Cognitive Radio Technology for Improving Capacity of Mobile Communication Systems in Palestine

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1. Introduction
Radio frequency regulators in the world found that most part of the spectrum was inefficiently utilized [1]. Fixed spectrum assignment prevents rarely used frequencies from being used even when any unlicensed users would not cause noticeable interference to the assigned service. Joseph Mitola [2] proposed the technology of Cognitive Radio (CR), during his PhD thesis in 1998, as a promising technology to balance between spectrum underutilization and spectrum scarcity. CR [3] is a model for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently without interfering with licensed users. A transceiver in CR can intelligently detect which communication channels are in use and which are not, and instantly move into vacant channels while avoiding occupied ones. This optimizes the use of available spectrum bands while minimizing interference to other users. Hence CR has the potential to exploit the inefficiently utilized licensed bands without causing interference to incumbent users.

Historically, up until now, the mobile industry has relied on spectrum dedicated for mobile communication and licensed to a certain operator. However, in situations where licensed spectrum is not available, other possibilities for increasing the spectrum availability are of interest. This could include the use of unlicensed spectrum, or secondary spectrum primarily used for other communication services, as a complement to operation in the licensed spectrum. Broadcast spectrum not used in some areas is often referred to as “white space” [4]. The applicability of CR to cellular communication relies on software-defined radio (SDR) [5] and it is a relatively new area where further studies are required to assess the feasibility and impact of such usage.

In CR, spectrum sensing locates unused spectrum segments and optimally use these segments without harmful interference to the licensed user. This includes measuring which frequencies are being used, when they are used, estimating the location of transmitters and receivers, and determining signal modulation. Results from sensing the environment would be used to determine radio settings.

The main purpose of the research is to evaluate the gain of applying cognitive radio technologies on mobile networks’ capacities and is organized as follows: Section 2 presents main types of cognitive radio and defines spectrum holes for both GSM and UMTS bands based on previous
measurements and studies. In section 3, capacity of multiple channels was investigated based on trunking theory where approximated linear equations are derived for the relation between traffic intensity and the number of channels per cell for the different values of grade of services. Section 4 illustrates the expected overall gain of applying cognitive radio technologies on Palestinian mobile networks’ capacities and section 5 concludes the article.

2. Cognitive radio (CR)

As the radio spectrum becomes a more scarce resource and the needs for frequency bands are in steady increase, regulatory bodies all over the world started to look at how to use spectrum more effectively by the idea of CR.

2.1 Types of cognitive radio

Depending on transmission and reception parameters, the main types of cognitive radio [6]:

- Full Cognitive Radio, in which all observable parameter by a wireless node is considered.
- Spectrum-Sensing Cognitive Radio, in which only the radio-frequency spectrum is considered. Most research work focuses on sensing methods where the chief problem is designing high-quality spectrum-sensing devices and algorithms for exchanging spectrum-sensing data between nodes.
- Licensed-Band Cognitive Radio, capable of using bands assigned to licensed users
- Unlicensed-Band Cognitive Radio, which can only utilize unlicensed parts of the radio frequency spectrum.

After detecting (sensing) the spectrum holes the following steps are carried out for spectrum management:

- Spectrum decision: choose the best available spectrum channel
- Spectrum sharing: Provides a fair spectrum-scheduling method; share the spectrum with primary users,
- Spectrum mobility: Process, by which a cognitive-radio user changes its frequency of operation, allowing radio terminals to operate in the best available frequency band.
2.2 Unused Spectrum (Spectrum Holes)

A spectrum hole is defined as a frequency band that is assigned to a primary user exclusively, but is not allocated by this user at a specific time and place [7]. A spectrum hole is also called white spaces where these spaces are free of local interferers. White spaces can support dynamic allocation techniques. On the other hand, black spaces are highly occupied by local interferers and hence are no proper candidates for dynamic spectrum allocation. Grey spaces come in between where these spaces are partially occupied by interferers and can partially support dynamic allocation techniques. The CR is expected to operate in the UHF band (frequency range from 300MHz to 3GHz) within which the propagation of the electromagnetic waves is favorable for mobile wireless communications devices.

