♦ Ultra-Broadband Femtocells via Opportunistic Reuse of Multi-Operator and Multi-Service Spectrum

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Recently, two important trends concerning cellular networks operating in licensed spectrum have emerged. First, the cellular operators are considering femtocells deployed in indoor environments such as homes and enterprise buildings as a complement to macrocells for the purposes of enhancing capacity and coverage indoors. Second, standards such as Long Term Evolution (LTE), and Worldwide Interoperability for Microwave Access (WiMAX) are designing air interfaces that use increasingly wider bands of spectrum (e.g., up to 20 MHz per channel) to increase access rates. However, given the restricted size of operator licenses, the number of wideband channels is limited. As broadband wireless access gains adoption and media-rich end user devices (e.g., iPhones) proliferate, the next frontier will be ultra-broadband wireless access which inevitably needs more spectrum. Given end users often spend 40 percent of their time indoors, femtocells may be the first user equipment to offer such ultra-broadband access. In this paper, we propose a novel way to enable such ultra-broadband femtocells by opportunistically accessing wider swaths of spectrum. Our solution is based on three new concepts—intra-operator spectrum white space reuse, multi-operator spectrum sharing, and multi-service spectrum reuse—which exploit the spectrum of multiple cellular operators and of multiple non-cellular services such as digital television (DTV) broadcasts in femtocells deployed in a relatively isolated indoor environment. We describe an end-to-end architecture consisting of four main components: a multi-operator spectrum server (MOSS), a femto coordination/controller server (FCS), a cognitive femto base station, and associated end user devices that support a new air interface operating in non-contiguous spectrum bands. We also describe application of our concepts and solutions in the context of refarming the Global System for Mobile Communications (GSM) spectrum worldwide to enable smooth evolution of GSM to third generation (3G) LTE standards.
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Panel 1. Abbreviations, Acronyms, and Terms

2G—Second generation
3G—Third generation
3GPP—3rd Generation Partnership Project
3GPP2—3rd Generation Partnership Project 2
4G—Fourth generation
ADC—Analog-to-digital conversion
CDMA—Code division multiple access
DAC—Digital-to-analog conversion
DTV—Digital television
EV-DO—Evolution data optimized
FC—Femtocell
FCC—Federal Communications Commission
FCS—Femto coordination/controller server
FTTH—Fiber to the home
FTTN—Fiber to the node
GSM—Global System for Mobile Communications
HSDPA—High speed downlink packet access
HSPA—High speed packet access
LTE—Long Term Evolution
MOSS—Multi-operator spectrum sharing
NC-OFDM—Non-contiguous OFDM
OFDM—Orthogonal frequency division multiplexing
OFDMA—Orthogonal frequency division multiple access
OSS—Operations support system
PCS—Personal communications service
Rev.—Revision
RF—Radio frequency
SMR—Specialized mobile radio
SUDU—Spectrum usage decision unit
TDMA—Time division multiplex access
TV—Television
UMB—Ultra mobile broadband
USA—United States of America
vDSL—Very high bit rate digital subscriber line
WiMAX—Worldwide Interoperability for Microwave Access

Introduction

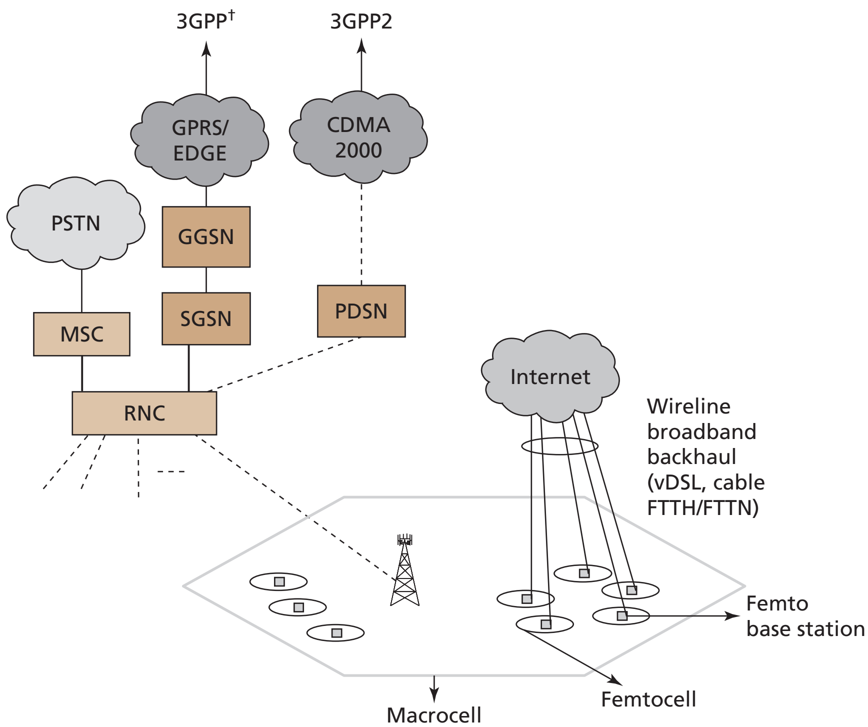
Recent years have seen explosive growth in wireless services worldwide. In addition to reliable, ubiquitous coverage, wireless end users now increasingly expect high throughput data services. Third generation (3G) broadband wide-area cellular services such as high speed downlink packet access (HSDPA)/high speed packet access (HSPA), and evolution data optimized (EV-DO) revision (Rev.) A represent the first step in meeting this expectation. However, as these services gain widespread adoption, the next generation of wireless services must evolve to ultra-broadband (multi-megabits per second per user) speeds. Two core and complementary approaches to improving wireless speeds are:

1. Aggressive reuse of spectrum in the most efficient fashion, and
2. Increasing the amount of spectrum available for use.

Recently, large service providers have started considering deployment of femtocells. As shown in **Figure 1**, femtocells are cells with a small spatial footprint, deployed in a home, enterprise building, or public place and connected to the Internet via a broadband wireline connection, e.g., very high bit rate digital subscriber line (vDSL), cable, fiber to the home (FTTH), or fiber to the node (FTTN). As a tool to maximize utilization of operator-licensed spectrum, femtocells therefore represent approach (1) mentioned above.

The first generation femtocell deployments will use spectrum in one of the following ways:

1. *Static allocation.* In this simple option, the operator will statically reserve a portion of its licensed spectrum to be exclusively used in femtocells. This eliminates mutual interference between macrocells and femtocells and guarantees their seamless coexistence.
2. *Concurrent co-channel reuse.* In this option, the femtocells concurrently reuse the same licensed spectrum that macrocells use. This however poses serious technical challenges such as (a) signaling storms that result from a dramatic increase in signaling traffic in the core network in dense femtocell deployments, and (b) scalable auto-configuration and power management.



3GPP—3rd Generation Partnership Project
3GPP2—3rd Generation Partnership Project 2
CDMA—Code division multiple access
EDGE—Enhanced data rates for GSM†† Evolution
FTTH—Fiber to the home
FTTN—Fiber to the node
GGSN—Gateway GPRS support node
GPRS—General packet radio service
GSM—Global System for Mobile Communications††
MSC—Mobile switching center
PDSN—Packet data serving node
PSTN—Public switched telephone network
RNC—Radio network controller
vDSL—Very high bitrate digital subscriber line

† Trademark of the European Telecommunications Standards Institute.
††Registered trademarks of the GSM Association.

