The Cost of Knowing:

An economic evaluation of context acquisition in DSA systems

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Abstract

Much of the research in Dynamic Spectrum Access (DSA) has focused on the details of the enabling technologies. While this has been quite useful in establishing the technical feasibility of DSA systems, it has missed an important aspect of the overall DSA problem space: in order for operators, regulators and users to be interested in deploying DSA based networks, the expected costs should be in proportion to what the users are realistically willing to pay for services. Consequently, it is important to conduct cost estimates for different DSA approaches in parallel with the technical research.

In this paper, we will explore how the cost experienced by primary and secondary users can influence their incentives for participation in DSA. To do this, we compare the costs and cost structures of four context awareness approaches from each of them. The costs we will consider are incremental capital costs over a basic software radio using four different context acquisition approaches (sensing, databases, sensor networks, and cooperative sharing). Since DSA is still a relatively new research field, there is a lot of uncertainty associated with incremental cost analyses. As a result, the cost analysis is parameterized to allow for explicit reasoning about the bounds of cost components.

1. Introduction

Dynamic Spectrum Access (DSA) technology promises to increase spectrum sharing and help overcome the lack of available spectrum for new wireless services. DSA is an approach that can improve spectrum sharing where the concept of spectrum sharing is not a new, but it has been limited to simple applications with low power transmission devices (i.e. short range devices). DSA will only provide significant economic benefits if it becomes broadly obtainable and utilized; that is, if wireless services based on DSA are commercially successful.

Much of the research in DSA has focused on the details of the enabling technologies. While this has been quite useful in establishing the technical feasibility of DSA systems, it has missed an important aspect of the overall DSA problem space: in order for operators, regulators and users to be interested in deploying DSA based networks; the expected costs should be in proportion to what the users are realistically willing to pay for services. Consequently, it is important to estimate cost for different DSA approaches in parallel with the technical research.

Several approaches have been proposed by which radios could gain the context awareness necessary for sharing: on-board sensing, databases, sensor network and cooperative sharing [***1***]. Since Mitola's proposal for Cognitive Radios (CR), DSA research has been dominated by opportunistic sharing [***2***]. However, this is only one of several approaches that are available to users and operators. An alternative to opportunistic sharing is cooperative sharing, in which primary and secondary users explicitly coordinate their actions. Some research on cooperative DSA has been done. Peha and Panchipapiboon [***3***] showed that GSM operators would have an incentive to participate in secondary use; Tonmukayakul and Weiss delimited the circumstances under which potential secondary users would engage in secondary use [***4***] and Caicedo and Weiss considered the liquidity (hence viability) of secondary markets in spectrum [***5***]. Chapin and Lehr [***6***] analyze ways to use time-limited leases in spectrum rights, which mainly addresses the time dimension. The body of DSA research, by contrast, is focused on non-cooperative secondary sharing and considers frequency awareness (usually through sensing) and perhaps location awareness (through GPS). Research on cooperative systems generally focuses on the institutional context, but much less so on the spatio-temporal context. Thus, the context awareness of the DSA systems that researchers focus on is relatively limited.

This paper builds on previous work [***1***] which examined operating context acquisition approaches for DSA and feasible applications for secondary use for various kinds of spatio-temporal spectrum holes. It argued that the spatio-temporal operating context of specific environments matters to the selection of the appropriate technology for learning context information. In this research, we will explore how the cost experienced by each major stakeholder (e.g., primary user and secondary user) can influence his incentives for participation in DSA. To do this, we compare the costs and cost structures of four context awareness approaches from each stakeholder perspective.

The remainder of this paper is organized as follows: section II, characterizes cost modeling of learning approaches; section III, discusses and analyzes the primary users perspective; section IV, discusses and analyzes the secondary users perspective; section V, illustrates the economic evaluation including cost estimates and cost comparison; finally, section VI concludes the paper and point summarize the findings.

2.0 Cost Modeling of Learning Approaches

In our previous work [***1***], we characterized the types of spatio-temporal environments that DSA systems might encounter. Creating context awareness in a cost effective manner means that system designers need to consider the portfolio of environments and approaches to acquiring context information. Context awareness may be established in a number of ways, for example through the use of databases [***7***] or sensor networks [***8***] [***9***] or communications channels.

While most DSA researchers would freely acknowledge that spectrum holes are a spatio-temporal phenomenon, few of the proposed systems or context awareness approaches seek to establish the spatial as well as the temporal boundaries of the spectrum hole. A notable exception is found in [***10***] [***11***], which explicitly seek to measure and model spatial factors but still focus on non-cooperative secondary sharing. Similarly, in [***12***] the authors explicitly treat the spatial aspects of spectrum holes.

2.1 Spatio-Temporal Environments

Table 1 identifies 12 different types of spatio-temporal environments and begins to map applications into each category. There are some in which the cells of the table are blank; those may not be feasible combinations, or they may be ones for which applications have not yet been identified. As with all taxonomies of this kind, some actual systems may be hybrids of several categories; though for the purposes of this paper, we assume that all can be uniquely classified.

Table 1: Operational Contexts for DSA Systems (spatio-temporal environments)

		Spatial Characteristic		
		Static	**Periodic**	**Stochastic**
Temporal characteristic	**Static**	TV White Spaces	Sensor network	CDMA mobile
	Periodic	Daytime broadcast	Rotating Radar	-
	Fast periodic	LTE cell site	-	LTE mobile
	Stochastic	WiFi	-	Public safety

2.2 Learning Approaches

As we discussed above, context awareness in the broad sense has many dimensions. It should include (but not limited to): technical awareness, regulatory awareness, institutional context awareness and coordination mechanism awareness. Several approaches have been proposed by which radios could gain context awareness: (1) sensing, (2) databases, (3) sensor networks, and (4) cooperative sharing.

In this paper, these approaches will be evaluated and compared on the basis of their cost-effectiveness, which led to different outcomes based on the particular operating environment mentioned in Table 1. The cost effectiveness of a system can be evaluated from a number of viewpoints:

- **Regulator's perspective:** This is focused on the total system cost and is part of the total social welfare. This viewpoint was discussed in detail in our previous paper [***1***].
- **Secondary user's perspective:** This consists of the costs will be paid (or incurred) by secondary users; these users will compare spectrum sharing with different alternatives (related work in [***4***]).
- **Primary user's perspective:** As with secondary users, primary users are interested in incremental costs involved in sharing (related work in [***3***]).

In this paper, we will explore how the cost experienced by primary user and secondary user can influence his incentives for participation in DSA (i.e. primary and secondary user's perspective). So, we compare the costs and cost structures of four context awareness approaches from each stakeholder perspective. The costs we will consider are incremental capital costs over a basic software radio using the four different context awareness approaches (sensing, databases, sensor networks, and cooperative sharing).

In our previous work we focused only on the total system cost (i.e. the regulator's perspective). While this is useful from a social welfare perspective, it does not address the question of participation incentives for primary and secondary users. Thus, in this paper we explore the incentives that cost minimizing primary and secondary users have in each of the operating scenarios[1].

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[1] If revenues from each approach are equivalent, then a profit maximizing or secondary user will seek to minimize costs.

In the following subsections, we will summarize the main elements of incremental cost for the four different context awareness approaches.

