Dynamic Geospatial Spectrum Modelling:
Taxonomy, Options and Consequences

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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. In this paper, we argue that the spatio-temporal operating context of specific environments matters to the selection of the appropriate technology for learning context information. We identify twelve potential operating environments and compare four context awareness approaches (on-board sensing, databases, sensor networks, and cooperative sharing) for these environments. Since our point of view is overall system cost and efficiency, this analysis has utility for those regulators whose objectives are reducing system costs and enhancing system efficiency. We conclude that regulators should pay attention to the operating environment of DSA systems when determining which approaches to context learning to encourage.

1. Introduction

Since Mitola's proposal for Cognitive Radios (CR), the "mindshare" and research in Dynamic Spectrum Access (DSA) has been dominated by opportunistic sharing [***1***] (see, for example, Akyldiz et.al. [***2***] for a survey). 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 addressing the time component/dimension.

1.1 Typology of DSA

Several typologies of DSA have been proposed by various authors (see, for example [***7***] [***8***] [***9***]). The taxonomies in [***7***]and [***8***] have the same perspective (albeit using slightly different terminology), while the taxonomy offered by [***9***] does not meaningfully incorporate cooperative sharing. Table 1, taken from [***7***], separates DSA approaches into cooperative and non-cooperative, depending on whether the primary user participates *ex ante* in the decision to transmit or not. If they do, Weiss and Lehr consider the DSA to be cooperative; if they do not, they consider it to be non-cooperative. In addition to the engagement of primary users, the relationship between the users is of significance. Primary sharing occurs when the DSA participants have equal rights to the spectrum resource and secondary sharing occurs when one user does not have equal rights to the spectrum as the other. Real systems may be hybrids within this typology, but Table 1 nonetheless serves to provide a useful structure to DSA systems.

So, following this typology, WiFi would be an example of non-cooperative primary sharing since all stations have an equal right to access the spectrum (primary sharing), but they do not coordinate ex ante (non-cooperative sharing). Cooperative primary sharing is exemplified by secondary spectrum trading, because ex ante coordination occurs (via a trade) and the buyers and sellers are peers in the transaction. In non-cooperative secondary sharing (exemplified by most cognitive radio research), users opportunistically take advantage of idle spectrum through databases, sensing, or other techniques. Finally cooperative secondary sharing is exemplified by negotiated sharing agreements (eg. Mobile Virtual Network Operators and the kind of secondary use studied in [***4***]).

Table 1: Typology of DSA

	Non-Cooperative	**Cooperative**
Primary	Unlicensed, WiFi	Secondary markets (spectrum license trading)
Secondary	Easements, Opportunistic use, TV White Spaces, UWB	MVNO, secondary use (negotiated)

1.2 Observations of DSA Research

Mitola's original conception of a cognitive radio is one that was aware of its context in a broad sense[1]. The body of DSA research, being focused on non-cooperative secondary sharing, considers frequency awareness (usually through sensing) and perhaps location awareness (through GPS). The research on cooperative systems generally focuses on institutional context, but much less so on the

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[1] See Mitola [***1***], p. 13.

spatial or spectral context. Thus, the context awareness of the DSA systems that researchers focus on is relatively limited.

Systems based on non-cooperative secondary sharing may miss some significant spectrum holes because of the nature and capabilities of sensing technology. For example, these systems would miss spectrum holes in TDMA and CDMA systems[2]. Many modern systems (such as WiMAX and LTE) are based on Orthogonal Frequency Division Multiple Access (OFDMA; detecting spectrum holes is very difficult in these systems due to the dynamic allocation of radio resources [***10***] [***11***]. The practical realities of these next generation systems requires some level of cooperation, even if is not fully consistent with the cooperative secondary sharing as described in [***4***]. As a generalization of [***12***] , context awareness may also need to include information related interference tolerance.

Thus, one might imagine that timing information (necessary for TDMA), code information (necessary for CDMA) would be important aspects of context that potential secondary users should be aware of, even for non-cooperative sharing. The willingness of primary users to share this information is an interesting question, since it requires that they reveal critical aspects of their operations that may expose vulnerabilities or expose important business information. For cooperative sharing, knowledge of industry structure, license holders, markets and negotiation mechanisms, etc. are important if a sharing relationship is to be established.

Context awareness may be established in a number of ways, for example through the use of databases [***13***] or sensor networks [***14***] [***15***] or communications channels (such as the Cognitive Pilot Channel [***16***]). 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. A notable exception is [***17***] [***18***], which explicitly seek to measure and model spatial factors but still focus on non-cooperative secondary sharing. Similarly, in [***19***] the authors explicitly treat the spatial aspects of spectrum holes.