Figure 1.
Femtocells.

Recent research efforts addressing these challenges have been reported in [2, 5]. Note that in both spectrum usage scenarios, the maximum amount of spectrum available for use in the femtocells is limited to the amount of operator-owned licensed spectrum.

In order to realize future ultra-broadband rates, option (b) mentioned above, wherein the amount of spectrum available for air interface technologies is increased dramatically, needs to be explored. Emerging new air interfaces for wide area cellular technologies such as Worldwide Interoperability for Microwave Access (WiMAX) ranging from 1.25 MHz to 20 MHz, 3rd Generation Partnership Project 2 (3GPP2) ultra mobile broadband (UMB) ranging from 1.25 MHz to 20 MHz, and 3rd Generation Partnership Project (3GPP*) Long Term Evolution (LTE) from 1.4 MHz to 20 MHz, have already shown the need for wider spectrum bands for higher data rates. Unfortunately, spectrum scarcity resulting from near-full allocation of spectrum [12] makes the prospect of obtaining ever larger numbers of wide-band channels a very challenging task. To that end, new technologies that allow cellular networks to access and share more valuable spectrum are necessary. Our paper represents a novel effort in this direction in the context of low power femtocells.

We propose three new methods for obtaining more spectrum for femtocells via dynamic sharing or reuse of previously allocated licensed spectrum:

1. *Intra-operator spectrum white space reuse,* where femtocells reuse an operator's own spectrum that is otherwise spatio-temporally unused.
2. *Multi-operator spectrum sharing,* where femtocells dynamically share spectrum owned by multiple cellular operators across all operator-owned femtocells in a region.
3. *Multi-service spectrum reuse,* where the femtocells opportunistically reuse unused spectrum licensed to other services such as television (TV), public safety, and specialized mobile radio (SMR).

We describe in detail a novel architecture called "SpectrumHarvest" designed to enable such spectrum use in a scalable fashion.

Outline of the Paper

The rest of this paper is organized as follows. The section immediately following introduces three new spectrum use models, namely intra-operator white space reuse, multi-operator spectrum sharing, and multi-service spectrum reuse in the context of femtocells. Next, we describe our SpectrumHarvest system architecture and its various components and associated technologies in greater detail. Finally, we offer our summary and conclusions.

New Techniques to Increase Spectrum Availability in Femtocells

In the following, we illustrate three new techniques to increase the amount of spectrum available in femtocells. These techniques rely on two key insights:

1. Multiple entities can dynamically share licensed spectrum used in cellular fashion for aggressive low-power reuse in small spatial footprints.
2. Spectrum that is allocated and licensed but spatio-temporally unused—commonly termed as "spectrum white space"—can be opportunistically exploited.

Multi-Operator Spectrum Sharing in Femtocells

In the United States of America (USA), cellular operators currently use spectrum in the following spectrum bands: 824–849 MHz and 870–894 MHz for paired cellular; and 1850–1910 MHz and 1930–1990 MHz for personal communications service (PCS), as illustrated in **Figure 2**. Each operator typically owns one block of

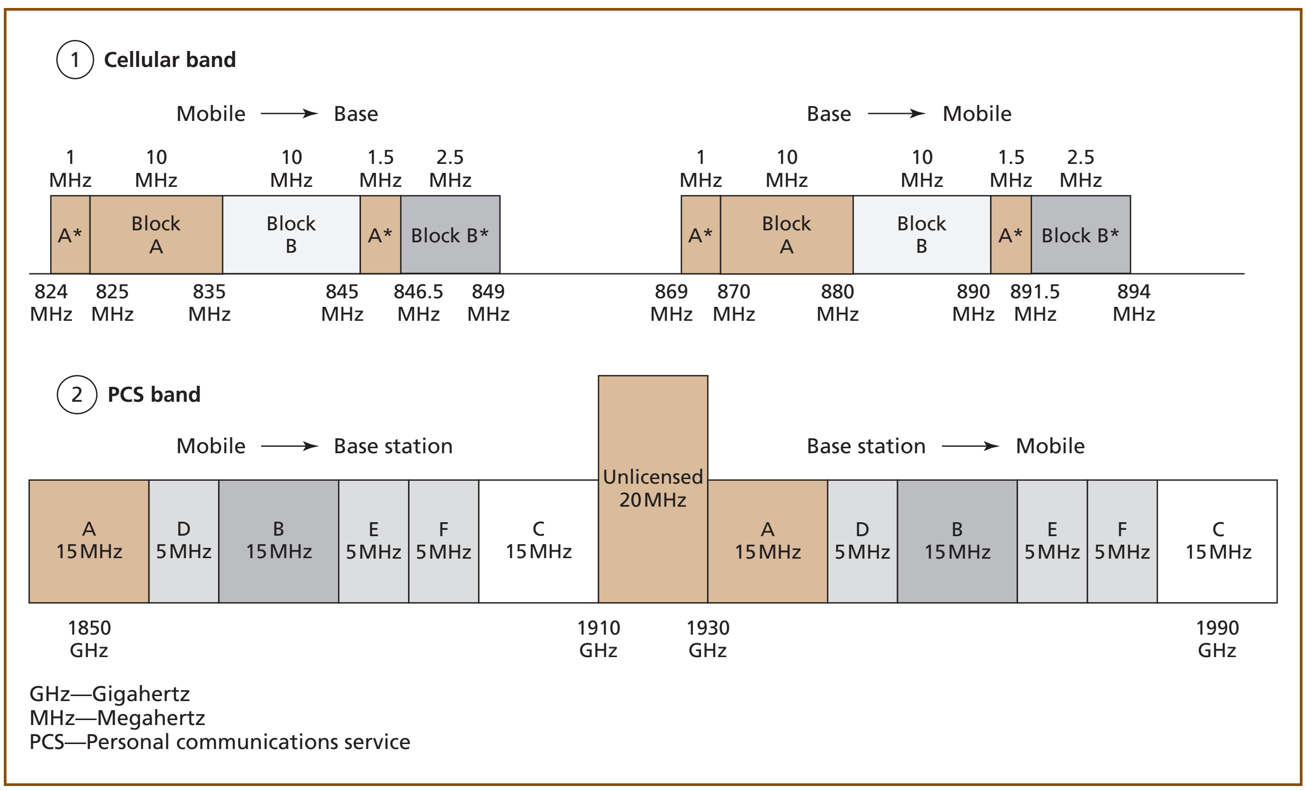


Figure 2.
Cellular and PCS spectrum in the United States.

cellular band (block A or block B) and/or one or more PCS blocks (blocks A to F). By the license terms, a service provider can operate its networks only in these blocks.

The concept of multi-operator spectrum reuse in femtocells is a novel concept that allows each operator to use the full cellular and PCS band in a low-power mode. An example in **Figure 3** illustrates this concept: It shows the macrocellular networks of three providers Verizon, T-Mobile, and Cingular, with corresponding cellular/PCS spectrum license assignments in a region 10 square kilometers around Murray Hill, New Jersey. Here, Verizon owns spectrum block B in the cellular band and owns PCS band blocks C and F. Similarly, Cingular/AT&T owns cellular block A and PCS block A, while T-Mobile owns PCS block D.

