Dynamic Cellular Cognitive System

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ABSTRACT

High quality communications among a diverse set of cognitive radio (CR) nodes is permitted while minimizing interference to primary and other secondary users by employing Dynamic Spectrum Access (DSA) in a Dynamic Cellular Cognitive System (DCCS). DCCS can be used for, not limited to white space devices communications. Diverse device types interoperate, cooperate, and communicate with high spectrum efficiency and do not require infrastructure to form the network. The dynamic cellular cognitive system can expand to a wider geographical distribution via linking to existing infrastructure. The DCCS can quickly form a network to accommodate a diverse set of devices in natural disaster areas, for example, earth quake and Katrina. It can also recover the infrastructure in a blind spot, for example, subway or mountain area. Portable size and cost reduction enable the feasibility of its commercial applications.

1. INTRODUCTION

Traditional communication systems like the Global System for Mobile Communications (GSM) and the Long Term Evolution (LTE) are based on pre-defined channel allocation and sets of protocols. Relying on fixed base stations reduces robustness in emergently situations. Predefined channel allocation scheme produce the resource challenge because of the scarcity of current spectrum. Technology development history decides that cellular system and Wi-Fi infrastructure are independent and utilizing different spectrum and devices. This generates lack of interoperability among devices and a waste of spectrum. The DCCS system is designed and implemented by the motivation to solve the above challenges. White space has attracted attentions from many companies and researchers. White space is defined as the spectrum that is allocated to a broadcasting service while not used locally[1]. The recent transaction from analog TV to digital TV (DTV) generates a great amount of white space, which can be opened to qualified white space devices. DCCS can be implemented in the white space to provide communication schemes not causing interference to TV receivers.

DCCS defines a cognitive radio network and a set of protocols that each CR node inside the network must adopt to be considered a user within the group. A CR adapts to channel conditions using the process of sensing an existing wireless channel, configuring a radio's operation to accommodate the perceived wireless channel, and evaluating what happens when a change is made. Subsequently, multiple secondary users cooperate based on a fair and efficient scheme without losing the flexibility and self adaptation features of CR. DCCS allows users within the group to transmit without interfering with the primary user or secondary users outside the group. Lastly, it makes computational complexity more reasonable for the individual nodes within the group.

Similar to a cellular network, base station and mobile terminals both exist in DCCS networks. The difference is that the CR nodes in DCCS can switch the roles between base stations and mobile terminals based on its observation of the network distribution. A CR node functioning as base station is called Picocell Cognitive Node (PCN), and called Cognitive Mobile Terminal (CMT) when it is functioning as a mobile terminal. Each of the nodes appearing in the area has the ability of sensing the environment and being aware of positioning in the cell of an existing PCN by a three why messages exchange. Based on the result, it will automatically decide whether to switch to a PCN status or a CMT status. Cell adjustments are used to guarantee a optimal use of the resources. The dynamic connections among PCNs are wideband mobile Ad hoc network. Within each cell, a PCN manages the spectrum allowing a group of secondary users accessing the spectrum to avoid interference with primary user and user outside of this cell using different types of devices and modulations. A PCN can serve as a gateway to other infrastructure (e.g. cellular, Wi-Fi), a forwarding relay, a devices accommodator, and a spectrum manager.

2. BACKGROUNG

Compared to other intelligent communication technologies like the smart antenna, cognitive radio (CR) mitigates the interference by corporately sensing the spectrum and using idle channels model [2]. In 2004, when Qualcomm analyzed the feasibility of using CR in cellular wireless communications, it is claimed that" Unless a Cognitive Radio(CR) can measure the effect of its transmission on all possible receivers, taking a useful interference temperature measurement may not be feasible" [3]. However, it is not an easy task for the transmitter to sense the environment of the entire set of possible receivers when the receiver distribution is geographically large. Hidden terminals add more challenges to this problem. One solution is to user the combination of sensing and geographic information, which is proposed for white space application. Another solution is corporately sensing, which is used in DCCS. CR is a self observing, self learning and self decision making radio. When it is performing as the sole secondary user, it is efficient and can reach optimal utilization of the resources. However, when multiple secondary users exist, the competition among the secondary users is a waste of resources. DCCS is designed to organize cognitive radio nodes and provide more efficient communications.