2.2.1 Sensing

In this approach, cognitive radios sense the environment directly and make operational decisions based on those inputs. Sensing the environment involves the use of on-board sensors that measure the signal power of license holders, which may be augmented by cooperative sharing of sensing information with other DSA radios, which may or may not be communications partners. Cooperative sensing is widely studied, but its effectiveness depends on the density and distribution of the cooperating radios. Insufficient densities or uneven distributions can result in an higher likelihood of false positive or false negative spectrum hole detection decisions.

Estimated Cost Since all on-board secondary radios would need sensors, the cost of the system would be higher than the base software radio cost by $C_I = N_S \times C_S$, where N_S is the number of secondary users and C_S is the incremental cost of the sensing apparatus. No cost would be incurred by the primary user since the use is opportunistic. In cooperative sensing arrangements, radios would need a control channel to communicate with each other. For the sake of completeness, the total cost of this is $N_S \times C_C$, where $C_C$is the incremental cost of the control channel. So, the total incremental cost is $C_I = N_S \times (C_S{+}C_C)$.

2.2.2 Databases

The FCC, in their "White Spaces" decision, specified the use of a database that would have to be consulted before a radio could be used. But the use of database approaches is more widespread: the IEEE 802.22 standards committee is considering them, they are included in the Cognitive Pilot Channel (CPC) proposals [***13***], and they are implicit in the REM concept [***14***].

Estimated cost The incremental system cost for this approach would be $C_I = C_{DB} + [N_S \times (C_S + C_M + C_L + C_C + C_U + \ Cq)]$, where $C_{DB}$is the total cost of the database, C_M is the cost of memory to store the database on the device, C_L is the cost of the location-aware components, C_U is the additional cost for updating the database (Note: C_U is different than C_C; where C_C is the incremental cost for control channel that mainly between secondary users; as it is illustrated in sensing approach; so, C_U is to count for additional cost due to the existence of the database), and $C_q$is the cost of querying the database ($C_q \geq C_U$). Since C_M , C_U and C_q are relatively very low (C_U and C_q may be covered with/under C_C cost); So, the total incremental cost is: $C_I = C_{db} + N_S \times (C_S + C_L + C_C)$.

2.2.3 Sensor Network

In this approach, a cognitive radio would acquire context information by querying the sensor network. Thus, some kind of control channel (such as a CPC) is assumed. One of the key objectives of this approach is to simplify the radios, which would result in reductions in cost and energy consumption. Another is to improve the availability of spectrum holes based on superior local knowledge.

Estimated Cost In general, we expect that the incremental system cost for sensor network approach would be: $C_I = C_{SN} + N_s \times (C_C + C_L)$ since the radios need not have sensing functionality.

2.2.4 Cooperative sharing

White spaces can be identified by explicit communication between the primary and secondary users, as discussed in [***4***], [***5***] and [***6***]. In fact, as shown in [***3***], explicitly coordinated approaches would possibly provide more spectrum for sharing, since license holders can monetize their spectrum resources more effectively. In this approach, no sensing or sharing protocols are required, since the secondary user would have exclusive use for a limited period.

Estimated Cost The incremental costs of this approach are the cost of the control channel for both the primary and the secondary users and the cost of the broker, so $C_I = C_B + N_s \times (C_C + C_L) + (C_{CP} \times N_P)$, where C_B is the cost of the broker, C_{CP} is the incremental cost of the control channel for the primary user, and N_P is the number of primary users. If there is a centralized interface for the primary user to feed the required data to the secondary users through the control channel, then we can set $N_P = 1$.

3.0 Primary Users Perspective

In this section, we will evaluate and compare the four different approaches on the basis of their cost-effectiveness from the perspective of the primary users, across the twelve environments that were described in Table 1. This means we will try to find the primary users preference among leading approaches in each environment.

Since DSA is still a relatively new field, there is a lot of uncertainty associated with incremental cost analysis. As a result, the cost analysis is parameterized to allow for explicit reasoning about the bounds of cost components. In our analysis in this section, we assume the following:

- A third party will pay for the "cost elements" that intermediate primary and secondary users. Examples of these kinds of costs include the cost of databases, costs associated with establishing a spectrum broker and the costs of constructing the sensor network. Presumably, the third party will recover these costs from the primary and/or secondary users through some sort of fees, though we set these to zero this analysis for simplicity[2].
- There are four different approaches in each environment that we can compare. We will choose the most cost efficient one out of the two leading awareness approaches for each environment listed.
- In temporal fast periodic environments, spectrum holes occur periodically but have a very short period such $T_s \geq T_h$ (T_s: the time required to sense the spectrum hole, T_h: the period of the spectrum hole). In such cases, a cognitive radio device could not use the spectrum hole without some kind of external support. So, in all three related environments, the cooperative approach prevails.

Table 2 summarizes the results of our analysis. To illustrate the approach we take in our analysis, we describe the temporally and spatially static operating environments in some detail. There are two leading awareness approaches in this static-static environment: Database and Cooperative approaches.

- **In database approach:** a primary user does not have to bear any cost, since the related cost of this approach will be carried by secondary users and the third party.
- **In cooperative approach:** the primary users will have to take the incremental cost of control channel for the primary users (C_{CP}).

So, from primary user's perspective, database approach prevails.

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[2] Both Google and Microsoft do not anticipate charging secondary users for access to their White Spaces database at the time of this writing, to the best of the knowledge of the authors. We generalize this to all intermediated services.

Table 2 - Context Learning approaches by operating environment

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<tr><th colspan="2" rowspan="2"></th><th colspan="3">Spatial Characteristic</th></tr>
<tr><th>Static</th><th>Periodic</th><th>Stochastic</th></tr>
<tr><th rowspan="4">Temporal Characteristic</th><th>Static</th>
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<tr><th>Fast periodic</th>
<td><table><tr><th></th><th>C_S</th><th>C_C</th><th>C_L</th><th>C_{DB}</th><th>C_{SN}</th><th>C_B</th><th>C_{CP}</th></tr><tr><td>Cooperative</td><td></td><td>S</td><td>S</td><td>T</td><td></td><td>T</td><td>P</td></tr></table></td>
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<tr><th>Stochastic</th>
<td><table><tr><th></th><th>C_S</th><th>C_C</th><th>C_L</th><th>C_{DB}</th><th>C_{SN}</th><th>C_B</th><th>C_{CP}</th></tr><tr><td>Sensing</td><td>S</td><td>S</td><td></td><td></td><td></td><td></td><td></td></tr><tr><td>Sensor Net</td><td></td><td>S</td><td>S</td><td></td><td>T</td><td></td><td></td></tr></table></td>
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P	Primary users cost
S	Secondary users cost
T	Third party cost

We follow the same process for the remaining environments (space does not allow for a full exposition) and the results are summarized in Table 3. In four environments, a primary user has no preference over either sensing or the sensor network approach (it is marked as "non" in the table).

