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What spectrum-sharing techniques can be used to implement cognitive radio systems to ensure coexistence with other users?

Two systems are said to coexist with one another if the operation of each system could negatively impact the performance of the other and the operation of one system does not preclude the operation of the other.

In cognitive radio research circles, coexistence techniques have emphasized a closely related objective –minimizing the negative impact of one system on the performance of another. For radio systems, minimizing negative impact generally means minimizing interference, but different coexistence metrics can be applied at different layers and the exact impact of interference is dependent on the signalling features of both systems. Besides being characteristic of a "polite" cognitive radio system, an assurance that a cognitive radio system will minimize the negative impact on other users is likely necessary to assuage the fears of primary users. Additionally, when considering coexisting cognitive radio systems, minimizing the interference between systems will generally (subject to certain constraints) maximize both systems' performance.

If we focus primarily on layer 1 and 2 coexistence issues, coexistence of radio systems implies spectrum sharing. To share spectrum, radio systems' operational parameters are implemented so both systems have some access to the spectrum, possibly interference-free. While many parameters such as transmitted power (e.g., transmit power control), frequency (e.g., dynamic frequency selection) and time (e.g., predictive scheduling) directly impact coexistence metrics and are obvious candidates for cognitive radio control, many other parameters can be set to ensure and enhance coexistence such as route selection (choosing routes to minimize interference), network association (preferentially connecting to a network with greater protective measures), and application layer parameters (such as reducing video quality which reduces occupied bandwidth). Conceptually, virtually every parameter, setting, and/or process which influences the transceiver operations of a radio can be controlled to ensure or enhance the coexistence of cognitive radio systems with other users.

In theory both traditional radio systems and cognitive radio systems can set the same parameters or processes to maximize coexistence. But in traditional radio systems, operational parameters and the processes to control them were defined statically prior to deployment, e.g., the frequency reuse patterns defined by spectrum regulators and service providers. Of course, because traditional systems are unable to leverage situationally varying information, these spectrum sharing techniques led to significant spectrum under-utilization. By providing the means to gather locally relevant information and implement design (decision) processes to adapt operational parameters so as to minimize the negative impact on other users and to ensure that its operation does not degrade other users below a minimal performance level, a cognitive radio system provides the possibility for radio system coexistence with relatively improved spectrum utilization/efficiency.

Because the ability to process information and adapt its operation based on that information are the key differences between a cognitive and a traditional system, this response focuses on the techniques by which a cognitive radio system defines its parameters and gains locally relevant information.

Design/Decision Processes

The following breaks down the enormous number of possible design and decision processes into what we believe to be a manageable and largely representative set of classifications of techniques which have been proposed to design/decide cognitive radio operational parameters to facilitate coexistence with other users. Rather than viewing these as discrete mutually exclusive categorizations, we believe that varying mixes of the following techniques will be utilized in most systems.

Static and dynamic partitioning

Static spectrum partitioning divides the spectrum into a set of predefined and orthogonal channels and assigns these channels to different radio systems. This partitioning can occur along a variety of different dimensions such as by space, frequency, or time. Static spectrum partitioning is the spectrum sharing technique which has been used for decades to allow the sharing of spectrum between different applications and radio technologies (e.g., the static spectrum partitioning between FM, AM, TV, cellular, public safety, and military spectrum). This approach best ensures a predefined limit on interference between radio systems but is the slowest to adapt to the changing spectral needs of society and generally leads to underutilized spectrum.

With dynamic partitioning, transmission rights change frequently, but transmissions remain orthogonally partitioned. Examples of dynamic orthogonal partitioning include transmission scheduled services (e.g., EVDO or WiMAX where a base station (BS) schedules transmissions of its subscribers or 802.16h where BS's collaborate to schedule orthogonal transmissions), spectrum markets and auctions.

Note that the more flexible a dynamic partitioning scheme is, the greater the need for software defined radios. Also note that static allocations necessarily are unable to capture and capitalize on temporal variations. Finally, note that one primary reason for including static partitioning in our list of available design/decision techniques is to make explicit the fact that all traditional coexistence techniques can be applied to cognitive radio. That is to say, cognitive radio augments the set of tools/techniques available for ensuring the coexistence of radio systems.

Centralized and distributed control

In a centralized scheme, the coexistence of users is managed by a single entity. In a distributed scheme, coexistence is managed by multiple entities who generally (though not always) have conflicting priorities and operate with different information sets.

Examples of centralized control include national spectrum allocations, intra-cell scheduling, traditional enterprise spectrum management systems, and various proposed centralized optimization routines (e.g., local searches, network wide genetic algorithms). Examples of distributed control for coexistence include the 802.11 CSMA/CA algorithm, inter-cell power control effects (e.g., cell breathing), graph-coloring algorithms, and algorithms rooted in game theory.

