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Cognitive Radio 무선 다중홉 릴레이 네트워크의 Throughput 용량

(Throughput Capacity of a Wireless Multi-hop Relay Network using Cognitive Radio)

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요 약

본 논문은 cognitive radio (CR) 기능을 갖는 무선 멀티홉 릴레이 네트워크의 throughput 용량에 대한 연구 결과이다. 본 논문에서는 TDMA/FDMA에 기반한 프레임 구조를 갖는 릴레이가 기지국과 통신할 때 CR 기술을 이용하여 현재 사용되고 있지 않는 주파수 자원을 측정하여 동적으로 이용하는 시스템을 제안하고 이의 throughput 용량 모델을 제안 하였다. 특히, 본 논문에서는 Utilization factor를 이용하여 제안된 시스템을 위한 throughput 용량 모델을 제안하였다. 해석 모델링 결과 본 논문에서 제안한 CR 기반 멀티홉 릴레이 시스템은 throughput 용량을 매우 향상하는 결과를 보였다.

Abstract

In this paper, we investigate the throughput capacity of a multi-hop relay with cognitive radio (CR) enabled relay stations (RS). We suggest a TDMA/FDMA based frame structure where RSs dynamically select unused channels to communicate with the base station (BS) using CR techniques to analyze the throughput capacity. We develop the throughput capacity model for the proposed system based on utilization factor. The analytical results based on those equations show significant improvement in throughput capacity for CR enabled multi-hop relay system.

Keywords : Wireless multi-hop relay, cognitive radio, throughput capacity, throughput per cell

I. Introduction

Multi-hop relay technology has intensively been studied in the area of ad hoc and peer-to-peer networks. In cellular networks, integration of multi-hop capability is considered to enhance the performance significantly. Relaying can extend the coverage of the cell to provide high data rate service to a greater distance and in the shadowed regions[1]. Also as the low data rate links between base stations and terminals are replaced by high data rate links with relays, the system capacity improves dramatically. Significant work has been done to characterize the capacity gain obtained using multi-hop techniques[2],[3].

The multiple access methodology for these works are based on frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA) or orthogonal frequency division multiple access (OFDMA).

In this paper, we analyze the throughput capacity for multi-hop relay communication when CR is

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employed based on TDMA/FDMA multiple access technique. CR is able to reliably sense the spectral environment, detect the presence of any primary user and use the spectrum only if communication does not interfere with the primary user[4]. Different analytical models of such radios have been proposed and results of their capacities were derived in [5] and [6]. However, for cognitive radio based multi-hop relay networks no analytical study has been done so far.

In this paper, we propose a system model where relay nodes with CR capabilities such as spectrum agility are deployed. We formulate new throughput capacity model for our system model and evaluate our results for different loading conditions. In this work, primary users are modeled using the temporal utilization factor of each primary user.

Ⅱ. System Model

In a wireless multi-hop cellular network, the BS covers a fraction of all the mobile stations (MS) and communication to these MSs is carried out through direct path. To extend the coverage of the cell CR enabled RSs are deployed on the periphery of the BS's range. These RSs can intercept the packets sent from BS and relay those packets to MSs which are within its transmission range. So, communication with the MSs outside the coverage of the BS is carried out through an indirect path.

In our system model, decode-and-forward and reallocation forward relaying technique are assumed, so that the noise is not propagated along the path. Also, we assume that RSs have sufficient knowledge about the locations of the MSs and it only relays the traffic if the MS is within its transmission range. The RSs can however forward the traffic to another RS if the MS is beyond its range and similarly the packet can hop multiple times before it reaches the destination.