Currently, Verizon femtocells deployed in this area can use only cellular block B and PCS blocks C and F. In our model of multi-operator sharing, the Verizon femtocells can use cellular block A, PCS block A from Cingular, and PCS block D from T-Mobile, in addition to Verizon's own cellular block B. In this manner, the femtocell of any operator can potentially access the entire 25 MHz (paired) cellular band or 60 MHz (paired) PCS band and dramatically increase available spectrum. Such a form of sharing is predicated on the fact that the low power operation of femtocells ensures negligible interference to the macrocells of all operators.

In the short run, such multi-operator sharing can be easily applied when each operator statically reserves a portion of licensed spectrum for femtocells. The spectrum can readily be used in other femtocells that are not within the interference distance without any impact to either the macrocells or other femtocells. For example, if Verizon reserves one 1.25 MHz

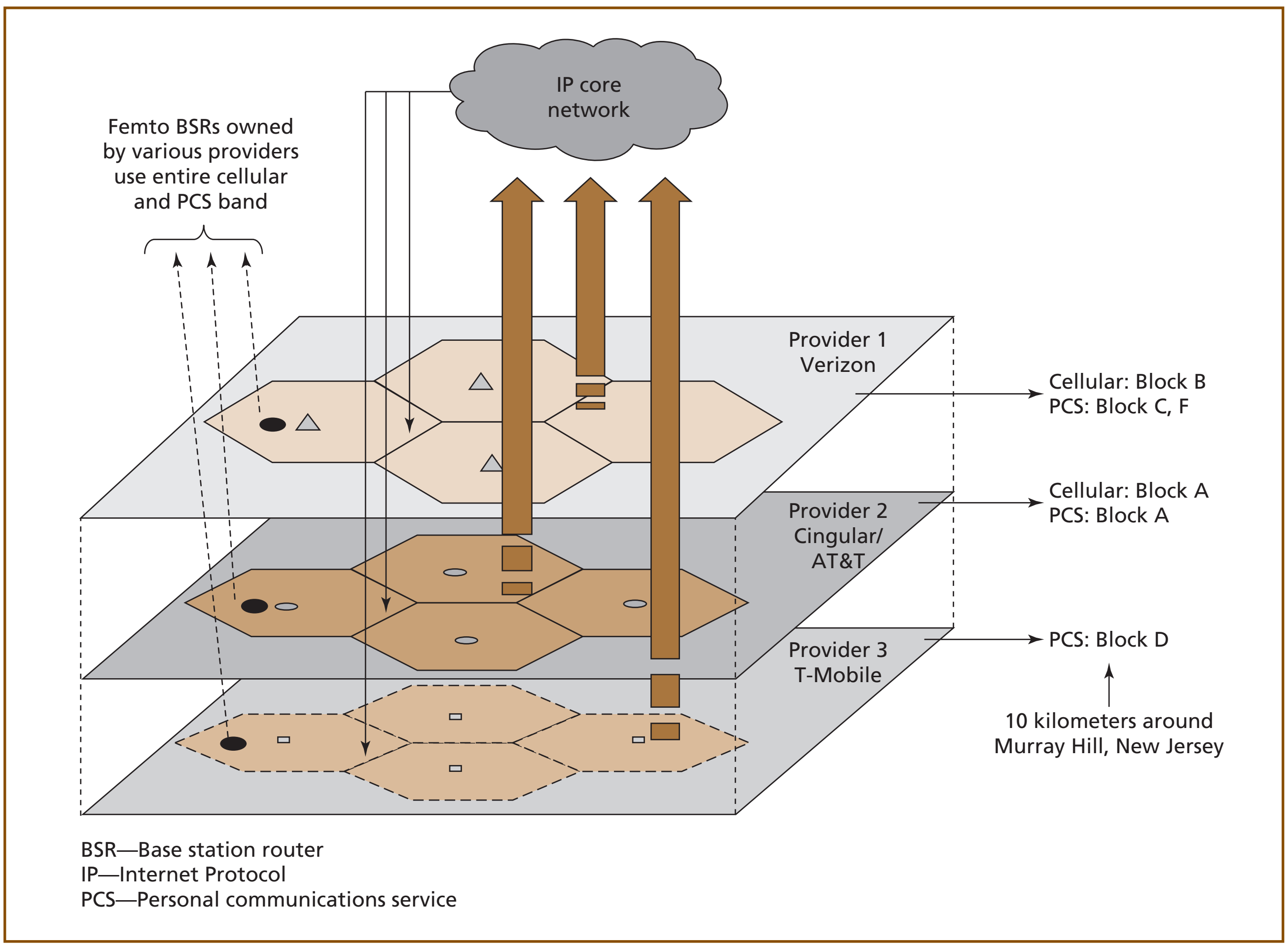


Figure 3.
Multi-operator sharing concept.

EV-DO Rev. A channel in cellular block A, and Sprint reserves a similar channel in block B, femtocells owned by both operators can share both channels and double the amount of femtocell capacity without any tangible impact on the macrocells.

Needless to say, this form of sharing requires that the operators are willing to consider new business models in which they allow their competitors to use their spectrum for femtocells for a fee or in exchange for being allowed to use others' spectrum.

Intra-Operator Spectrum White Space Reuse

The cellular concept divides the network coverage area into smaller cells and sets the transmitter power in each cell appropriately to limit inter-cell interference, and this in turn enables the reuse of a fixed amount of spectrum to achieve large scale network coverage. The physical layer technology used dictates what fraction of total spectrum can be employed in each cell, which then results in a spatial reuse pattern that is characterized by a parameter called frequency reuse factor *k*. **Figure 4** illustrates this with the example of networks such as Global System for Mobile Communications* (GSM*) that employ a time division multiplex access (TDMA) physical layer. The interference constraints dictate that a channel that is used in a given cell can be reused in another physically distant cell. The example shows a cell layout with a reuse factor of 1/7, where channel f used in cell 1 cannot be used in neighbor cells {2. . .7} and can be reused in cell 8. Consider a femtocell, FC, embedded in cell 1. The frequencies $\{f_2, \ldots f_7\}$ used in macrocell 2 through macrocell 7 are not used in cell 1 and can be safely reused in the FC.

The low transmit power in an FC, low path loss to mobile terminals camped in it, and the high degree of isolation to the outdoor macrocells due to wall attenuation allows such reuse. With N channels and a reuse factor of 1/K, N/K channels are used in each cell, and as such, an FC can potentially use $[(N)(K - 1)/K]$ channels as white space. A GSM operator therefore can deploy femtocells that can aggressively use a large part of its own licensed spectrum. For example, in the U.S., an operator with a license for block A or block B in the cellular band has a maximum of 12.5 MHz at its disposal. With a 1/7 reuse, each FC can have a maximum of about 10.7 MHz for such reuse.

