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Spatio-temporal spectrum modeling: Taxonomy and economic evaluation of context acquisition

Martin B.H. Weiss *, Mohammed Altamimi, Liu Cui

School of Information Sciences, University of Pittsburgh, 135 North Bellefield Avenue, Pittsburgh, PA 15260, USA

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ABSTRACT

Much of the research in dynamic spectrum access (DSA) has focused on opportunistic access in the temporal domain. While this has been quite useful in establishing the technical feasibility of DSA systems, it has missed large sections of the overall DSA problem space. This paper argues that the spatio-temporal operating context of specific environments matters to the selection of the appropriate technology for learning context information. It identifies twelve potential operating environments and compares four context awareness approaches (on-board sensing, databases, sensor network, and cooperative sharing) for these environments. 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 analysis for different DSA approaches in parallel with the technical research. Regulators and major stakeholders should pay attention to the operating environment of DSA systems when determining which approaches to context learning to encourage.

The incremental capital costs; over a basic software radio; have been compared for the four context awareness approaches after an estimation analysis for each cost component. 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. In fact, 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

* Correspondence to: School of Information Sciences, University of Pittsburgh, 604 IS Building, 135 North Bellefield Avenue, Pittsburgh, PA 15260, USA. Tel.: +1 412 624 9430; fax: +1 412 624 2788.

E-mail addresses: mbw@pitt.edu (M.B.H. Weiss), altamimi333@yahoo.com (M. Altamimi), cuiliu1231@gmail.com (L. Cui).

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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 (Weiss, Altamimi, & Cui, 2010). Since Mitola's proposal for cognitive radios (CR), DSA research has been dominated by opportunistic sharing (Mitola, 2000). 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 Panichpapiboon (2004) showed that GSM operators would have an incentive to participate in secondary use; Tonmukayakul and Weiss (2008) delimited the circumstances under which potential secondary users would engage in secondary use and Caicedo and Weiss (2010) considered the liquidity (hence viability) of secondary markets in spectrum. Chapin and Lehr (2007) 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.

Context awareness may be established in a number of ways, for example through the use of databases (FCC, 2008) or sensor network (Weiss, Delaere, & Lehr, 2010; Grøndalen, Lähteenoja, & Grønsund, 2010) or communications channels such as the Cognitive Pilot Channel (Delaere & Ballon, 2008). Finally, 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. Notable exceptions are Wellens, Riihijärvi, Gordziel, and Mähönen (2008) and Wellens, Riihijärvi, and Mähönen (2009), which explicitly seek to measure and model spatial factors but still focus on non-cooperative secondary sharing. Similarly, in Tandra, Mishra, and Sahai (2009) the authors explicitly treat the spatial aspects of spectrum holes.

The remainder of this paper is organized as follows: Section 2, characterizes the cost awareness in DAS; Section 3, discusses the different learning approaches; Section 4, discusses and shows the comparison and consequence of all approaches; Section 5, illustrates the economic evaluation including cost estimates and cost comparison, and finally, Section 6 concludes the paper and summarize the findings.

2. Context awareness in DSA

Establishing context awareness in a cost effective manner means that designers and regulators need to consider the portfolio of environments and approaches to acquiring context information. This section characterizes the types of spatio-temporal environments that DSA systems might encounter.

Buddhikot (2007) states that spectrum licenses are defined by a six tuple: frequency, transmit power, transmitter location, licensee, use type (allocation), and duration. A potential secondary user is less interested in the license dimensions than in the dimensions relevant to sharing:

- What frequency band has spectrum holes that can be used? (spectral context).
- When does a spectrum hole in a particular band begin, and when does it end? (temporal context).
- Where does the spectrum hole in a particular band at a point in time exist? (spatial context).
- What can this spectrum hole be used for and what requirements must be observed? And how much it will cost compare to other options? (operational context).

This broad sense context awareness determines the transmission capacity and QoS for secondary users. It has been formalized into the notion of a radio environment map (REM) (Zhao, Morales, Gaeddert, Bae, Um, & Reed, 2007; Zhao, Le, & Reed, 2009). The discussion below will focus on the spatio-temporal aspects of spectrum holes in a particular band. Subsequently, it will address the need to obtain operational context as well.

2.1. Spectrum holes

Spectrum may be considered underutilized when the signal to noise ratio of the primary transmission is above the minimum needed for successful communications. Thus, secondary transmission opportunities can exist by adding small levels of transmission power or by identifying periods and spaces of no (or very low) primary user signal power and utilizing those at higher power levels. If the secondary user uses spectrum in a low power mode of operation, it is called underlay because it is working under the noise floor of the primary user. On the other hand, if that user works above the noise floor of the primary user (i.e., higher power mode), it is called overlay. In overlay mode, the user utilizes the spectrum in the cases where the primary user is idle.

