Opportunistic use of 3G uplink licensed bands

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Abstract—Radio frequency spectrum is a highly expensive commodity. However, UMTS UL bands capacity has been mainly underutilized due typical Internet traffic asymmetry. In this paper we consider a secondary wireless system that operates over the UMTS UL bands in an opportunistic way. The opportunistic radios (OR) sense the path loss between its location and the UMTS base station. With this sensing information the ORs adapts its power to avoid harmful interference with the UMTS system. Sensing is performed exploiting cyclostationary features of the UMTS signal and no cooperation between the two networks is assumed. Spectrum opportunities are computed and coexistence between the two wireless networks is analyzed.

Keywords—opportunistic radio, UMTS FDD, spectrum sharing, sensing.

I. INTRODUCTION

It is expected that the demand for wireless services will continue to increase in the near and medium term, calling for more capacity and putting more and more pressure on the spectrum availability. While the use of advanced signal processing techniques may enable a very efficient usage of the spectrum even in the traditional framework of command and control spectrum policy, there is a worldwide recognition that these methods of spectrum management have reached their limit and are no longer optimal and new paradigms must be sought [1]. In fact independent studies carried out in different places (e.g. [2]) have shown that most of the assigned spectrum is under-utilized. Thus the problem is in most cases a problem of inefficient spectrum management rather than spectrum shortage. The development of frequency agile terminals that can sense “holes” in the spectrum and adapt their transmission characteristics to use these “holes” may provide one tool to address and take advantage of this spectrum under-utilization. The evidence of the change and evolution in the approaches of spectrum management can already be seen in the development of the IEEE 802.22 cognitive radio based standard for fixed, point-to-multipoint, wireless regional area networks that operates on unused channels in the TV VHF/UHF bands between 54 and 862 MHz on a non-interfering basis [3].

The detecting of “holes” and the subsequent use of the unoccupied spectrum is referred to as opportunistic use of the spectrum. An Opportunistic Radio (OR) is the term used to describe a radio that is capable of such operation [4]. In this paper we propose an opportunistic radio system that shares the spectrum with an UMTS cellular network. This is motivated by the fact that UMTS radio frequency spectrum has become, in a significant number of countries, a very expensive commodity, and therefore the opportunistic use of these bands could be one way for the owners of the licenses to make extra revenue. The UMTS Terrestrial Radio Access (UTRA) consists of two modes, a frequency division duplex (FDD) mode and a time division duplex (TDD). The TDD mode supports duplexing UL/DL by allocating time slots in a common 5 MHz band as a function of the service asymmetric level, in consequence, UMTS TDD can be matched to fit the service asymmetry without wasting spectrum capacity. The UMTS FDD mode uses 5 MHz paired uplink and downlink bands and is currently being adopted in main Europe and US operators. In the case of Internet based applications the traffic patterns are asymmetric with much lower usage of the uplink band due to a negligible amount of control traffic in comparison to a large amount of data downloading. This means that UMTS FDD is a downlink capacity-limited system and UL bands have been under utilized by the cellular operators. To confirm this, recently spectrum occupancy measurements performed in Europe [5] pointed out that a power spectrum density (PSD) measured at UL bands 20 dB below the measured at DL bands. The proposed OR system exploits the UMTS UL bands, therefore, the victim device is the UMTS base station, likely far from the opportunistic radio, whose creates local opportunities due the path loss and shadowing between the OR transmitter and the UMTS base station. These potential opportunities in UMTS FDD UL bands are in line with the interference temperature metric proposed by the FCC’s Spectrum Policy Task Force [6]. The interference temperature model manages interference at the receiver through the interference temperature limit, which is represented by the amount of new interference that the receiver could tolerate. As long as OR users do not exceed this limit by their transmissions, they can use this spectrum band. However, handling interference is the main challenge in CDMA networks, therefore, the interference temperature concept should be applied in UMTS licensed bands in a very carefully way. An example of this care is the current debate in European regulators about the permission of UWB devices to use IMT 2000 (3G) bands. For example, OFCOM report [7] proposes a limit of PSD equal to -85 dBm/MHz, which is more severe than the -51.3 dBm/MHz allowed within US by FCC. The main concern occurs when the UWB device is used in close proximity to existing UMTS terminals (interference with DL bands). As the UWB device has no way to sense if the UMTS terminal is close or far away, the allowable UWB transmit power is limited by a predefined spectrum mask. The idea of a spectral mask is in some way a worst case approach since it requires UWB devices to avoid emissions in a given band.
even if it is not in use by any other UMTS terminal within the limited range of the UWB signal. A large number of technical studies have been performed by a range of bodies to assess the potential interference that UWB might cause in UMTS networks, e.g., [8] [9] [10]. In this paper we propose a different approach to reutilize UMTS bands. We envisage an opportunistic radio network which nodes are able to sense the path loss between the UMTS base station (BS) and its location. Using a path loss estimate the OR controls the transmit power in order to avoid harmful interference within the UMTS UL bands. The key issues to make this possible is to implement a reliable sensing algorithm and define a strictly non interference rule for OR and UMTS coexistence. The paper is organized as follows: In Section II the scenario is defined. In Section III the maximum interference tolerable by the UMTS BS is computed. In Section IV we propose a technique to estimate the path loss between the OR node and the UMTS BS. Some illustrative results are presented in Section V and finally, in Section VI conclusions are made and future challenges highlighted.