Table 3 – Primary Users Preferences

		Spatial Characteristic		
		Static	Periodic	Stochastic
Temporal characteristic	Static	Database	Sensor Network	Non
	Periodic	Database	Sensor Network	Non
	Fast periodic	Cooperative	Cooperative	Cooperative
	Stochastic	Non	Non	Non

4.0 Secondary Users perspective

In this section, different approaches are evaluated from the perspective of the secondary users. From section 2.2; we can notice that more cost elements are related to secondary users than to primary users. That does not mean the secondary users will have to pay a larger portion of spectrum sharing cost, rather the single cost element will vary from environment to another over the different approaches (more details in [***1***]). In addition, we will keep the same assumptions we made in the preceding section.

Table 2 summarizes the results of our analysis. Again, to illustrate, we describe the temporally and spatially static operating environments in some detail. There are two leading awareness approaches in this static-static environment: Database and Cooperative approaches.

- **Database approach:** the secondary users will bear the cost of three cost elements: C_S, C_L, and C_C. However, since we are in the static-static environment, it is not necessary to have a sensing component in the secondary user's radios (except to coordinate channel sharing), as has also been recognized by the FCC in their White Spaces proceeding. So, the secondary users will bear the cost of C_L and C_C only. As we assume before, the database is developed by a third party. .

- **Cooperative approach:** the secondary user will have to assume the cost of C_L and C_C as well.

So, from a secondary user's perspective, database approach has the same cost elements as the cooperative approach. Since we are in static-static environment, we expect that the cost of a control channel between the secondary users (C_C) in the cooperative approach will be higher due to the involvement of spectrum broker rather than simple database. The rationale for this belief is that acquiring context information from a database consists of a query and response (two messages). In a cooperative approach, a secondary user has to issue a query to learn about the options, then, at least two messages must pass (an offer and an acceptance), but perhaps more. Hence, we believe that C_C will be at least as high as the database case. To be conservative, we assume, the secondary users do not have a preference (it is marked as "non" in the table).

Let us consider the case of temporally static and spatially periodic operating environment for further illustration. Here, there are two leading awareness approaches: Sensor network and Cooperative.

- **Sensor network:** the secondary users will bear the cost of C_L and C_C.
- **Cooperative approach:** the secondary user will have to take in his side the cost of C_L and C_C as well.

From a secondary user's perspective, sensor network approach has the same cost elements as cooperative one. However, C_C in sensor network approach will be less than cooperative, because, like the database, the necessary messages require simply a query and response. Because the parameters of the environment are more complex, we expect the bargaining to require more messages. So, the secondary users in this case will have a preference for the sensor network approach.

Following a similar analysis for the remaining environments; we end up with Table 4, which summarizes the results.

Table 4 – Secondary Users Preferences

		Spatial Characteristic		
		Static	Periodic	Stochastic
Temporal characteristic	Static	Non	Sensor Network	Sensor Network
	Periodic	Cooperative	Sensor Network	Sensor Network
	Fast periodic	Cooperative	Cooperative	Cooperative
	Stochastic	Sensor Network	Sensor Network	Sensor Network

5.0 Capital costs of context acquisition

Few attempts exist in the research literature that set out to perform cost estimation of spectrum sharing technologies. An exception is found in [***15***] [***16***], where the authors proposed and evaluated different business case scenarios for the deployment of a sensor network aided cognitive radio system in a typical European city. The problem they faced is that it is very challenging to correctly identify the cost of the different system components needed for spectrum sharing scenarios. Since DSA is still a relatively new research field, there is a lot of uncertainty associated with incremental cost analyses.

In this section, we aim first to construct the upper and lower bounds of all the main cost elements discussed above and then apply our cost evaluation over different context awareness approaches. We will compare all the context acquisition options from an overall cost perspective (which we have previously called the "regulator's perspective").

5.1 Cost Estimation

In the following subsections, we will try to estimate the cost of seven different components that we used in our analysis above. It is very important to note that some of these costs are the incremental capital costs over a basic software radio device.

5.1.1 Cost of radio sensing $\{ C_s \}$

The incremental cost to have sensing capability (as *embedded system*) in the radio devices is very difficult to estimate. It will be embedded as part of a complete device, which may ultimately be integrated, and here we wish to estimate only the incremental cost to allow spectrum sharing. In general, embedded systems are mass-produced, benefiting from economies of scale. Since cognitive radios have not reached this scale yet, estimating the future cost requires knowing the cost trajectory over time. Since we cannot know this, we will estimate the cost by examine some radio sensing equipment available today.

Crossbow's TelosB Mote TPR2400 [***17***] is an open-source platform designed to enable cutting-edge experimentation for the research community; it was developed by the University of California, Berkeley. This spectrum sensor operates in the 2.4 GHz ISM band with sensing bandwidth of 5 MHz. According to Crossbow Technology company, TelosB is priced at $99 [***18***]. Based on TelosB datasheet, it is very limited wireless sensor to 2.4 GHz. However, we will use this price as a benchmark.

Rice University's WARP [***19***] is a scalable and extensible programmable wireless platform, built from the ground up, to prototype advanced wireless networks. In 2007, the Rice team starting distributing WARP hardware to wireless researchers at select institutions. Starting in the summer of 2008, Mango [***20***] assumed responsibility for the manufacturing, sales and support of WARP hardware. As of April 2011, the platform has been adopted by 100+ research groups around the world. It is priced at $3,500 and $6,500 for Academic and commercial usage, respectively [***20***].

Ettus Research company manufactures the USRP platform [***21***], which is designed for applications requiring RF modulation in frequencies up to 6 GHz with wide bandwidths and MIMO configurations. The Universal Software Radio Peripheral (USRP) board has become an indispensable hardware component. A USRP board consists of one mother board and up to four daughter boards. The price for the mother board is $700 and daughter boards cost between $75 and $275 each. A USRP2 Package

(Datasheet [**22**]); which includes Motherboard, Enclosure, SD Card, 2 SMA-Bulkhead Cables, Ethernet Cable, Power Supply, and Hardware Package; costs around $1,400 [**21**].

TelosB Mote TPR2400, WARP and USRP platforms are used in the deployment of an experimental spectrum sensor test-bed for constructing indoor radio environmental maps [**23**]. From the above, and by taking economics of scale into account, we will assume the incremental cost of sensing (over radio devices cost) is around $500 to $750.

Secondary users need sensing capability in the first two approaches: sensing and database. However, in the database approach, the radios will need less sensing ability since they get their needed information about the environment from the database. As a result of that, we will assume two different costs for each approach: $650 for sensing approach (C_{S1}) and $450 for database approach (C_{S2}).

5.1.2 Cost of database $\{ \boldsymbol{C_{DB}} \}$

A database is an organized set of data to model relevant aspects of reality in a way that supports processes requiring this information. In our case, the database will contain all needed information to utilize the spectrum holes and mange related secondary users. There are many ways the database can be classified. It can be classified by the hierarchal design, type of their contents or by application area; and in each case the cost will vary significantly.

There are not many detailed cost estimates of database systems that have been published. In general, the cost of these systems is a function of the transaction rate and the response time requirement. Since these apply primarily to static systems, we do not expect the transaction rate to be high, especially initially, nor is the response time requirement particularly stringent. One of the comparison that was published by Sybase [**24**] (Advantage vs. Oracle vs. Microsoft) assumes a 50 users network environment using a client/server database application. By their estimate, the average total cost will be around $53,000. This cost only includes software, hardware, installation and administration.