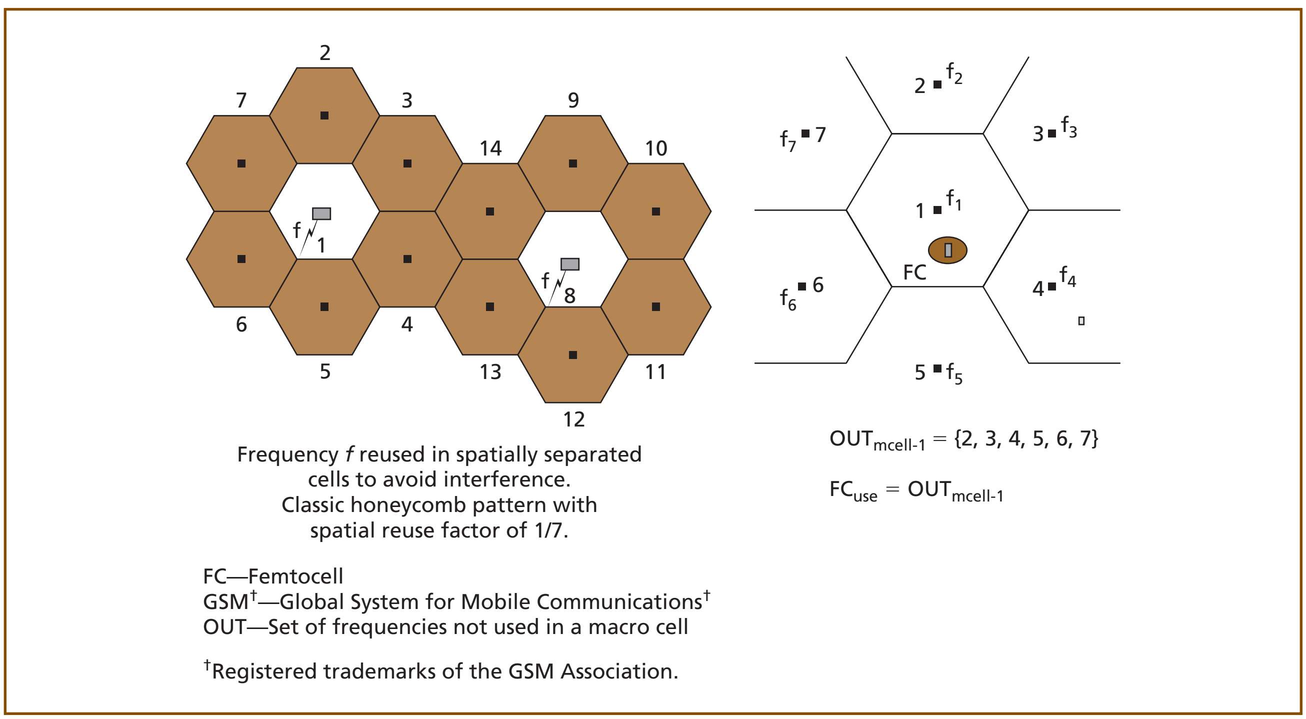


Figure 4.
GSM spectrum white spaces.

Multi-Service Spectrum White Space Reuse

Figure 5 illustrates the concept of multi-service spectrum reuse. Here, the femtocell attempts to opportunistically use the spectrum of multiple services, specifically public safety, broadcast digital television (DTV), and specialized mobile service, and spectrum detailed in **Table I**. Such opportunistic reuse dramatically increases the spectrum pool available for femtocell use to an excess of 300 MHz.

Consider the TV broadcast spectrum in the USA after the impending digital TV transition in February 2009, when digital broadcast TV will use legacy National Television System Committee (NTSC) channels 2 to 51 and the rest of channels—channel 52 through channel 69, which account for 108 MHz of spectrum—will be freed for use by other services such as public safety and cellular. Due to interference constraints, not all DTV channels can be used in a given region. A carefully designed channel allotment table that describes TV channels available to registered TV transmitters in various regions in the country (called "markets") has been developed by the Federal Communications Commission (FCC) [11]. This suggests that depending on the number of TV transmitters deployed in a given region, at any given location, there will be a subset of TV channels that will be unused. Such channels are often called "TV white space." In fact, a study reported in [1] argues that the fraction of the DTV band—channels 2 through 51—that will be vacant after the DTV transition ranges from 30 percent in the most congested coastal markets (e.g., Trenton, New Jersey) to 80 percent or more in small town and rural markets (e.g., Fargo, North Dakota). Given that broadcast TV is used only in about 15 percent of all homes in the U.S. [7], a lower power transmitter in such suburban homes in the unused TV channels should have negligible impact while providing valuable spectrum for achieving high data rates. Unlicensed reuse of such white space TV spectrum has also been proposed by the Wireless Innovations Alliance [13]. FCC approval is of course required for such systems and is currently being explored [10].

Table I. Spectrum allocations in the United States of America.

Service	Spectrum allocation (MHz)
Public safety	450–470, 470–512, 764–776, 794–806, 806–824, 851–869
Broadcast DTV	14–51, 470–698
Specialized mobile service	809–824, 854–869, 896–901, 935–940

DTV—Digital television
MHz—Megahertz

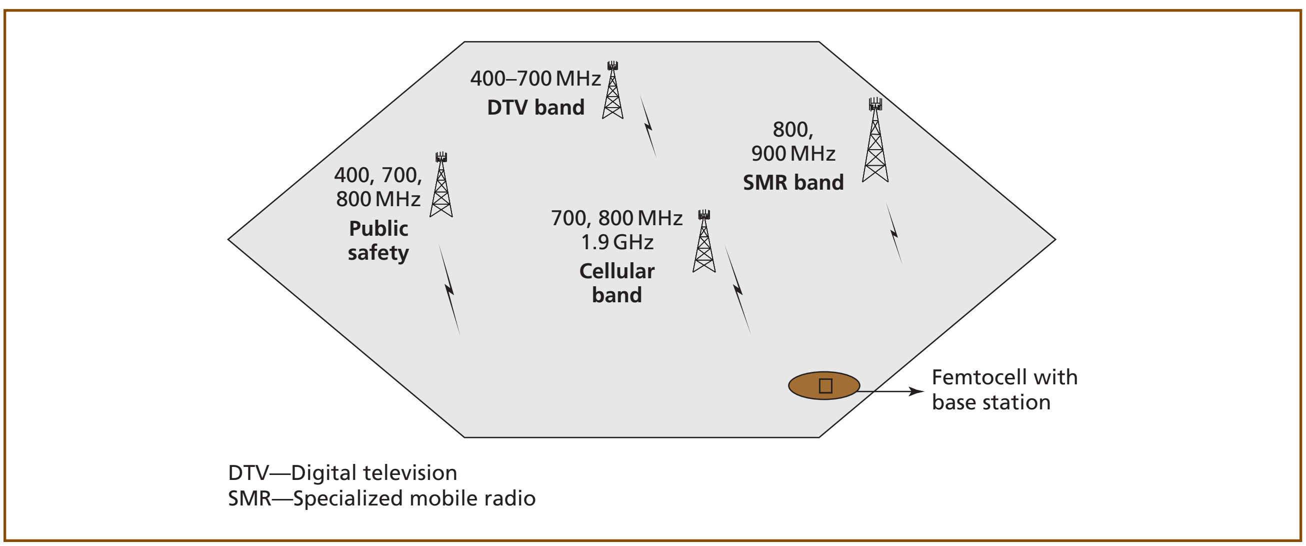


Figure 5.
Multi-service spectrum use by femtocells.