In most cases, spectrum holes are considered overlay rather than underlay phenomena. One of the attempts to define the spectrum holes is Tandra et al. (2009) where the authors tried to find strategies for sensing spectrum holes based on

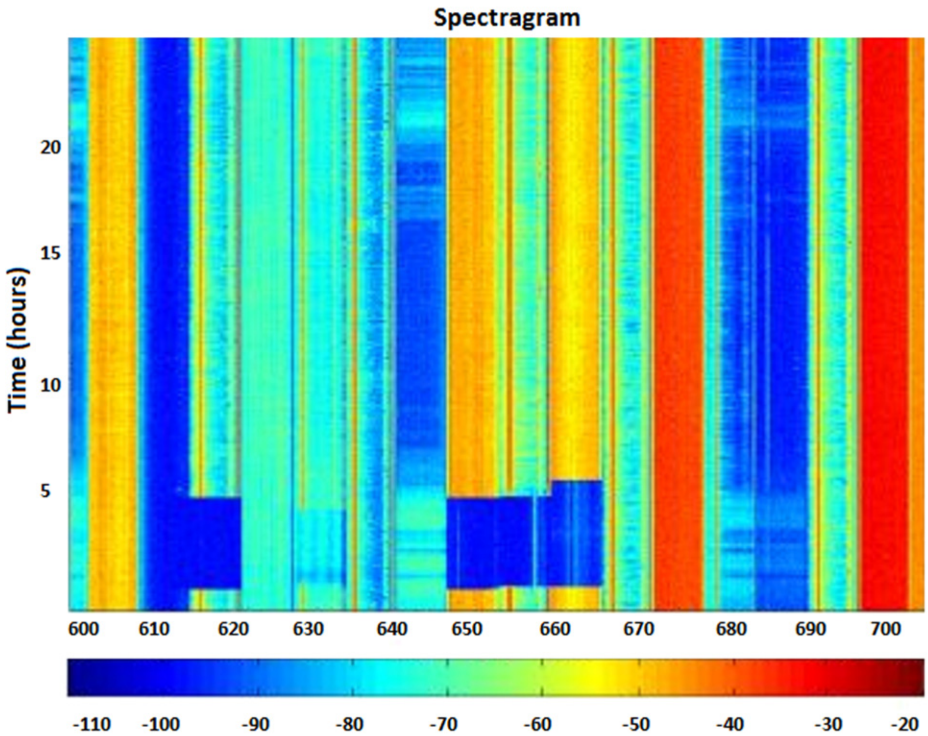

Fig. 1. Spectrum measurement. (Retrieved from the WINCOM lab at Illinois Institute of Technology (http://www.cs.iit.edu/~wincomweb/24hrtv.html) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

probabilistic models. In addition, the density of spectrum holes is based on the sensitivity of sensing methodology and the amount of interference the primary user can tolerate to allow sharing.

2.2. Temporal context

The temporal context is illustrated in Fig. 1. This figure represents signal power measurements in Chicago IL for 24 h (on May 22, 2008) from 600 MHz to 700 MHz (the UHF television band). Dark blue colors represent very low signal power levels, while bright red colors represent high signal power levels. Since spectrum holes are most valuable to spectrum sharing, let us examine the blue areas more closely. In this figure, there are three types of temporal behavior: static, periodic, and stochastic. The static temporal context is characterized by the band around 610 MHz. Here, the band is always free. Assuming this 24 h measurement period is similar to other 24 h periods, there is periodic behavior in several bands, one around 615 MHz and another from around 645 MHz through approximately 660 MHz.[1] Finally, around 640 MHz and 675 MHz through 685 MHz could be characterized as stochastic behavior, since it may not be reasonable to assume that the aqua-colored bands in the associated frequency bands would repeat in the same way that the bands characterized as periodic would.

It is important to further distinguish periodic behavior for the purpose of a more complete exposition. The periodic behavior illustrated in Fig. 1 is one where the time required to sense the spectrum hole, T_s, is much smaller than the period of the spectrum hole (T_h), or $T_s \ll T_h$. This property makes this spectrum hole usable for opportunistic access.

Another kind of periodic spectrum hole exists, one that would occur with TDMA systems, or 4G systems that utilize LTE. These spectrum holes occur periodically but have a very short period such $T_s \geq T_h$. In such cases, a cognitive radio could not use the spectrum hole without some kind of external support. The latter type of situation is called fast periodic (as opposed to simply periodic).

2.3. Spatial context

Just as classifying the kinds of contexts in the temporal domain, characterizing contexts in the spatial domain can be done as well. Since communication must occur between multiple devices distributed over space, it is important to

[1] It is reasonable to assume that the transmitters went off the air during these periods, which are the hours from 1 am to 5 am.

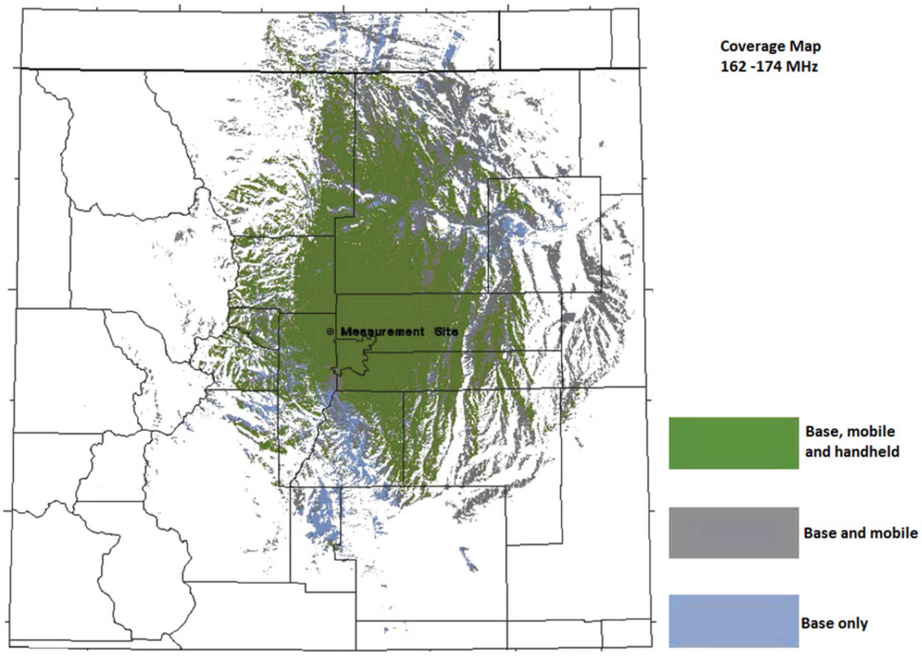

Fig. 2. Example of a spatial coverage map (calculated). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Operational contexts for DSA systems.