3. SCENARIO DESCRIPTION AND SYSTEM OVERVIEW

3.1. Scenario Description

After June, 12, 2009, the last day for full-power television stations to broadcast in analog, all over-the-air TV broadcasts are in digital. The white space is officially opened to qualified unlicensed devices. Great market potential and research opportunities attract a great amount of attention from companies and researchers, for example, the wireless innovation alliances[4]. For an individual node, by sensing technology, it is not reliable to make the decision whether the spectrum is usable. By implementing DCCS, the probability of causing interference to the primary users, which are the DTV receivers, is dramatically decreased. By organizing the nodes behavior, DCCS performs an efficient communication system which is set up instantly.

When lacking infrastructure, DCCS connects nodes within the area, bridges to the outside, and accommodates as many types of devices as possible. As it is shown in Figure **1**, because of the natural disaster or other reasons, previous existed infrastructure are destroyed. Devices relying on infrastructures cannot function properly. It is very difficult to communicate for first responders. To solve the problems in this situation, we can implement DCCS. When first responders carrying DCCS devices, including PPCNs and CMTs arrived in the area, they can distribute to different locations. A DCCS system is set up at the same time. The spectrum they use can be white space or other available spectrum. If the PCNs that located in the edge of the disaster area have the access to the national wide network, they will perform as the bridge, and connect the entire DCCS system to the outside. Then, the people who are besieging in the disaster area can not only communicate with each other, but also set up nationwide connection.

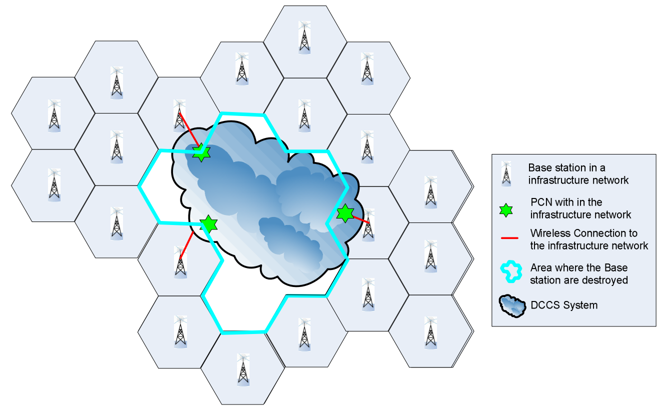

Figure 1: DCCS application scenario when lacking infrastructure

3.2. System Overview

In Figure **2**, architecture of a DCCS example is illustrated. The first step of a PPCN node is to decide whether to stay as a PCN or a CMT by sending out short messages looking for nearby existed PCN. These messages are only sent when the channel is idle by sensing. If no response is received in a pre-defined time, the PPCN will become a PCN based on the assumption that there are no reachable existing PCNs. If response is received, the PPCN will become a CMT, associates with one of the responders, and send back a message to acknowledge the relationship. The connected CMT and PCN are called being associated with each other. This is the initiation stage of DCCS. Cell management, channel allocation, intra-cell communication and inter-cell communication are 4 of the key technologies for DCCS system. We will briefly describe the first 3 parts in this paper. The inter-cell communication can be seen a flat mobile ad hoc network (MANET) and is not specifically described in this paper. More detailed design and implementation information can be referred in [5].