We believe an alternate model that licenses such white spaces has several advantages: By careful coordination of devices in licensed spectrum, concerns expressed by the TV broadcasting community on the potential for DTV receiver impairment can be alleviated. The licensed model is amenable to centralized or distributed coordination and control, and will allow easier detection of secondary user devices that impact primary DTV receivers and also allow better spatial understanding of the interference impact of these devices. A study reported in [6] estimates that under interference protection rules designed for a licensed environment, 97 percent of the U.S. population lives in locations with at least 24 MHz of spectrum available in the TV white space. On the contrary, interference rules imposed by the FCC for unlicensed models will lead to about a 50 percent reduction of available spectrum [6]. Thus, in addition to raising valuable revenue for the federal government through the licensing and auctioning of such spectrum, the shared spectrum model makes a large amount of spectrum available to service providers to accelerate the deployment of broadband services, offer tiered services and pricing, and potentially lower costs to end users.

Discussion

A use case scenario for combining intra-operator white space and multi-operator spectrum sharing, details around the properties of spectrum available in the new models, and the potential impact on end user handsets and base stations follow below.

Combining intra-operator white space and multi-operator spectrum sharing. In the context of GSM networks worldwide, the concept of intra-operator white space and multi-operator spectrum sharing can be combined to increase the total amount of white space spectrum available for reuse in femtocells. For example, in the U.S., two GSM operators, AT&T and T-Mobile, can pool their intra-operator white space in the cellular or PCS bands.

This notion is even more attractive in the rest of the world where spectrum in the 900 MHz and 1800 MHz bands is often exclusively reserved for GSM operations. In fact, refarming of second generation (2G) spectrum for 3G and fourth generation (4G) networks is an emerging activity that is likely to become increasingly important in Europe and other parts of the world. Owners of 2G spectrum worldwide will want to gradually migrate to 4G orthogonal frequency division multiple access (OFDMA)-based air interfaces such as 3GPP's LTE and 3GPP2's UMB. The current plan considered by spectrum regulators (especially in Europe) is to refarm the GSM spectrum by allocating gradually increasing blocks of spectrum to these new air interfaces, vacating the same spectrum of the current 2G transmitters. Implementation of the spectrum reuse concepts proposed in this paper would allow for accelerating the reuse of 2G spectrum for 3G/4G installations in femtocells first, while the macrocells still use 2G technologies in the same spectrum. The benefit here is that 4G femtocell operation can begin without a global vacating of particular frequency blocks.

Properties of spectrum available in new models. The spectrum available under the aforementioned spectrum access models has two important properties that make it different than current licensed or unlicensed spectrum: (1) contiguity of available spectrum, and (2) the statistical nature of spectrum availability.

- *Contiguity of available spectrum.* Traditionally, spectrum allocated under licensed or unlicensed models consists of contiguous chunks. However, spectrum white spaces often present non-contiguous spectrum bands. In the case of GSM white space, each sub-carrier is 200 KHz and the sub-carriers active in the macrocell covering a given location are not necessarily contiguous. Also, the frequency hopping pattern used to combat multipath effects periodically changes the set of in-use and unused sub-carriers in a macrocell and therefore restricts the white space available to a femtocell. When the white space spectrum of multiple GSM operators is combined, the aggregate spectrum may exhibit significant non-contiguity, as shown in **Figure 6**. In the case of DTV, in most markets, channels adjacent to in-use DTV channels are vacant. This means that the white space channels, each 6 MHz in width, are separated by at least 6 MHz or more, as is also clear in Figure 6. The contiguity of multiple white space channels has implication on the design of the air interface used to exploit those white spaces.

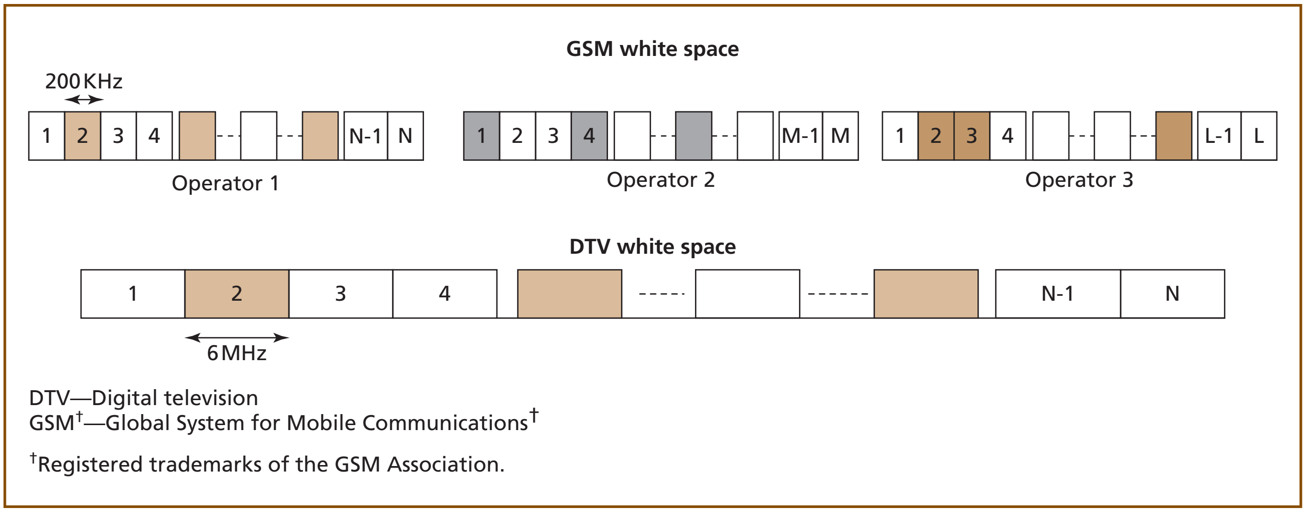


Figure 6.
Contiguity of spectrum white spaces.

- *Statistical nature of spectrum availability.* Unlike the spectrum used for cellular networks, which is licensed for very long time spans (e.g., 10 years in the U.S.) and over large spatial regions (e.g., a national or regional scope), the availability of white space channels varies spatio-temporally. In the case of GSM, available white space has a scope limited to a macrocell, and it changes predictably with a hopping pattern. In the case of DTV, the FCC TV channel allocation table varies from place to place and the asynchronous use of unused TV channels by wireless microphones can change a channel from white space to an in-use channel in an unpredictable fashion. Most service providers of today are averse to offering services in spectrum that does not have rigid guarantees in terms of long-term availability and controlled interference environment. The statistical nature of white space needs a simple-to-understand characterization to ease its adoption in the cellular networks of today. Given their small spatial footprint, femtocells are ideally suited to tolerate this statistical variation. However, a business model in which there is some level of flexibility in terms of network service availability and reliability is required. This is similar to the situation with DSL service today, where some homes cannot get higher data rate service.