Note that the differentiating between centralized and distributed systems is frequently a function of scale so that at a sufficiently small scale every system is centralized (even if the controlling entity only controls the allocation for a single radio or single link) and at a sufficiently large scale, systems are necessarily distributed, e.g., national frequency allocations look distributed at an international level and enterprise allocation systems look distributed in areas with multiple enterprise deployed.

Because centralized systems eliminate the possibility of resource conflicts, a centralized algorithm should perform at least as well as a distributed system in theory. In practice, the presence of large numbers of radios and rapid variations in local operating conditions and user needs (localized information) frequently lead to situations where the information processing and communications requirements make a centralized system impractical or degrade its performance. It is hard to define a bright dividing line where conditions favour either a distributed system or a centralized system, but as the amount of information needed to implement the system grows (e.g., more rapidly changing channel environments, more users, more user variation, more varying topologies), the more likely it is that a practical distributed system can be designed which outperforms a practical centralized solution.

Also note that while static partitions are more amenable to centralized allocation techniques, static allocations can still have a degree of distribution in the allocation process. For example, see the spectrum allocation decisions of the FCC and the NTIA.

Cooperative and noncooperative processes

In a distributed system, coexistence decisions can be made either cooperatively or noncooperatively. When made cooperatively, decisions are made by a group of entities (with potentially conflicting objectives) and the decisions bind subsequent actions of those entities. When made noncooperatively, the coexistence decisions of one cognitive radio system are made independently of other systems, though possibly with input from other spectrum controlling entities.[1] Examples of cooperative processes include 802.16h and 802.22 inter-BS allocations; examples of non-cooperative processes include the

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[1] If spectrum controlling entities first consulted with each other and then were free to act in any way they saw fit (i.e., without being bound to a group decision), this would also be an example of a noncooperative process.

802.11 CSMA-CA algorithm, the white space coalition's proposed approach to coexistence for low-power transmitters, and most proposed algorithms rooted in game-theory.

Cooperative and noncooperative approaches exhibit many of the same tradeoffs as seen between centralized and distributed algorithms. Namely that as networks scale in numbers of decision makers and in terms of information variance, cooperation becomes more difficult to implement efficiently, but in theory, a cooperative process can outperform a noncooperative process due to the elimination of resource conflicts.

Procedural and non-procedural processes

The techniques used to ensure coexistence can be defined either procedurally with a well-defined algorithmic definition or non-procedurally with only generalized principles or operational guidelines. Many currently considered or proposed coexistence techniques are defined procedurally, i.e., prescribing particular actions in response to particular events. Examples of procedural algorithms in include how power is stepped up or down in response to SINR variations, the 802.11 CSMA-CA algorithm which controls WiFi transmission times, or scheduling algorithms defined for varying standards. However, coexistence can also be achieved and enhanced without specifying what action should be taken in response to an event. For example policy definitions frequently place broad restrictions on operational parameters, but exactly what action a radio should take may be undefined; a game theoretic coexistence technique defines objective / utility functions for the radios but leaves decision processes largely undefined; and a radio etiquette may define principles of operation which the radio must considers when making its decisions but will generally not define what action should be taken in every situation. Note that non-procedural processes could be implemented as some system's decision process, e.g., a system could adapt transmit power policy based on the number of users or a system could specify changes to radio objectives as the mix of users changes.

Information Processing

The processes described in the preceding classifications can only be guaranteed to perform well when armed with reasonably accurate information. In general the higher the quality of the available information (i.e., more timely and more accurate), the better the decision and design processes will perform. Thus, the processes by which cognitive radio systems gain information are intricately linked to any technique intended to ensure and enhance coexistence with other users.

Information processing in a cognitive radio is defined by two complementary processes – observation and orientation. An observation process gathers raw data and an orientation process assigns meaning to the data. Examples of observation processes include power spectral density measurements to detect the presence of signals; cyclostationarity techniques to extract signal characteristics (e.g., modulation and bandwidth); and trilateration to infer transmitter location. Examples of orientation processes include ontological reasoning processes and classifiers (e.g., neural nets or hidden Markov models).

While almost any piece of layer 1 and layer 2 information could be applied to coexistence algorithms, some of the more commonly cited gathered information types include the presence and location of other users, other users' signalling parameters, and environmental propagation characteristics. To give a feel for the wide range of information which could be applied to coexistence consider that user preferences could be used to anticipate how interference impacts perceived performance, radio performance characteristics could be used to predict performance impact, and biometric information could be used to authenticate that another user has priority. As such, an exhaustive listing of the kinds of information that a cognitive radio system may find useful for promoting coexistence is perhaps impossible. Instead, the following classifies the means by which cognitive radio systems can generate the information needed for its decision processes.

Collaborative and noncollaborative information processing

In collaborative information processing, multiple systems collaborate on the observation and/or orientation processes. In contrast, a system implementing a noncollaborative information processing technique must rely solely on its own capabilities.

