Improving Spectrum Efficiency in Heterogeneous Networks Using Granular Identification

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Abstract. Given the ever-increasing demand for wireless services and the pending explosion of the Internet of Things (IoT), demand for radio spectrum will only become more acute. Setting aside (but not ignoring) the need for additional allocations of spectrum, the existing spectrum needs to be used more efficiently so that it can meet the demand. Other than providing more spectrum there are other factors (like, transmit power, antenna angles, QoS, bandwidth, and others) that can be adjusted to cater to the demand and at the same time increase the spectrum efficiency. With heterogeneity and densification these factors are so varied it becomes necessary that we have some tool to monitor these factors so as to optimize our outcome. Here we propose a PHY layer granular identification that monitors the physical and logical parameters associated with a device/antenna. Through a simple optimization problem, we show how the proposed identification mechanism can further the cause of spectrum efficiency and ease coordination among devices in a heterogeneous network (HetNet) to assign resources more optimally. Compared to received signal strength (RSS) way of assigning resources the proposed approach shows a 138% to 220% increase (depending on the requested QoS) in spectrum efficiency. Ultimately, this research is aimed at assisting the regulators in addressing future spectrum related efficiency and enforcement issues.

Keywords: Spectrum efficiency · Identification
Heterogeneous networks · Spectrum sharing · Optimization
Radio resource management

1 Introduction

The Cisco VNI report [1] suggests there will be a global increase in the devices and connection per capita to 3.5 Billion by the year 2021, which will take a

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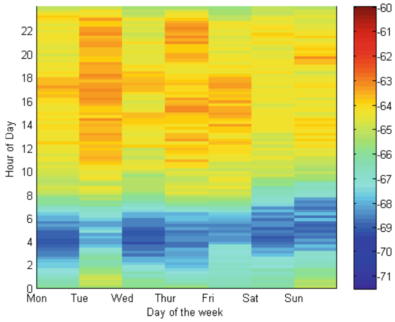
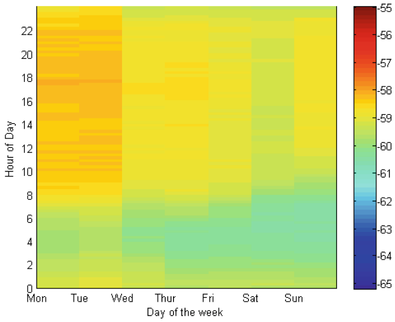
toll on the demand for spectrum. This impending demand for wireless services, and eventually requiring more spectrum, will drive fierce regulatory battles. As deployments become denser, we will likely face increasing issues of harmful interference and a rising noise floor, compounding the already difficult task of enforcement and efficiency for regulators. Furthermore, as devices become more densely deployed, it is likely that current methods for radio spectrum management will fall short, demanding novel radio access methods.



(a) LTE Profile for 746-756 MHz.



(b) LTE Profile for 1930-1990 MHz.

Fig. 1. Average aggregated spectrum occupancy waterfall chart for Chicago downtown measured by the received signal strength in dBm for year 2015–2017 (Color figure online)

It has been argued that we have faced a spectrum crunch [2] scenario for the last few decades. There has always been a notion that we need to get more spectrum to cater to this increasing demand for spectrum. However, most of the prime frequencies in the sub-6GHz spectrum are already occupied by government and/or licensed owners. The rapidly increasing demand for spectrum requires that the user equipments (UEs) are provided with more easy access to spectrum either through reassignment, reallocation, or access to higher spectrum through millimeter waves and most recently terahertz frequency [3]. However, these methods are often cumbersome and face deadlock due to huge cost, slow pace of technological advancement or political agenda.