Impact on end user handsets and base stations. In the case of intra-operator white space reuse and multi-operator spectrum sharing scenarios, end user handsets as well as femto base stations operate in the same radio frequency (RF) bands as the macrocell and therefore, can be realized using present-day RF and systems technology. However, with multi-service white space reuse, they require RF front ends capable of tuning over wider bands of RF spectrum ranging from 400 to 900 MHz. The widespread availability of Qualcomm's MediaFlo* [8] handsets that operate in channel 55 (lower 700 MHz block) and also support 800 MHz/1.9 GHz cellular/PCS networks suggest RF components that operate in this range can be cost-effectively integrated in handsets and base stations. However, the channel width of the air interface used impacts the required analog-to-digital conversion (ADC), digital-to-analog conversion (DAC), and power amplifier performance requirements. If the white spaces exhibit a high degree of discontinuity over a wide band, their use in a single air interface may be infeasible due to the requirement of high speed ADC/DAC and associated power consumption. Also, note that in all the new models for spectrum access, a new air interface may need to be designed that can operate in non-contiguous spectrum bands.

Regulatory and market environment. In the case of multi-service spectrum reuse, the FCC needs to approve secondary reuse of spectrum on a licensed basis for cellular operators to consider utilizing it for femtocells. New business models between operators are called for in the case of multi-operator spectrum sharing. While the incentives may be strong for two operators with similar spectrum ownership and comparable levels of femtocell deployment to allow secondary reuse, some kind of secondary reuse market or licensing fee will be required for all operators to be involved. We believe that the ever-increasing demand for high data rates, especially within the home for video entertainment, is likely to steer market forces to overcome the regulatory and technical hurdles.

SpectrumHarvest Architecture and Key Technology Enablers

The first generation of femtocell deployments explored by the operators use femto base stations which are managed by a femto controller or a coordination server that is part of the service provider's operations support system (OSS). **Figure 7** illustrates our new proposed SpectrumHarvest architecture that enhances the current architecture and enables our new models of spectrum access and sharing in femtocells. It relies on a new kind of cognitive femto base station, shown in **Figure 8**, and an inter-operator server called the multi-operator spectrum server (MOSS). In the following, we discuss these components and the associated new technologies necessary for realizing the above architecture.

Multi-Carrier/Multi-Band Transmission

With spectrum sharing, it is possible that the spectrum that is available for use is a non-contiguous set of carriers, possibly even in different bands. To enable high data rates, it may thus be necessary to transmit data over multiple carriers using an air interface technology designed for that carrier in that band. For example, if multiple 1.25 MHz carriers in a code division multiple

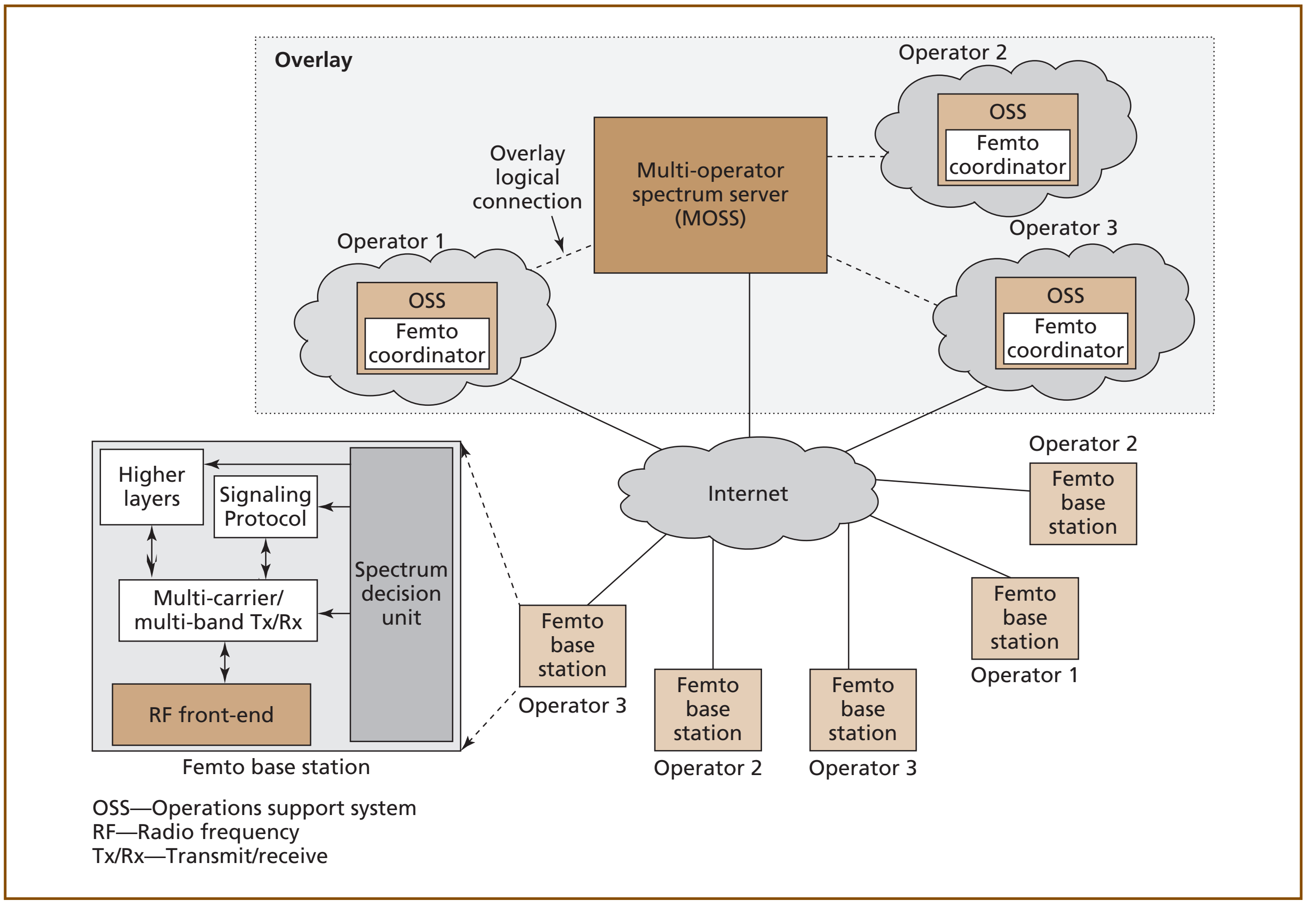


Figure 7.
Hierarchical architecture and key technologies for multi-operator/multi-service spectrum reuse in femtos.

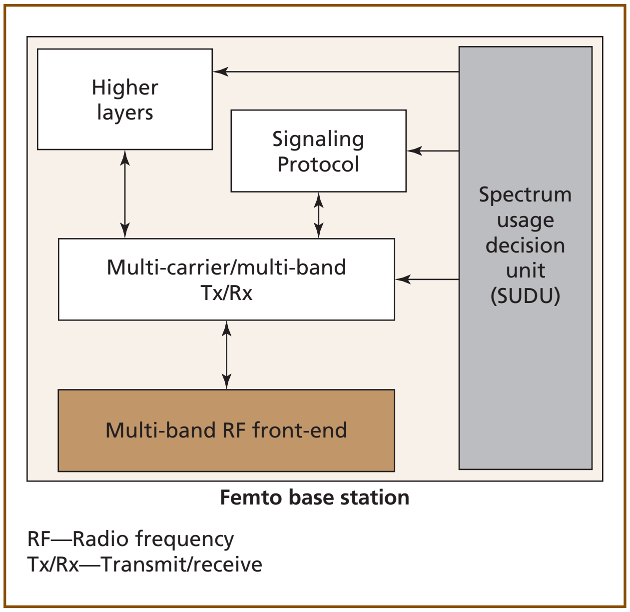


Figure 8.
Details of the cognitive femto base station.

access (CDMA) system are available, multi-carrier CDMA signaling needs to be used; here, base band signals are separately generated for each carrier, modulated to the appropriate carrier, and then combined.

