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# 무선인지 멀티홉 릴레이 네트워크의 시스템 스루풋

# ( System Throughput of Cognitive Radio Multi-hop Relay Networks )

임룰하싼*, 노 창 배*, 송 주 빈*

( I. Hassan, Chang-Bae Rho, and Ju Bin Song )

## 요 약

제한된 전파 스펙트럼 자원은 전파 네트워크의 빠른 발전에 큰 장벽이 되고 있다. 대부분의 전파 스펙트럼은 면허 방식으로 분배되어 서비스에 이용되고 있다. 반면 비면허 방식으로 분배된 전파 스펙트럼은 전파를 이용한 서비스와 기술을 크게 향상하는데 큰 기여를 하였다. 최근에 무선인지 기술은 이러한 전파 스펙트럼 자원의 부족을 해결하기 위한 기술로써 주목받고 있다. 이 기술은 전파 스펙트럼을 효율적으로 사용 가능하도록 한다. 한편으로 멀티홉 기술이 에드훅 및 피어 투 피어 네트워크에서 집중적으로 연구되고 있으나 이동통신 네트워크에서 성능 향상을 위하여 멀티홉 기술의 연구는 최근에야 이루어지고 있다. 멀티홉 기술은 음영 지역에 고속의 데이터를 제공하고 적은 비용으로 서비스 영역을 효율적으로 확장할 수 있는 기술이다. 이동통신 시스템에서 스펙트럼 이용률을 극대화하는 무선인지 멀티홉 기술의 연구는 그 유용성에도 불구하고 아직까지 많지 않았다. 따라서 본 논문에서는 시스템 스루풋을 최대화 하는 무선인지 멀티홉 기술을 적용한 네트워크를 제안한다. 본 논문에서 제안된 시스템의 스루풋 성능을 주사용자와 부사용자의 전파 반경 및 이용률 파라메터와 같은 다양한 파라메터를 사용하여 해석적으로 모델링하고 수치해석을 통하여 제안된 시스템의 성능이 현재의 시스템에 비하여 크게 향상됨을 보였다.

## Abstract

The need for radio spectrum is recently considered as a huge hurdle towards the rapid development of wireless networks. Large parts of the spectrum are allocated to licensed radio services in proprietary way. However, enormous success of the wireless services and technologies in the unlicensed bands has brought new ideas and innovations. In recent years cognitive radio has gained much attention for solving the spectrum scarcity problem. It changes the way spectrum is regulated so that more efficient spectrum utilization is possible. Multi-hop relay technology on the other hand has intensively been studied in the area of ad hoc and peer-to-peer networks. But in cellular network, only recently the integration of multi-hop capability is considered to enhance the performance significantly. Multi-hop relaying can extend the coverage of the cell to provide high data rate service to a greater distance and in the shadowed regions. Very few papers still exist that combine these methods to maximize the spectrum utilization. Thus we propose a network architecture combining these two technologies in a way to maximize the system throughput. We present the throughput capacity equations for the proposed system model considering various system parameters like utilization factor by the primary users and primary users' transmission radius and through extensive numerical simulations we analyze the significance of work.

**Keywords** : Cognitive radio, multi-hop relay networks, throughput, opportunistic spectrum sharing

## I. Introduction

Previously, multi-hop relay technology has intensively been studied in the area of ad hoc and peer to peer networks. Recently, integration of multi-hop capability is also considered to enhance the performance significantly in cellular networks. Multi-hop relaying can extend the coverage of the cell to provide high data rate service to a greater distance and in the shadowed regions[1~2].

Also as the low data rate links between base

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* 정회원, 경희대학교 전자전파공학과,
산학협력기술연구원, IT융합연구센터
(Dept. of Electronics & Radio Eng., Kyung Hee University)

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stations and terminals are replaced by high data rate links with relays, the system throughput improves dramatically. Significant work has been done to characterize the throughput gain obtained using multi-hop techniques[3].

Another way to improve the system throughput is to use cognitive radio techniques. Cognitive radio (CR) is a new technology that can improve the efficiency of spectrum usage. It will change the way the radio spectrum is regulated, but also requires new enabling techniques. Such techniques include improved spectrum sensing and dynamic spectrum assignment techniques. Cognitive radio term was first introduced by Mitola for software defined radios capable of sensing their environment and making decisions instantaneously, without any user intervention[4~5]. This allows them to rapidly change their modulation schemes and communication protocols so as to better spectrum usage.