Nevertheless, the demand for spectrum is bursty in nature and is a function of the time of day or day of the week. We performed a spectrum occupancy analysis based on time and days of the week as shown in Fig. 1a and b on a color scale of blue to red, where red signifies most activity. These are the popular LTE downlink frequencies, which highlights the fact that even in a highly populated city like Chicago, the cellular bands are not being utilized to the fullest. The spectrum data was collected by a directional antenna with a direct line-of-sight (LOS) from downtown Chicago [4]. The LTE Profile seems to have particular peak time of usage depending on the demand of the UEs. Not surprisingly, the pattern repeats at particular hours of the day (mostly 10am-8pm) and particular days of the week (mostly weekdays). Thus, instead of providing more spectrum through above-mentioned methods it will be benefiting that we use the existing resources (the frequency band) to the optimal level. Therefore, it will be valuable to combine applications/devices to operate cooperatively and utilize the same frequency by reducing the frequency reuse, so as to improve efficiency. Heterogeneous Networks (HetNets) have proved to be the best example where the spectrum efficiency can be increased by adjusting other technical parameters of the devices, like transmit power, antenna angles (azimuthal and vertical), Quality of Service (QoS), bandwidth, modulation schemes and others, to use spectrum more opportunistically.

In this paper, we propose a methodology to monitor these resources at a granular level through an identification (ID) structure. Today's cognitive radios are capable of causing or mitigating interference by adjusting the technical parameters associated with the device(s)/antenna(s). Thus, this makes it necessary that we identify these devices not only physically, but also logically by their operating parameters (i.e., the different technical parameters associated with that device) and provide it in a way that other devices and networks can recognize. However, while trying to cover more users in the process, we might risk causing harmful interference, which can quickly enter into a vicious cycle of demand for more spectrum. With ID structure, device(s)/antenna(s) can be informed about an impending interference and try to avoid it or may try to ease the enforcement process, which follows an interference scenario.

It reasons that knowing the IDs of other devices (particularly from HetNet systems) could be useful in optimizing resource use; nonetheless, it is necessary to show how such an ID could be used. Therefore, we use a granular layer monitoring of resources to show an increase in efficiency without adding additional spectrum or causing unwanted harmful interference. In the next sections, we will explore the need for going beyond the existing IDs and try to identify devices not only to find its owner, but also to unearth the mode of its operation to increase spectrum efficiency.

2 Related Work

One way of addressing the demand for spectrum is to increase spectrum efficiency through such methods as adaptive phase array antenna, beamforming and improved coding schemes. Recent 5G field tests [5] on advanced modulation schemes like sparse code multiple access (SCMA) and polar coding have shown improvement in spectrum efficiency. There is even a proposal for changes in hardware by using high-speed switches to make communication full duplex [6], where a transceiver can transmit and receive data at the same time and frequency. Still, complex interference issues like overload and spill-over can result in as a roadblock to these advancements if we do not monitor the devices' operations.

Generally, the notion for the service providers to cater to the demand has been to increase infrastructure, like buying more spectrum, deploying more small cells, adding a directional antenna, investing in multi-input-multi-output

(MIMO) antennas. However, by increasing the infrastructure we also increase the chances of harmful interference and uncertainty for the coexistence of devices for spectrum sharing. Thus, the spectral efficiency apparently decreases after a certain inflection point [7] for each new addition of infrastructure. The issue is that even if we have a lot of infrastructures we do not use it optimally. A solution is to keep track of the detailed parameters of an antenna so that they can be optimally allocated, e.g., through Radio Resource Management (RRM). Our proposed ID structure keeps track of the device(s)/antenna(s) physical and logical parameters.

There exists some research in HetNets that aim at controlling the parameters to improve the system efficiency, like a centralized greedy solution to optimize the transmit power in a HetNet [8]. In [9] it proposed power control strategies in femto cells depending on the demanded QoS of the users and the environment. While calculating the efficiency they proposed that the users should be provided with the minimum data rate so that they can still use the web applications. However, with 5G at the doorstep, the users are becoming more data-savvy than ever, which power control alone will not be able to cater to this need.