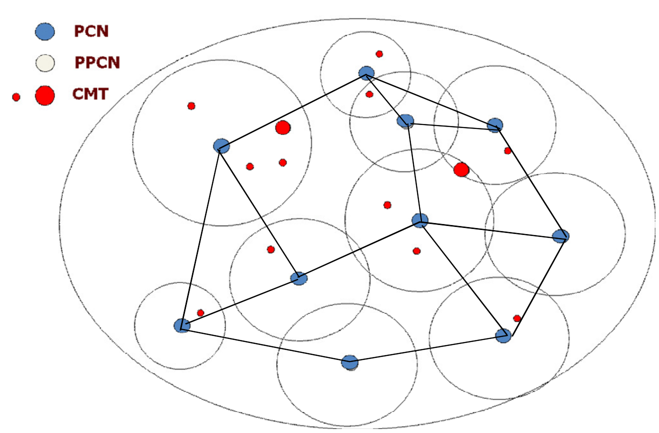

Figure 2: The coverage and node distribution of DCCS

A more specific description of DCCS structure is shown in Figure 3. The green part represents for a cell associated with PCN1. The yellow part represents the inter-cell communication. The blue part, IP network represents for an existing infrastructure. Within DCCS system, all the PCNs are IP based, and CMTs are not necessary IP based. Having an IP based structure of inter-cell communication makes a more general interface to most of the infrastructure network. Without a requirement of the IP based intra-cell communications can accommodate more types of devices in DCCS, especially the non-IP based devices, FRS radio for example.

In the following sections, cell management, intra-cell communication, and channel allocation will be introduced separately.

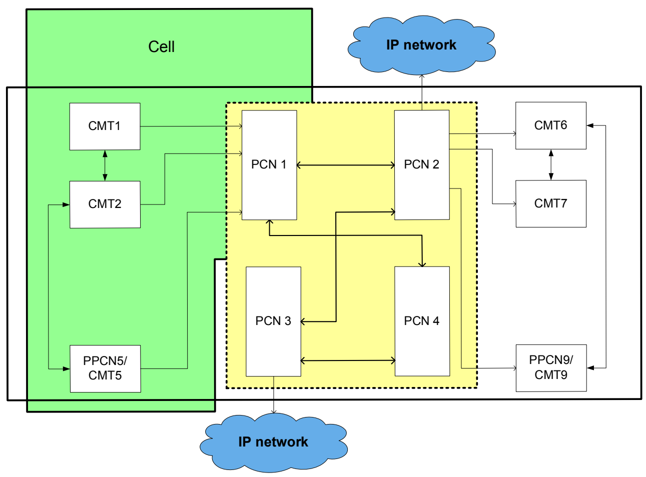

Figure 3: Structure of DCCS

4. DETAILED DESCRIPTION OF DCCS

4.1. Cell Management

In the initial stage of DCCS, a PPCN make the decision of becoming PCN or CMT by whether the response messages can be received. Apparently, there is an improving space for such a simple decision. The distribution of the nodes is varying, so the adjustments of the PPCN role and cell association are necessary. In this section, two types of behavior to optimize the cell range are defined: cell splitting and cell merging.

Based on the mobility and dynamic of the entire system, it is often required to split or merge cells to make the system more efficient. Unlike other standard cellular system, the cell range is changing and the PCN of a cell is also moving around, as well as the mobile terminals associating with the PCN. The issues in term of cell splitting and merging are mainly in two aspects: the conditions and schemes of splitting and merging, and handoff processing during and after the splitting and merging. In this section, we will discuss these two aspects separately.

We set up a model Cell Splitting and Merging Model (CSM) to describe the conditions and schemes. The objective of this model is to determine whether a splitting or a merging should be adopted based on the following principles.

1. If the connections of PCN with its associated mobile terminals exceed certain number, the splitting is necessary.
2. If the distance between a mobile terminal and a PCN exceeds a certain distance, and the mobile terminal cannot be re-registered with another existed PCN, a split is necessary.
3. A CMT noting being covered and the CMT cannot be allocated a channel when requested is considered equally bad influence in CSM.
4. A bad influence factor is used to determine whether a split or a merge operation should be adopted.
5. The global optimization is not considered in CSM, which means that the influence on other cells by the operation in the system is not considered.