This need for radio spectrum is becoming a huge problem. The electromagnetic radio spectrum is a precious natural resource. Despite the recent advancements in communication technology such as Multiple Input Multiple Output (MIMO) antennas, third generation cellular networks and their integration with wireless Local Area Network (LAN) IEEE 802.11TM, it is difficult to increase radio spectrum.

Large parts of the spectrum are allocated to licensed radio services in a proprietary way. Open access to most of the radio spectrum is only permitted for radio systems with minimal transmission powers in an underlay sharing approach. Ultra wideband is an example of underlay sharing. The overlay sharing approach, i.e. the free access to open spectrum, is generally not permitted. Only some fractions of the radio spectrum, the unlicensed bands, are openly available. Unlicensed bands cover a very small fraction of the entire radio spectrum. However, throughout the last decade, these bands enabled a variety of enormously successful wireless technologies and services, among others the popular wireless LAN IEEE 802.11TM.

The cognitive radio approach promotes a technology as well as changes in radio regulation to overcome the existing barrier. Cognitive radios improve the efficiency of spectrum utilization. They typically operate at frequencies that were originally licensed to radio services such as incumbent or primary users as well as at available frequencies in unlicensed bands such as secondary users. However, a cognitive radio is not necessarily restricted to the existing licensing for primary radio systems and operates at any unused frequency, whether the frequency is assigned to licensed primary services or not. This is referred to as overlay sharing, which obviously requires new protocols and algorithms for spectrum sharing. It also involves important regulatory aspects: Cognitive radios must not interfere with the operation of licensed radio systems when identifying spectrum opportunities and during operation in licensed spectrum.

Two models of such radios have been proposed and analytical results of their capacities were derived in [6]. In the work, primary users were modeled using the temporal utilization factor of each primary user. The spatial opportunities resulting from different sizes of footprint were considered in [7]. The authors also showed effect of temporal and spatial correlation on the secondary user's system throughput. However, CR enabled cellular multi-hop relay networks have not been intensively studied so far. Specially, no system throughput results for such networks exist.

Therefore, in this paper, we formulate a network architecture and find out the system throughput of such networks. In our proposed model, cellular multi-hop relay network is used to connect the mobile stations (MS) to the base station (BS) and CR relay stations are used opportunistically select frequency channels. Relaying ensures high data rate in all the links and CR techniques enable efficient frequency reuse pattern.

We have used extensive simulation to analyze the system with utilization factor and footprint of primary users as main parameters and showed the effect of such parameters on the system throughput. From the results we see that CR enabled multi-hop relay network can significantly improve the overall system throughput. Also we notice that the system benefits most when the primary users' activity in the vicinity is minimal, thus improving the spectrum efficiency significantly.

## Ⅱ. Suggested System Model

The throughput capacity of a cognitive radio network was calculated using the Shannon's theory and the utilization factor[6]. The spectral utilization of a cognitive radio network is measured by the total amount of time when a secondary network can access a channel (or spectral bandwidth) for transmission. Once this channel access time is estimated, we can convert it to the raw channel throughput using Shannon's capacity equation. This metric is used to measure the utilization of a cognitive radio network so as to not confine to any specific MAC and modulation schemes.

The blocking time for a cognitive radio network is defined as the time interval during which a secondary network has no spectral opportunity to utilize. Based on the above high level behavioral definition of the cognitive radio network, we will show the capacity advantages of the cognitive radio networks. The model considered in this paper is shown in Fig. 1.

The Shannon's channel capacity in the presence of Additive White Gaussian Noise (AWGN) is given by

$$C = B\log_2(1+\frac{S}{N_0B}) \qquad (1)$$

Here B denotes the bandwidth, S is the signal power and N0 is the noise power spectral density. To derive alternate capacity formulas for cognitive radios, we consider as shown in Fig. 1.

Let W denote the spectral bandwidth of the Radio Frequency (RF) front end of cognitive radio. This bandwidth is not wholly occupied by this cognitive radio at all times for transmitting data, but it uses small chunk B to transmit data. As an example, the current day WLANs have their RF front ends designed to operate over W=400 MHz bandwidth but for the proper WLAN operation it uses only a small spectral band of B=20 MHz. Since this cognitive radio system can access the channel if and only if the particular spectral band B is not occupied by a primary over the range W. We need to evaluate this utilization, which is the function of the primary, and include it in the Shannon's capacity, which is equation (1). Equation (1) is modified to include the extra utilization that can be obtained by a cognitive radio network as