In recent years, classic orthogonal frequency division multiplexing, a frequency domain modulation technique that uses sub-carriers that are contiguous in frequency space, has emerged as the preferred air interface for several state-of-the-art technologies such as WiMAX, 3GPP LTE, and 3GPP2 UMB. Such an air interface can be modified to a variant called non-contiguous orthogonal frequency division multiplexing (NC-OFDM) [9], which allows occupied sub-carriers to be separated in frequency space. In the context of opportunistic use, NC-OFDM can selectively turn off the sub-carriers in portions of the spectrum where a primary signal or interference is strong. We can also use the selective on/off feature to control aggregate interference to certain type of (primary) signals (e.g., CDMA). NC-OFDM is thus a natural fit for the opportunistic spectrum reuse concept. It is also being considered as an air interface for next-generation air interfaces for macrocellular networks in LTE-Advanced standards activities; femtocells could be the first user equipment to adopt it.

Multi-Operator Spectrum Server

A multi-operator spectrum server, shown in **Figure 9**, is a network resident server that coordinates the use of spectrum across multiple operators and informs the femto controller/femtocell of each operator as to the aggregate spectrum available for femtocell use in each region. This is achieved by collecting information about spectrum availability for femto use from each operator, and possibly combining it with additional spectrum measurement information received from one or more operating femtocells. The server can also perform collaborative spectrum sensing by processing localized spectrum sensing information from various femto base stations to draw dynamic inferences about spectrum usage and availability. It may perform time synchronization and spatio-temporal scheduling of sensing operations at various femtocells required for such collaborative sensing. Other policy enforcement functions with respect to spectrum sharing—for example, which spectrum an operator would allow for secondary use, at what specific times, and in what spatial regions—can be implemented in the MOSS.

Femto Controller/Coordination Server

The femto coordination/controller server (FCS) is a network resident server deployed as part of the operation support system (OSS) of each service provider and serves as the coordinator of the femto base stations of that operator in a region. It serves as a registration, authentication, and auto-configuration server. Based on the collective information received from the MOSS, it also facilitates opportunistic spectrum usage by providing a range of information to femto base stations such as spectrum usage and power levels of neighboring femtocells, locations of macrocell base stations, or transmitters of primary users.

Spectrum Usage Decision Unit

The femto base station may contain a spectrum usage decision unit (SUDU) to determine what spectrum to use for transmission. The SUDU, shown in **Figure 10**, may use information from multiple sources to make this decision:

1. *Information from FCS and MOSS.* The femto base station uses connections to the FCS and MOSS to obtain information on the type of primary users,

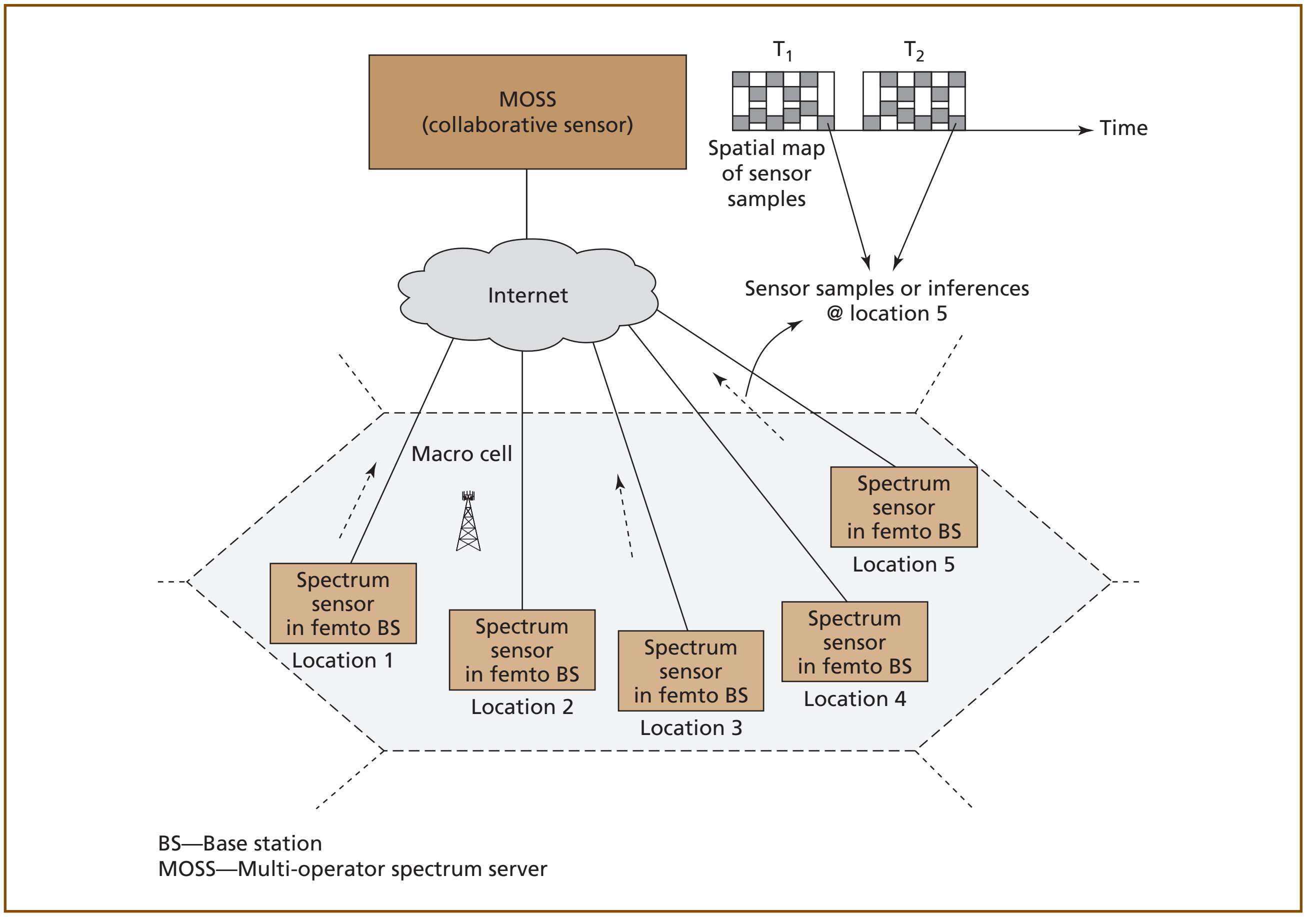


Figure 9.
Collaborative sensing via MOSS.

the type of their signals, and the locations of their transmitters present in various spectrum bands. As an example, a femto base station using only cellular operator spectrum will scan the entire 800 MHz cellular and 1.9 GHz PCS bands and use the FCS or MOSS to potentially obtain the exact location of a macrocell base station.