Based on the above principles, the model can be described mathematically as follows.

Parameter Definition:

n_{pcn1}: Number of mobile terminals associate with PCN1

n_{pcn2}: Number of mobile terminals associate with PCN2

n_{max1}: Maximum numbers of mobile terminals associated with PCN1

n_{max2}: Maximum numbers of mobile terminals associated with PCN2

d_{max1}: Maximum distance between a CMT associated with PCN1 and PCN1

d_{max2}: Maximum distance between a CMT associated with PCN2 and PCN2

d_{12}: Distance between node 1 and node 2

$P_{mt}(n_s, n_{pcn1}, n_{pcn2})$: The probability that a new MT cannot be registered before the operation while can after the operation

$P_{ch}(C_s, n_{pcn1}, n_{pcn2})$: The probability that a CMT can be allocated a channel before the operation while can't be allocated a channel after the operation

p_r: The probability that a new MT arrives

p_c: The probability that an associated MT requests a channel

c_s: The available channel number at this moment

As it is shown in Figure 4, the model can be described as:

$$\begin{cases} H_1: f(n_{pcn1}, n_{pcn2}) \geq 0 \\ H_2: f(n_{pcn1}, n_{pcn2}) < 0 \end{cases}$$

$$s.t.: n_{pcn1} < n_{max1} \quad \dots\dots\dots\dots\dots\dots (1)$$

$$n_{pcn2} < n_{max2} \quad \dots\dots\dots\dots\dots\dots (2)$$

$$d_{12} < d_{max1} \quad \dots\dots\dots\dots\dots\dots (3)$$

$$f(n_{pcn1}, n_{pcn2}) = p_r * P_{mt}(d_{12}, d_{max1}, d_{max2}) + P_{ch}(p_c, C_s, n_{pcn1}, n_{pcn2})$$

$$P_{mt}(d_{12}, d_{max1}, d_{max2}) = {d_{max1}}^2 / \left(\frac{\alpha}{2} * d_{max2}^2 - \cos\left(\frac{\alpha}{2}\right) * \sin\left(\frac{\alpha}{2}\right) * d_{max2}^2 - \beta * d_{max1}^2 + \cos(\beta) * \sin(\beta) * d_{max1}^2\right)$$

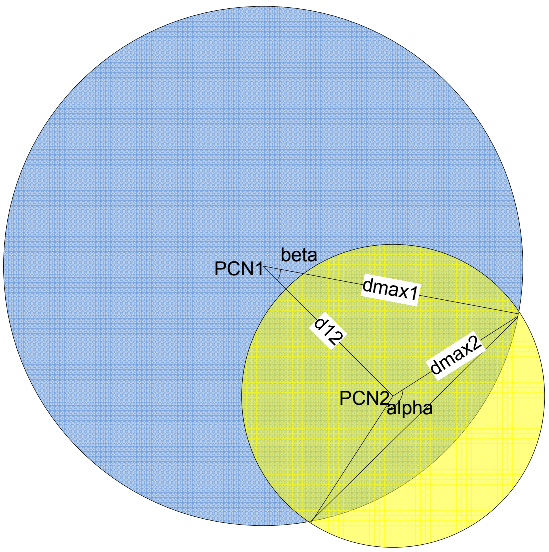

Figure 4: Cell Splitting and Merging

Where, as indicated in **Error! Reference source not found.**,

$$\alpha = 2\pi - 2\arg\cos\left(\frac{d_{12}^2 + d_{max2}^2 - d_{max1}^2}{2d_{12}d_{max2}}\right)$$

$$\beta = argcos\left(\frac{d_{12}^2 + d_{max1}^2 - d_{max2}^2}{2d_{12}d_{max1}}\right)$$

