Identifying Scenarios with High Potential for Future Cognitive Radio Networks

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Abstract: Opportunistic spectrum access is a great prospect for future wireless networks. The key requirements for an opportunistic user are to avoid interference with any licensed users of the same spectrum and also to cooperate fairly with other opportunistic users. There are many scenarios where an opportunistic network could provide a system that has the potential to provide a better business case than conventional wireless networks. The most promising scenarios for opportunistic users that are on the move and have a requirement for managed quality of service are identified in this paper. The processes used to develop these scenarios are also presented.

Keywords: Cognitive Radio, Future Networks, Mobility, Opportunistic Access, Quality of Service, Secondary Access, Scenarios, Whitespaces

1. Introduction

There is a growing regulatory trend to allow for licence-exempt users to use opportunistically obtained spectrum that is in underutilised licensed spectrum bands. The aim is that currently congested spectrum does not become more congested, and that underutilised spectrum is more fully utilised. An opportunistic user has to act as a cognitive radio as it is required to avoid interference with primary/licensed users and cooperate fairly with other secondary/licence-exempt/opportunistic users.

Spectrum that can be available for opportunistic access is commonly referred to as ‘whitespace’. One issue with whitespaces is the need for fairness among other opportunistic users. This can mean that it is difficult for a commercial system to provide high quality of service (QoS) guarantees using whitespaces alone. This is because the load contributed by opportunistic users is unpredictable, whereas the provision of even a minimal service level imposes a lower limit on the available bandwidth required. In some scenarios whitespaces may be used in addition to some licensed spectrum, to provide congestion relief and added functionality, whereas other systems may be able to function purely on the whitespaces alone.

Tools and techniques to allow for opportunistic use of spectrum for users that are moving and have a requirement for managed quality of service (QoS) are needed. In this view, six scenarios which show the most potential to be successfully deployed in real world future networks are described in this paper. The description of the evaluation process that led to their selection is also provided.

Identifying scenarios at an early stage in system development is important as this can keep further development aligned, working with a common goal in mind. The scenarios
identified in this paper are being used by the QoSMOS project [1] to help guide the development of tools and techniques to bring these cognitive radio concepts closer to real-world systems. The requirements for systems that could operate in these scenarios have been produced in [2]. However these scenarios can also offer guidance for cognitive radio developments outside of the QoSMOS project [3].

The structure of the paper is as follows. In Section 2 a description is given of the process that led to the selection of the six scenarios identified to have the greatest potential. In Section 3 each of the scenarios are described. This is followed by a summary of the paper in Section 4.

2. Scoring Shortlisted Scenarios

A relatively wide range of the possible stakeholders of opportunistic communications, able to consider also political and societal implications, was composed by the QoSMOS project partners along with its external advisory board (EAB). This group evaluated the shortlist of scenarios, as shown in Table 1, using a process described in the remainder of this section. These scenarios result from discussions within the above group as to which scenarios offer high potential for future networks within the scope of the QoSMOS project.

Table 1 – Scenarios shortlisted as offering good success potential for future networks

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Scenario Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural broadband</td>
<td>Provides Internet connectivity to homes in rural areas. The links from homes to the base station may be several kilometres</td>
</tr>
<tr>
<td>Wireless backhaul</td>
<td>Provides a wireless backhaul service that could be more robust and cost effective than conventional technology</td>
</tr>
<tr>
<td>Emergency backhaul</td>
<td>This provides a backhaul service for emergency situations. As a result this type of scenario may require quick deployment and will have to be extremely reliable</td>
</tr>
<tr>
<td>Cellular extension in whitespaces</td>
<td>Allows a cellular operator to use whitespaces in addition to its own licensed spectrum</td>
</tr>
<tr>
<td>Emergency ad hoc network</td>
<td>This provides an ad hoc network in emergency situations. This may, for example, allow for emergency services to communicate with each other from an incident location. This service will have to be extremely reliable</td>
</tr>
<tr>
<td>Cellular extension inside to outside</td>
<td>Base stations within buildings (e.g. picocells and femtocells) provide access to the cellular network for devices outside of the building</td>
</tr>
<tr>
<td>Direct terminal-to-terminal in cellular</td>
<td>Here, mobile devices are able to communicate directly with no data going through the base station</td>
</tr>
<tr>
<td>Cognitive femtocell</td>
<td>Connected to the cellular network, femtocells provide ‘hot spots’ in homes and public areas</td>
</tr>
<tr>
<td>Cognitive ad hoc network</td>
<td>Allows for close by devices to form an ad hoc network for efficient communication and sharing of resources. This may include providing access to a core network such as the Internet</td>
</tr>
</tbody>
</table>