The Sensor Network Aided Cognitive Radio (SENDORA) project [**15**] proposed a ”fusion center” that connects the sensor network and the communication network and acts as an aggregation point for the data from the sensors in the sensor network. In many ways, this is functionally similar to the proposed database, so their cost estimate can serve as a useful reference point. They estimated the capital cost to be $216,000 with a cost of $14,400 for installation. To be conservative, we assume the cost to be $250,000 for no more than 10,000 users.

5.1.3 Total cost of the sensor network $\{ C_{SN} \}$

There are many important parameters that will drive the cost of a sensor network, including the sensors density, the type of sensing technology and the sensor's base-station cost. The sensor density is dependent on a variety of factors, including the spectrum band, the characteristics of the primary signal and the sensing bandwidth.

Installation and Base Station Cost

A new sensor base station or site sharing cost depends on the network deployment topology. It can be as costly as building new cellular network or as cheap as a minor network upgrade cost (if a mobile operator will allow free site sharing). We will assume the installation cost of a sensor base station is similar to the cost of outdoor WiFi station (only the station not WiFi access point).

By going over the outdoor WiFi deployments and initiatives, we can get some estimates of the cost to install a simple sensor base station. The cost to install a small radio is the same whether the radio equipment is expansive or cheap. Based on 2005 report prepared by Joseph Bardwell, CEO of Connect802 Corporation [***25***], the industry average (supported by the Wireless Fidelity Alliance -WiFi) tend to suggest that there is an up-front cost of roughly $1000 per radio for installation. Jay Horwitz, Senior Analyst at Jupiter Research, estimated the average cost of building and maintaining a municipal WiFi is $30,000 per square mile each year[***26***]. This cost includes the WiFi access point. To get more insight on this, Google has implemented a wireless mesh in Mountain View and the city of Corpus Christi with 400 routers covering 12 sq-miles and 300 routers covering 18.5 sq-miles, respectively. Similarly, Huang developed a model for municipal WiFi coverage [***27***]. So, by averaging these, we end up with $1,200 as cost of each outdoor access point.

In addition, an economic analysis of networking technologies, done by UC Berkeley, estimated the cost of installing WiFi access point by $500 [***28***]. In another business case study in Spain [***29***], they estimated the cost of installation is $426 (€300) per access point. From the above, we can estimate the installation cost (including the base-station) to be $800 per sensor station.

Sensor Cost

As far as we are aware, there is only one study that estimated the cost of sensors as part of sensor network (not as secondary user's radios). In the SENDORA project, three business case scenarios are proposed and evaluated for deployment of a sensor network aided cognitive radio system in a typical European city; where the sensor cost estimated to be $433. In the previous section, we estimated the incremental cost of a sensor in a radio to be $650, so we think SENDORA is underestimating the cost. We believe that $1,000 to $1,500 per sensor is a better initial cost estimate. Adding the cost of installation to this, the estimated cost of sensor network is $2,000 per sensor station.

Sensor Density

In the SENDORA project, they based their analysis of sensor density on a case study with LTE as the primary system. They consider two input parameter sets: the strict parameter set includes parameters that make sensing more challenging, and the loose parameter set relaxes some physical constraints and requirements. The result is that they use a sensor density of 65 sensors/km^2, which is the mean of the values of the strict and loose LTE cases. We will rely on their analysis and assume the same sensor density.

5.1.4 Cost of the broker $\{ C_B \}$

A Secondary spectrum broker is an entity that will manage the secondary spectrum market in some or all of the available spectrum bands. It will require an interface between primary and secondary users as well as database of the managed spectrum inventory. We assume that this is similar to the database that was discussed earlier. In addition to the database, there is a control channel which will be discussed below. So, for simplicity, we assume the capital cost of the broker is approximately the same as the database, or $250,000 for 10,000 users. Since both primary and secondary users must use this broker, the number of users is the sum of primary and secondary users.

5.1.5 Cost of control channel $\{ C_C \}$

It is not easy to estimate the incremental cost of the secondary user's control channel. We do not expect that the control channel cost would result in a major monetary cost since the secondary radios must communicate with each other anyway. Since the control channel cost exists on all the four context awareness approaches (sensing, databases, sensor networks, and cooperative sharing), and because we compare them based on the cost parameters; we ignore this cost in this (incremental cost) analysis as a common cost.

5.1.6 Cost of the location-aware components $\{ C_L \}$

Since the localization is very important in spectrum sharing, we will need to include this cost in our analysis even though it is relatively low. The cost of GPS chipset (applications into mainstream mobile phones) varies from $1 to $35, based on price comparison over multiple manufacturers globally. For example, based on iSuppli Estimates[3], the GPS component in the iPad cost $2.6 whereas in the iPhone 4 the baseband-GPS combo has an estimated cost of $16.41. In this analysis, we will assume the cost of location-aware components is $15.

5.1.7 Cost of control channel for the primary user $\{ C_{CP} \}$

The cost of the primary user's control channel is the incremental cost for the primary user assuming there is cooperation between the primary and secondary users. If the primary user is fixed and the environment is semi-static, the control channel between the primary and secondary users could be very simple and hence low cost, such as a virtual channel on an existing network. The capacity and efficiency of this channel depends heavily on the communications intensity. We will assume that no communications facility exists for the primary user, so we will presume $1,000,000 for all costs related to the primary user control channel including channel interfaces with the broker and secondary users.

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[3] iSuppli Corporation; Feb 2010.

5.2 Cost Evaluation

To evaluate the cost and compare the different approaches, we developed a simple case and applied the estimated parameters. We consider an urban area of 100km^2, with fewer than 10,000 secondary users. The resulting number of base stations is 6,500 (based on 65 sensors/km^2).

Table 5 – Summary of Cost Estimates

Cost Component	Cost Estimate ($)	Remarks
C_{S1}	650	Sensing; Per radio
C_{S2}	450	Database; Per radio
C_C	-	Ignored
C_L	15	Per radio
C_{DB}	250,000	For all
C_{SN}	2,000	Per station
C_B	250,000	For all
C_{CP}	1,000,000	For all

To do the analysis, we will group the 12 environments mentioned in Table1 into 3 groups, based on the similarities between them to do the cost comparison; as follows:

Group-1: It contains static-static environment only. In this set, both sensing and database approaches will not need sensing capability over the secondary radios, due to the static nature of spectrum holes.

Group-2: It contains static-periodic, periodic-static and periodic-periodic environments.

Group-3: It contains the rest of the environments.