$$P_{ch}(p_c, C_s, n_{pcn1}, n_{pcn2}) = \sum_{k=C_s+1}^{n_{pcn1}+n_{pcn2}} \frac{\left((n_{pcn1} + n_{pcn2}) * p_c\right)^k}{k!} e^{-(n_{pcn1}+n_{pcn2})*p_c} - (1 - \sum_{k=0}^{C_s\frac{n_{pcn1}}{n_{pcn1}+n_{pcn2}}} \frac{(n_{pcn1} * p_c)^k}{k!} e^{-n_{pcn1}*p_c} - \sum_{k=0}^{C_s\frac{n_{pcn2}}{n_{pcn1}+n_{pcn2}}} \frac{(n_{pcn2} * p_c)^k}{k!} e^{-n_{pcn2}*p_c})$$

If H_1 is true, then, Node 1 and Node2 should be independent, which means if they are both PCNs, then, they should keep the status and do not merge; and if Node 2 associated with Node 1, they should be spitted.

If H_2 is true, then, Node 1 and Node 2 should be associated, which means if CMT2 is associated with PCN2, then, they should keep the status and do not split; and if they are both PCNs, they should merge to be associated.

The above process is only activated when any one of equation (1), (2), (3) are violated.

"In cellular telecommunications, the term handoff refers to the process of transferring an ongoing call or data session from one channel connected to the core network to another." [6]. In DCCS system, the handoff doesn't only include ongoing call or data session, but also include any registered mobile terminals transferring from the current associated PCN to another PCN. The change doesn't only include channel change, but also associated PCN change. When a cell splitting or merging happens, the handoff need to be processed include two categories: ongoing communication and registered but current not ongoing communications. For ongoing communications, there are two types of handoff: soft handoff and hard handoff. The advantage of a hard handoff is that any moment any time, one call only use one channel, and the advantage of a soft handoff is that "the connection to the source cell is broken only when a reliable connection to the target cell has been established and therefore the chances that the call will be terminated abnormally due to a failed handoff are lower [6]". Both the current and targeted PCN are aware of the happening of the splitting and merging, thus, there are sufficient reasons to choose soft handoff.

A special case for ongoing communication handoff processing is for the communication between two MTs within the same cell. Because in this case, the channel is allocated to the two MTs and they are communicating directly. However, after splitting, there is possibility that they are in different cell. And according to the basic channel allocation principle, the direct communication between them needs to be relied by PCNs. We made an exception in this case; the direct communication among these two will be continued until the termination of the communication. The reason is to reduce the handoff frequency.

4.2. Intra-cell communication

The types of modulation types for intro-cell communication are described in Table 1.

Table 1: Intra-cell communication types

Cognitive Radios	Legacy Radios			
	Public safety Radio	FRS radio	GSM or CDMA (other types of cellular radio)	WiFi devices
MPSK, QAM, FM, AM,FSK etc	FM, FSK	FM	Predefined modulation types, GMSK etc based.	Predefined modulation types, OFDM based

Intra-cell communications between CMTs work cognitively, which means that the CMTs calculate the optimal resource utilization and modulation scheme, while satisfying the restriction of the distributed spectrum in the cell. Intra-cell communication includes the communication between two CMTs within the cell, and between a CMT and the PCN in the cell. The communication could be multiple narrow band modulations including MPSK, FM, AM, FSK, or it could be OFDM based wideband communication. Each CMT chooses the mode that best fits the current environment and individual transmission requirements. The communications between CMTs in different cells are coordinated through PCNs. PCN's execute inter-cell communication using wideband transmission schemes such as WiFi or WiMAX. WiFi and WiMAX or other broadband communications are preferred because the sums of inter-cell communication payloads are relatively large. Among them, WiMAX is preferred because it covers longer distance with a scheduled MAC layer principle. Also, a PCN as a powerful CR node has the ability to classify signals and perform synchronization[7], thus, it can accommodate multiple modulation types.