This shortlist of scenarios covers a variety of expected transmission ranges; the first four are seen as long range scenarios, the next three as medium range, and the final two as a short range.

Three criteria were identified that allow for the shortlisted scenarios to be evaluated. These were used to identify the relative strengths and weaknesses among these scenarios. A description of each criterion is provided here:
• **Criterion 1: Benefit of opportunistic network QoSMOS solutions** – For a new cognitive radio network solution to have a reasonable chance of success in the market it should offer a significant benefit over conventional mainstream technology. For example, mainstream technologies such as 3GPP long term evolution (LTE), which is progressing towards LTE-Advanced, and Wi-Fi have a great momentum in the communications market.

• **Criterion 2: Benefit for the actors** – A new system should offer a commercial attractiveness to the actors. The actors identified at this point were: existing cellular operator, existing fixed line/broadband operator, service provider, regulator, spectrum database owner, equipment vendor and the end user.

• **Criterion 3: Requirement for mobility and QoS** – The selected QoSMOS scenarios should be challenging enough to demonstrate the potential of the systems developed. Therefore the scenarios should have high mobility and/or high QoS requirements, both increasingly required by users.

A survey was developed to assess the shortlisted scenarios using the above criteria. The aim was to use the results of the survey to give each scenario a score; therefore questions were developed so that answers could be given on a scale ranging from 0 to 4. A high score would be positive for that scenario and a low score negative. The questions in the survey were denoted by $Q_{x,y}$ where $x$ represents the criterion being assessed and $y$ represents the question number for assessing criterion $x$. The questions asked for each of the shortlisted scenarios were as follows:

- $Q_{1,1}$ – Could this scenario be served by conventional technology?
- $Q_{1,2}$ – Do you believe cognitive radio will have the potential to serve this scenario significantly better?
- $Q_{2,1}$ – Which actor/stakeholder do you represent? (This question is not used for the scoring process, but simply to gain extra background information for $Q_{2,2}$. The responders select the type of actor/stakeholder that they represent from a list),
- $Q_{2,2}$ – How high do you believe the benefit of a cognitive radio system is for the actor you have chosen (for this scenario)?
- $Q_{3,1}$ – Which QoS classes should be supported in this scenario? (1=best effort only, ..., 4=real time conversational),
- $Q_{3,2}$ – Which degree of user mobility does the scenario comprise? (0=stationary, ..., 4=high mobility fast car or train).

Equation (1) shows how the overall score, $S$, for each scenario was calculated based on the survey responses.

$$S = \frac{W_i \cdot (4 - s_{i,1}) + W_2 \cdot s_{i,2} + W_3 \cdot (s_{i,1} + s_{i,2})}{2W_i + W_2 + 2W_3}$$  \hspace{1cm} (1)

Here, $s_{x,y}$ represents the average score (based on all of the survey responses) given for question $Q_{x,y}$ and $W_i$ represents the weight given to criterion $x$ where $W_1 + W_2 + W_3 = 100$. It was felt that each of the three criteria are equally important so all weights were given an equal value. However, later in this paper, we demonstrate the reliability of our results by showing how adjusting these weights does not significantly affect the relative overall scores of the scenarios. The $(4-s_{1,1})$ term accounts for the fact that $Q_{1,1}$ had a reversed scale.