2.2.1 GSM band’s spectrum holes

Figure 1 shows the identification and clustering of unoccupied frequencies within the uplink GSM band (“spectrum holes”), evaluated over a time interval of 8ms, within which a CR would be permitted to operate. The identification of spectrum holes is based on the estimation of the power spectral density (PSD) based on the 97.5% confidence boundary [8]. If the PSD estimate is below this level, potentially transmission can be accomplished at an SNR greater than zero. However, a spectrum hole should first contain a defined minimum bandwidth. Second, a minimum defined distance should be obeyed to frequency bands where the estimated PSD suggests occupancy in order to cause a minimum of interference for a legacy user. Such guard bands can take Doppler shift due to user mobility into account.

![Figure 1: GSM uplink band from 890--915MHz: identification and clustering of unoccupied frequency bands (“spectrum holes”) within which a CR would be permitted to operate, source from [8].](image-url)
It could be deduced from Figure 1 that on the average 70% of GSM uplink spectrum (890--915MHz) are considered as spectrum holes within which a CR terminal would be permitted to operate. The downlink band (935-960MHz) is busy as indicated by measurements from Victoria University during 5 minute snapshot [9], Figure 2.

- Spectrum measurements from Victoria University
  - GSM Band 5 minute snapshot

![Image of GSM spectrum](image1)

- Busy GSM Down Link (DL)

Figure 2: Spectrum holes in GSM band, measurements from Victoria University during 5 minute snapshot, source from [9].

2.2.2 UMTS band’s spectrum holes

Regarding the UMTS expansion band from 2.5--2.69GHz, It is easily deduced from Figure 3 that on the average 80% of UMTS spectrum are considered as spectrum holes within which a CR terminal would be permitted to operate (slightly more than GSM uplink band).

![Image of UMTS spectrum](image2)

Figure 3: UMTS expansion band – identification of spectrum holes and clustering of frequency bands suitable for operating a CR, source from [8].
3. Cellular System Capacity Improvement

In general, the relationship between the capacity of a single channel and its bandwidth is highlighted by a logarithmic formula developed by the mathematician Claude Shannon [10] and referred to as Shannon Capacity, appendix-1. In general when the bandwidth of the channel increases, the capacity will be increased to an upper limit; if the capacity is limited, increasing bandwidth will increase noise (more noise is admitted to the system), thus, SNR decreases.

However, to study the capacity of multiple channels generally encountered in fixed (wire-line/wireless) or mobile systems, trunking theory applies. Trunking theory was developed by a Danish mathematician A. K. Erlang who based his studies on the statistical nature of the arrival and the length of calls. Erlang developed the fundamentals of trunking theory while investigating how a large number of users can be served by a limited number of channels. Statistical behavior of users accessing the network is discussed in the assumptions of the Erlang B formula [11], appendix-2. Erlang B formula is a nonlinear relation allows for the calculation of the number of channels required to offer an amount of traffic in Erlangs based on the Grade of Service (GOS). GOS, or blocking probability, is a measure of the probability that a user may not be able to access an available channel because of congestion.