In this paper, we propose expanding the research into DSA (1) to consider context awareness more broadly than just temporal spectrum holes and (2) to explicitly consider a spectrum hole as a spatio-

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[2] TDMA systems divide spectrum into many short timeslots that are shared by a system's users, so spectrum holes are unused timeslots. CDMA system separates users by spreading codes, so spectrum holes are unused codes. These "holes" can be used by potential secondary users, but they require closer coordination between primary and secondary users than is assumed by most non-cooperative systems.

temporal phenomenon. With these starting points, we will examine how DSA might proceed and what the economic and policy consequences of this approach might be.

2.0 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. In this section, characterize the types of spatio-temporal environments that DSA systems might encounter.

Buddhikot [***9***] argues that spectrum licenses are defined by a six tuple: frequency, transmit power, transmitter location, licensee, use type (allocation), and duration. Following [***19***], we define a spectrum hole by a three tuple: frequency, time and spatial (geographical) location. As discussed above, a broad sense context awareness would include five of Buddhikot's six parameters (license duration, in most current applications is effectively infinite) as well as interference tolerance, modulation, access method and negotiation details. This broad sense context awareness has been formalized into the notion of a Radio Environment Map (REM) [***20***] [***21***].

2.1 Temporal context

It is easiest to address the temporal context in relation to Figure 1. This figure represents signal power measurements in Chicago IL for 24 hours (on May 22, 2008) from 600MHz to 700MHz (the UHF television band). Dark blue colors represent very low signal power levels, while bright red colors represent high signal power levels. Since we are interested in spectrum holes, let us examine the blue areas more closely. In this figure, we see 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 hour measurement period is similar to other 24 hour periods, we see periodic behavior in several bands, one around 615 MHz and another from around 645 MHz through approximately 660 MHz[3]. Finally, around 640 MHz and 675 MHz through 685 MHz we see what 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 we characterized as periodic would.

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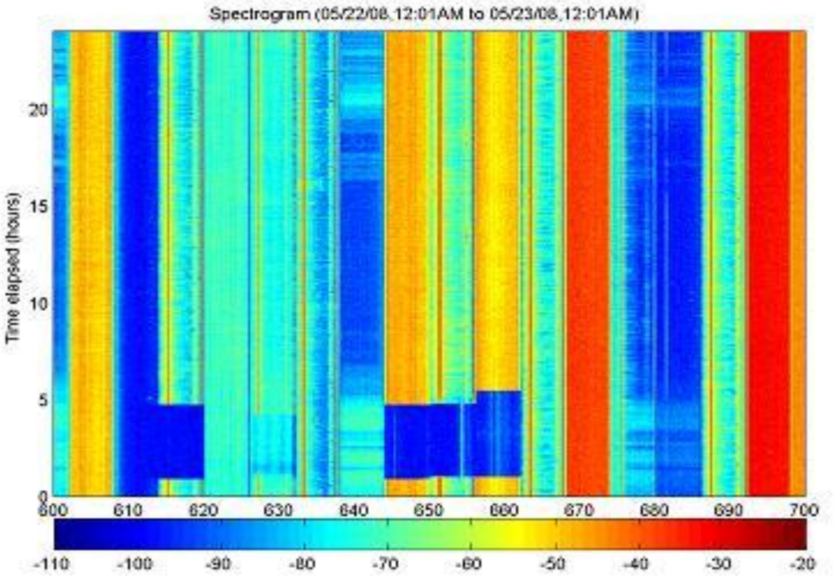
[3] It is reasonable to assume that the transmitters went off the air during these periods, which are the hours from 1am to 5am.

Figure 1: Spectrum measurement[4]



We would like to further distinguish periodic behavior for the purpose of a more complete exposition. The periodic behavior illustrated in Figure 1 is one where the spectrum sensing time, Ts, is much smaller than the period of the spectrum hole (Th), or Ts ≪ Th. This property makes this spectrum hole usable for a cognitive radio. Suppose, however, the case where we have a periodic signal pattern where Ts ≥Th, as could be the case with TDMA systems, or 4G systems that utilize LTE. In that case, a cognitive radio could not use the spectrum hole without some kind of external support. We call the latter type of situation fast periodic (as opposed to simply periodic).