	Spatial characteristic		
	Static	**Periodic**	**Stochastic**
Temporal characteristic			
Static	TV white spaces	Sensor network	CDMA mobile
Periodic	Daytime broadcast	Rotating ant. radar	–
Fast periodic	LTE cell site	–	LTE mobile
Stochastic	WiFi	–	Public safety

determine to what extent the spatial parameters of the spectrum hole meet the spatial communication requirement of the secondary user.

Let us start by assuming that there are similar classes of spectrum holes as in the temporal context. So, a static spatial context is one in which the signal power (or, rather lack thereof) is invariant over the region of interest. A periodic spatial context is one in which the spectrum hole varies over space in a regular pattern. Finally a stochastic spectrum hole is one whose contours are neither static nor predictable.

Modeling the spatial context poses some new challenges and thus requires new techniques (see, e.g., Riihijärvi, Mähönen, Petrova, & Kolar, 2009). For the purposes of this paper, let us consider Fig. 2, taken from Carrol, Hoffmann, and Matheson (2008), as an example of a spatial coverage map at a single point in time.

In this case, the coverage is calculated, not measured. The different colors represent signal strength categories, with the green being the highest signal strength, the gray a medium value, the blue the lowest value and white represent no coverage. The green areas close to the point labeled measurement site are spatially static (in this illustration, it is spatially static spectrum usages not a spectrum hole). As moving toward the bottom right, there are examples of nearly periodic coverage (the result of topographic features). Finally, as moving to the bottom left, it shows examples of what might be considered spatially stochastic spectrum holes.

The ability to detect spatial spectrum holes spatially is related to the spatial resolution of the detector system. The spatial resolution of a detection system depends on the sensitivity and density of spectrum sensors in a region.

2.4. Spatio-temporal spectrum classification

Table 1 joins the two classifications 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, it is assumed that all can be uniquely classified. Some researchers (e.g., Do & Mark, 2009) have begun spatio-temporal modeling, but this work is in its infancy, so this approach is systems oriented rather than oriented toward developing a model.

TV white spaces is classified as a spatially and temporally static operational context for DSA because the location, transmit power, and propagation of the primary users are well known. Thus, the identification of white spaces on a spatio-temporal basis is also well known. In the US, some AM radio stations have a license for transmitting only during daylight hours because of the enhanced signal propagation around 1 MHz that occurs at night. These stations have static spatial characteristics, since their signal power is fixed and the transmitter location is fixed, but periodic temporal characteristics, since they transmit on a predictable pattern. An example of a spatially static but fast periodic spectrum hole would be an LTE cell site, where an idle time slot would be 1 ms long and repeating every 10 ms (Astély et al., 2009). Finally, an example of a temporally stochastic but spatially static context would be a WiFi hot spot, where the spectrum availability varies stochastically with time.

Spatially periodic systems exist as well. A sensor network might temporally static transmission characteristics, but because the sensors may be distributed in a pattern, it would produce spatially periodic spectrum holes. If the sensors in the sensor network woke up on a regular basis instead of transmitting constantly, then it would be spatially periodic and temporally periodic. Such a network could even be a fast periodic network if the periodic transmissions were exceptionally short (as they might be if the sensor network was energy aware). A rotating antenna radar would produce spectrum holes that are both spatially and temporally periodic.

The most obvious operating contexts that are spatially stochastic are those that involve mobile devices, though there may be others as well. The distinctions in the temporal dimension are perhaps a bit finer, but they may end up being relevant when considering the approaches to obtaining the operational contexts. A spatially stochastic approach would be produced by a mobile device using CDMA; here, varying demand patterns would cause signal energy to appear stochastic in space. Because the signal energy is spread over the entire operating band, it would appear as temporally static to the potential secondary user. Using the same line of argument, a mobile LTE device would result in fast periodic spectrum holes that are spatially stochastic. Finally, operating contexts that are spatially and temporally stochastic are represented by public safety and military applications, since it is difficult to predict when, where and how these primary users would use their spectrum.

As an observation, it is worth noting that DSA research has largely focused on the spatially and temporally stochastic operating context, which is probably the most difficult situation to address. The technologically easier problem, spatially and temporally static operating context, has only recently gained research attention, motivated in large part by the FCC's white spaces decision (FCC, 2008).

3. Context awareness approaches

The major challenges for secondary users are first to robustly sense a spectrum hole and then to exploit the acquired information by matching it to a transmission requirement. To achieve the first challenge optimally, the secondary user should understand the full context. As 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 network, and (4) cooperative sharing. Those alternative approaches will be evaluated and compared on the basis of their (1) cost effectiveness, (2) spatial and temporal precision, (3) transmission efficiency, and (4) the ability to acquire regulatory and institutional context. For full detailed analysis, please refer to Weiss, Altamimi, and Cui (2010) and Weiss, Delaere, and Lehr (2010).