The survey was distributed to all members of the evaluation group. There were 10 responses from project members and 9 from the EAB. Most of the responses were completed fully, although a couple of the responses only provided scores for a subset of the shortlisted scenarios. Based on the feedback from question $Q_{2,1}$ the responders represent the following actors: existing cellular operator (1), existing fixed line/broadband operator (1), service provider (1), regulator (4), spectrum database owner (1), equipment vendor (5), end user (1) and other (8). Some responders represented more than one actor/stakeholder. The
responders who selected “other” as the actor/stakeholder that they represent were found to be mainly broadcasters and research institutions.

Figure 1 shows the overall scores for each of the shortlisted scenarios using the survey feedback. These results show that some scenarios are clearly seen to have more potential than others.

![Image of Figure 1](image)

**Figure 1 – QoSMOS survey response (Average Scores)**

For the results in Figure 1 to be considered reliable it is important to demonstrate that adjusting the weightings from equation (1) does not affect the relative scores of the shortlisted scenarios, unless extreme weightings are used. Otherwise, it could be argued that the relative scores of the scenarios are based on the weightings that have been chosen rather than being a true reflection of the opinions of the survey responders. Figure 2a shows the average scores for the survey results for several sets of weightings. It is easy to see that adjusting the weightings has not had a significant effect on the overall average scores.

![Image of Figure 2](image)

**Figure 2 - Analysis of questionnaire feedback**

(a) Average scores using different criteria weightings. Weightings are shown as percentages in the form \(W_1, W_2, W_3\)

(b) Average ranking scores for question 3: Overall and individual scores.
As seen, to have success potential, a selected scenario should have high mobility and/or high QoS requirements. Figure 2b shows the average scores for questions Q_{3,1} and Q_{3,2} as well as the overall (average) score for these two question responses. All scenarios score very highly in QoS requirements (Q_{3,1}), however there is a great variation in the mobility requirements (Q_{3,2}). The peaks and troughs of the overall Q_3 score match with the peaks and troughs in the Q_{3,2} plot. By also comparing Figure 2b with Figure 2a it can be seen that the peaks and troughs also match. This shows that all scenarios score closely in most aspects of the survey, except for Q_{3,2} which acts as the main differentiating factor.

In order to create the final list of scenarios a final phase of rationalisation was done. This involved discussions with evaluation group members (i.e. the QoSMOS project partners and its EAB) and took the survey results as an input. One important decision made was that emergency scenarios should be given a higher priority as it was agreed that a cognitive radio solution for emergency scenarios could have a significant benefit over conventional technology.

The final list of scenarios should be a list of unique scenarios, so any scenarios that share many common characteristics should be merged into one. The following scenarios were produced during the merging process to replace the scenarios that they merge:

- Dynamic backhaul – Merging emergency backhaul and wireless backhaul,
- Cognitive femtocell – Merging cellular extension inside to outside to the previous cognitive femtocell scenario,
- Cognitive ad hoc network – Merging emergency ad hoc network to the previous ad hoc network scenario.

This merging process results in six remaining scenarios. It was decided these would become the final QoSMOS scenarios. The reason being that there is now a good coverage of long and short range scenarios which covers both cellular and non-cellular types of network. This is shown in Figure 3.

![Figure 3 – Coverage of long/short range and cellular/non-cellular by the final scenarios](image)

All of the original shortlisted scenarios are still included to some extent in these final scenarios. The survey responses have been used to identify the strengths and weaknesses in the original shortlisted scenarios and stimulated the discussions for this final rationalisation stage.
3. Final Scenarios

In this section, each of the six scenarios selected for the QoSMOS project, are described. These scenarios can be seen to fit into two generic scenarios: Long range (3.1, 3.2 and 3.3) and short range (3.4, 3.5 and 3.6). Diagrams for each of these scenarios, described in the following, are provided in Figure 4.

3.1 – Dynamic Backhaul

The dynamic backhaul provides wireless backhaul connections from access networks and remote terminals to a core network. The access side of the network and the backhaul nodes could be stationary, nomadic or mobile. For emergency situations there will also be a need for the dynamic backhaul to be quickly deployable.

Towards the access side of the backhaul connections traffic may be highly variable but further along the backhaul, after stages of aggregation, the traffic is likely to be less variable and could have a high capacity demand.