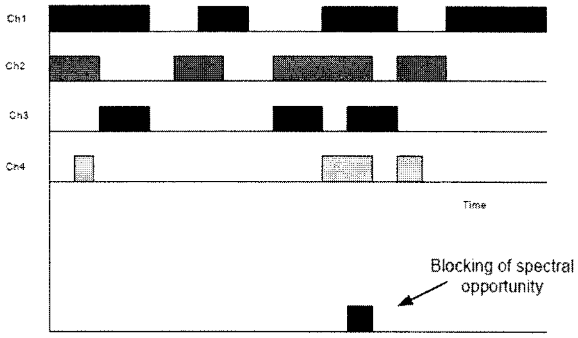

그림 1. 무선인지 시스템에서 스펙트럼 기회
Fig. 1. Spectrum opportunities for cognitive radio systems.

$$C_{CR} = U_{CR}B\log_2(1+\frac{S}{N_0B}) \qquad (2)$$

Here UCR refers to the spectral bandwidth utilization that is available for the cognitive radio network considering the primary occupancy. Similar analysis appeared in [8] and UCR is computed as follows. Suppose there are N primary networks with N designated channels (one designated channel per primary network in the spectral band of W), and M cognitive radio networks seeking spectral opportunities. The usage pattern of the primary network in each channel is assumed to be an independent and identically distributed (i.i.d.) ON/OFF random process with independent ON and OFF periods. An ON period represents the time period when the particular channel is occupied by a primary radio system, while an OFF period is regarded as a potential opportunity for cognitive radio networks.

To simplify our analysis, we assume that the distributions of both ON and OFF periods in each channel are exponentially distributed with their means equal to Tprimary_on and Tprimary_off, respectively. Additionally, we assume that each cognitive radio network has an infinite amount of traffic to transmit and each cognitive radio network has resources to scan a channel, switch to a channel, and vacate a channel (when claimed by the primary network) instantly without incurring any control overhead or delay. The control overhead and delays are implementation dependent, and are not considered. The UCR is given by

$$\begin{aligned} U_{CR} &= 1 - U_{primary} \\ &= 1 - \left(\frac{T_{primary\_on}}{T_{primary\_on} + T_{primary\_off}}\right)^{N} \end{aligned} \tag{3}$$

Equation (3) quantifies the additional time that the cognitive radios have when their RF front end provides a large W resulting in more operational channels B (N=W/B). Equation (3) approaches the theoretical limit of equation (1) when N goes to infinity. Substituting the value of N=1 in the above equation, we get the efficiency of the conventional networks available today that operate in a fixed channel (no dynamic spectrum assignment). The conventional networks have to vacate the channel in the presence of primaries and will have to come back to the channel if the channel is vacated by the primary. For N>1, the equation reflects the availability of dynamic spectrum assignment, i.e., DFS. If N=1, then the Shannon's channel capacity as defined in equation (2) reduces to

$$\begin{aligned} C_{CR} &= \frac{T_{primary\_off}}{T_{primary\_on} + T_{primary\_off}} \\ &\quad * B \log_2 \left(1 + \frac{S}{N_0 B}\right) \end{aligned} \tag{4}$$

In case there are more number of secondary radios (M>1) utilization of the cognitive radio can be given as

$$U_{CR} = \sum_{k=0}^{N} \min(M,k) \binom{N}{k} (1-u)^{k} u^{N-k} / M \tag{5}$$

where, N is the number of primary radios, M is the number of cognitive radios and u is the primary user utilization.

After we get the utilization factor for a number of cognitive radios, we consider the scenario in terms of cognitive radio network. First we need to define our system model for cognitive radio network. In our system, we consider two types of users: primary users and secondary users. The primary users communicate among themselves using licensed bands in a command and control manner. They have the privilege for exclusive spectrum access preventing any sort of potential interference. However, most of the primary users are not active most of the time, resulting in inefficient use of spectrum. Secondary users are CR enabled relays that can use the spectrum in a non exclusive manner. They constantly scan the spectrum which is unused by primary users at any time instant in a particular location and utilize the spectrum opportunities to relay traffic.

When a primary user is communicating using a channel, it consumes some space which is termed as its footprint. CR relays outside the footprint of primary users are allowed to transmit on the channel given the maximum transmission power constraint. The size of the footprint of a primary user depends on the transmission power and receiver sensitivity. CRs within the footprint of a primary user can only utilize the channel when the primary user is inactive. So, unlike the work in [6], we need to consider two types of spectrum utilization: spatial and temporal spectrum utilization. To elaborate our system model we draw a conceptual figure for our network model.