The cost effectiveness of a system can be evaluated from a number of viewpoints. A regulator might be interested in the system cost (whether total or incremental) for the purpose of minimization. Secondary users would be interested in the usage costs associated because they would be compared to the alternatives available. Primary users would also be interested in incremental costs, but also in revenues. This paper focuses on the incremental system cost; that is, the additional capital cost that would be required over a basic software radio from regulatory perspective (total social benefits standpoint). A more complete analysis and comparison of those three different perspectives is in (Weiss and Altamaimi, 2011).

It is important to define the concept of precision more carefully. Spatial precision refers to the ability of a particular context sensing method to detect the spatial contours of a spectrum hole. While it is easier to think of them as sharp contours, the reality is that these boundaries are characterized by greater or lesser interference to the license holder (Marshall, 2010), something which may be negotiated (Weiss & Lehr, 2009).

Temporal precision must be defined a bit differently. Since a secondary user's radios cannot sense low power primary user signals while transmitting, all secondary users must periodically cease their transmissions and sense their environment.[2] The precision of identifying the temporal contour of a spectrum hole, then, depends on the frequency of

[2] If the precise location(s) of the primary user's transmitter(s) are known, one can imagine that a highly directional antenna could be directed at those sources to mitigate the need for pauses in the secondary users' transmissions. The real question is whether this is cost-effective.

sensing periods. Thus, a tradeoff emerges between the throughput of a secondary user's system and temporal precision of detecting a spectrum hole.[3]

3.1. On-board 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:

(1) *Cost-effectiveness:* 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 $C_I = N_S \times (C_S + C_C)$. However, control channel cost is not expected to result in a meaningful monetary cost since the radios must communicate with each other anyway.
(2) *Spatial and temporal precision:* the spatial precision of this approach is poor if radios are not cooperating, since the scope of the spectrum hole is determined by the sensing radius of the radio. Under cooperative sensing, the scope of the spectrum hole is a function of the spatial distribution and density of the cooperating radios (this is elaborated in Weiss, Altamimi, & Cui, 2010; Weiss, Delaere, & Lehr, 2010).
(3) *Transmission efficiency:* transmission efficiency is the ratio of time available to usable time. The illustration below contains a frame that is repeated regularly, and alternating between sensing, MAC (for mediating channel access among multiple radios) and transmission. Thus, transmission efficiency per frame can be expressed as $\varepsilon_T = T_T/(T_s + \overline{T_M} + T_T)$, where T_s is the sensing time per frame and $\overline{T_M}$ is the average MAC time per frame.[4]
(4) *Ability to acquire broader context:* broader context can be acquired, though this will be limited to what the radios can sense and what they can learn. The ability to learn is one way in which context may be obtained (Zhao et al., 2009), although learning can have some negative consequences as well (Zargar, Weiss, Caicedo, & Joshi, 2009). Without involving a control channel to the primary user or a database, the radios cannot obtain context information such as regulatory requirements, local industry structure, modulation and access method, interference tolerance, etc.

3.2. 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 (Delaere, 2010), and they are implicit in the REM concept Zhao et al. (2009).

(1) *Cost-effectiveness:* the incremental system cost for this approach would be $C_I = C_{DB} + [N_S \times (C_S + C_M + C_L + C_C + C_U + C_q)]$, 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) *Spatial and temporal precision:* the spatial precision of this system depends on the spatial precision of the database. Higher spatial precision implies either more database entries or better propagation models, but spatial precision is now decoupled from local circumstances, such as the density of cooperating radios. Temporally, the precision is the same as for the on-board sensor approach, since radios still have to sense and share the white space.
(3) *Transmission efficiency:* because sensing and channel sharing is still involved, the transmission efficiency is no better than the sensing-only approach. If a database query is required before each transmission, it could be lower. It could be expressed as $\varepsilon_T = T_T/(T_s + \overline{T_M} + T_T + T_q/F_q)$, where T_q is the time to query the database, and F_q is the number of frames per query, since it is unlikely that it would be necessary that the database would have to be queried before each sensing and transmission interval. If F_q is large, then the database query time is not meaningful in this computation.

[3] The actual temporal precision that results is a function of the operating context as well as the frequency channel/bandwidth.
[4] An average is used here because the MAC time varies based on instantaneous traffic demand in the spectrum hole.

(4) *Ability to acquire broader context:* since a database is capable of encoding and storing a wide range of information, it is possible for radios to obtain any piece of context information that the database designers thought to encode. While the radios would be able to learn from their local environments, their ability to obtain context information that was not included in the database would be as limited as it was for the on board sensing case.

3.3. Sensor network

Another approach that has been suggested involves the use of an off-board sensor network as discussed by Weiss, Altamimi, and Cui (2010), Weiss, Delaere, and Lehr (2010), and Grøndalen et al. (2010). 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.