Now if a CRN manages to increase the available bandwidth by sensing spectrum holes, from the unused spectrum, then what is the expected overall gain in cell capacity or traffic intensity in Erlangs at a specific GOS? Unfortunately the answer is not so clear from Erlang B formula due to its nonlinearity; it does not give a smooth answer for how much the network capacity (traffic intensity in Erlangs, $A$) will increase when the number of channels for each cell, $C$, is increased for a fixed GOS! To ease the evaluation of the gain of applying cognitive radio technologies on the capacity of cellular systems and to have a close insight at the effect of the number of trunked channels on the traffic intensity per cell, the traffic intensity, $A$ in Erlangs, is evaluated for various numbers of channels per cell and different values of GOSs. The numerical values are plotted in graphical form in Figure 4 for two values of GOS: 0.02 represents the standard threshold and 0.005 represents a privilege value that indicates a much higher

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1 The well-known equations are presented in appendices
quality of service. Then, two linear equations, Eq.1, for the relation between traffic intensity, \( A \), and the number of channels per cell, \( C \), are approximated\(^2\), for the two values of GOSs as shown near actual curves in Figure 4.

\[
\begin{align*}
A_{\text{GOS}=0.02} &= 0.975C - 4.060, \cdots (a) \\
A_{\text{GOS}=0.005} &= 0.831C - 3.808, \cdots (b)
\end{align*}
\]

**Eq.1: Linear equations approximated for Erlang B formula.**

To find the relation between the numbers of served users per cell, \( U \), as a function of the numbers of channels, \( C \), the traffic intensity per cell is to be converted to a number of served users. This conversion is straightforward as the total traffic intensity per cell, \( A \), equals the number of users per cell, \( U \), multiplied by the average traffic generated by each user, \( Au \). Meanwhile, \( Au \) equals the average number of user's calls request per hour, \( \lambda \), multiplied by the average duration of a typical call in seconds, \( H \).

In ordinary situations, investigations indicated that a residential user generates 0.02 Erlangs of traffic [12]. Figure 5 shows the number of served users per cell as a function of the number of trunked channels for GOS=0.02

\(^2\) See appendix-3
and for GOS=0.005 separately. Linear equations, Eq.2, were approximated for the two cases with their lines shown near actual curves in Figure 5:

\[ U_{GOS=0.02} = 49.38C - 203.6, \quad \text{...............}(a) \]
\[ U_{GOS=0.005} = 41.57C - 190.4, \quad \text{...............}(b) \]

**Eq.2: Linear equations approximated for number of served users per cell, \( U \), as a function of number of channels, \( C \), at \( Au = 0.02 \) Erlangs.**

It is easily shown from Figure 5 that the number of served users at GOS=0.02 is higher than at GOS=0.005 due to the high level of QOS achieved. In general, increasing the number of channels per cell (as a result of sensed spectrum holes) yields a significant increase in cell capacity, and hence, increase in the number of served users.

Based on trunking theory, cell capacity (traffic intensity in Erlangs and hence the number of served users per cell) depends on the number of trunked channels per cell which, in turn, depends on the amount of the available spectrum. Suppose that the available total bandwidth for a trunking system is \( W \)Hz (for each uplink and downlink direction) and the bandwidth of the channel is \( B \)Hz then the number of the overall available channels is \( W/B \) channels. If the trunking system uses cluster size of \( N \) cells; \( N \)-cell reuse factor is used, then the number of channels for each cell \( C \), is given as \( C = W/BN \) since the overall available channels are equally divided on the \( N \) cells in the cluster. Substituting this value in Eq.2 gives an approximate linear relation between the number of served users per cell and the total available bandwidth as:
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\[ U_{GOS=0.02} = 49.38 \frac{W}{BN} - 203.6, \ldots (a) \]
\[ U_{GOS=0.005} = 41.57 \frac{W}{BN} - 190.4, \ldots (b) \]

**Eq.3:** Approximated linear equations for number of served users per cell, \( U \), as a function of total available bandwidth

Finally if the total number of working cells in the trunked cellular system is \( K \), then the total number of served users \( U_t \) is given by

\[ U_{t, GOS=0.02} = 49.38 \frac{KW}{BN} - 203.6, \ldots (a) \]
\[ U_{t, GOS=0.005} = 41.57 \frac{KW}{BN} - 190.4, \ldots (b) \]

**Eq.4:** Approximated linear equations for the total number of served users as a function of total available bandwidth

If the average traffic generated by each user, \( A_u \), is increased to 0.05 Erlangs then, from Eq.1 and solving for \( U = A/A_u \):

\[ U_{GOS=0.02} = 19.5C - 81.2, \ldots (a) \]
\[ U_{GOS=0.005} = 16.62C - 76.16, \ldots (b) \]

**Eq.5:** Linear equations approximated for number of served users per cell, \( U \), as a function of number of channels, \( C \), at \( A_u = 0.05 \) Erlangs.