In Fig. 1, the communication between BS and MS through RS is depicted showing the coverage of the BS as well as the coverage of the RSs. Communication among BS, RSs and MSs is achieved

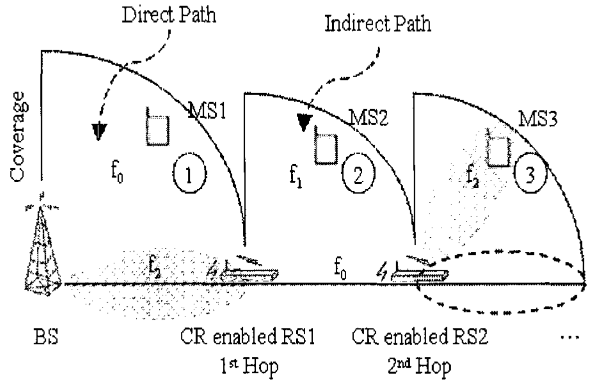

그림 1. CR 기반 다중홉 셀 구조
Fig. 1. CR based multi-hop cell architecture.

through multiple frequency bands namely f_0, f_1 upto f_N as shown in Fig. 1. The BS and RSs use a particular band for serving MSs while they choose a different band for relaying. One possible frequency reuse scheme is shown in Fig. 1, where communication between BS to RS1 and between RS2 to MS3 is occurring simultaneously using f_2 band.

To clarify the relaying scheme, we consider three cases. Case 1 deals with the direct path communication between BS to MS1 using f_0 band. The other two cases are two examples of indirect path communication. In case 2, two hop communication is achieved from BS to MS2 relayed by RS1 using f_2 and f_1 bands. Case 3 shows three hop communication where RS1 relays BS packets to RS2 and finally RS2 serves MS3.

Fig. 2 shows the TDMA/FDMA frame structure for CR multi-hop relay communication. In the frame structure scheduled by the BS, some slots are assigned for direct MSs while other slots are assigned to the RSs and indirect MSs. The downlink (DL) and uplink (UL) communication are time duplexed and they are similar in terms of frame structure.

In Fig. 2, three different cases as discussed earlier, are marked along with the usage of three different frequency bands. Some frequency bands are spatially reused like f_0 is used for direct path communication between BS to MS1 as well as for indirect path communication between RS1 to RS2. Case 1 communication is achieved using a single frequency

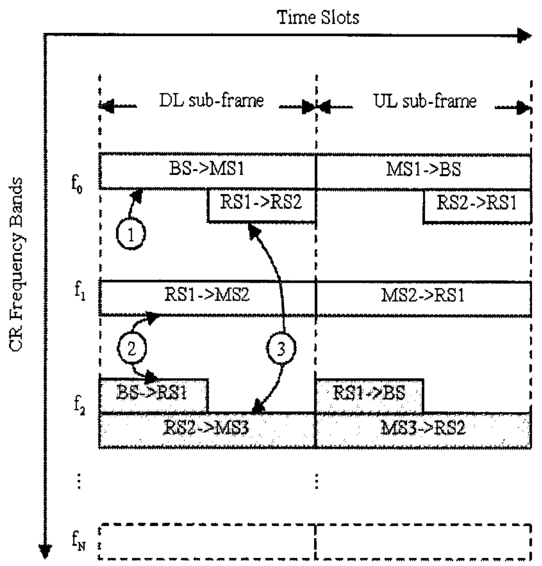

그림 2. CR 릴레이를 위한 TDMA/FDMA 프레임 구조

Fig. 2. TDMA/FDMA frame structure for CR relay support.

band while both case 2 and case 3 require two bands each. For example in case 2 relay link from BS to RS1 is achieved through f_2 band while for access link from RS1 to MS2 f_1 band is utilized. This can be generalized if there is N number of CR frequency bands are available.

Ⅲ. Throughput Analysis

The RSs are deployed with cognitive radio capabilities such as spectrum agility as described in [4]. The capacity of such cognitive radio is derived from the Shannon's capacity equation as

$$C_{CR} = U_{CR} B \log\left(1 + \frac{S}{N_0 B}\right) \quad (1)$$

Here U_{CR} refers to the utilization factor for the cognitive radio network considering the primary occupancy[5]. Suppose there are N active primary users and only one cognitive radio seeking spectral opportunities. We assume that the mean on time and off time for the primary users are equal to $T_{primary\_on}$ and $T_{primary\_off}$, respectively. Then the U_{CR} is given by

$$U_{CR} = 1 - U_{primary} = 1 - \left(\frac{T_{primary\_on}}{T_{primary\_on} + T_{primary\_off}}\right)^N \quad (2)$$

