rounded variable V1 in term X1 indicates by one or zero whether it is beneficial for the current RB to be used by eNB i on mode m or not. As mentioned earlier, only three modes are specified on each RB. The term X1 ensures that each eNB has been assigned to only one mode. However, in the case where no modes are indicated, the eNB i will be restricted to benefit the other interfering eNBs. In a similar way, the term X2 propagates this inter-relationship to the first and the second dominant interfering eNBs. To resolve any in-eNB conflicts among the eNB i and the two dominant interfering eNBs $j1$ and $j2$ in $G^{i,m}$, the rounded sum of X1+X2 should be either 0 or 1.

The solution given by (7) is returned to all eNBs involved. According the solution, each eNB should now assign the best user from the candidate list or not assign at all. By removing the user allocation process from the ICIC problem, the computational complexity is reduced significantly. The revised problem has a lower complexity bargain and increases only with the number of interfering eNBs and the number of indicated modes, (O(i, m)). To understand the effect of optimality loss with global optimum Vs complexity loss in run-time we present Table II. The small optimality gap is solely due to the removal of the overly complex allocation sub-problem from the general ICIC problem. Note that the complexity loss in Table II does not include the gain achieved by distributing the centralized problem between up to N network entities.

V. SIMULATION STUDY

The simulation study is performed on the downlink using the freely available LTE-based system-level simulator [8] in order to evaluate the performance of the proposed distributed ICIC vs. the state-of-the-art interference avoidance schemes. Since the existing platform is based on classical frequency reuse (reuse-1) and no benchmark schemes are employed, these were implemented under the proportional fairness (PF) scheduler. To distribute the proposed algorithm, several network-processing entities are placed at various locations of the network. Apart from the outdoor eNB network, a closed-access low-power HeNB (Home eNB) network is implemented to simulate a multi-cell indoor scenario. In the case of the indoor scenario, the multi-user diversity is limited as the number of served users is fixed to one. Each HeNB block is accompanied by a network gateway that can deal with some processing tasks. Table III gives the main simulation parameters used in this simulation study.

We observe the average cell throughput as the system performance and the 5th percentile point of CDF of UE throughput as the critical performance. For fair comparison, the total transmitted power in each eNB (or HeNB) is fixed and the same for all the investigated techniques. To avoid excessive interference from HeNB network, a high-interference indicator (HII) signaling [9] is used behalf of outdoor UEs to indoor HeNB to suppress the excessive interference on allocated RBs. Similarly, to observe the trends from employing avoidance schemes in the low-power deployment, we assume that the all indoors UEs served by HeNB experienced the same interference from the eNB network in all schemes.

TABLE II. PERFORMANCE COMPARISION OF THE PROPOSED SCHEME WITH THE GLOBAL OPTIMUM

Metric	Optimality gap		Complexity loss (Speedup[1])
	Objective	Cell Throughput	
Mean	0.0416 %	0.060 %	99.3% (137.3)
Std	0.0153 %	0.024 %	0.055 (10.1)

TABLE III. MAIN SYSTEM SIMULATION PARAMETERS

Parameter	Assumption or Value
Outdoor scenario deployment	2-tier tri-sectorized sites (19-sites) with total of 57 eNBs
Indoor (Home) scenario deployment	Block type: 5x5 grid, 10% HeNBs House dimensions: 10x10 m^2
Inter-Site Distance (ISD)	500 m
Total bandwidth	10 MHz
Total Resource Blocks (RB)	50 RBs
Total bandwidth per RB	180 KHz
Total eNB/HeNB Power	43 dBm / 10 dBm
Outdoor path loss model	$L = 128.1 + 37.6 \log_{10}(R)$, R[KM]
Indoor path loss model	$L = 127 + 30 \log_{10}(R)$, R[KM]
External wall penetration loss	20dB
Outdoor/indoor Shadowing's standard deviation	8 dB / 10 dB
Outdoor/indoor Shadowing's correlation distance	50 m / 3 m
Fast fading models	ITU models [13]
Antenna mode	Single-input single-output
User Noise figure/ thermal noise	9 dB/ −174 dBm
Simulation time	500 TTIs
Num of UEs per sector area	10
HeNodeB blocks per sector area	1
HeNodeB deployment / activation ratio	0.1/1.0