And the linear equations approximated for the total number of served users as a function of total available bandwidth are approximated as follows:

\[ U_{GOS=0.02} = 19.5 \frac{W}{BN} - 81.2, \ldots (a) \]
\[ U_{GOS=0.005} = 16.62 \frac{W}{BN} - 76.16, \ldots (b) \]

**Eq.6:** Linear equations approximated for the total number of served users as a function of total available bandwidth at \( A_u = 0.05 \) Erlangs.
4. Existing Palestinian Cellular Systems and expected overall gain

Although the political and economic situation in Palestine is considered as the most unstable among all the middle-east countries, the Palestinian telecom sector has been developing at a continuous rate over the last ten years. In the mobile sector, there is, in practice, a competitive market between the two legal and licensed Palestinian companies, Jawwal" and "Wataniya Mobile", and four unlicensed and illegal Israeli mobile operators, "Orange", "Cellcom", "Pelephone" and, to a small extent, "MIRS". These Israeli operators use their base stations located inside the Israeli settlements and offer their products and services illegally in the so-called "border coverage overlap areas. Jawwal and Wataniya provide state-of-the-art mobile voice and data telecommunications services in the West Bank and Gaza Strip. Wataniya has the right to establish and provide a third generation (3G) network and international telecommunications services but no spectrum offered yet for 3G!

4.1 Frequency bandwidths assigned to Palestinian Operators

The total bandwidth offered for Jawwal to operate GSM 900 was around 2x2.4 MHz where 2.4 MHz are available for each direction (uplink or downlink) in addition to 2.4 MHz share with Orange. Similarly, Wataniya is allocated two blocks of 2.4MHz, one at 900MHz and one at 1800MHz, with the former being temporary while a more permanent allocation was sought [13]. That permanent allocation was supposed to come from Orange's operations in Israel, or from the Palestine incumbent Jawwal.

4.2 Expected overall gain in Palestinian mobile networks’ capacity

As mentioned above, the total bandwidth offered for Palestinian operator (whether Jawwal or Wataniya) to operate GSM network was around 2.4 MHz in each direction (uplink and downlink). Taking into account that the GSM channel bandwidth is 200 KHz, hence, from Equation 3, 2400/200=12 total available frequency-channels. If N-cell cluster size is used then the number of frequency-channels per cell will 12/N. Remembering that TDMA is also implemented in GSM system where each channel is divided into 8 time slots, hence 12*8/N useful resources (time slots-channel) is available for each cell. The capacity of a cellular system is directly proportional to the number of times a cluster is replicated in a fixed service area. The cluster uses the complete set of available channels, W/B. If N is reduced while the cell size is kept constant, more clusters are required to cover the service area and hence more capacity is achieved. The increased capacity is due to increased number of channels allocated per cell. Even though, the smallest
value of $N$ is desirable, however, reduced $N$ yields increased co-channel interference because co-channel cells are located much closer.

Figure 6 shows the number of served users per cell as a function of total available bandwidth for two values of GOS (the standard GOS= 0.02 and the privilege GOS= 0.005) and two values of cluster size $N$ ($N=7$ and $N=4$). It is easily indicated that the number of served users per cell is higher at cluster size $N=4$ than at $N=7$ regardless of the value of GOS. This is, as illustrated in the previous paragraph, due to more clusters required to cover the service area and hence more capacity is achieved. Besides, more capacity is achieved for GOS=0.02 than for GOS =0.005 due to strict QoS conditions; very low blocking probability imposed at GOS=0.005.