2.2 Spatial context

Just as we were able to classify the kinds of contexts in the temporal domain, we can characterize contexts in the spatial domain. Let us start by assuming that we can observe similar classes of spectrum holes as we did in the temporal domain. So, a static spatial context is one in which the signal power is (relatively) 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

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[4] From the WINCOM lab at Illinois Institute of Technology (http://www.cs.iit.edu/~wincomweb/24hrtv.html)

neither static nor predictable. It is not clear that it is useful to introduce the notion of fast periodic spatial spectrum holes.

Modelling the spatial context poses some new challenges and thus requires new techniques (see, for example [***22***]). Conceptually, it is a bit more challenging to visualize spatially non-static spectrum holes. In part, this is the case because of the paucity of spatial spectrum measurements; taking measurements over space at a point in time effectively assumes the existence of a sensor network that is capable of taking accurate measurements in the band of interest (such systems have been proposed [***14***] [***15***], and some researchers have made some spatial measurements [***23***]). The classic "hidden node" problem of wireless systems is a manifestation of the spatial properties of spectrum holes, whether static, periodic, or stochastic.

The principal spatial model is a static one that is based on antenna height, transmit power, and a propagation model for the frequency in question. This tends to generate spatial coverage areas that are roughly circular. The use of directional antennas can alter this model, as can topographical features, such as mountains. Graphically, spatially periodic spectrum hole (or its converse, spatially periodic spectrum occupancy) would appear as a regular pattern in space. Such a pattern may be caused by directional transmission services, such as rotating antenna radars. Spatially stochastic models are those that neither exhibit periodic behavior nor are spatially static.

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.

2.3 Spatio-Temporal spectrum classification

Table 2 joins the two classifications and attempts to map applications into each category[5]. 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; for the purposes of this paper, we assume that all can be uniquely classified. Some researchers (e.g., [***24***]) have begun spatio-temporal modelling, but this work appears to be in its infancy, so our approach is systems oriented rather than oriented toward developing a model.

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[5] Some real-world systems may be hybrids of these categories.

Table 2: 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

We classified TV white spaces 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 1MHz 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 1msec long and repeating every 10msec [***25***]. 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. There were no obvious existing operating contexts that could be identified as being spatially periodic but temporally fast periodic or stochastic; this does not mean that they do not exist or will not exist in future.

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 we consider 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 interesting to note that DSA research has largely focused on the spatially and temporally stochastic operating context, which is probably the most difficult of the problems to solve. The technologically easier problem, spatially and temporally static sharing, has only recently gained research attention, motivated in large part by the FCC's "White Spaces" decision [***13***].

3.0 Approaches to Learning Context

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 we discussed above, context awareness in the broad sense has many dimensions. It should include:

- Technical awareness: technical parameters of spectrum holes, modulation, access method, such as the frequency, the bandwidth of targeted band and their spatial scope;
- Regulatory awareness: the regulatory factors associated with the spectrum hole, including permissible uses, maximum transmit power, which service can be offered, etc.;
- Institutional context awareness: certain factors are associated with the spectrum hole, such as the license's owner, type of frequency modulation technology, and channel access

method is in use by the license holder and also what information is considered private or proprietary (e.g., synchronization parameters);

- Coordination mechanism awareness: including cooperative sensing, sensing networks, acceptable medium access control protocols for secondary users, and communications mechanisms (such as a Cognitive Pilot Channel [***26***] or IEEE 1900.4[6]).

Several approaches have been proposed by which radios could gain context awareness: on-board sensing, databases, sensor network and cooperative sharing (as well as combinations thereof [***21***]). These alternatives should 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. We will show that different outcomes should be expected based on the particular operating context described in Table 2.

The cost effectiveness of a system can be evaluated from a number of viewpoints. A regulator might be interested in the ystem 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 (following [***4***]). Primary users would also be interested in incremental costs, but also in revenues (following [***3***]). In this paper, we focus on the incremental system cost; that is, the additional capital cost that would be required over a basic software radio-based transmission arrangement.

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 [***12***], something which may be negotiated via Coasian bargaining [***7***]. In practice, spatial precision is easiest to understand if we assume the existence of a detection radius around each sensor. This notion has been suggested by [***27***] in a different context and is clearly a function of the sensitivity and selectivity of the spectrum sensor as well as the directionality of the antenna. In terms of the analysis in [***18***], the sensing radius should be proportional to the "range" parameter (ϕ).