(1) *Cost-effectiveness:* in general, the incremental system cost for a basic sensing service manager (SSM) would be $C_I = C_{SN} + N_S \times (C_C + C_L)$; where radios will not have sensing functionality.
(2) *Spatial and temporal precision:* the spatial precision depends on the design of the sensor network. It is anticipated that further studies will show that a tradeoff exists between spatial precision and cost.
Since the system is still based on sensing, secondary users will still have to allow for a synchronized quiet period to enable the sensor network to obtain fresh readings on the spectrum holes. Higher level SSMs may be able to minimize the MAC periods, but that does not affect temporal precision. Temporal precision would be improved if the SSM would be able to actively coordinate secondary use with the primary user(s).
(3) *Transmission efficiency:* the transmission efficiency is $\varepsilon_T = T_T/(T_T + T_s + \overline{T_M} + T_{SN}/F_q)$, where T_{SN} is the time used by sensor network to sense the environment. At worst, it is equal to the MAC time; at best, it is the time for secondary users acquire spectrum information from the sensor network. Therefore, it will be no worse than the on-board sensor approach. A higher level SSM might be able to reduce the MAC periods through careful resource management, but that would be a function of load.
(4) *Ability to acquire broader context:* because the SSM is rooted in a region, it would be a small matter for it to obtain broader context information, either through a database or based on a history of sensing results. For example it would be a small matter for a SSM to determine spatially and temporally periodic spectrum holes; furthermore it is not hard to imagine that an SSM might serve as an intermediary for primary users who may wish to share spectrum holes that are difficult to sense (e.g., fast periodic).

3.4. Cooperative sharing

White spaces can be identified by explicit communication between the primary and users, as studied in Tonmukayakul and Weiss (2008), Caicedo and Weiss (2010), and Chapin and Lehr (2007). In fact, as shown in Peha and Panichpapiboon (2004), explicitly coordinated approaches would possibly provide more spectrum for sharing, since license holders can monetize their spectrum resources more effectively. In this approach, neither sensing nor MAC protocol is required, since the secondary user would have exclusive use for a limited period. While this simplifies the radio functionality considerably, it can result in high transaction costs if small numbers bargaining exits. It also requires that systems be built to facilitate transactions (such as exchanges or brokers), and it may be required to retrofit incumbent's equipment.

(1) *Cost-effectiveness:* 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 where it feeds the required data to secondary users through the control channel, then $N_P = 1$. The cost per transmission to the user would consist of a transaction fee (paid to the broker to cover C_B and a spectrum use fee, which varies with demand).
(2) *Spatial and temporal precision:* the spatial precision in this approach is very high, since there is direct cooperation between the users; the spatial precision should be at least as good as sensor network spatial precision. Temporal precision is also high due to the cooperation.
(3) *Transmission efficiency:* the main overhead that detracts from transmission efficiency is the negotiating overhead prior to each transmission. Thus, $\varepsilon_T = T_T/(\overline{T_N} + T_T)$, where $\overline{T_N}$ is the average time to negotiate.
(4) *Ability to acquire broader context:* all context information would be passed from the broker to the secondary user, so it only be limited by capacity of the control channel and the capabilities of the secondary user's device.

4. Comparison and consequence

The main thesis of this paper is that different approaches to obtaining context information dominate in different operating contexts. This section will examine this in more detail. Since there is no exact data for the variables described

Table 2
Summary of context awareness approaches and their incremental system cost from total social benefits standpoint (regulators perspective).

Approach	Cost	Cost based comparison						
		C_S	C_C	C_L	C_{DB}	C_{SN}	C_B	C_{CP}
Sensing	$C_I = N_S(C_S + C_C)$	√	√					
Database	$C_I = C_{db} + N_S(C_S + C_L + C_C)$	√	√	√	√			
Sensor network	$C_I = C_{SN} + N_S(C_C + C_L)$		√	√		√		
Cooperative	$C_I = C_B + N_S(C_C + C_L) + (C_{CP}N_P)$		√	√			√	√

C_I: Incremental system cost; C_S: Incremental cost of the radio sensing apparatus; C_{DB}: Total cost of the database; C_C: Cost of control channel; C_M: Cost of memory to store the database on a device (ignored); C_L: Cost of the location-aware components; C_U: Cost of the updating the database (ignored); C_q: Cost of querying the database (ignored); C_{SN}: Total cost of the sensor network; C_B: Cost of the broker; C_{CP}: Incremental cost of control channel for the primary user; N_P: Number of primary stations; N_S: Number of secondary users.

above, this paper will determine the boundary conditions where one approach begins to dominate over another. Table 2 summarizes the analysis in Section 3.

4.1. Efficiency comparison

As stated above, this paper defines efficiency as the fraction of how much of the spectrum hole is used for transmission. Thus, before getting in a position to assess efficiency, it must assume that context has been acquired and that a suitable spectrum hole exists in space and time. From Section 3, the following conclusions can be drawn:

- The database approach results in transmission efficiency that is essentially the same as the on-board sensor approach, though it is less efficient if F_q is small.
- The sensor network approach may or may not result in a more efficient outcome, depending on how often the network must be queried and what the level of functionality of the SSM is. If a higher functioning SSM can coordinate transmissions, $\overline{T_M}$ will be smaller (or even 0), resulting in a more efficient transmission if $\overline{T_M} > T_{SN}/F_q$.
- The cooperative approach is more efficient if $\overline{T_N} < \sum(T_s + \overline{T_M})$, where the summation is over all transmission frames in a session.