Fig. 2. shows an example of opportunistically available channels for the CRs at a particular time instance. We assume three channels, namely A, B

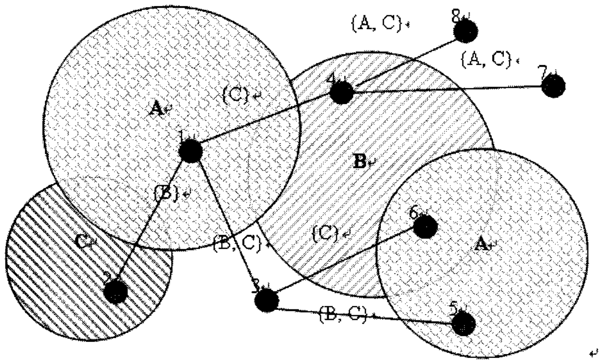

그림 2. 2차 사용자간 통신을 위한 CR 멀티홉 기술
Fig. 2. The CR multi-hop technique for communication among the secondary users.

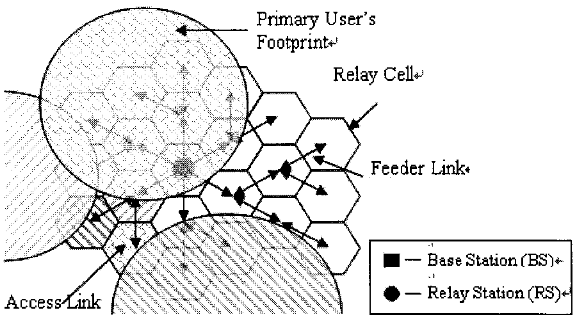

그림 3. CR 멀티홉 기술을 사용한 피더링크 및 엑세스 링크를 위한 기회적 채널 사용
Fig. 3. Opportunistic channel usage for feeder links and access links using CR multi-hop technique.

and C, are in service for the primary users. The larger circles represent footprints of the primary users and within each footprint its corresponding channel is marked. The smaller circles represent the CR relays which are connected to each other to carry relayed traffic shown by straight lines. Two CRs can communicate using a particular channel whenever both of them are outside the footprint of that channel. The channel may also be available within the footprint provided the primary user is inactive at that moment. The available channels for each of the links between CR relays are shown beside the lines within { } as shown in Fig. 2.

For example, communication link between CR relay 1 and CR relay 4 can only be established using channel C, as CR relay 1 is within the footprint of channel A and CR relay 4 is within the footprint of channel B. However, both the channels A and C are available for the link between CR relay 4 and CR relay 8.

The CR relays in our system are organized in a cellular multi-hop relay architecture. The BS is similar to any other CR relay with the only difference of being directly connected to the wireless backbone network. All other CR relays relay the traffic to or from the BS. The area covered by one BS is divided into smaller relay cells each of which is covered by one CR relay. All the MSs within a relay cell are served by that CR relay using opportunistically available channel. However, when a relay cell is using one channel, it might not be used again in the adjacent relay cell, even if it is not being used by primary users. This way, excessive interference in the access link is avoided.

A CR based multi-hop cell architecture is shown in Fig. 3, where the small hexagons represent the relay cells. In the middle of each relay cell, there is a CR relay. They are connected with each other through wireless links called feeder links. The feeder links carry traffic from every CR relay to the BS. In each relay cell, the MSs communicate with the CR relay through access links.

As shown in Fig. 3, channel assignment for the access links depends on the usage of that channel by the primary user. Within a particular relay cell, the assigned channel is shared among all the MSs using arbitrary multiple access scheme.

In our system model, we assume that the relay cells are large enough to have uniform load distribution among them. Also, we assume perfect synchronization for upload and downlink transmission among all the CR relays, so that the same channels can be dynamically reused in successive hops in different relay cells.

The system throughput for a CR based network heavily depends upon the characteristics of the primary users. Specifically, the portion of space covered by the primary users, Ps, and the temporal utilization of the channels by them, Pt, are of most importance. A particular channel can be used in a particular relay cell if the relay cell is outside the footprints of the primary users using the same channel. However, even if it is inside the footprint, the channel becomes free time to time. So, the channel is available for access link in a relay cell with probability, Pa, expressed as

$$P_a = P_s(1-P_t) + (1-P_s) \tag{6}$$

where Pt is the temporal utilization and Ps is the spatial utilization by the primary users. If we consider that primary users' footprints can overlap, then Ps can be expressed as

$$P_s = \exp(-\lambda_p \pi R_p^2) \tag{7}$$

where λp is the density of primary users and Rp is the radius of primary user's footprint.