2. *Localized spectrum sensing.* The SUDU performs localized measurements to detect presence or absence of primary transmissions as well as the presence of other secondary femtocells. It may also receive information from other sensors or from neighbor femto base stations on their real-time measurements. Detection may be based on a combination of techniques such as the spectral energy present in the band, signal-specific characteristics such as cyclo-stationary features, and primary signal-specific information (e.g., DTV pilot, GSM frame structure, or CDMA pilots.). This detection may process primary signals in a frequency domain or use coherent time domain processing. Detection of signals from nearby secondary femtocells may also be based on known signatures (e.g., on an OFDM signature, if an OFDM air interface is used in the femtocell).

Approaches that rely on energy detection are quite susceptible to noise and improve in accuracy with the use of collaborative sensing which combines measurements from multiple spatially distributed sensors [3, 4]. Therefore, the SUDU measurements can also be supplied to a MOSS to perform such sensing. The spectrum white space (availability) information can then be communicated back to the SUDU from the MOSS over the wireline backhaul connection. This

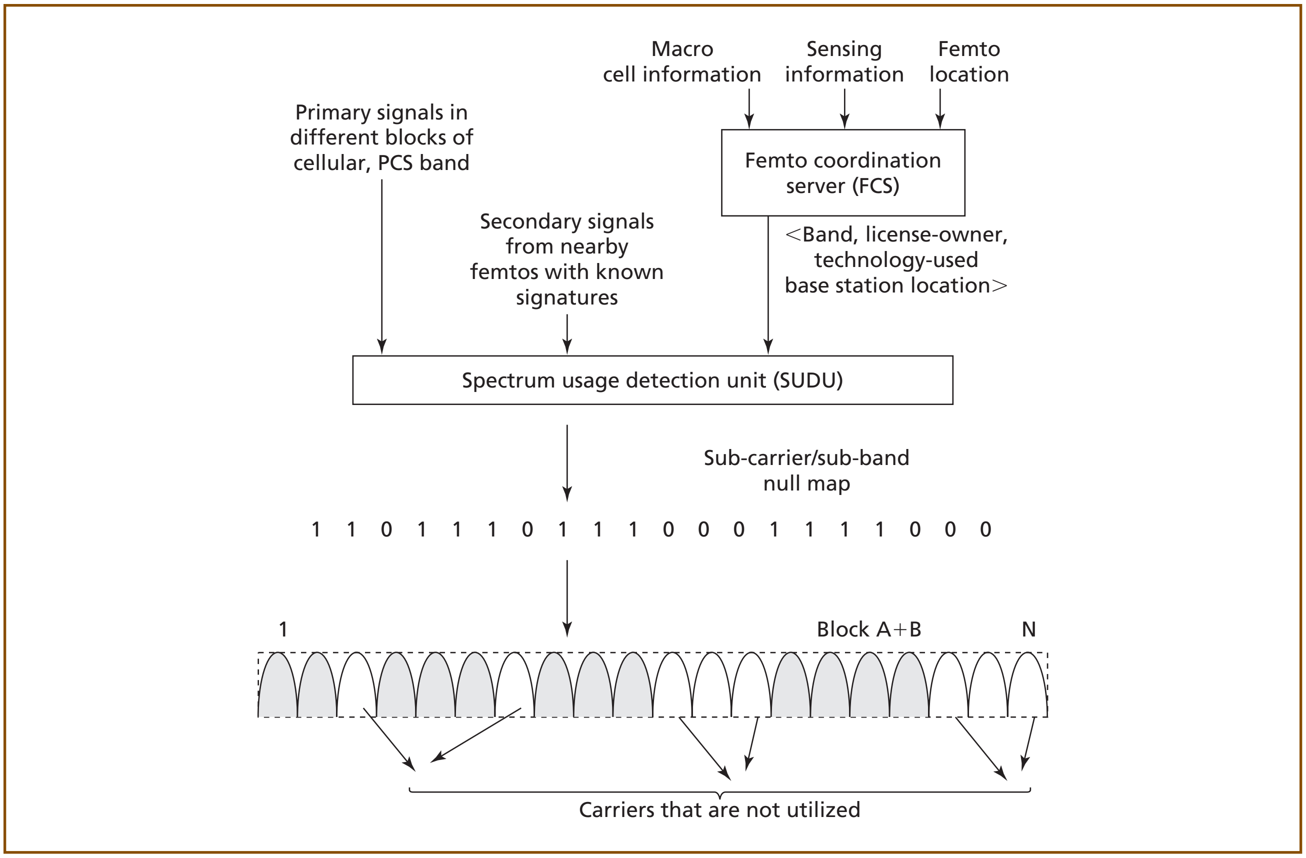


Figure 10.
Spectrum usage detection unit.

approach is particularly valuable when the spectrum that is reused is utilized only in certain geographical areas in a macrocellular fashion using high transmit powers. In these cases, the collaborative sensing based on information received from many SUDUs can be used to accurately determine the boundaries of the region where spectrum sharing is prohibited.

The SUDU uses all information at its disposal to periodically (e.g., every 100 milliseconds) provide a spectrum band null map, which contains band-specific numbers which can be 0, 1 or a range-limited (< 100) positive number called the strength-number. In the context of the NC-OFDM air interface, this map may be called sub-band or sub-carrier null map where the resolution of the map equals the sub-carrier separation. Number 0 in the map indicates that the band/sub-carrier is not used by a primary user and can be used by the femto. Number 1 indicates that the femtocell should not attempt to use that specific band. A non-unit positive number indicates the extent of the primary user's activity (expressed as a fraction less than 1 multiplied by 100), which can be used in threshold- based schemes for deciding if a femtocell should use a specific spectrum band.

The sub-carrier null map is used by the NC-OFDM layer to decide which sub-carriers to activate and which ones to null.

Signaling Protocol

The available bandwidth is coordinated between end user devices and the femto base station using a signaling protocol. The protocol supports appropriate control channels to convey multi-carrier system-specific parameters within the network. It may also include other standard information such as power control, pilot, paging, messaging, synchronization, and any other auxiliary information. It may support a bi-directional channel between the base station and the end user device to enable bi-directional signaling for the reporting of various parameters such as channel condition measurements and required bandwidth from mobile station to base station.

Note that this signaling protocol should be mapped on a part of spectrum used by the air interface protocol that is time invariant or varies with a known pattern. Without this guarantee of an “anchor location in spectrum,” correct operation of air the interface cannot be guaranteed when the femtocell and associated user devices periodically tune to different bands.

Conclusions

Significant pent-up demand exists for broadband wireless access and new exciting applications are envisioned as such access becomes widespread. Since about 40 percent of wireless sessions are initiated indoors, operators have considered the use of indoor femtocells. Though first generation femtocells are designed for off-loading voice traffic from macrocells, in the future they will be used for broadband data sessions. An indoor turbo mode of service that complements wide-area cellular broadband service will be of great interest to end users and also to help operators better use their precious spectrum. However, such a turbo mode requires wide-band channels and therefore, more spectrum, which is hard to come by. In this paper, we propose novel concepts of intra-operator spectrum white space reuse, multi-operator spectrum sharing, and multi-service spectrum reuse in femtocells to address this problem. We describe, in detail, candidate architecture and associated novel technologies—namely a cognitive femto base station, a femto coordination/controller server, and a multi-operator shared spectrum server. We also described the non-contiguous OFDM air interface and server-assisted spectrum sensing. We are currently exploring a prototype implementation of these technologies.

*Trademarks

3GPP is a trademark of the European Telecommunications Standards Institute.

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