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[6] http://grouper.ieee.org/groups/scc41/4/index.htm

Temporal precision must be defined a bit differently. Since radios cannot sense for low levels of primary signals, they must periodically cease their transmissions and sense their environment. All radios using a particular spectrum hole must do this at the same time[7]. The precision of identifying the temporal contour of a spectrum hole, then, depends on the frequency of sensing periods. It is clear that a tradeoff emerges between the throughput of a secondary user's system and temporal precision. The actual precision that results is a function of the operating context as well as the frequency band. Thus, we would expect the spatial and temporal precision to vary across context acquisition approaches: database approaches could offer high spatial and temporal precision in bands where multipath propagation is not a significant phenomenon and where the operating environment is static or periodic. In a sensor network, the precision is dependent on the density of the sensors. Finally in on-board (presumably cooperative) sensing, the precision depends on the density of the cooperating nodes.

3.1 On-board Sensing

The "traditional" approach for DSA systems is to sense the environment 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. Generally speaking, this cooperative behavior also involves using a medium access control (MAC) protocol that allows all interested DSA radios to gain access to a spectrum hole in an orderly fashion.

On-board sensing based approaches allow radios to operate in all operational contexts described in Table 2. Because of signal fading and the hidden node problem, we assume that on-board approaches are cooperative in the sense that multiple radios collaboratively share sensing information. The main question is whether this as efficient, as complete, and as cost effective as other approaches if the possible operating contexts are more limited. Because of the emphasis on sensing, it would not be possible to build complete REMs.

Cost-effectiveness – Since all secondary radios would need on-board 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 a sensing apparatus. No cost would be incurred by the

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[7] 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.

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, we do not expect that control channel cost would result in a meaningful monetary cost since the radios must communicate with each other anyway. A more comprehensive treatment of might include other cost, such as interference related costs, that might apply as well[8]. Interference costs can show up in a number of forms, for example in higher receiver costs (to mitigate interference) or in performance penalties (due to the effects of interference).

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. Figures 3 and 4 illustrate this idea. The circles in these figures are the sensing radii; signals falling into the spatial boundaries of the circles would result in detected signal energy. The contour of the spectrum hole is defined by the threshold of signal energy that indicates the presence of the primary user's signal (often defined as a matter of public policy [***28***]). It is easy to see that a higher density of radios would enable the cooperating radios to more clearly detect the spatial boundary of the spectrum hole. In fact, this would be aided by de-tuning the sensors to decrease the sensing radius when the density of cooperating radios is high.

As it was explained in previous section, temporal precision depends on the frequency of the sensing interval. In fact, it is a directly proportional to the transmission interval T_T plus the MAC time interval T_M; that is the time spent not sensing.

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[9].

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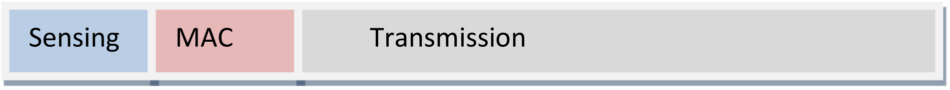
[8] We only address the direct capital investment costs. These other costs are described for completeness but are not included in this first-order analysis.

[9] We use an average here because the MAC time varies based on instantaneous traffic demand in the spectrum hole.

Figure 2: sequences of different time intervals needed to transmit



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 [***21***], although learning can have some negative consequences as well [***29***]. 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.