4.2. System's costs comparison

When comparing the cost, this paper compares the system costs summarized in Table 2. As stated earlier, it only examines the system costs, which are nominally the costs of interest to the regulator. Costs and benefits perceived by the primary and/or secondary user are also important, as they provide strong behavioral incentives; despite their importance, they are outside of the scope of this paper. The costs identified are only direct, measureable costs associated with infrastructure deployment. The conclusions that are drawn from this are:

- The on-board sensing approach always cheaper than the database approach if the cost of the sensors identical across approaches. In static environments and those where some interference can be tolerated, the cost of database-oriented systems may be cheaper. In fact, the database system would be cheaper if $C_{db} < N_S(\Delta C_S - C_L)$, where ΔC_S is the difference in sensor costs. Clearly, the difference in the costs of the two sensing subsystems would have to be greater than additional cost of the location subsystem, and the number of secondary users would have to be large for this to occur.
- The sensor network approach would be cheaper for than the on-board sensing approach if $C_{SN} < N_S(C_S - C_L)$. That is, this approach could be cheaper if the cost of sensing subsystem were much higher than the cost of location subsystem and the number of users were sufficiently large.
- The cooperative approach would be cheaper than the on-board sensing approach if $C_B < N_S(C_S - C_L) - N_P C_{CP}$. It is expected that $N_S \gg N_P$, especially in infrastructure networks, so even if $(C_S - C_L)$ were only slightly larger than C_{CP}, then this outcome could result.

4.3. Analysis results

This paper began with a discussion of operating contexts for DSA, which summarized in Table 2. Let us now return to this and consider what the impact of operating context is on the factors that influence the choice of approaches for learning context. Table 3 summarizes the results of the entire analysis, and it contains the two leading awareness approaches for each situation. There are some assumptions considered throughout this analysis, such as the assumptions where the on-board sensor systems are built for environments that are both temporally and spatially stochastic.

To illustrate the approach in the analysis, this paper describes the temporally and spatially static operating environments in some detail. Space does not permit a full exposition of the analysis for each of these operating environments.

Table 3
Context learning approaches by operating environment.

	Spatial characteristic		
	Static	**Periodic**	**Stochastic**
Temporal characteristic			
Static	Cooperative Database	Cooperative Sensor network	Sensing Sensor network
Periodic	Database Cooperative	Sensor network Cooperative	Sensing Sensor network
Fast periodic	Cooperative	Cooperative	Cooperative
Stochastic	Sensing Sensor network	Sensing Sensor network	Sensing Sensor network

In spatially and temporally static environments, sensing is not necessary in most cases, except to the extent that MAC must be executed to allow fair use of spectrum holes. If this is the case, then the cost of the database need only be lower than $N_S(C_S - C_L)$; since C_L is the cost of adding a GPS receiver, it is likely to be substantially lower than the cost of the systems needed to sense spectrum. When this is multiplied by a large number of (potential) secondary users, the database approach looks attractive both from a cost as well as from an efficiency perspective (especially if the conservative harmful interference standards are relaxed (Marshall, 2010; Marcus, 2010)).

Compared with the database approach, the cooperative approach dominates in cost if $C_{db} > C_B + N_P C_{CP}$. From the perspective of efficiency, the cooperative approach is superior as long as $\overline{T_N} < (\overline{T_M} + T_q/F_q)F_S$, where F_S is the total number of frames in a session; it is necessary to include this here because negotiations occur only once per session. Without concrete measurements, the dominant approach cannot be determined.

Sensor network dominate the database approach in cost when $C_{SN} < C_{db}$, an outcome that appears unlikely.[5] In transmission efficiency, the two approaches are essentially identical, as they are in other parameters. Thus, the sensor network approach does not appear to be a likely candidate for the static operating environment.

5. 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 Grøndalen (2011) and Grøndalen et al. (2010), 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.

This section aims first to construct the upper and lower bounds of all the main cost elements discussed above and then apply cost evaluation over different context awareness approaches. The following sections will compare all the context acquisition options from an overall cost perspective.

5.1. Cost estimation

To make this study more realistic, the cost of seven different cost components that used in the analysis above (summarized in Table 2) will be predictable based on real cost estimate criteria. It is very important to note that some of these costs are the incremental capital costs over a basic software radio device. To evaluate the cost and compare the different approaches, a simple case has been illustrated/developed to apply and the estimated parameters. This paper considers an urban area of 100 km^2, with fewer than 10,000 secondary users. The resulting number of base stations is 6500 (based on 65 sensors/km^2). This cost estimation analysis is very lengthy to fit in this paper, the summary are presented in Table 4, where full details can be found at Weiss and Altamaimi (2011).

The 12 environments mentioned in Table 1 have been grouped into 3 groups, based on the similarities between them to do the cost comparison; as follows.

5.1.1. 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. Table 5 summarizes the related cost elements to database and cooperative approaches, since there are the two leading awareness approaches in this group.

[5] Some work on sensor network cost has been done (Grøndalen et al., 2010), though it, too is parameterized research.

Table 4
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}	2000	Per station
C_B	250,000	For all
C_{CP}	1,000,000	For all

Table 5
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	

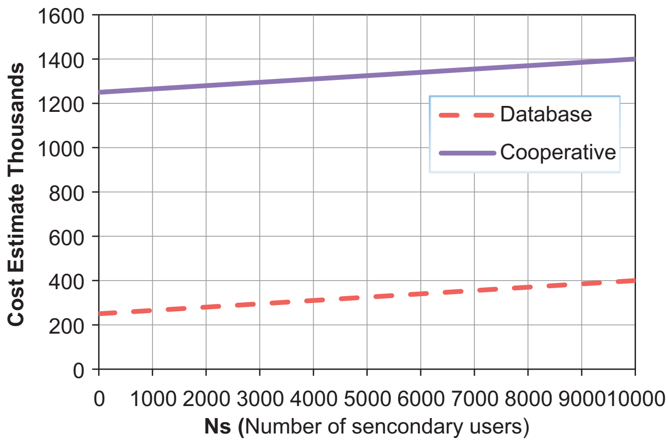

Fig. 3. Cost estimate curves for Group 1.