Fig. 2 shows the CDF of UE throughput for five major different schemes employed by outdoor deployment i.e. reuse-1 (FR1), reuse-3 (FR3), fractional frequency reuse (FFR) [10], and the proposed ICIC scheme, in which one (ICIC-1) or two (ICIC-2) dominant interference(s) can be mitigated. To avoid ambiguity and enable the reader to clarify each others' performance, each of the evaluated schemes is associated with a specific marker and color. For simplicity of illustration and for convenience in overall performance, we display the system and critical performance for all the schemes in Fig. 3. In the same way, Fig. 4 shows the overall performance in the indoor deployment for all different schemes employed.

As expected for all multi-cell deployments, the FR1 scheme shows minimum cell-edge performance since no interference is mitigated. On the other hand, the FR3 exhibits superior critical performance by sacrificing a big chunk of its system throughput. A good compromise is the FFR which employs a

[1] Speedup is defined as the ratio of the execution run-time of initial algorithm over the optimized algorithm.

mixture of reuse-1 and reuse-3. Similar to the FFR, the soft frequency reuse (SFR) with power amplification and power restriction technique in different regions shows an analogous performance trade-off [11]. Interestingly, the invert frequency reuse (IFR) [12] achieves a cell-throughput gain compared with FR1, however this trend can be observed only in the eNB deployment. This scheme is more susceptible (compared to SFR and FFR schemes) in unplanned deployments, such as HeNB network, where their operation or their location can vary from house to house. The proposed scheme outperforms all schemes in average cell performance and by mitigating up to two dominant interferences, the ICIC-2 slightly surpasses the eNB FFR in critical performance; however, at the expense of system performance. The same performance trend for the proposed scheme can been observed in Fig. 4 for indoor scenarios. Here, the ICIC-2 can narrow down the gap to FR3 in critical performance since the unplanned nature of HeNBs hinders the performance of FR3.

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REFERENCES

[1] Sesia, Toufik, Baker, LTE - The UMTS Long Term Evolution: From Theory to Practice, *Wiley*, pp.296-299, 2009.

[2] M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, Y.-D. Kim, E. Kim, Y.-C. Cheong, “An Overview of Radio Resource Management in Relay-Enhanced OFDMA-Based Networks”, *IEEE Comm. Surveys & Tutorials*, vol.12, no.3, pp.422-438, 3rd Quarter 2010.

[3] M. Rahman, H. Yanikomeroglu, “Inter-Cell Interference Coordination in OFDMA Networks: A Novel Approach Based on Integer Programming”, *IEEE 71st VTC 2010-Spring*, vol., no., pp.1-5, May 2010.

[4] A.B. Sediq, R. Schoenen, H. Yanikomeroglu, Z. Chao, “A novel distributed ICIC scheme based on projected subgradient and network flow optimization”, *IEEE 22nd International Symposium on PIMRC*, , vol., no., pp.1595-1600, Sep. 2011

[5] E. Dahlman, S.Parkvall, J.Skold, P. Beming, “3G Evolution: HSPA and LTE for Mobile Broadband”, 2nd Ed., *Academic Press*, pp.327, Oxford, UK, 2008.

[6] Sesia, Toufik, Baker, LTE - The UMTS Long Term Evolution: From Theory to Practice, *Wiley*, pp 163, 2009

[7] GLPK (GNU Linear Programming Kit). Version 4.47. [Online]. Available: http://www.gnu.org/software/glpk/.

[8] J.C. Ikuno, M. Wrulich, M. Rupp, “System Level Simulation of LTE Networks”, *IEEE 71st VTC 2010-Spring*, vol., no., pp.1-5, May 2010.