This dynamic backhaul can become more economically viable than conventional backhaul systems. The quick deployment of a system makes it well suited for both emergency situations and temporary events. The dynamic nature of the backhaul also means that it is more robust to changes that could occur at any point along the backhaul. Controlled aggregation load ensures fairness towards other opportunistic players.
Providing a fixed, high capacity service using opportunistic spectrum is a key challenge for satisfying this scenario, which may opt for the use of higher frequencies. Mobility requirements are low for this scenario, which may lead to a simplified architecture implementation.

3.2 – Cellular Extension in Whitespace

This scenario is where a cellular operator uses whitespaces in addition to its own licensed spectrum. Operators can gain from increased operational bandwidths, improved link quality and more flexible services.

To enhance coverage, long range links would be required which means that lower frequency whitespace spectrum would be ideal. Conversely, for capacity enhancement, short range links would be more appropriate meaning higher frequency whitespace spectrum would be ideal.

This scenario sets high requirements on the interworking and mobility across radio access technologies (RATs).

3.3 – Rural Broadband

This scenario provides Internet connectivity to homes in rural locations. Because of the intended long range, this scenario is ideally suited to whitespaces in lower frequency spectrum bands due to the favourable propagation characteristics.

This scenario is seen as an economically viable way for network operators and service providers to provide broadband connectivity to homes in locations where there is either no current fixed line connectivity or the fixed line connectivity can only provide low datarates. This is why rural locations are seen as the best candidate for this type of access.

This scenario has very high QoS requirements but typically will not involve any mobility.

3.4 – Cognitive Ad Hoc Network

This scenario involves a network which could contain many types of nodes (end user terminals, server nodes, etc.). All nodes must comply with regulatory requirements and so are likely to require, as a network, an Internet connection (for database access); otherwise strict sensing functionalities will probably be necessary.

A typical deployment could be for an emergency situation where emergency services require communications between one another.

This scenario has a high level of dynamics due to the node mobility, reorganisation and changing QoS requirements. As a result a cognitive solution for an ad hoc network that can opportunistically gain spectrum to satisfy its current demand should have a distinct advantage over conventional systems.

3.5 – Direct Terminal-To-Terminal in Cellular

In a cellular network all traffic from a mobile network typically goes through a central controller, such as a base station. Direct terminal-to-terminal allows for mobile terminals within a cellular network to communicate directly without the need for data passing through the central controller.

The benefit of such a scenario is that there is a reduction in the amount of shared resource used. For example, a packet transaction now only has to traverse one link (mobile terminal A to mobile terminal B) rather than two (mobile terminal A to base station, then base station to mobile terminal B). This can be deployed when the mobile terminals are
close to one another, and so should result in lower transmission power and better battery lifetime than a conventional system.

Strict requirements on the spectrum management is necessary in this scenario, implying a combination of geolocation and sensing.

3.6 – Cognitive Femtocell

Femtocells will always have a connection to the cellular core network. The femtocell will be deployed as what is often referred to as ‘hotspots’, where access to the cellular core network is provided for mobile devices. These end user devices are typically phones, smartphones, tablets and laptops and could also include RFID type devices.

Examples of femtocell deployments include wireless access points in homes and public hotspots. Also, indoor femtocells could be deployed so that they provide coverage for the outdoor areas.

The centralised control of the cellular network can mean that cognitive femtocells can cooperate to provide much lower interference and better user experience than conventional systems.

In this scenario a lower whitespace frequency is a benefit for inside to outside coverage due to better through-wall propagation characteristics. For the same reason, those whitespaces may not be preferred for indoor coverage because of the increased interference with the outdoors.

4. Conclusions

In this paper six scenarios have been described which are believed to have great potential for real world deployment in future cognitive radio networks. These scenarios cover a variety of ranges (short and long) for both cellular and non-cellular networks. The rationalisation process that led to the selection of these six scenarios is also described, including results from the survey carried out.

The results will be used to guide the QoSMOS project which will result in new tools and techniques that will cater specifically for these scenarios, taking these current cognitive radio concepts closer to fruition as real world deployed systems.

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References