Also, it shows the percentage of change needed to alter the result for each cost element. From the result, 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%. Fig. 3 shows the relation between the cost estimate and number of secondary users.

5.1.2. Group-2

It contains static–periodic, periodic–static, and periodic–periodic environments. The analysis of group 2 environments follows the same procedure as group 1 and is shown in Table 6 and Fig. 4. Sensitivity analysis locates at the end of this section.

5.1.3. Group-3

It contains the rest of the environments. The analysis of group 3 environments follows the same procedure as group 1 and is shown in Table 7 and Fig. 5. Sensitivity analysis locates at the end of this section.

5.2. Cost comparison

This section compares the total system cost based on the case model and cost estimates that were described above. From Fig. 6 following conclude can be made:

- For $N_S < 2000$ 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.

Table 6
Summary of Group-2 cost analysis.

Cost component	Cost estimate ($)	% Change to alter the result	Remarks
C_{S2}	450	−79%: Turning point at N_S=10,000 0%: Turning point at N_S=2200 +100%: Turning point at N_S=1000	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 at N_S=500 0%: Turning point at N_S=2200 +350%: Turning point at N_S=10,000 *Note*: more than +1275%, sensor net start to be cost effective over the cooperative	

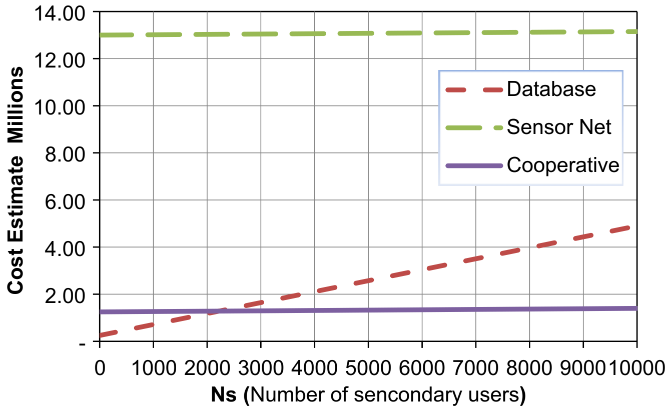

Fig. 4. Cost estimate curves for Group 2.

Table 7
Summary of Group-3 cost analysis.

Cost component	Cost estimate ($)	% Change to alter the result	Remarks
C_{S1}	650	−79%: Turning point at N_S=10,000 0%: Turning point at N_S=2000 +100%: Turning point at N_S=1000 *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 at N_S=7500 0%: Turning point at N_S=2000 +510%: Turning point at N_S=10,000 *Note*: more than +1175%, sensor net start to be cost effective over the cooperative	

- For $2000 < N_S < 10{,}000$ 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 the subjective analysis outcome at Table 3 and previous work (Weiss, Altamimi, & Cui, 2010; Weiss, Delaere, & Lehr, 2010).

5.3. Sensitivity analysis

From last section, it is clear that there are three significant cost components that are highly uncertain and where the outcome of analysis would change if the cost estimates changes. Those are C_{S1}, C_{SN}, and C_{CP}. This section examines the

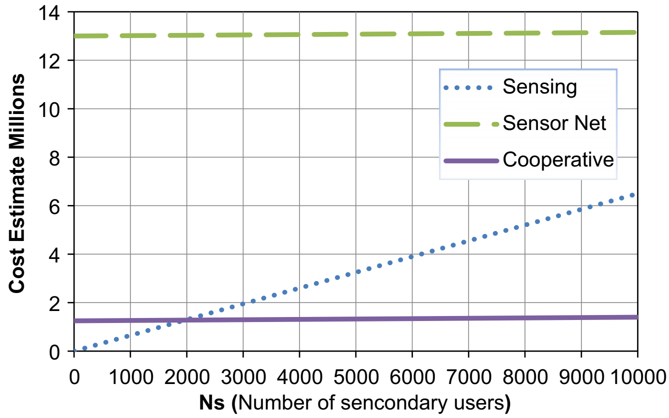

Fig. 5. Cost estimate curves for Group 3.

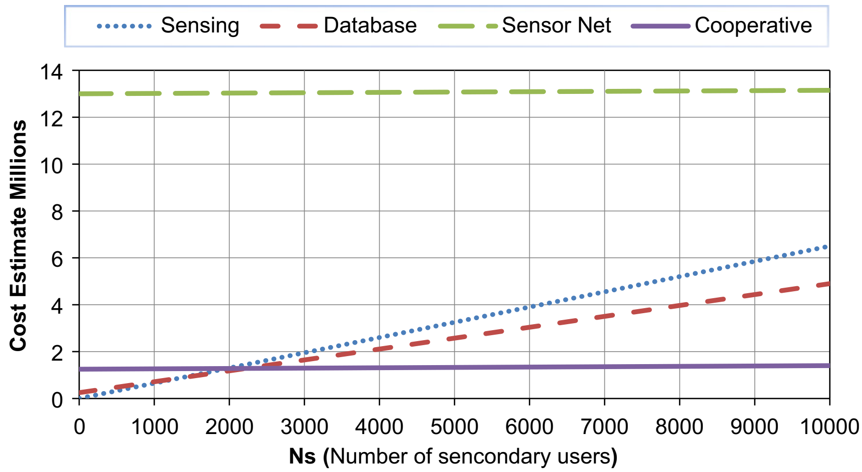

Fig. 6. Cost comparison based on total system cost.

sensitivity of the outcome for each one of these separately. To do this, all cost estimate curves for the four context awareness approaches will be plotted then each cost element will be varied to determine how that affects the outcome.