[9] Z. Bharucha, A. Saul, G. Auer and H. Haas, “Dynamic Resource Partitioning for Downlink Femto-to-Macro-Cell Interference Avoidance”, *EURASIP Journal on Wireless Comm. and Networking*, 2010.

[10] M. Sternad, T. Ottosson, A. Ahlen, A. Svensson, “Attaining both coverage and high spectral efficiency with adaptive OFDM downlinks”, *IEEE 58th VTC 2003-Fall*, vol.4, no., pp.2486-2490, Oct. 2003.

[11] 3GPP R1-050507, Huawei, “Soft frequency reuse scheme for UTRAN LTE”, *TSG RAN WG1 Meeting #41*, Athens, Greece, May 2005.

[12] 3GPP R1-050594, Alcatel, “Multi-cell Simulation Results for Interference Co-ordination in new OFDM DL”, *TSG RAN WG1 LTE Ad Hoc on LTE*, Sophia Antipolis, France, Jun. 2005.

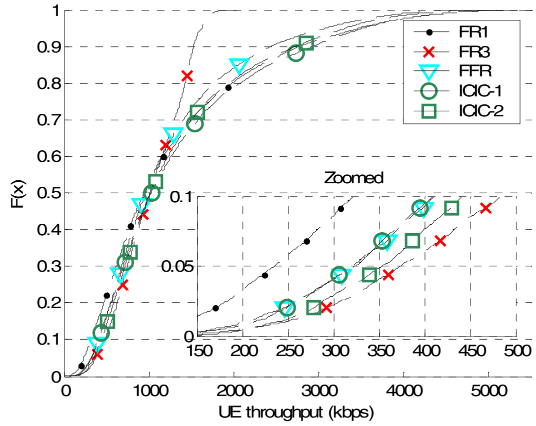

Figure 2. CDF of the UE throughput for major schemes in the outdoor deployment

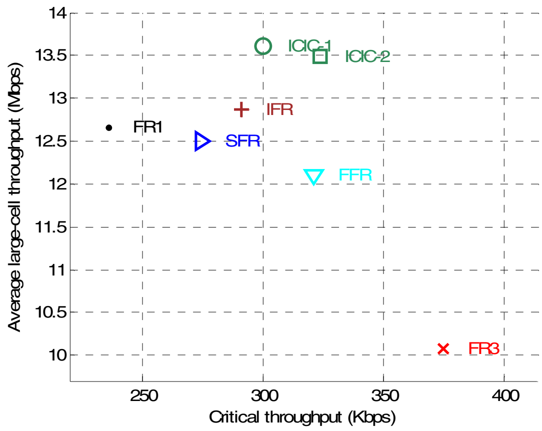

Figure 3. Average cell throughput vs. critical throughput for all the different schemes in outdoor environment.

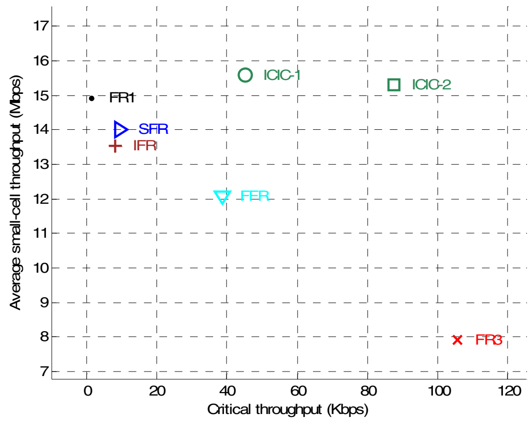

Figure 4. Average cell throughput vs. critical throughput for different schemes in indoor environment.

[13] ITU,Report ITU-R M.2134, “Guidelines for evaluation of radio interface technologies for IMT-Advanced”, Tech. Rep., Dec. 2009.