When number cognitive radios, M, is more than one, then all cognitive radios may not get unused channel. The probability of finding K empty channels is

$$P_{N,K} = \binom{N}{K}(1-u)^K u^{N-K} \quad (3)$$

Also, if the number of unused channels is more than M, then they can not be utilized. So, the combined utilization factor for the cognitive radio network is calculated by summing over all possible number of unused channels as

$$U_{CR} = \sum_{K=0}^{N} \min(M,K)\binom{N}{K}(1-u)^K u^{N-K}/M \quad (4)$$

where u is the average utilization factor for the primary users defined as

$$u = \frac{T_{primary\_on}}{T_{primary\_on} + T_{primary\_off}} \quad (5)$$

We analyze the throughput capacity of a multi-rate multi-hop relay network. Then we incorporate CR relays with that model and calculate the overall throughput capacity. Firstly, for the fixed multi-hop relay networks we consider a system with k different rates. Thus, for the k discrete rates, the cell would have k concentric rings. The data rate for the innermost ring is the maximum and it decreases for outward rings. To analyze this system, we consider a cell of radius R with users uniform randomly distributed over the entire cell. Let ρ be the density of active users and $A_1, A_2, \cdots, A_i, \cdots, A_k$ be the areas of the $1, 2, \cdots, i, \cdots, k$ rings respectively. We assume data rate perceived by a user in the i-th ring as C_i Kbit/sec ($i=1,\cdots,k$). The number of users in i-th ring is ρA_i. The expected number of total active users, N, in the cell can then be given by

$$N = \sum_{i=1}^{k} \rho A_i \quad (6)$$

We analyze the time-slotted system from the simple round robin scheduling, where the fairness criteria is maintained. Then after N slots, in an idealistic scenario of round robin scheduling policy, where each user gets an equal number of slots, every active user would have obtained exactly one slot. The total amount of data received, D, by the users in these N slots is given by

$$D=\sum_{i=1}^{k}\rho A_i C_i \tau \tag{7}$$

where duration of each slot is given by τ seconds. Therefore, the throughput capacity of the system, T, is obtained by dividing the total data transferred by the time duration of N slots. Thus

$$T=\frac{\sum_{i=1}^{k}\rho A_i C_i \tau}{\tau \times \sum_{i=1}^{k}\rho A_i}=\frac{\sum_{i=1}^{k}\rho A_i C_i}{\sum_{i=1}^{k}\rho A_i} \tag{8}$$

It can be noted that the throughput capacity is not dependent on the number of users in the system. More users in the cell would simply mean that each user would get less to account for the capacity constraint of the base station. Thus, the throughput capacity of an individual user for various distances from the base station in a system of N active users, can be given by

$$T_j=\frac{C_j}{\sum_{i=1}^{k}\rho A_i} \tag{9}$$

Now let there be L relay nodes each of which is forming relay cell of radius r. If L is sufficiently large such that all the relay nodes entirely cover the cell, then the expected number of users under one relay node is N/L. However, if L is small, all the users might not be covered by the relay nodes as the coverage area of the relay nodes is usually small. But users covered by a relay node get the highest data rate possible.

Let us define ar as the area of the relay cell. Therefore, the expected number of users that fall within the L relay cells are $\rho a_r L$. These $\rho a_r L$ users then have the choice of choosing either the direct path from the BS or indirect path through RSs depending on the signal strength. Let us assume that $\rho a_r L < N$, i.e., not all users belong to relay cells. The remaining ($N< \rho a_r L$) active users then must receive their signals from the BS through the direct path during their allocated time slot. If we assume idealistic round robin scheduling policy to maintain the fairness criteria, then after N number of slots each user would receive exactly one slot. As a result, the throughput capacity for the system with L RSs can be given by

$$T_{RS}=\frac{\rho a_r \mathrm{L C}\tau+\sum_{j=l}^{N-\rho a_r L}\mathrm{C_j}\tau}{N} \tag{10}$$

where τ is the duration of each slot, C is the highest data rate at which the relay nodes are transmitting and Cj is the data rates received by the MSs which are not covered by the RSs.