At the 2400 KHz, currently allocated for Palestinian GSM operators, and $N=4$, GOS=0.02, the number of served users per cell is 981. If the allocated bandwidth is doubled (to 4800 KHz) by sensing spectrum holes, then the number of served users per cell will be increased to 2166 which represents 221% of the original value. While the number of useful resources (time slots-channel) per cell is doubled (from 24 to 48), the number of served users is 21% more than the doubled value. This gain is illustrated by trunking efficiency as a measure of the number of users that can be served with a particular GOS given a particular configuration of specific number of useful resources (time slots-channel). The number of served users by a system depends on the way in which useful channels are grouped. Hence, the overall system capacity is strictly altered by the allocation of spectrum and hence channels in a trunked system.
The standard total bandwidth allocated for GSM 900 system is 25 MHz [14] of which a small percentage (less than 10%; 2.4 MHz) is granted for Palestinian operators and the rest is used by the Israeli operators. The application of cognitive radio will clearly increase the capacity of Palestinian cellular systems by searching the unused spectrum at the Israeli side and use it at the free time. Then, what is the average percentage of the unused spectrum (Spectrum Holes) of the Israeli part and for how much average time? Hence, what is the expected overall gain in Palestinian systems capacity? Given that 70% of GSM spectrum (about 17.5 MHz) is considered as identified spectrum holes within which a CRN would be permitted to operate, this unused spectrum constitutes a huge room for increasing bandwidth and the number of served users in a specific time and location. It should be stressed on the fact that not all the 70% of unused spectrum could be used by the CRN without interference in a specific time and location. The amount of sensed spectrum holes depends on the efficiency of the CRN and the applied spectrum sensing techniques. At some time and location, the bandwidth available to CRN could be doubled a number of times given that efficient spectrum sensing techniques are used. At other time and same or other location the bandwidth available to CRN could to be increased at some percentage.

If the Palestinian GSM network, enhanced with CR, manages to sense 35% of the spectrum holes in this band, then the expected increase in bandwidth will be about 6 MHz; (0.35*17.5 MHz). The ratio 35% is chosen since the power of the Palestinian mobile networks represents, at maximum, half the power of the Israeli mobile networks. Adding 6 MHz to 2.4 MHz yields 8.4 MHz and from Figure 6, 8400 KHz serves 3944 users per cell at GOS=0.02 and cluster size of 4. Comparing this result with only 981 users per cell at the current available 2400 KHz, the gain is more than 400% increase in number of served users. At higher cluster size (N=7) with same GOS =0.02, lower number users per cell are served, enjoying lower co-channel interference. However the increase in bandwidth form 2400 KHz to 8400 KHz gives a slightly higher gain in number of served users; 457%, from 473 users per cell to 2166. When GOS=0.005, Figure 6 shows higher numbers of served users at N =4 than at N=7 for GOS =0.02. This indicates that the effect of decreased size of the cluster is more significant than the effect of decreased GOS. The lowest numbers of served users is seen at N=7 for GOS=0.005 as expected.
The benefits of CRN do not stop at increasing the number of served users. However, if no need to increase the number of served users in a specific area, benefits of CRN could be reflected in the following aspects:

- increasing the cluster size, hence inter-cell interference is decreased,
- increasing the average traffic generated by each user, hence more service is offered,
- decreasing the GOS (blocking probability), hence more user’ satisfaction is achieved

The network operator has the flexibility to adapt the cluster size, GOS and the average traffic generated by each user, $Au$, according to traffic and service requirements. If the $Au$ is increased to 0.05, then the expected numbers of served users will be decreased, Equation 11, as can easily be shown by Figure 7 for different values of cluster size and GOS.