II. SCENARIO DEFINITION

The UMTS is a DS-CDMA system, thus all users transmit the information spreaded over the 5 MHz bandwidth at the same time and therefore users interfere with one another. Figure 1 shows a typical UMTS FDD paired frequencies in Europe. $S^f$ is the length of the spreading code. The asymmetric load creates spectrum opportunities in UL bands since the interference temperature (amount of new interference that the UMTS BS can tolerate) is not reached.

In order to fully exploit the unused radio resources in UMTS UL bands, the OR network should be able to detect the vacant channellization codes using a classification technique [11]. Thus, the OR network could communicate using the remaining spreading codes which are orthogonal to those used by the UMTS terminals. However, classification and identification of specific spreading codes is a very challenging problem, especially for real time applications. Moreover, synchronization between UMTS UL signals and the OR signals, mandatory to keep the orthogonality between codes, will be a difficult problem without cooperation between the two networks. We propose a simpler approach, i.e., fill part of the available interference temperature with a certain amount of extra interference cause by the OR network operation. For simplicity we consider that the aggregated signal coming from the OR network is AWGN and causes a noise rise equal to $\mu$ dB, as shown in Figure 1. Figure 2 illustrates the scenario addressed in this paper. We consider a OR network of $M$ nodes operating overlapped to the UMTS FDD cell. The OR network acts as a secondary system that exploit opportunities in UMTS UL bands. The OR network has an opportunity management entity which computes the maximum allowable transmit power for each OR node in order to not disturb the UMTS BS. In Figure 2 the grey area represents the forbidden regions around the UMTS BS where, due the BS proximity, the allowed OR power level is insufficient to guarantee a specified QoS target.

\begin{equation}
10 \log \left( \sum_{k=1}^{M} \frac{P_{\text{OR}}(k) + G_{\text{OR}} + G_{\text{BS}} - L_p(k)}{10} \right) < 10 \log \left( 10^{\frac{\text{Nth} + \mu}{10}} - 10^{\frac{\text{Nth}}{10}} \right) - \Gamma
\end{equation}

Where $G_{\text{OR}}$ is the OR antenna gain, $G_{\text{BS}}$ is the UMTS BS antenna gain, $L_p$ is the estimated path loss between the OR node and the UMTS BS, performed by a sensing algorithm, and $\text{Nth}$ is the thermal noise floor. $\mu$ is a margin of tolerable extra interference that, by a policy decision, the UMTS BS can bear. Finally, $\Gamma$ is a safety factor to compensate shadow fading and sensing’s impairments. Notice if the margin of tolerable interference is set $\mu=0$ the OR network must be silent. It is straightforward to extend this scenario to a 3G multi-operator case where several UMTS UL frequencies cover the same region. In this case, the OR can exploit a spectrum pool of some UMTS UL carriers. Figure 3 shows a spectrum pool mechanism. As basic principle, the OR node rent the most appropriate UMTS UL band to transmit the required power ($\text{POR}_{\text{target}}$) to meet a QoS target. Whenever the $P_{\text{OR}}$ is sufficient, the OR signal is formatted by the spectrum shaping module, for instance, using an OFDM modulator. If during the OR transmission the allowed $P_{\text{OR}}$ becomes lower than the target, the OR leaves that frequency and switch to another one. Sensing is done on a periodic basis to follow the OR’s node movement and the correspondent path loss change.
III. MAXIMUM TOLERABLE EXTRA INTERFERENCE

In this section we compute the maximum extra interference that the UMTS BS can bear without significant degradation of the network performance. Two coexistence metrics are considered: the impact on UMTS UL capacity and the impact on cell coverage due the OR network activity.