For each relay cell we assume that one channel is required for the access link. The assigned channel can not be used by any of its adjacent relay cells. So, from all the channels used in the system, a number of channels, Nch(a), is allocated for access links. Rest of the channels, Nch(f), are used for feeder links. As a relay cell can not use the channel if it is used by any of its six adjacent relay cells, the probability of finding a channel for access link is at most

$$1-(1-P_a)^{N_{ch(a)}-6} \tag{8}$$

So, assuming per channel throughput as RB and total number of relay cells as N, the throughput for all the access links, Ta, is

$$T_a = N(1-(1-P_a)^{N_{ch(a)}-6})R_B \tag{9}$$

For the feeder links a channel must be available at both relay stations. However, the probability of channel availability is highly correlated when the relay stations are close to each other. On the other hand, when their distance is larger than Rp then channel is available at communicating relay stations independently. The correlation of channel availability among different secondary users [7] can be extended to find out the feeder link probability, Pf, as following

$$\begin{aligned} P_f = {} & \exp(-\lambda_p(\pi R_p^2 - A))(1-P_t) \\ & + (1-\exp(-\lambda(\pi R_p^2 - A))) \end{aligned} \tag{10}$$

where

$$A = \begin{cases} 2R_p^2 \cos^{-1}\left(\dfrac{R_s}{R_p}\right) - \sqrt{3}R_s\sqrt{(R_p^2 - R_s^2)} & , \text{for } R_p \ge R_s \\ 0 & , otherwise \end{cases} \tag{11}$$

Now, the first hop feeder links are the bottle neck for a network. So, finding the probability of the first hop link availability gives good estimation for the entire feeder link. The total feeder link, Tf, throughput is given by

$$\begin{aligned} T_f = {} & \sum_{1}^{N_{ch(f)}} \min(i, N-1)\binom{N_{ch(f)}}{i} \\ & * P_f^i (1-P_f)^{N_{ch(f)}-i} R_B \end{aligned} \tag{12}$$

Now, the first hop feeder links are the bottle neck for a network.

Once we obtain the throughput for access link and feeder link, we observe that the system throughput per cell is constrained by the minimum of those two throughputs and thus it is given by

$$T = \min(T_a, T_f) \tag{13}$$

In our best knowledge, the throughput capacity of a CR relay network is firstly suggested in this paper. The feeder link and access link concept were suggested to analyze the throughput capacity of a CR relay network. This suggested system will be evaluated in terms of system throughput in the following chapter.

## Ⅲ. Results and Discussion

In the previous chapter the system model has been presented and the throughput capacity for such system has been derived. In this chapter we evaluate our system model through numerical simulation and discuss the significance of the results. We also change some critical design parameters and observe their effect on the throughput capacity.

Firstly, we show the capacity enhancement for a cognitive radio over a conventional radio in Fig. 4. from equation (2) for throughput capacity for a cognitive radio.

From the figure it is clear the conventional system represented by the lowest curve has lower capacities when the utilization of the primaries increases. This is due to the fact that conventional radios can not switch between channels whenever primary user is using the channel.

On the contrary, for large number of primary channels, the capacity of the cognitive radio of type one approaches the theoretical limit as shown in figure for large utilizations of primaries. However, even for small number of channels we observe significant improvement of throughput capacity for cognitive radio over conventional radio.

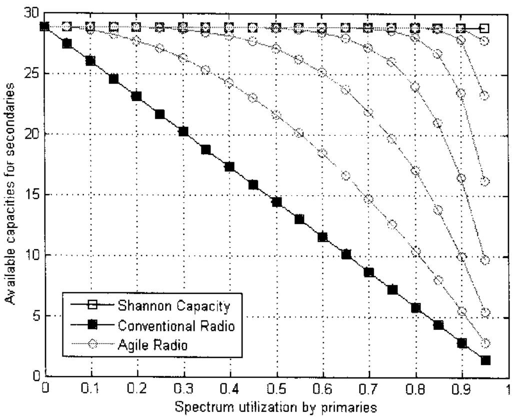

그림 4. CR 시스템에 의해 성취 가능한 채널 용량

Fig. 4. Capacities achieved by the cognitive radio systems.

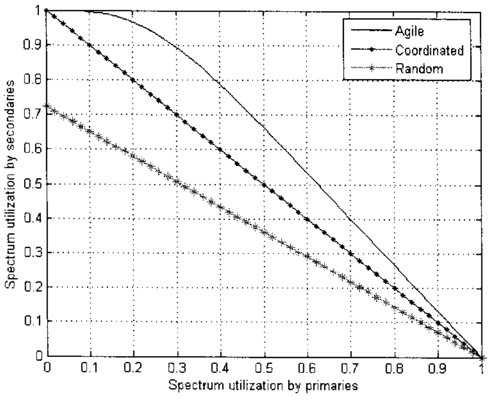

그림 5. N=12, M=9 때 CR에 의한 스펙트럼 사용도

Fig. 5. Spectrum utilization by cognitive radio for N=12, M=9.