Moreover, with densification and the existing conservative strategies it perhaps may become difficult to even reach the bare minimum data rate in some cases. In [10] the authors proposed a similar argument where they used fractional frequency reuse coupled with transmit power control to coordinate interference between the APs in a HetNet. Moreover, with coordinated multipoint (CoMP) [11] steadily taking pace in the 5G deployment strategies, it shows that through coordination of technical parameters it is possible to further the process of efficiency. However, coordination has its own tradeoff like increased control message and scheduling. In CoMP joint processing, multiple antennas are involved to form an array of virtual antennas coordinated by APs to improve the signal strength. This makes the enforcement process much more complicated as there is now an array of virtual antennas that can cause unwanted harmful interference. ID can be used in this scenario to identify these virtual antennas.

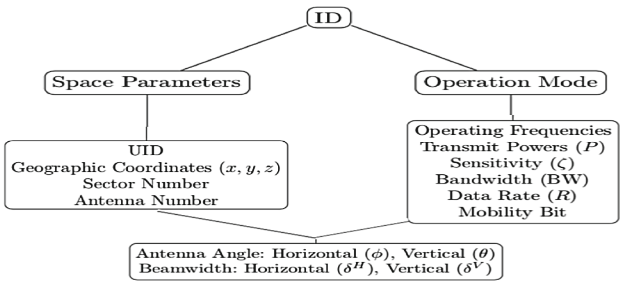


Fig. 2. Proposed ID structure

3 Identification Structure

Some radio communications traditionally made use of explicit methods for ID of participating entities, like call signs in amateur radios (e.g., AD0VT). However, identifiers have mostly been used for "name claim" to associate a device with its owner. Presently there exist many types of IDs in wireless networks, including IP addresses, Ethernet addresses, subscriber ids (in cellular networks), catalog numbers (in satellite systems), or International Mobile Equipment Identity (IMEI). Currently, there are devices in the market that can co-exist in more than one services and might have more than one of these IDs. With more heterogeneous devices assessing common frequency bands (due to advancement in technology and/or promotion of spectrum sharing) it may be useful (e.g., for enforcement purposes) to know more about the devices using these bands. By explicitly providing granular IDs in the physical layer, we allow a common ground for these heterogeneous devices to perform ex-post enforcement either in a centralized or a distributed fashion, potentially leading to improving network/spectrum efficiency. Similar benefits might be reaped by the homogeneous device operations, such as considering less conservative device level constraints to mitigate harmful interference.

As pointed in the earlier sections that there is a need for monitoring technical parameters and identifying these devices/antennas uniquely, we propose a detailed ID to identify device(s)/antenna(s) based on their space and operation mode as shown in Fig. 2. The space parameter consists of information like geographical coordinates of the device, and detailed placement of the antenna based on the sector and antenna numbers (if any). The space parameter will also have a Unique ID (UID) so as to keep track of redundancy when the device is mobile. On the other hand, the operation mode should consist of technical parameters, which can be adjusted dynamically, like operating frequencies, transmit power or receiver sensitivity based on the antenna type, bandwidth (for carrier aggregation), requested data rate based on user subscription/application. We assume that the receivers will use their corresponding transmitter to communicate its ID structure. Moreover, space for an RF radio is also dependent on the antenna angles and placement, so the parameters, like horizontal and vertical angles and beamwidth should also be included. Since these parameters can also be adjusted for methods like beamforming, it is considered as a part of both branches. This proposed ID structure will not only help allocate resources more optimally, but also ease the process of interference resolution and enforcement.

Generally, a device will try to sense the ID structure so that it can get knowledge about its neighbors and their respective operating parameters. However, due to the hidden node and the exposed node issues devices might not be able to sense the ID properly. Therefore, the devices can use a backbone Internet or relay system to avoid these issues. The method for transmission of ID will be dependent on the system and the tolerance level of the system for increased network load. For example, a mobility bit is present in the operation mode, which will check if a device is mobile or not, this can be used as a factor for how frequently the device(s) need to broadcast its ID. Another effort to reduce the network load for distributed systems would be to have a cluster head number in the operation mode branch. The cluster nodes will be responsible for multiple transmission of IDs if required, as in the case of LTE, access points (APs) can be cluster heads for the UEs.