A. Impact on UMTS UL capacity

Assuming perfect UL power control the ratio between the bit energy and the interference level ($Eb/I$) measured at the UMTS base station is given by [12],

$$\frac{E_b}{I} = \frac{SF \cdot P}{(1-\beta)(K-1)P + I_{\text{inter-cell}} + N_{\text{th}}}$$  \hspace{1cm} (2)

We assume the same SF for all K uplink traffic channels (TCH). $P$ is the average received power coming from each user / TCH. $\beta$ denotes the percentage of intracell interference being removed by multi user detection receivers, typically between 60%-70%, depending on the cell load. $I_{\text{inter-cell}}$ is the inter cell interference due adjacent cells using the same frequency. $N_{\text{th}}$ is the thermal noise power measured within the 5 MHz bandwidth. In order to evaluate the impact of an opportunistic network that operates in a licensed UMTS UL band we introduce an extra interference term ($\mu$). Using (2), the uplink network capacity, i.e., the maximum allowable number of TCHs to meet required $Eb/I$ constraint ($\gamma$) is given by,

$$K \leq 1 + \frac{SF}{\gamma(1-\beta)} \frac{I_{\text{inter-cell}} + N_{\text{th}} + \mu}{P(1-\beta)}$$  \hspace{1cm} (3)

This formula was applied to a UMTS cell using the parameters presented in Table 1. Three services with the following UL bit rates were analyzed: 64 kbit/s, 144 kbit/s and 384 kbit/s.

![Figure 3. UMTS spectrum pool mechanism.](image)

The inter cell interference is computed assuming six adjacent cells, each of them with a UMTS terminal transmitting its maximum power (21 dBm) in a cell border. The path loss ($L_p$) follows the COST231-Walfish-Ikegami model [14] for base station antenna height of 25 m, mobile station height of 1.5 m, $L_p = 143 + 38 \log_{10}(d[km])$ \hspace{1cm} (4)

Considering a base station antenna gain equal to 18 dBi and a negligible gain of the UMTS terminal antenna, the total $I_{\text{inter-cell}} = -108$ dBm. Figure 4 shows the impact on UMTS UL cell capacity due the extra interference caused by the OR network operating within the same UMTS UL band. We can see that $\mu=1$ dB rise of the noise floor, from -107 dBm to -106 dBm, causes a negligible degradation of the UL capacity.

![Figure 4. Relative reduction of uplink cell capacity (traffic channels) due the noise floor rise.](image)

B. Impact on UMTS coverage

For a particular service, a specific $E_b/N_0$ needs to be maintained at BS receiver to guarantee a target quality of service. Figure 5 shows an example of Block Error Rate (BLER) measured at BS in a full and half load situation. The half load scenario exemplifies the typically underutilization of UMTS UL bands. From Figure 5, is possible to see that, in order to achieve BLER=0.1, the full load scenario needs an $E_b/N_0=2.3$ dB, while for half load $E_b/N_0=1.4$ dB is sufficient. As the cell is planned to operate in full load (worst case), this means that in the half load scenario the noise floor can be increased 0.9 dB without a perceptible BLER degradation, creating a 0.9 dB margin to accommodate extra interference. This margin depends on the particular UL cell load and the particular BS receiver (RAKE or multi-user detector).

| Cell radius | 2 km |
| Data services, UL bit rate | 64 kbit/s, 144 kbit/s, 384 kbit/s |
| SF | 16, 8, 4 |
| $\gamma$ required (BLER=1%) | 3.3 dB, 3 dB, 2 dB [12] |
| $\beta$ | 0.6 |
| $N_0$ (thermal noise floor) | $-174 + 10\log(5MHz)= -107$ dBm |
| $P$ (perfect power control) | $-100$ dBm |

![Figure 5. An example of Block Error Rate (BLER) measured at BS in a full and half load situation.](image)

TABLE I. PARAMETERS FOR CELL’S CAPACITY COMPUTATION.
As mentioned before, the OR network operation is allowed to increase the noise floor $\mu$ dB at UMTS BS receiver. Therefore, if a UMTS terminal is in the cell edge and its maximum transmit power has been reached, an increase in the required transmit power, in order to compensate the noise rise at the BS, will result in a decrease in the maximum distance a mobile can be from the UMTS BS, thereby reducing coverage. Based on uplink budget analysis we compute the maximum allowed propagation loss in a cell and applying the path loss model (3) the cell range is estimated. As an example, we consider a cell edge path loss equal to $L_p=140$ dB. Figure 6 shows the relative reduction in the cell’ s area as a function of the noise floor level for a full and half load scenario. In half load scenario we consider, as explained before, that the UMTS BS can accommodate 0.9 dB of extra interference without BLER degradation. As a general approximation we can see from Figure 6 and full load scenario that $\mu=1$ dB reduces the cell area by some 10%, however assuming an half load occupancy the effect on cell coverage is insignificant. Nevertheless, the amount of extra interference that the UMTS BS can bear above the thermal noise floor will be in any case a policy decision.