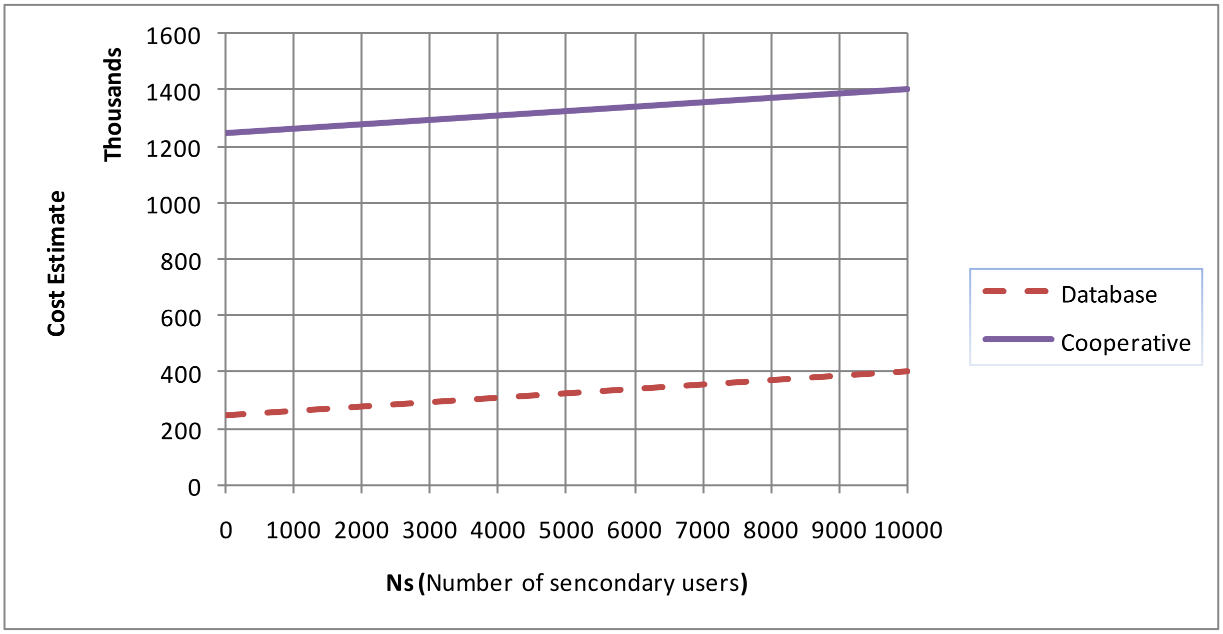
5.2.1 Group-1

Table 6 summarizes the related cost elements to database and cooperative approaches, since there are the two leading awareness approaches in this group. Also, it shows the percentage of change needed to alter the result for each cost element. From the result, we see that the database is always the better option in group 1 cases. This result will change only if the cost estimates of the database increased by 400% or the cost estimate of primary control channel decreased by 100%. Figure 1 shows the relation between the cost estimate and number of secondary users.

Table 6 – Summary of Group-1 Cost Analysis

Cost Component	Cost Estimate ($)	% change to alter the result	Remarks
C_{S1}	0	-	The leading awareness approaches in this group are: Database and Cooperative
C_{S2}	0	-	
C_L	15	Never	
C_{DB}	250,000	+400%	
C_B	250,000	Never	
C_{CP}	1,000,000	-100%	

Figure 1– Cost Estimate curves for Group 1



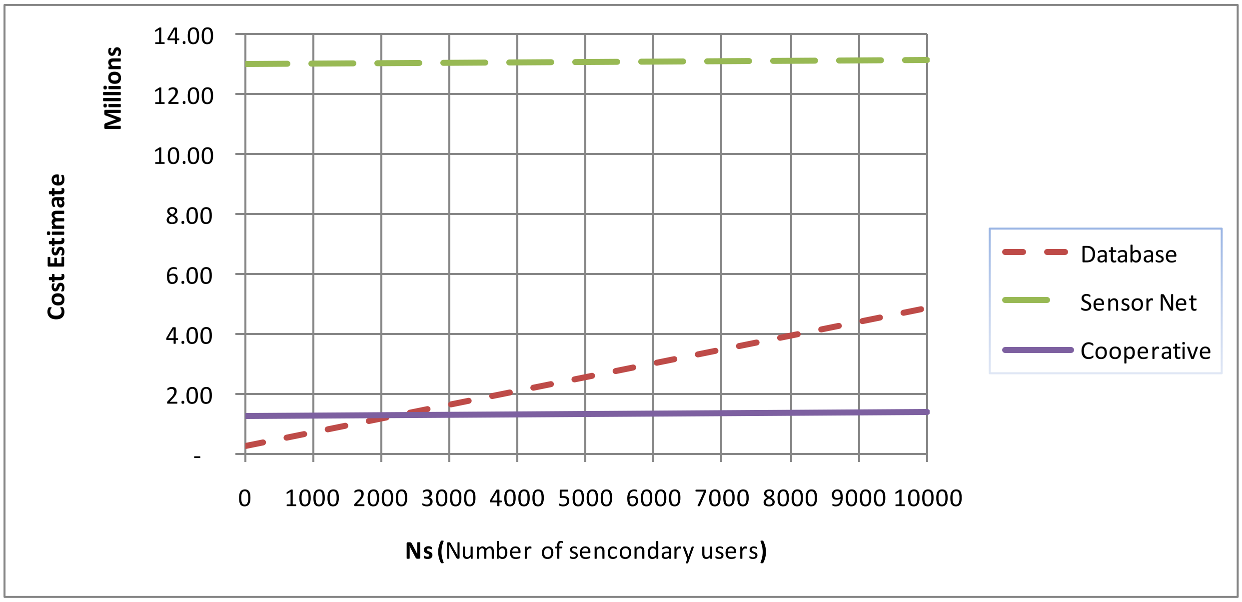
5.3.2 Group-2

The analysis of group 2 environments follows the same procedure as group 1 and is shown in Table 7 and Figure 2. We will do sensitivity analysis at the end of this section.

Table 7 – Summary of Group-2 Cost Analysis

Cost Component	Cost Estimate ($)	% change to alter the result	Remarks
C_{S2}	450	-79% : turning point @ N_S=10,000 0% : turning point @ N_S=2,200 +100% : turning point @ N_S=1,000	The leading awareness approaches in this group are: Database, Sensor Network and Cooperative
C_L	15	Never	
C_{DB}	250,000	+400% : Coop. is the less at N_s=1	
C_{SN}	13,000,000	-63% : Sensor Net start to be cost effective compare to Sensing	
C_B	250,000	Minor change	
C_{CP}	1,000,000	-80% : turning point @ N_S=500 0% : turning point @ N_S=2,200 +350% : turning point @ N_S=10,000 **Note:** more than +1275%, Sensor Net start to be cost effective over the Cooperative	