4 Spectrum Efficiency Model

In this section we propose a spectrum efficiency model, which will use the information provided through the ID structure, as communicated by the device(s)/antenna(s) in the system. Efficiency can be defined in many ways in terms of technical, economical and spectral application as defined in [12]. However, here we define spectrum efficiency η at a given time instance as, $\eta = \frac{UC^R}{BW * S_f}$, which is the number of users covered UC^R per spectrum resource available in $Erlang/MHz/Km^2$, where the spectrum resource signifies the bandwidth BW and the coverage area S_f. Generally, the BW remains constant for a system, other than systems that use carrier aggregation to increase bandwidth dynamically. The user coverage and the coverage area changes very frequently and is dependent on multiple factors. We say a user is covered if it is satisfied with a QoS of R, which is specific to a users' plan and its surrounding neighbors. Let the cumulative coverage area for the APs operating in the same frequency be S_f. The geographical space covered by a particular frequency band f is dependent on several factors, like transmit power, antenna type, and antenna angles. With ID, devices can access the above-mentioned information and adjust it to maximize their individual/system spectrum efficiency.

Let the set of transmitters and receivers be TX and RX respectively. Let Ω be the cartesian combination of all resource options available to a transmitter. The number of independent channels available F_r can also affect the user coverage. Thus, the APs operating in the same frequency after assignment be Ψ_f, where $|\Psi_f| = N_f$. For $i \in TX$, $j \in RX$ and $k \in \Omega$ we construct the optimization problem as shown in Eq. 1 and constrained by Conditions 2–4.

$$\max \frac{1}{F_r} \sum_{f=1}^{F_r} \sum_{i=1}^{N_f} \frac{\eta_{if}}{N_f} \tag{1}$$

subjected to,

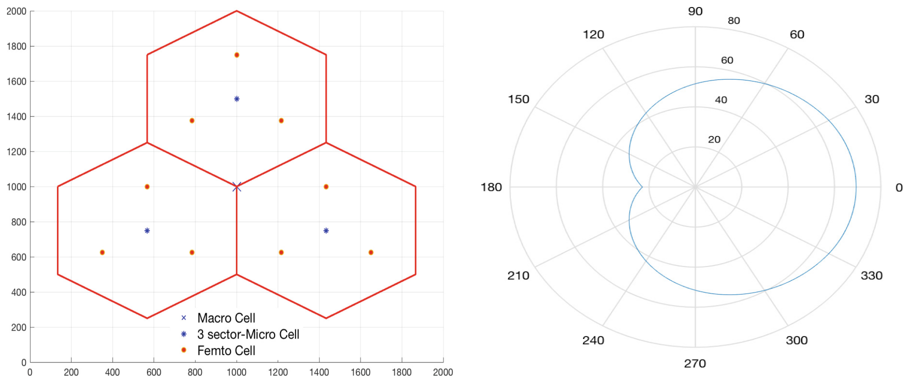
$$R_{jk} \geq R_j^* \forall j \in RX, \exists k \in \Omega \tag{2}$$

$$\sum_{j \in RX, k \in \Omega} a_{ijk} P_{ij} \leq \alpha P_i^{max} \forall i \in TX \tag{3}$$

$$\sum_{i \in TX} a_{ijk} c_{jik} \leq \zeta_j \forall j \in RX, \exists k \in \Omega \tag{4}$$

Condition 2 checks the user coverage based on the requested data rate R_j^* extracted from the ID structure. Let a_{ijk} be an integer variable, which is 1 if a transmitter and receiver pair is assigned a resource k and 0 otherwise. Condition

3 caps the APs from crossing the allocated transmit power αP_i^{max} for a transmitter i, where α is the fraction of power available for the transmitter. While trying to cover more users we might risk causing harmful interference to other users thus affecting the total system efficiency. Therefore, condition 4 makes sure that the aggregated system interference c_{ijk} for a transmitter-receiver pair for a particular resource combination k be less than the receivers' sensitivity ζ_j.