![Figure 7: Number of served users per cell as a function of total available bandwidth, $Au=0.05$ Erlangs.](image)

Table 1 summarizes the effects of increasing the current available bandwidth, for Palestinian GSM networks, by sensing 35% of the unused band at different average user traffics, GOSs and cluster sizes. While the bandwidth is increased by 350% (from 2.4 to 8.4 MHz), the gain in the number of served users exceeds 400% at all different aforementioned parameters.
Table 1: Number of served users/cell at different values of cluster size, GOS and average traffic generated by each user.

<table>
<thead>
<tr>
<th>Average traffic generated by each user ($Au$)</th>
<th>GOS (Blocking Probability)</th>
<th>Cluster Size ($N$)</th>
<th>Number of users/cell at 2.4 MHz</th>
<th>Number of users/cell at 8.4 MHz</th>
<th>Gain% in number of served users</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Au=0.02$ Erlangs</td>
<td>GOS=0.02</td>
<td>$N=4$</td>
<td>981</td>
<td>3944</td>
<td>402%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N=7$</td>
<td>473</td>
<td>2166</td>
<td>457%</td>
</tr>
<tr>
<td></td>
<td>GOS=0.005</td>
<td>$N=4$</td>
<td>802</td>
<td>3301</td>
<td>409%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N=7$</td>
<td>379</td>
<td>1804</td>
<td>476%</td>
</tr>
<tr>
<td>$Au=0.05$ Erlangs</td>
<td>GOS=0.02</td>
<td>$N=4$</td>
<td>386</td>
<td>1556</td>
<td>403%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N=7$</td>
<td>186</td>
<td>854</td>
<td>459%</td>
</tr>
<tr>
<td></td>
<td>GOS=0.005</td>
<td>$N=4$</td>
<td>322</td>
<td>1319</td>
<td>409%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$N=7$</td>
<td>151</td>
<td>721</td>
<td>477%</td>
</tr>
</tbody>
</table>

5. CONCLUSION

The paper used the cognitive radio technology to substitute the lack of the current available frequency bandwidth in Palestine and increase the capacity of cellular systems. Numerical results showed that while the current bandwidth was increased by 350%, the gain in the number of served users exceeded 400% at different average user traffics, GOS and cluster sizes. The cognitive radio network is expected to have spare hardware capability to accommodate the increase in the number of sensed channel. If the sensed spectrum is much more than the hardware capacity then the gains of cognitive radio could be reflected in decreasing inter-cell interference, offering more service and enhancing user' satisfaction. The network operator has the flexibility to adapt the cluster size, GOS and the average traffic generated by each user according to traffic and service requirements. The spectrum sensing techniques that will be used by the Palestinian operators imply that user equipments and core networks must be software upgraded. This is a challenge for another future research area.

References
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[14] 3GPP TS 05.05 version 8.20.0 Release 1999 Pages 9 and 10

Biography
Anwar Mousa is currently working as an Associate Professor at the College of Information Technology at the University of Palestine. He was granted his PhD on 4G Cellular and WLAN Inter-working Networks from the National Technical University of Athens, Department of Electrical and Computer Engineering in 2004. He obtained his DEA in Digital Telecommunication Systems from EcoleNationaleSupérieure des Télécommunications, Paris in 1996 and BSc in Electronic Engineering from Middle East Technical University, Ankara in 1992.
Appendix

1. 

\[ C = B \log_2 (1 + \text{SNR}) \text{ bits/s} \]

*The Shannon Capacity*

2. 

\[ GOS = \frac{A^c}{C!} \sum_{k=0}^{c} \frac{A^k}{k!} \]

*The Erlang B formula*

3. *The lines near actual nonlinear curves in Figure 4 represent secant lines, of the corresponding curves, that best approximate values with small and tolerable error ratios in the chosen domain. The resulting linear functions give the accuracy we want for specific applications and are easier to work with. For instance, the maximum error ratio in Eq.1(a), for the secant line of the curve at GOS=0.02, is 3% and occurs at C=70.*