Fig. 5. shows utilization by secondary radios with agility and two types of no agility for different utilization by primary users. For the simulation we have used N=12 primary radios and M=9 secondary radios.

From the above figure it is clear that cognitive radio can perform better compared to conventional radio for both random and coordinated channel access mechanism. The following two figures shows improvement ratio compared with two types of no agile radio.

Fig. 6. and Fig. 7. elaborates the advantage of cognitive radio over random scheme and coordinated scheme separately. Maximum enhancement for

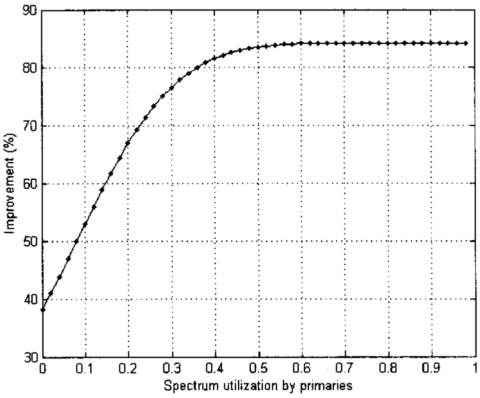

그림 6. 랜덤채널선택 기법의 경우 기존 방법에 대한 CR의 향상

Fig. 6. Cognitive radio vs. conventional radio with random channel selection (UCR/Urandom-1).

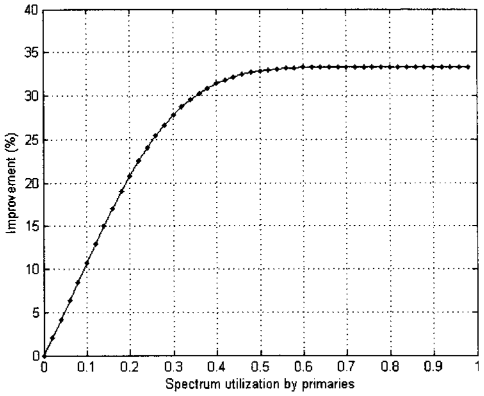

그림 7. 고정스펙트럼기법의 경우 스펙트럼 에질리티의 향상

Fig. 7. Spectral agility vs. no agility with coordinated channel selection (UCR/Ucoord-1).

cognitive radio over random access scheme is achieved 84% whereas over the coordinated scheme it is around 34% which is still a significant improvement.

The system throughput equation derived in previous chapter has been simulated for different values of utilization factor of primary users, Pt and footprint radius of primary users, Rp. For the simulations, number of relay cells, N, is assumed to be 20. This value corresponds to a maximum of three hops from BS to MS. Also, the per channel throughput is chosen as 10 Kbps and radius of the CR relays is assumed to be 100 m. These values are arbitrarily chosen just to show relative improvement over conventional system.

Fig. 8. shows the system throughput per cell for different values utilization factors of primary users with radius of footprint of the primary users is chosen to be 500 m. From the figure it is seen that, the system throughput per cell increases up to a saturation value. The saturation value of the system throughput is close to the product value of number of relay cells and per channel throughput. Also, it can be observed that the saturation point is reached for lower values of number of channels in case of low utilization factor by primary users. Before the saturation point, the system throughput is proportional to the resource unutilized by the primary users (1-Pt).

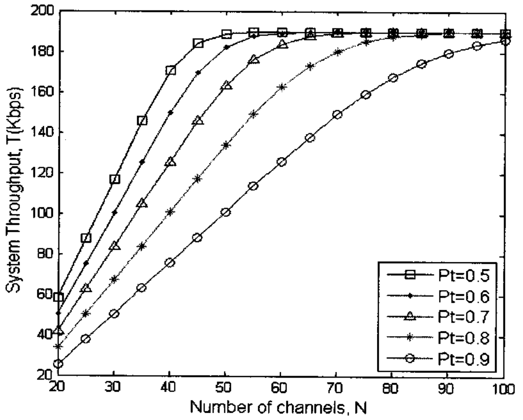

그림 8. 주사용자의 사용율, Pt에 따른 셀당 시스템 스루풋

Fig. 8. System throughput per cell for different values of temporal utilization factor, Pt, of the primary users.