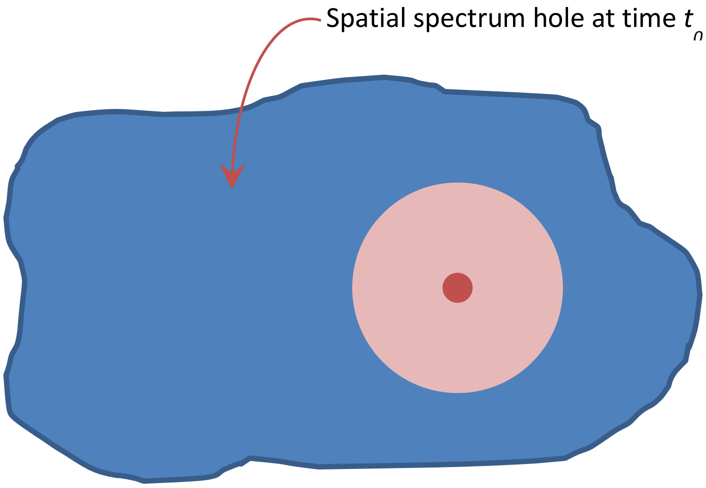


Figure 3 - Single detector

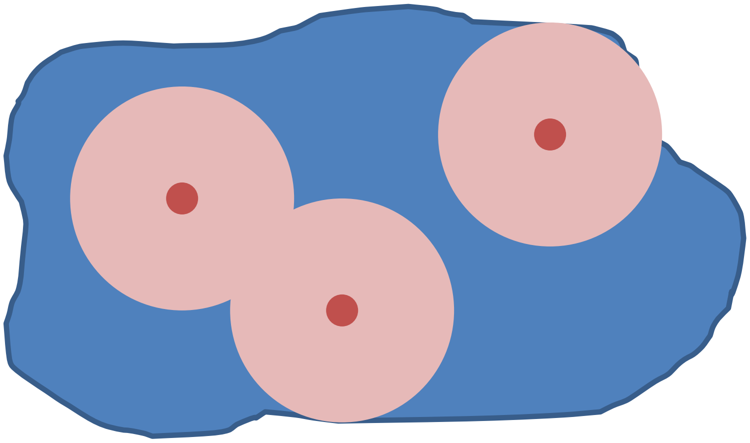


Figure 4 - Cooperative detection

3.2 Databases

The FCC, in their "White Spaces" decision, specified the use of a database that would have to be consulted before a secondary use radio could be used. The IEEE 802.22 standards committee is also considering a database, and a database is included in the Cognitive Pilot Channel (CPC) proposals [***30***] and it is implicit in the REM concept [***21***]. In a pure database solution, radios need to be capable of sensing other secondary users, so they need a MAC protocol to facilitate white space sharing but not sensing of primary users. Furthermore, most databases assume that the radios know their location in physical space, which implies that they have to have a GPS receiver or some location awareness technology.

Two usage modes are possible for database approaches, and the performance and application varies depending on the one that is used.

<u>On-board database</u>: In this approach, radios would store the entire database on board and update it on relatively infrequent intervals[10]. Since memory is not expensive and static environments change only slowly, this is feasible for spatially and temporally static operating contexts.

<u>Database service</u>: In this usage mode, the device would query the database frequently, either after relocating or before each transmission. This approach would require the existence of a control channel over which queries can be made and answered; it would be suitable for more dynamic environments.

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[10] This would work much like GPS navigation devices, where the map database is stored locally and is updated periodically (if ever) by the user, for a fee.

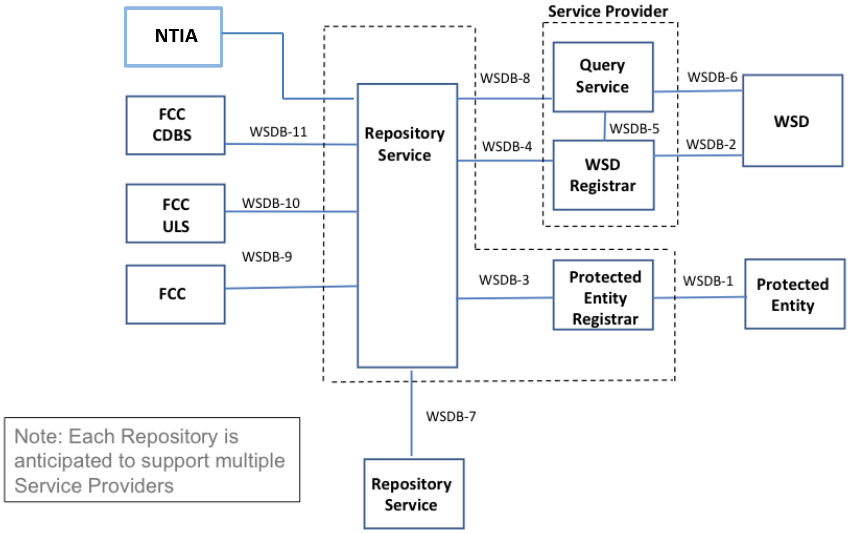

Figure 5 - Example of Database approach[11]

(1) Cost-effectiveness – The incremental system cost for Model 1 would be $C_{I1} = C_{db} + [N_S \times (C_S + C_M + C_L + C_C + C_U)]$, 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, and C_U is the additional cost for updating the database (Note: C_U is different than C_C; Where C_C is to count the incremental cost for control channel that mainly between secondary users; as it is illustrated in on-board sensing; so, C_U is to count for additional cost due to the existence of the database). Since the database would have to be maintained and operated, there would probably be a cost to the user for using the database. For Model 2 (query-based approach), the incremental cost to the user would be

$C_{I2} = C_{db} + [N_S \times (C_S + C_L + C_C + C_q)]$; where 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), we can derive one cost equation for both models as follows:

$$C_I = C_{db} + N_S \times (C_S + C_L + C_C)$$

(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,

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[11] Source: White Spaces Database Group *ex parte* submission dated April 10, 2009 – Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186)

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 $\varepsilon_{\mathrm{T}} = T_T/\left(T_s + \overline{T_M} + T_T + T_q/F_q\right)$, 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.