Because the variance of an estimation of a process is reduced as the number of independent samples used to make the estimation increases, collaborative information processing will generally improve information accuracy. Further, because of hidden node effects and variances in device capabilities, collaborative techniques can make information available to cognitive radio systems which would otherwise be unavailable. Examples of proposed collaborative information processing techniques include the collaborative detection techniques proposed for 802.22 and various proposed database techniques such as the Radio Environment Map. Both of these techniques are largely focused on collaborative observation processes, but collaborative orientation processes such as data fusion and distributed processing could also be employed.[2]

Note that collaborative information processing techniques will generally yield superior performance to noncollaborative techniques, but practical considerations (e.g., a rapidly changing phenomenon or limited processing resources or bandwidth) may make collaborative techniques unfeasible. Also note that our definition of collaborative information processing does not restrict collaboration to cognitive radio systems. In fact, many of the most promising collaborative techniques involve collaboration with a system which does not implement any radio functions. For example, 802.11y and various proposals for the TV band coexistence assume the existence of databases which store and make available the location and characteristics of fixed protected users so that a cognitive radio capable of only observing its own location can be aware of the presence of protected users. Likewise, the structure of collaborative information processing can take on many forms, e.g., between peers of cognitive radio systems, in a hierarchical system (ala 802.22), in a client/server information pull mode (like 802.11y's proposed database), or in an information push mode (as in proposed information beacons which can supply both observation and orientation information).

[2] SETI @ Home – an example of distributed processing - is arguably the largest example of a collaborative orientation process. However, SETI @ Home will not satisfy most definitions of a cognitive radio system and any coexistence benefits which might be gained via SETI @ Home are only theoretical at this point.

Cooperative and noncooperative information processing
In cooperative information processing, the observed user actively aids the observing cognitive radio system while in noncooperative processing a cognitive radio system has to gain relevant information without help from the user.

Out of necessity, most proposed techniques for gaining information about legacy systems (e.g., TV or satellite) adopt a noncooperative approach with cooperative techniques utilized more frequently for coexistence between cognitive radio systems (such as has been proposed for systems utilizing a Radio Environment Map). However, this need not be the case as with the proper inducements, legacy users could augment their existing systems to aid cognitive radio systems' observation/orientation processes. For instance, coexistence between public safety systems and commercial systems seems a natural candidate for cooperation and different agencies are making databases available for fixed transmitters (making those databases examples of cooperative collaborative information processing).

Pre-programmed and augmented information
Pre-programmed information refers to information which is available to a cognitive radio system prior to deployment. Augmented information refers to information which only became to the radio after deployment by means other than a software upgrade. Note that with collaboration, what is pre-programmed information for one radio may be augmented information for another.

All cognitive radios will come preprogrammed with some internally available information which we term innate information. For cognitive radio systems, innate information generally corresponds to pre-programmed models such as environmental models, radio operation models, and signalling models (e.g., what combination of observed signal parameters implies the existence of a particular class of users), but could define very specific pieces of information such as the IP address for a key database or expected locations for particular users. Other examples of pre-programmed information might include the fixed transmitter databases proposed for use with varying standards. Note that while cognitive radio systems will eventually be capable of reprogramming and programming new internal models (thereby augmenting that information), for most applications being considered today, internal models should be viewed as pre-programmed information.

Observed and predicted information
Most coexistence techniques react to observations of the current environment (or more accurately, the recent past). However, in time-varying situations, reacting to observations of the recent past necessarily leads to spectral inefficiencies. Greater efficiencies can be achieved when conditions are accurately predicted to occur before they are observable. For instance, when spectrum will be unoccupied when the primary user is a TV station which regularly powers down at night or a signal with a regular time-slot structure can be readily predicted which allows cognitive radio systems to optimize for how the spectrum *will be* as opposed to how it *was*. Similarly, many other potential types of information

can be predicted such as location based on observed velocity and transmit frequency for a regularly hopped transmitter or the presence of a fade based on past experience. Information prediction can even be extended to non-deterministic processes as long as the processes exhibit some degree of stationarity. For example hidden-Markov models have been applied to predict spectrum and occupy spectral holes created by random backoffs of 802.11 systems.

Joint Processing

While the preceding largely discussed cognitive radio decision and information gathering processes as separate entities or at least implied that information gathering processes operate independently of decision processes, this need not be the case. Certainly, the choice to operate in different bands in the presence of different users could require the use of different information gathering processes. Further, decision processes and information gathering processes could be jointly designed so that the actions by a cognitive radio enable or enhance information gathering. For instance, a cognitive radio system could coordinate regular periods where the radios do not transmit to minimize interference when attempting to detect incumbent users (e.g., the extended quiet periods proposed in 802.16h) or could transmit special signals to gain information about the environment (e.g., ranging in sensor networks or channel sounding to identify channel models). In general, any of the preceding classifications of cognitive radio decision processes and information gathering processes could be applied to the development of a joint processing solution.