In order to get the maximum allowable power for OR communications the OR nodes need to estimate the path loss between the UMTS BS and its particular location. Although we exploit opportunities in UL bands, we propose to sense DL signals; this is possible because there is a significant correlation between the average path loss of uplink and downlink bands of UMTS [14]. Since the BS antenna is typically situated in a high location, the DL signal is easier to detect than the multiple UL signals coming from different UMTS terminals. In addition, the DL signal arrives to the sensing antenna in a synchronized way, which facilitates detection through cyclostationary features of the UMTS signal. Moreover, sensing and transmit in different bands avoids allocate special quiet periods for sensing as it is done in IEEE 802.22 [15] system, boosting the OR’ s spectrum efficiency. The energy detector is a well-known technique to identify signal levels. However realistic limitations of the detector’ s knowledge of the noise level power produce serious degradation in the energy detector performance [16]. In the UMTS case, due the low power spectrum density of spread spectrum signal, the signal presence causes a very small fractional increase in the total energy, thus, uncertainly in the measurement of the noise seriously degrades the radiometer performance. In addition, for this scenario, the best opportunities occurs when the OR nodes are near the UMTS cell border, where the sensed signal have usually negative SNR values, not detectable by a simple energy detector. To overcome this limitation, we propose to exploit the cyclostationary features of the DS-CDMA signal [17]. We assume that the OR knows a priori the UMTS carrier frequencies and bandwidths, which has been isolated and brought to the baseband. DS-CDMA signals can be detected exploiting the baseband cyclostationary properties come from the redundancy between frequency components separated by multiples of the symbol rate, i.e., the cyclic feature appears at $\alpha=1/(SF \cdot T_c)$, where $T_c$ is the time chip duration. However UMTS FDD standard employ, in addition to user specific spreading, so called scrambling sequences, in order to improve the correlation characteristics of the signals and provide base station identification [18]. Scrambling take place over multiple symbols, with period equal to 10 ms, removing the cyclostationarity with the symbol rate. Nevertheless in UMTS standard, user signals have always the same chip rate, even if the individual SF and symbol rates differ. Thus, $\alpha=1/T_c$ (3.84 Mchip/s) is a common cyclic frequency to all UMTS channels and will be exploited to detect UMTS DL signals. An analytical formulation of the cyclic autocorrelation function for a UMTS FDD signal is detailed in [19]. Figure 7 represents the output detection statistic, $d$, as a function of the SNR measured at the OR’ s sensing antenna for observation times 10 ms, 30 ms and 100 ms. For a given observation time, $d$, only depends on the SNR, regardless the number of users and the specific spreading code used. From Figure 7 we can see that in order to detect low values of SNR, more observation time is required, for instance, with $SNR_{UL}=10$ dB and 10 ms observation time, the cyclostationary detector achieves an average value $d=1$ dB, however for $SNR_{UL}=15$ dB the detector needs 100 ms to get the same detection statistic. Obviously, there is a limit on the minimum detectable SNR which decreases with the observation time spent during the sensing process. In order to estimate the path loss between the UMTS BS and the OR node, Figure 9...
acts as calibration curves to estimate the SNR of the total received DL signal. For a particular detector outputs, $d$, and a fixed observation time, the estimated SNR is used by the OR node to compute the path loss between UMTS BS and the OR location through,

$$\hat{L}_p = \min(P_{gs} + G_{bs}) - \hat{P}_{rx}$$

$$\hat{P}_{rx} = \text{SNR}(d, \text{ObsTime}) + N_{th}$$

(5)

V. RESULTS AND CONCLUSION

In order to illustrate the opportunistic use of UMTS UL bands simulations were carried out for a single OR node. The extra interference that the UMTS BS can bear is set $\mu = 1$ dB. The shadowing effect was simulated through a log normal model with 4 dB standard deviation. It is assumed a safety factor $\Gamma = 10$ dB. Two observation times were considered: 30 ms and 100 ms. Figure 8 shows the SNR at the OR’s antenna and the allowed transmit power when the OR node moves away from the UMTS BS. As expected, the lower is the SNR the higher is the allowed $P_{t_{GR}}$. When the estimated SNR drop below the minimum detectable SNR, which depends on the observation time, the OR transmits at the minimum detectable SNR; as result, there is absolute limits on the OR transmit power, i.e., 17 dBm for 100 ms and 10 dBm for 30 ms observation time. If for instance, the OR node needs transmit 5 dBm (-2 dBm/MHz) to meet a given QoS target, then it can operate in 40% of the UMTS cell area which represents a significant level of spectrum opportunities. This result can be improved using a spectrum pool mechanism with several UMTS UL frequencies.

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