(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 [***14***] [***15***]. In this approach, a cognitive radio would acquire context information by querying the sensor network, as illustrated in Figure 6. Thus, some kind of control channel (such as a CPC) is assumed. Since the sensors are fixed in space, it is relatively easy to maintain broader context information, such as regulatory and institutional context. In principle it would be possible to maintain an arbitrarily high level of spatial precision in the definition of the spectrum hole.

Since this approach is still relatively early in the developmental stages, it is not clear exactly what services would be provided by the Sensing Service Manager (SSM). This could be a relatively low level query-response, where the radio has a lot of detailed knowledge[12]. On the other hand, one could imagine a system where the radio's query contains higher level requirements, such as the locations of the radios sharing the communications, the bandwidth requirements, the time period requirement, etc., and the SSM responds with a frequency they can use for the specified time period. Such a SSM would

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[12] See, for example, the Application Programming Interface (API) for Microsoft's WhiteFi system: http://whitespaces.msresearch.us/.

perhaps have global knowledge of all radios operating in their region, so that they could schedule their use.

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) <u>Cost-effectiveness</u> – In general, we expect that the incremental system cost for a basic SSM would be $C_I = C_{SN} + N_s \times (C_C + C_L)$; where radios will not have sensing functionality.
(2) <u>Spatial and temporal precision</u> – The spatial precision depends on the design of the sensor network; as illustrated in Figure 7, it would certainly be better than a low density cooperating cognitive radio system. We anticipate 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) <u>Transmission efficiency</u> – The transmission efficiency is $\varepsilon_{\mathrm{T}} = T_T / \left(T_T + T_s + \overline{T_M} + T_{SN}/F_q\right)$, 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) <u>Ability to acquire broader context</u> – 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).