Figure 2– Cost Estimate curves for Group 2



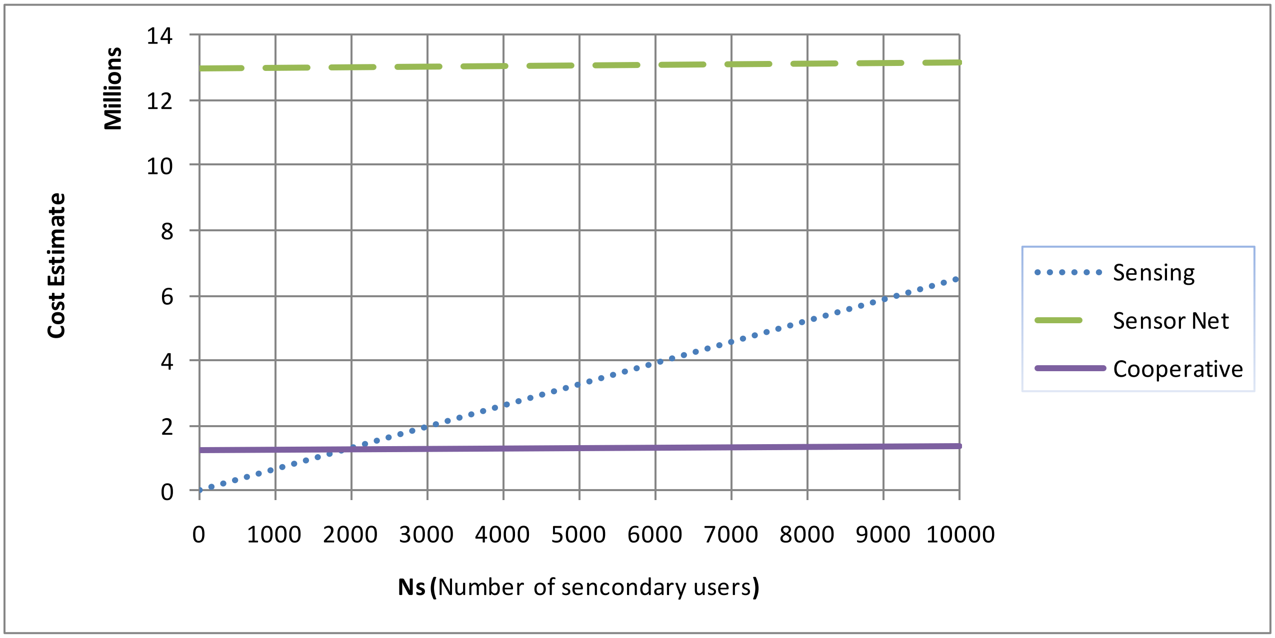
5.2.3 Group-3

The analysis of group 3 environments follows the same procedure as group 1 and is shown in Table 8 and Figure 3. We will do sensitivity analysis at the end of this section.

Table 8 – Summary of Group-3 Cost Analysis

Cost Component	Cost Estimate ($)	% change to alter the result	Remarks
C_{S1}	650	-79% : turning point @ N_S=10,000 0% : turning point @ N_S=2,000 +100% : turning point @ N_S=1,000 **Note:** over +100%, Sensor Net start to be cost effective over Sensing	The leading awareness approaches in this group are: Sensing, Sensor Network and Cooperative
C_L	15	Never	
C_{SN}	13,000,000	-51% : Sensor Net start to be cost effective compare to Sensing	
C_B	250,000	Minor change	
C_{CP}	1,000,000	-80% : turning point @ N_S=7500 0% : turning point @ N_S=2,000 +510% : turning point @ N_S=10,000 **Note:** more than +1175%, Sensor Net start to be cost effective over the Cooperative	

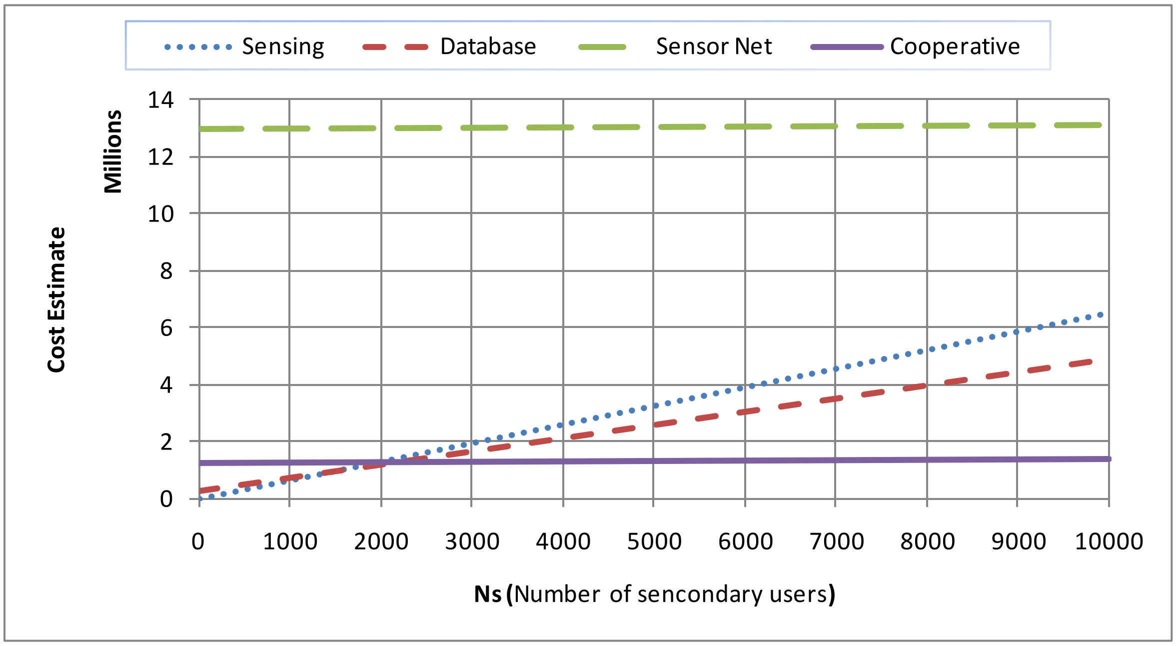
Figure 3– Cost Estimate curves for Group 3



5.3 Cost Comparison

In this section, compare the total system cost, as well as those borne by the primary secondary users, respectively, based the case model and cost estimates that were described above.

Figure 4– Cost Comparison based on Total System Cost



System cost perspective:

From Figure 4 we can conclude the following:

- For N_S< 2,000 the context awareness approaches in order of cost effectiveness is: sensing, database, cooperative and sensor network, so sensing is the most cost effective option for small numbers of secondary users.
- For 2,000 < N_S < 10,000 the order is: cooperative, database, sensing and sensor network, so cooperative approaches dominate for large numbers of secondary users.

Interestingly, these outcomes are consistent with our previous work [***1***].

Primary user's perspective:

In section 3, we concluded that the primary user will directly bear the cost of its control channel in cooperative approach only, and nothing in the other approaches. Thus, based only on incremental system costs primary users prefer all other approaches to context awareness above cooperative. Note that if the cost of interference were included, this outcome could change since cooperative sharing allows for explicit control of secondary user interference.

Secondary user's perspective:

Since cost of sensing (C_{S1} or C_{S2}) is the dominant cost that secondary user will have to consider, from Figure 4 we conclude that the ranking of secondary users is (1) cooperative or sensor network, then (2) sensing or database.

Cooperative and sensor network is its first option because the secondary users bear lower cost elements. Sensing and database are more or less identical from pure a cost analysis; however, in each specific environment this general result will change. One reason for that is we assumed that a third party will pay for the database cost. If this were not the case, secondary users would have to bear the database cost and, from Figure 4, would end up with the following preference ordering: (a) for $N_S <$ 2,000; the sensing approach is most cost effective, and (b) for $N_S >$ 2,000; the database is less costly when number of secondary users is high enough to compensate for the cost of database (since C_{S1} is more costly than C_{S2}).