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

5.3.1. Sensitivity analysis of C_{S1}

To do the sensitivity analysis for C_{S1}; all cost estimate curves for the four context awareness approaches are plotted then vary C_{S1} (which will affect only the sensing approach curve). As in Fig. 7, if this cost element (i.e., C_{S1}) increases by 100%, it 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 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.

5.3.2. Sensitivity analysis of C_{SN}

Given that sensing network approach is the most costly approach based in the cost estimates and case model, C_{SN} will move downwards only. As shown in Fig. 8, there is not any change in the outcome until decreasing 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 2000$; 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 the estimated outcomes. However, the cost of senor network is highly uncertain and varies 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.

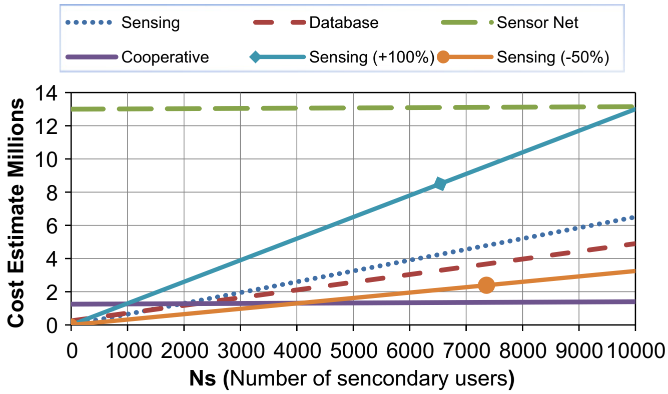

Fig. 7. Sensitivity analysis of C_{S1}.

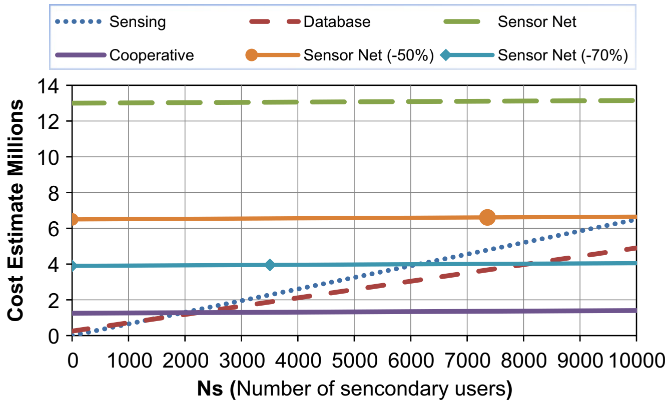

Fig. 8. Sensitivity analysis of C_{SN}.

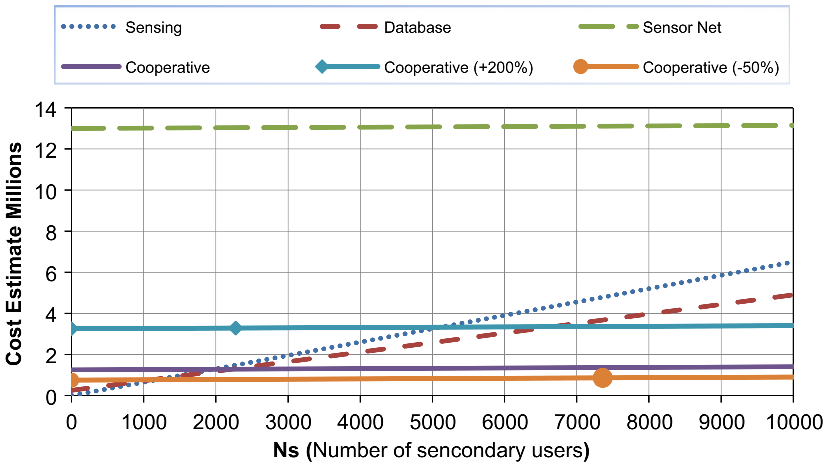

Fig. 9. Sensitivity analysis of C_{CP}.

5.3.3. *Sensitivity analysis of C_{CP}*

As shown in Fig. 9, the outcome of this 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 $N_S = 2000$ to around $N_S = 5500$. If it is decreased by 50%, the turning point occurs at $N_S = 1000$.

As it was mentioned before, estimation of the primary control channel cost is not built on very solid foundation, it has the lowest confidence in the estimate as compared to the others.

6. Conclusion

This paper shows that operating context matters when it comes to choosing an appropriate technology for context awareness in DSA systems using some simple analyses. In taking the system level approach, the target is to minimize total cost and maximize total efficiency (as a regulator might). By showing that different approaches dominate along these dimensions compared with other approaches, it demonstrates that it is important for regulators to pay attention to the operating context of the DSA system and to encourage the choice of appropriate approaches to learning context.

To make this study more realistic, this paper 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 previous work, it 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 are deemed as unlikely. A secondary benefit of this study is that it provides a better intuition of the proportionality and the relationship among the cost elements which help make further research more realistic.

There is clearly a long list of further research. 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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