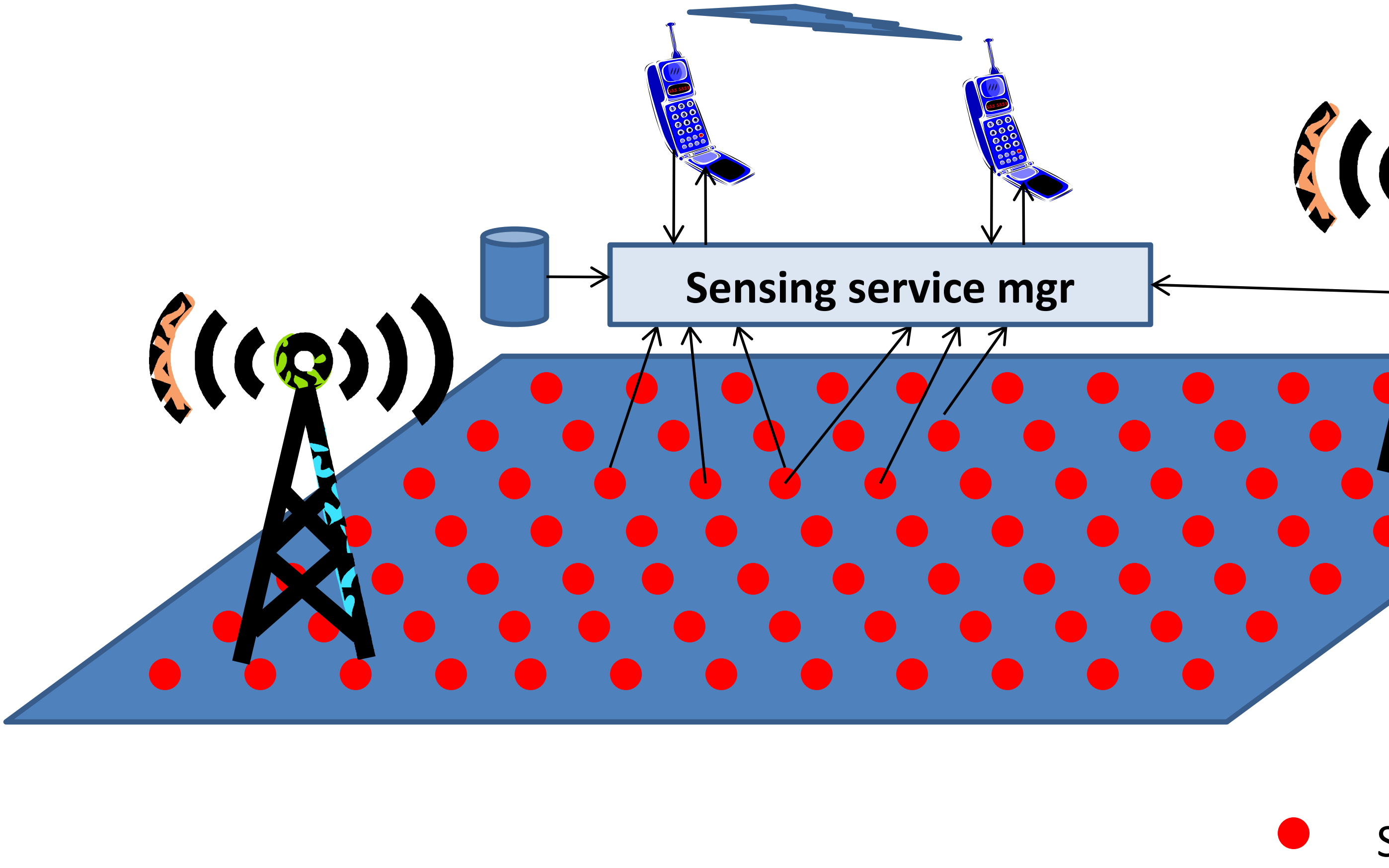

Figure 6 -- Spectrum sensor network

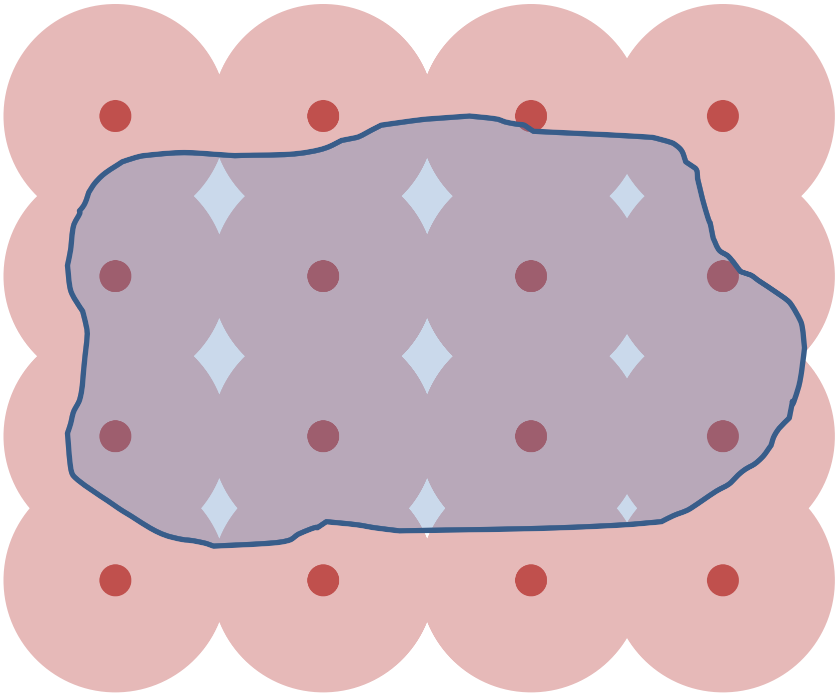

Figure 7 - Sensing a spectrum hole with a sensor network

3.4 Cooperative sharing

White spaces can be identified by explicit communication between the primary and users, as studied 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. This approach does not require sensing, nor does it require that the radio use a MAC protocol, 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.

4.0 Consequences

The main thesis of this paper is that different approaches to obtaining context information dominate in different operating contexts. In this section, we will examine this in more detail. Since we do not have exact data for the variables described above, we will determine the boundary conditions where one approach begins to dominate over another. Table 3 summarizes the analysis in Section 3 above. We will analyze each of the dimensions below.

4.1 Efficiency Comparison

As stated above, we define efficiency as the fraction of how much of the (temporal) spectrum hole is used for transmission. Thus, before we are even in a position to assess efficiency, we must assume that context has been acquired and that a suitable spectrum hole exists in space and time. Examining Table 3, we can draw the following conclusions

- 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 Comparison of System Costs

When comparing the cost, we compare the system costs summarized Table 3. As stated earlier, we are examining only 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.