5.4 Sensitivity Analysis:

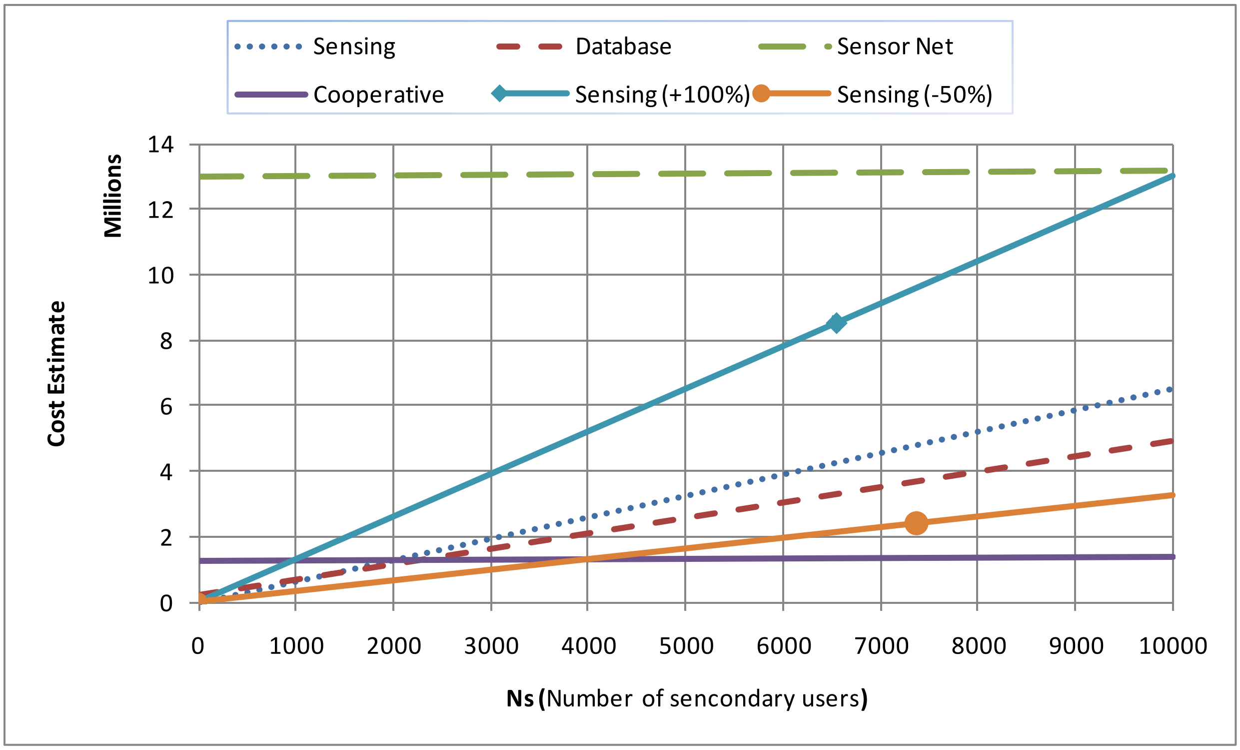
From last section, it is clear that we have three significant cost components that are highly uncertain and where the outcome of our analysis would change if the cost estimates changes. Those are C_{S1} , C_{SN} and C_{CP}. In this section, we examine the sensitivity of the outcome for each one of these separately. To do this, we will plot all cost estimate curves for the for four context awareness approaches then we will vary each cost element to determine how that affects the outcome.

In a previous section, we grouped the twelve environments to three groups and then studied each group separately by examining the leading awareness approaches to determine which option is the most cost effective. In this section we will study the level of variance that will affect the overall outcomes by varying each one of those three cost elements separately.

5.4.1 Sensitivity analysis of C_{S1}:

To do the sensitivity analysis for C_{S1}; we plot all cost estimate curves for the four context awareness approaches then we vary C_{S1} (which will affect only the sensing approach curve). As in Figure 5, if this cost element (i.e.C_{S1}) increases by 100%, we will reach a point where the sensor network approach is preferred over sensing when there are more than 10,000 secondary users. On the other hand, by decreasing our cost estimate of C_{S1} by 50%, the model indicates that the sensing approach is more cost effective than database approach all the time regardless of the number of secondary users.

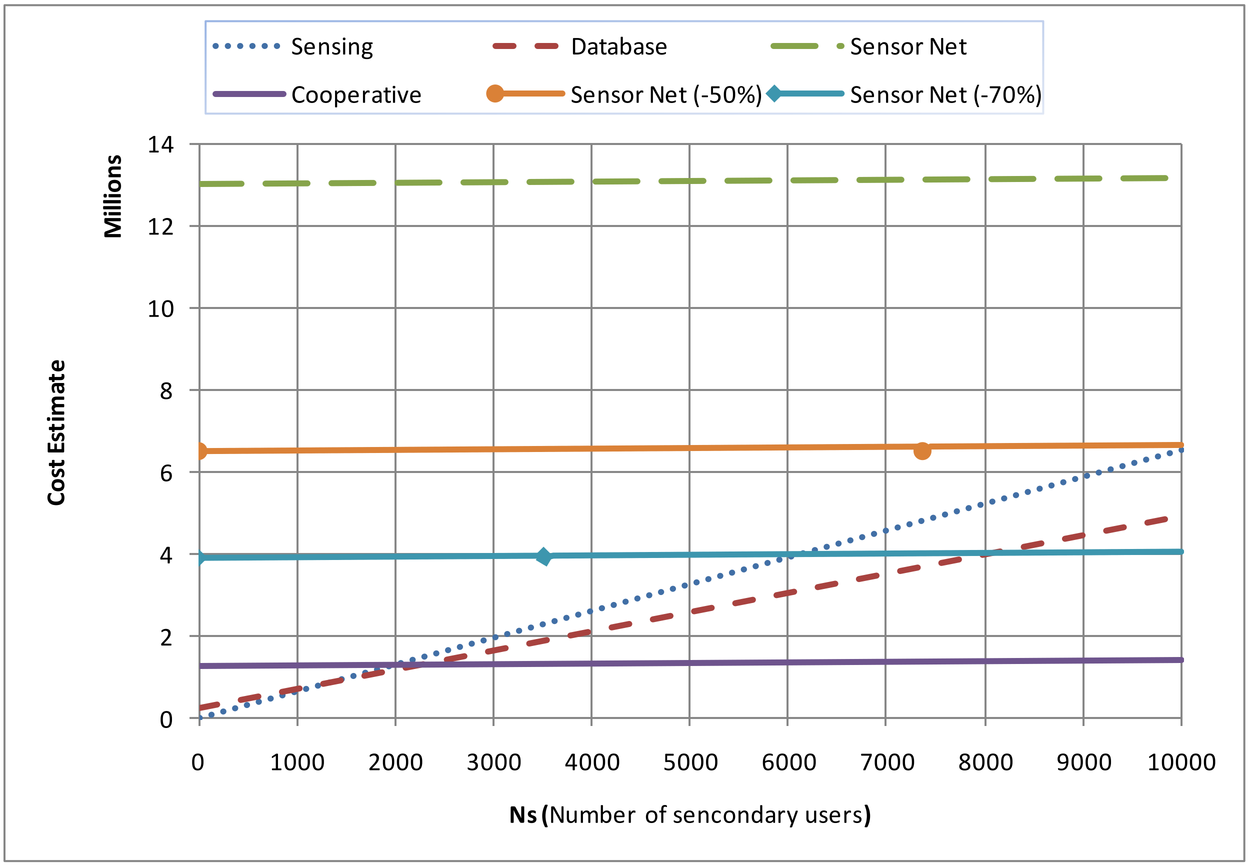
Figure 5– Sensitivity analysis of C_{S1}