PCN is the manager of intra-cell communications. The management or control message format is shown in Table 2.

Table 2: The messages format for intra-cell communication

	DST-ID	SRC-ID	MSG-TYPE	MSG-STATUS	RX-ID	Ch-Num
REGI(Registration with PCN)	FFFF	CMT#	RQST	REGI	FFFF	#########
	CMT#	PCN#	RSPD	REGI	FFFF	#########
	PCN#	CMT#	ACKW	REGI	FFFF	#########
CHAN (request channel)	PCN#	CMT#	RQST	CHAN	CMT#	FFFFFFFFF
	CMT#	PCN#	RSPD	CHAN	CMT#	#########
	CMT#	PCN#	RSPP	CHAN	CMT#	#########
	PCN#	CMT#	ACKW	CHAN	CMT#	#########
	PCN#	CMT#	ACKP	CHAN	CMT#	#########
RESU (resume communication)	PCN#	CMT#	RQST	RESU	CMT#	FFFFFFFFF
	CMT#	PCN#	RSPD	RESU	CMT#	#########
	PCN#	CMT#	ACKW	RESU	CMT#	#########
TERM(terminate communication)	FFFF	CMT#	RQST	TERM	CMT#	#########
	CMT#	PCN#	RSPD	TERM	CMT#	#########
	PCN#	CMT#	ACKW	TERM	CMT#	#########

There are 4 types of messages and 3 stages for each of them except for channel request message, there are 5 stages. The 4 types of messages include registering message, channel request message, communication resume message, and communication termination message. 3 stages represent for 3 way handshaking processing, including request, respond and acknowledgement. For channel request message, because the PCN needs to respond to both the proactive and passive radios the allocated channel information, and both of them need to acknowledge the receiving of the respond message, there are 5 stages.

4.3. Channel Allocation

A best duration sub-channel is defined as the sub-channel that can has the largest probability that it will not be taking back by the primary user during the request secondary user communication time. To choose the best duration sub-channel for when a sub-channel request received by a PCN, we need to be able to predict which channel has the least probability that if allocated to the secondary users, the communication will be interrupt by primary users coming back.

Another important factor that impacts the secondary user's communication is the SNR of a sub-channel. The best quality sub-channel is defined as the sub-channel that has the largest SNR.

Which one to choose, the best duration, or the quality, that is the tradeoff here. Generally speaking, for primary users, two parameters, the maximum interference powered level η without affecting the primary's communication and the maximum probability ζ that the interference power level perceived by the primary user may exceed η defines the interference constraints. [8] This description can also be used for secondary users with little modification.

In [9], the authors gave a very detailed survey for the channel allocation strategy. The authors focus on the method called "Opportunistic Spectrum Access (OSA)" for spectrum opportunity identification, exploitation, and policy regulation, where the primary users' behavior are modeled like this: " N channels are allocated to the primary users' network. The traffic statistics of the primary system are such that the occupancy of the N channels follows a Markov process with 2^N states, where the state is defined as the availability (idle or busy) of each channel." In [10], "the design of optimal sensing strategies has been formulated and addressed within the framework of partially observable Markov decision processes (POMDP)". In DCCS channel allocation; we adopted the similar primary users' behavior model with modifications on the above description.

To make the description easier and more accurate, we define the following variables.

N: Number of sub-channels in DCCS operation range.

$S_{channel} = [S_{ch1}, S_{ch2}, S_{ch3}, \dots, S_{chN}]$: The status (Idle/Occupied) of each sub-channel, where $S_{chi} \in (1 \text{ or } 0)$.

$\Lambda_{channel} = [\lambda_{ch1}, \lambda_{ch2}, \lambda_{ch3}, \dots, \lambda_{chN}]$: The accessing rate for primary users on sub-channels based on the observation.