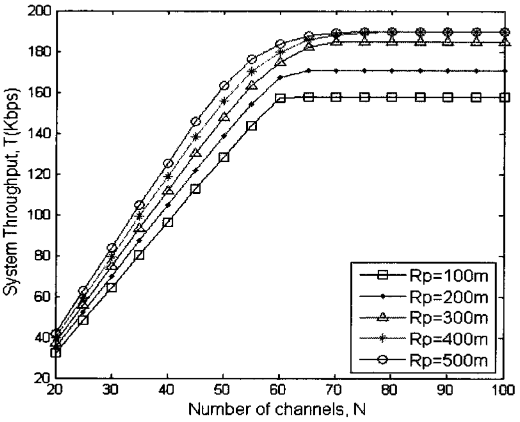

그림 9. 주사용자의 전파반경, Rp에 따른 셀당 시스템 스루풋

Fig. 9. System throughput per cell for different values of footprint radius, Pp, of the primary users.

Fig. 9. shows the system throughput per cell for different values of footprint radius of primary users with utilization factor of the primary users is chosen to be 0.7. This figure also suggests that, the system throughput per cell increases up to a saturation value. However, when Rp is low, then the throughput may not reach the saturation point. This occurs due to the fact that, in such case access link throughput decreases and limits the overall throughput.

Next we show the same results with different number of reserved access channels. As discussed in the system model, out of all the channels some are reserved for access links, the rest are used for the feeder links. By assigning too many channels for access channels, feeder links get less number of channels which in terms decrease the throughput in the feeder links. However, if few channels are reserved then the access links interfere with each other. So, a balance should be achieved to obtain better overall throughput. For the previous results, we have used for the number of reserved channels for access channels a value of 10.

Fig. 10 and Fig. 11. show the throughput per cell by varying primary utilization factor and primary user's radius; however, in this case the number of

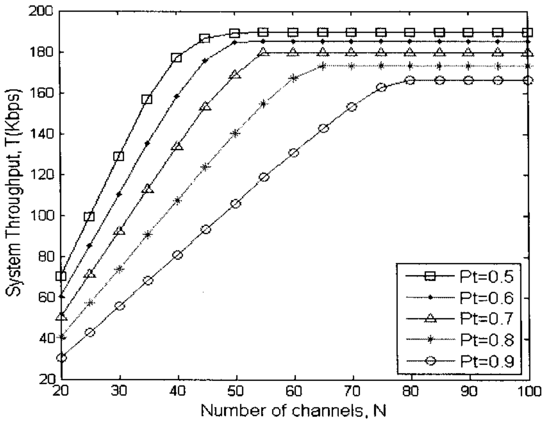

그림 10. 8 엑세스채널인 경우 Pt에 따른 셀당 시스템 스루풋

Fig. 10. System throughput per cell for different values of Pt with 8 of access channels.

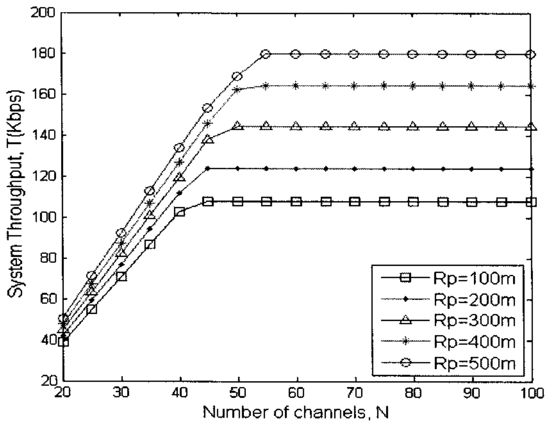

그림 11. 8 엑세스채널인 경우 Rp에 따른 셀당 시스템 스루풋

Fig. 11. System throughput per cell for different values of Rp with 8 access channels.

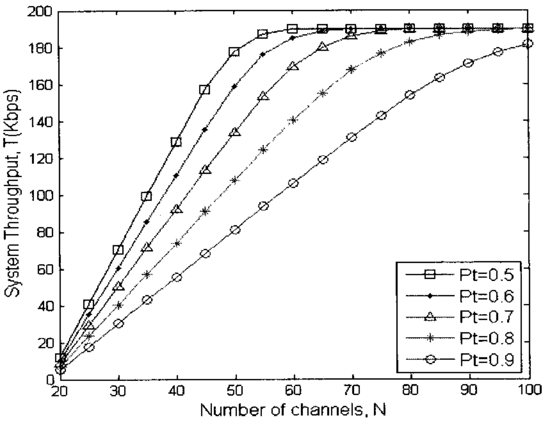

그림 12. 18 엑세스채널인 경우 Pt에 따른 셀당 시스템 스루풋

Fig. 12. System throughput per cell for different values of Pt with 18 of access channels.