5.4.2 Sensitivity analysis of C_{SN} :

Given that sensing network approach is the most costly approach based in our cost estimates and case model, we will vary C_{SN} downwards only. As shown in Figure 6, there isn't any change in the outcome until we decrease it by more than 50%. This decrease in C_{SN} would be as a result of the decrease in cost estimate per base station (estimated to be 2,000$; including the installation and sensing equipment) or by decreasing the sensors density (estimated to be 65 sensors/km^2). Thus, any reduction in the cost estimate less than 50% will not make any change which gives more confidence for our estimated outcomes. However, we belief that the cost of senor network is highly uncertain and vary significantly based on the way it will be deployed. Further, if the sensor network is designed to provide multiple services (e.g. enforcement), then the cost of that network could be amortized more broadly, resulting in a lower cost to DSA.

Figure 6– Sensitivity analysis of C_{SN}

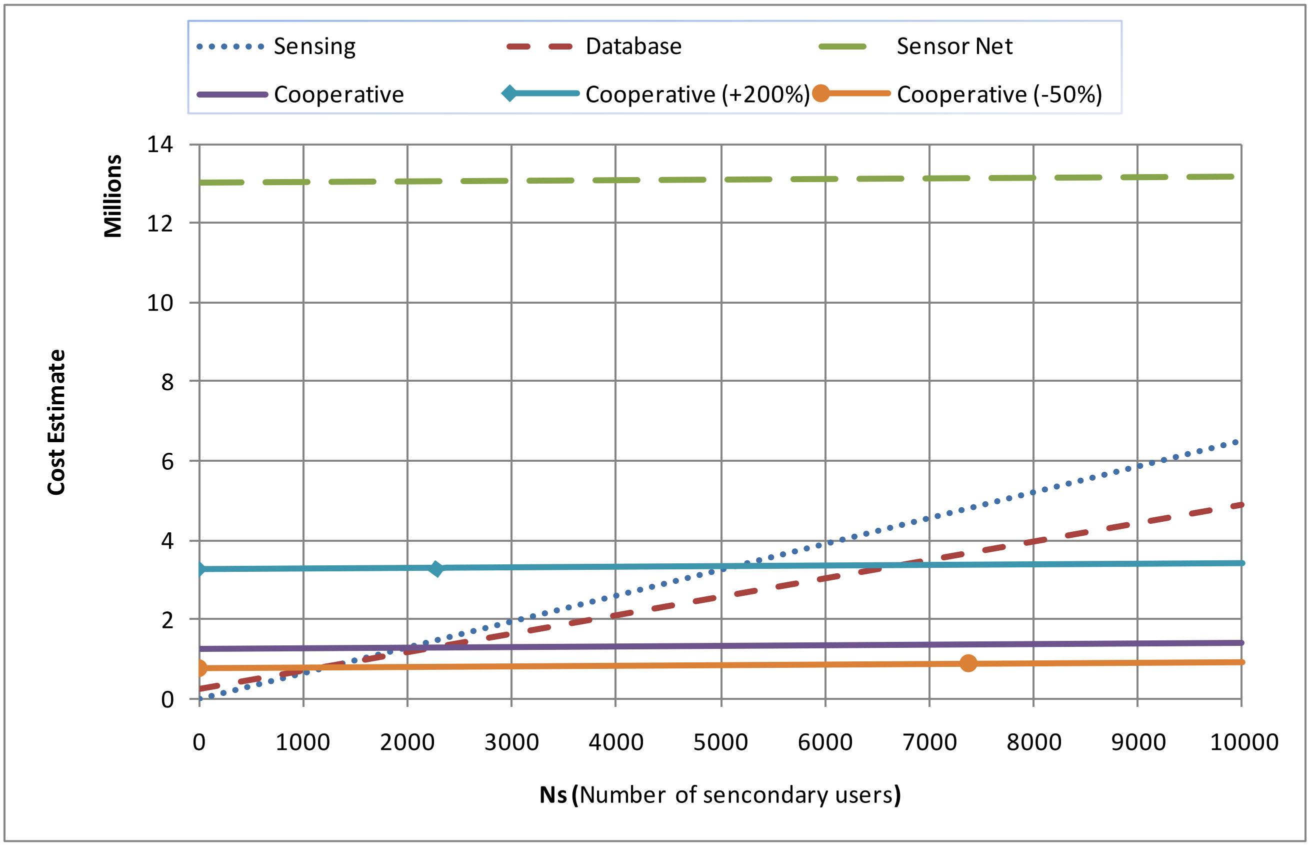


5.4.3 Sensitivity analysis of C_{CP} *:*

As shown in Figure 7, the outcome of our analysis is very sensitive to the primary control channel cost. If it is increases by 200%, the point at which cooperative sharing is preferred moves from N_S= 2,000 to around N_S= 5,500. If it is decreased by 50%, the turning point occurs at N_S=1000.

As it was mentioned before, we did not build our estimate of the primary control channel cost on very solid foundation, so we have the lowest confidence in our estimate as compared to the others.

Figure 7– Sensitivity analysis of C_{CP}



6.0 Summary and Conclusion

In this paper, we explored how the total system cost and the cost experienced by each major stakeholder (i.e. primary and secondary user) can influence the incentives for participation in DSA. We compared the costs and cost structures of four context awareness approaches from the primary user's perspective and the secondary user's perspective. Based on that, we had different outcomes for each of the major stakeholder.

To make this study more realistic, we estimated the costs for each of the major cost elements for each approach. It gives an indication of how much it would cost to choose one of those approaches. Consistent with our previous work, we considered only the incremental capital costs over a basic software radio. Since DSA is still a relatively new field, there is a lot of uncertainty associated with these estimates. As a result, the cost analysis is parameterized to allow for explicit reasoning about the bounds of cost components. The sensitivity analysis shows that the outcomes of this study will not vary that much by changing when the cost estimates change, unless the deviations are large, which we deem as unlikely. A secondary benefit of this study is that we have a better intuition of the proportionality and the relationship among the cost elements which help make our further research more realistic.

Moreover, generally speaking, it is obvious that sensor network is a very costly option in comparison to the others. Thus, for this approach to be successful either cost reductions are needed or it needs to be amortized over a larger number of services.

What is also notable is that regulators (who should be system cost minimizers), primary users and secondary users each had different preferences for context acquisition techniques based on system costs. Depending on the environment, regulators and secondary users prefer cooperative sharing, where, for primary users, this was their least preferred approach. Clearly, incremental capital costs are only one economic factor among many that should be considered (e.g., cost of interference is another) when examining stakeholder incentives. Nonetheless, the results of this research is suggestive of a range of interesting research topics related to Coasian bargaining among stakeholders, cost sharing approaches, regulation of spectrum sharing and bargaining under diverse stakeholder preferences, especially as they relate to the systems-level implementation of dynamic spectrum access systems.

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