(a) Simulation Environment. (b) Directional Antenna Pattern.

Fig. 3. Simulation environment

5 Evaluation

In this section we evaluate our spectrum efficiency model coupled with the proposed ID structure, to conduct discrete event simulations.

5.1 Environment Setting

To evaluate the benefit of a heterogeneous ID structure, we consider a HetNet setting with cell configuration shown in Fig. 3a. The environment is a 2 km × 2 km square area consisting of micro and femto cells, with a macro cell at the center, which is responsible for relaying data to the micro and femto cells, representing an umbrella cell. A list of radio parameters is shown in Table 1 [13]. We consider specific path loss PL models for the AP as shown in Table 1 [14,15]. We consider operating frequency of 2000 MHz with a bandwidth of 10 MHz.

The microcell is further divided into 3 sectors. These sectors are made by changing the horizontal beam-width with the main lobe of the antenna within the beam-width as shown in Fig. 3b [16]. We have considered a single-input-single-output (SISO) antenna structure with directional antennas for the femto cell. This allows the antennas to change their coverage by adjusting ϕ & θ, and fit the capacity of the users in that area. We assume the beamwidth horizontal δ^H and vertical δ^V to be fixed at 60° and 2.7° respectively [13] for the directional antennas; however, these parameters can also be altered to fit the user coverage.

The user arrival rate follows a Poison distribution with a mean arrival rate ranging from 50 to 400 UEs per second. We assume a random-way point model for the UEs for the direction and the speed of the users ranging from $0, 1.4, 9, 15\,\text{m/s}$. Detailed radio characteristics for UE are shown in [13].

Since the information in the ID structure is used to update the variables in the optimization problem shown in Sect. 4, the ID distribution factors into the efficiency of the approach. As explained in Sect. 3 that the distribution of the ID structure will be system and application dependent, which can either be centralized, maybe through Centralized Radio Access Network (C-RAN), or be completely distributed. The communication of the ID can either be through a backbone internet or control channels or even use of ledgers. Here we assume that the devices can communicate the ID through a control channel like architecture.

Table 1. Radio parameters

Parameters	Macro cell	Micro cell	Femto cell
P_i^{max}	46 dBm	33 dBm	23 dBm
G_i^{Atype}	16 dBi		5 dBi
Antenna type	Omni-directional	3 sector directional	Directional
Ht_{MAX}	40 m	15 m	5 m
PL	$10\alpha log(d_{ij}) + \beta + 10\gamma log(f_c) + \chi_\sigma$		$20log(f_c) + Nlog(d_{ij}) + Lf(n_w) - 28$

5.2 Discussion

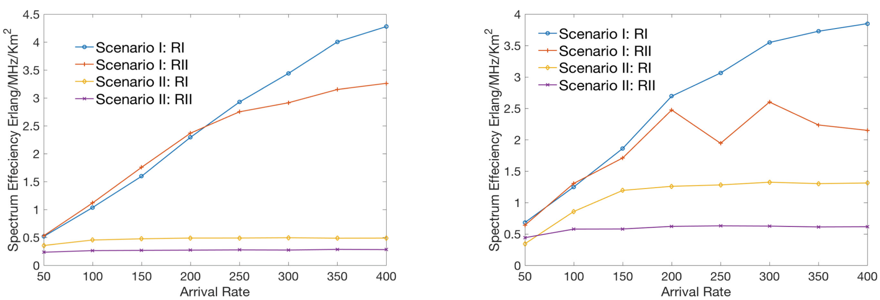
To measure the improvement in spectrum efficiency for our proposed ID structure method, we compare it to the classical RSS method of resource assignment. Let the ID approach be Scenario I and the RSS method be Scenario II. As explained in Sect. 4 that efficiency η is directly dependent on the user coverage; however, there is a tradeoff between coverage and throughput, so we define coverage for 2 sub-cases, RI: $R_j^* > 5\,\text{Mbps}$ and RII: $R_j^* > 12\,\text{Mbps}$. Different data rates signify different services, like web, voice, video stream. With two extremes cases of data rate demand, we try to estimate the worst-case bounds coverage for a 5G kind setup. The coverage area S_f is calculated dynamically based on the parameters selected. For Scenario I the frequency allocation is dynamic, while for Scenario II the frequency is allocated individually to avoid excess co-channel interference.