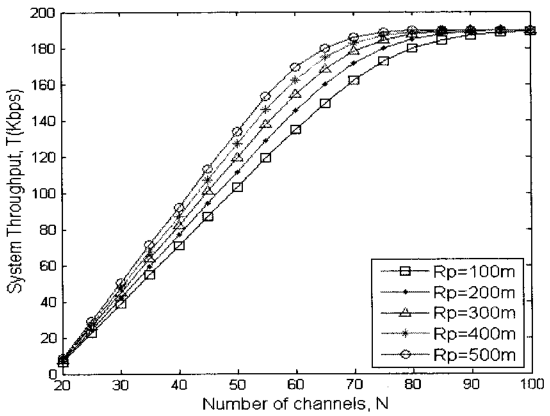

그림 13. 18 엑세스채널인 경우 Rp에 따른 셀당 시스템 스루풋

Fig. 13. System throughput per cell for different values of Rp with 18 access channels.

reserved channels for access links is reduced to 8. As a result of this reduction, the throughput capacity does not increase up to the saturation point most of the cases. This is due to interference among different relay cells which now have less number of channels to carry the users' data.

On the other hand, Fig. 12. how the throughput per cell by varying primary utilization factor with the number of reserved channels for access links is increased to 18. As a result, the throughput capacity always achieves the saturation point. However, the difference is now significant near the region specified by low number of nodes. Here we can see, the starting throughput capacity is far less than what we have seen earlier.

Fig. 13. also shows similar results though here primary user's radius is the changing parameter. We observe significantly less throughput capacity where number of channels is less. This can be explained by the fact that, by increasing the number of access channels, feeder links have fewer channels. So, the bottleneck is created on the feeder links. But, when number of channels is increased, this problem is alleviated and overall throughput capacity performs better.

## Ⅳ. Conclusion

In recent years cognitive radio has gained much attention for solving the spectrum scarcity problem. It changes the way spectrum is regulated so that more efficient spectrum utilization is possible. However, the benefits of cognitive radio can be far more exploited when combined with other technologies such as multi-hop relay. Multi-hop relay itself is a feasible solution capacity enhancement and range extension in wireless network.

Thus, we have proposed a network architecture for CR multi-hop relay networks in a way to maximize the system throughput. Multi-hop relaying is used to connect the mobile stations to the base station. The cognitive radio technology is integrated with the relay stations so that it can opportunistically select frequency channels. We have also formulated the throughput capacity equations for such a system considering various system parameters like utilization factor by the primary users and primary users' transmission radius.

Extensive numerical simulation has been done to analyze the system with utilization factor and footprint of primary users as main parameters and showed the effect of such parameters on the system throughput. From the results we see that cognitive radio enabled multi-hop relay network can significantly improve the overall system throughput. The work presented in this paper however can be improved by considering the effect of routing protocols on the throughput of such systems.

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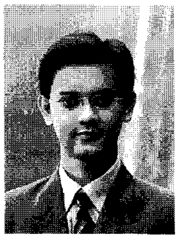
## 저 자 소 개



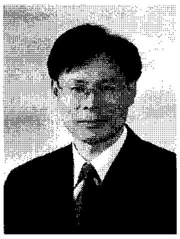
**임룰하싼(정회원)-교신저자**

2004년 IUT(방글라데시) 전자공학과 학사 졸업.

2005년 IUT(방글라데시) 전자공학과 전임강사.

2008년 경희대학교 전자전파공학과 석사 졸업.

<주관심분야 : 통신, 네트워크, Cognitive Radio>



**송 주 빈(정회원)**

2001년 Dept. of Electronic & Electrical Eng., University of London (UCL) 박사 졸업.

1992년-1997년 한국전자통신연구원(ETRI) 선임연구원.

2001년 UCL 전자전기공학과 Research Fellow.

2002년~2003년 국립한밭대학교 정보통신컴퓨터공학부 전임강사.

2003년~현재 경희대학교 전자전파공학과 부교수.

<주관심분야 : 통신시스템, Cognitive Radio, Cooperative Communications, BCN>

**노 창 배(정회원)**

2001년 대전대학교 컴퓨터공학과 학사 졸업.

2003년 한남대학교 전산교육전공 석사 졸업.

2006년 경희대학교 전자전파공학과 박사과정 수료.

2008년~현재 대덕대학 정보통신공학부 초빙교수

<주관심분야 : 알고리즘, Cognitive Radio Networks, 모바일컴퓨팅, 분산네트워크>