Table 4: Cost Based Comparison

	Ns	Cs	Cc	Cl	Cdb	Csn	Cb	Ccp*Np
On-board sensing	√	√	√					
Database	√	√	√	√	√			
Sensor Network	√		√	√		√		
Cooperative sharing	√		√	√			√	√

To gain insight into this analysis, we gather the cost components in Table 4. The costs identified are only direct, measureable costs associated with infrastructure deployment. We can see that the total system cost for each approach equals the sum of the marked purple columns times the sum of marked gray columns plus marked yellow columns. The conclusions we draw from this are:

	Cost	Precision	Efficiency	Broader Context
On-board Sensing	$C_I = N_s(C_s + C_C)$	Poor if not cooperative, depends on density if cooperative	$\varepsilon_T = T_T/(T_s + \overline{T_M} + T_T)$,	Very Limited
Database	$C_I = C_{db} + N_s(C_s + C_L + C_C)$	Depends on the spatial precision of the database	Similar to on-board sensing $\varepsilon_T = T_T/\left(T_s + \overline{T_M} + T_T + T_q/F_q\right)$	Full static context information
Sensor Network	$C_I = C_{SN} + N_s(C_C + C_L)$	Depends sensor network design, but better than on-board sensing and database approaches	Better than sensing and database approaches $\varepsilon_T = T_T/\left(T_T + T_s + \overline{T_M} + T_{SN}/F_q\right)$	Easy to acquire, either from database or based on a history of sensing result
Cooperative	$C_I = C_B + N_s(C_C + C_L) + (C_{CP} \cdot N_P)$	Arbitrarily high	$\varepsilon_T = T_T/(\overline{T_N} + T_T)$	Obtain from the broker.

C_I, incremental system cost
C_S, the incremental cost of the radio sensing apparatus
C_{db}, total cost of the database
C_M, the cost of memory to store the database on a device
C_L, cost of the location-aware components
C_C, cost of control channel
C_{SN}, total cost of the sensor network
C_B, cost of the broker
C_{CP} is the incremental cost of control channel for the primary user

N_P, the number of primary stations
N_S, the number of sencondary users
F_q, the number of xmission frames per query
T_T, the transmission time per frame
T_S, the sensing time per frame
$\overline{T_M}$, the average MAC time
T_q, the time to query database
T_{SN},the time used by sensor network.
$\overline{T_N}$, the average time to negotiate

Table 3 - Summary of Context Awareness Approaches

- The on-board sensing approach always cheaper than the database approach if the cost of the sensors is the same. 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 $C_B < N_S(C_S - C_L) - N_P \cdot C_{CP}$. We would expect 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 Impact of Operation Context

We began this paper with a discussion of operating contexts for DSA, which we 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 5 summarizes the results of our analysis, and it contains the two leading DSA methods 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 we take in our analysis, we describe the temporally and spatially static operating environments in some detail. Space does not permit a full exposition of our analysis for each of these operating environments. 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 [***12***] [***28***]).

		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

Table 5 - Context Learning approaches by operating context

Compared with the database approach, the cooperative approach dominates in cost if $C_{db} > C_B + N_P \cdot C_{CP}$. From the perspective of efficiency, the cooperative approach is superior as long as $\overline{T_N} < \left(\overline{T_M} + T_q/F_q\right)F_S$, where F_S is the total numbe of frames in a session; it is necessary to include this here because negotiations occur only once per session. Without concrete measurements, it is hard to say which approach dominates.

Sensor networks dominate the database approach in cost when $C_{SN} < C_{db}$, an outcome that appears unlikely. 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 this operating environment.

5.0 Conclusion

In this paper, we set out to show that operating context matters when it comes to choosing an appropriate technology for context awareness in dynamic spectrum access (DSA) systems. We have shown that this is the case using some simple analyses. In taking the system level approach as opposed to a user level approach, we situated ourselves as a regulator would who is seeking to minimize total cost and maximize total efficiency. By showing that different approaches dominate along these dimensions compared with other approaches, we demonstrate 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.

There is clearly a long list of follow up projects to this. One project consists of determining or estimating values for the variables defined in this paper so that we can get a better sense of when different approaches are better. Another project consists of revisiting this analysis from the point of view of the primary and secondary users. It may be that incentives exist to not adopt the socially efficient approach, and regulators need be aware of this. Finally, considerably more work needs to be done on defining some of the newer technologies, such as sensor networks and cooperative DSA, so that better estimates of cost and performance can be made.

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