As explained in Sect. 2 that increasing infrastructure/spectrum does not necessarily guarantee more user coverage as there are other factors, which needs to be monitored. We compare the average spectrum efficiency results to F_r values of 6 and 3. When $F_r = 3$ we consider it is a constrained resource scenario. We show in Fig. 4 that even reducing the frequency reuse from 6 to 3 our proposed ID structure is able to maintain spectrum efficiency by adjusting the other parameters; however, RSS is not able to do so.

When we compare Fig. 4a and b we observe that though there is an overall increase in the average efficiency for $F_r = 3$ the trend for the respective methods remains the same, with RI as the best case efficiency. The overall increase in efficiency in the constrained resource scenario is due to the APs getting compelled to reuse the channel for the same user demands. However, the Scenario II does not show an optimal way of resource allocation and thus falls short compared to Scenario I. Moreover, we see that for both Scenarios I and II, the gap between the RI and RII data distribution increases as we keep on constraining F_r. This shows that for a constrained resource scenario covering users with higher QoS demand will become more difficult. However, Scenario I maintains an overall increase in average spectrum efficiency. In Fig. 4b, Scenario I is able to show a 2.4 to 3.2 times improvement compared to Scenario II for RI and RII respectively.

The trend for Scenario I seems to have some variations with respect to arrival rate, while Scenario II shows a steady trend. Scenario I shows a variation of 0.02–0.5 E/MHz/km^2, which is due to the dynamic allocation of resources (like, frequency, transmit power and antenna angles) and UE locations, so that these resources are assigned more optimally. We see that in Scenario II, which assigns resources based on the strongest received signal, the efficiency decreases as it does not monitor the unwanted aggregated harmful interference, which is caused due to the assignment. Thus, the trend remain quite stable as the assignment criterion remains the same even with the increase of arrival rate.

We acknowledge that this method of identification comes with some open-ended challenges, including: where such IDs make sense and where they might not be necessary; what is the best method to communicate the IDs to other devices; and the benefits and costs of extending traditional ID requirements, particularly to shared or lightly-licensed spectrum bands. Additionally, this method of service/device/operation specific ID might be challenging to implement in terms of: (1) regulators updating policy, (2) carriers modifying operations, (3) user participation and cooperation, (4) manufacturers designing and implementing the devices, and (5) standards being created. However, with collaborative



(a) Frequency Reuse=6.

(b) Frequency Reuse=3.

Fig. 4. Average spectrum efficiency for different UE arrival rates and frequency reuse factors (with each point representing average of 100 simulations)

push from regulators and manufacturers this ID structure could be implemented and useful.

6 Conclusion

In this paper, we showed that with a granular level ID structure, of identifying device(s)/antenna(s) based on their space and operation parameters, we can further the cause of using resources more optimally. This ID structure will ease the ex-post enforcement process for the regulators to monitor for unwanted harmful interference mostly in the shared and lightly licensed bands. Complex interference issues like overload and spill-over can be resolved by just monitoring the ID parameters. Moreover, with heterogeneity and densification of APs and UEs this ID structure will allow a common ground for the devices to identify their operation modes uniquely in the system. Similar benefits can be reaped by homogeneous networks as well. Additionally, we showed that spectrum efficiency or user coverage per spectrum resource can be increased without adding additional spectrum. The ID structure comes with some tradeoffs and open-ended challenges; however, these could be resolved with coordination between the regulators and the industry to achieve the goal of an improved spectrum efficiency.

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