$T_{channel} = [t_{ch1}, t_{ch2}, t_{ch3}, \dots, t_{chN}]$: The time interval between decision making time (current time) and detected time

$P_{channel} = [p_{ch1}, p_{ch2}, p_{ch3}, \dots, p_{chN}]$:The power detected for each sub-channel.

$B_{ch} = [B_{ch1}, B_{ch2}, B_{ch3}, \dots, B_{chN}]$: The bandwidth for each sub-channel. In most cases for DCCS, the bandwidth for each sub-channel is the same. And using different bandwidth for each sub-channel is allowed.

p_{th}: If $p_{chi} > p_{th}$, then $S_{chi} = 0$, the ith sub-channel is not available for secondary users.

pa: The probability that a CMT can tolerant the link will be interrupted by primary user within the duration informed by its PCN.

B: The bandwidth of each sub-channel.

$P_{maximum}$: The maximum power allowed for secondary user regulated by FCC or Spectrum Owner (20dBm)

The above 4 vectors, $S_{channel}$ and $P_{channel}$ depends on the detection moment, $T_{channel}$ depends on last detection time, and $\Lambda_{channel}$ depends the accumulated history record.

As we mentioned earlier, which one to choose, the best quality or the best duration? Here, we use a different objective to integrate these two factors. The objective is the maximum throughput of the channel available for secondary user. The mathematic format is described as follows:

$$\text{Objective: } \max(S_i \cdot (1 - F_i) \cdot T_i \cdot C_i)$$

$$\text{s.t.:} \quad F_i = 1 - e^{-\lambda_{chi} t_{chi}}$$

$$T_i = -\frac{\ln(1 - pa)}{\lambda_{chi}}$$

$$C_i = B_i \log\left(1 + \frac{P_{maximum}}{p_{chi}}\right)$$

$$i = 1, 2, 3, \dots, N$$

In this model, the objective is to maximize the throughput of the sub-channel.

S_i represents for the availability for secondary user to access the ith sub-channel based on the observation. If the detected power of the ith sub-channel is less than desired thresholdp_{th}, S_i equals to 1, otherwise, S_i equals to 0.

F_i represents the probability of a sub-channel not being available while the detection results shows it is available. In other words, it represents the probability that a primary user comes at the duration between last detected time and decision making time. Thus, $1 - F_i$ represents the probability that the channel is still available at the decision making time given the condition that it was available for the secondary user last time it is observed.

T_i represents the time that the primary user appears after T_i second with probability $1 - pa$. In other words, $P_{possion}(t < T_i) = 1 - e^{-\lambda T_i} = pa$, where $P_{possion}(\cdot)$ is the passion distribution with parameter λ_i, which describes the primary users coming back time distribution.

C_i is the ith sub-channel capacity given the bandwidth of this sub-channel, the maximum allowed transmission power of a secondary user and the noise floor level of this sub-channel.

The basic principle of this sub-channel selection strategy is based on the assumption that the best channel is the channel that can let the secondary users to transmit the maximum amount of information. This is a general discussion, without the detail restrictions like actually secondary user transmission power range. When applying it, the detailed restrictions can be added to make this method more customized.

5. CONCLUSION

DCCS is first proposed first responders to communication in natural disaster area. DCCS provides high quality cognitive communications among CR nodes within the coverage area while reducing or eliminating interference to primary and other secondary users having reasonable computation complexity. Three key aspects of DCCS, the cell adjustment, intra-cell communications, and channel allocation are described in this paper. DCCS provides an efficient white space network with accommodating multiple types of communication devices.

6. ACKNOWLEDGEMENT

This project is supported by Grant No. CNS-0519959 awarded by the National Science Foundation, Award No. 2005-IJ-CX-K017 awarded by the National Institute of Justice, Office of Justice Programs, and US Department of Justice. The authors would like to thank the CWT members in Virginia Tech for their contribution to this project.

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