Instead of using the fixed assigned spectrum, the RSs can now switch to any of other vacant spectrum. To evaluate the throughput capacity in such case, we consider the RSs as secondary users. The capacity for the M CR enabled secondary users is expressed in (1) whereas the utilization is expressed in (4). Now due to the enhanced capacity of the secondary users the total throughput capacity is also increased. However, as only the secondary users are contributing to the increased throughput, the gain in throughput is dependent on the ratio of the number of secondary users to the number of all users (M/N). So, combining (4) with (10), we obtain the throughput capacity for a fixed relay network where the RSs have cognitive radio capabilities as

$$T_{RS,CR}=\frac{\rho a_r \mathrm{LC}\tau+\sum_{j=l}^{N-\rho a_r L}\mathrm{C_j}\tau}{N}\left(1+\frac{MU_{CR}}{N}\right) \tag{11}$$

When we consider the RSs as cognitive radios, the throughput capacity is significantly improved.

Ⅳ. Results and Discussion

Fig. 3 shows the performance of the CR system compared with the conventional radio. From the figure it is clear the conventional system has lower capacities compared with CR system. For large

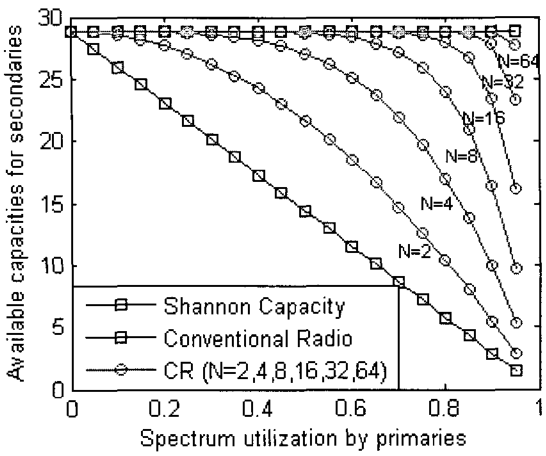

그림 3. Primary user의 변화에 대한 기존 radio 방식과 cognitive radio 방식의 용량 비교

Fig. 3. Capacities achieved by the conventional radios and cognitive radios for varying number of primary users.

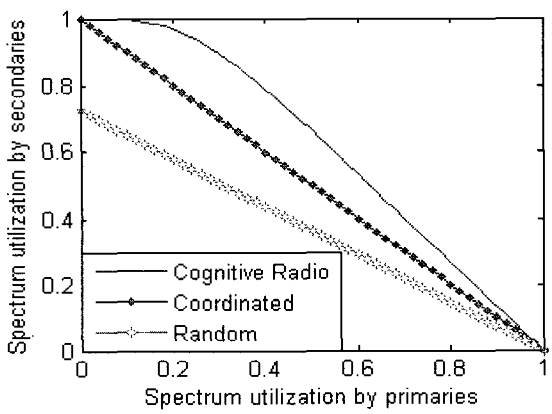

그림 4. N=12, M=9일 때 CR에 의한 스펙트럼 utilization

Fig. 4. Spectrum utilization by CR for $N=12$, $M=9$.

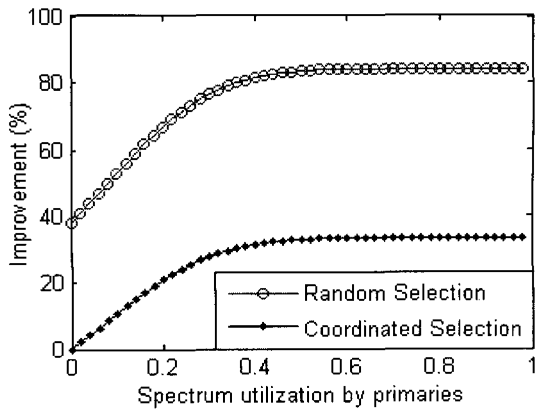

그림 5. 랜덤 채널 선택과 coordinated 채널 선택에 따른 cognitive radio 성능 비교

Fig. 5. Comparison among cognitive radio with random channel selection and coordinated channel selection.

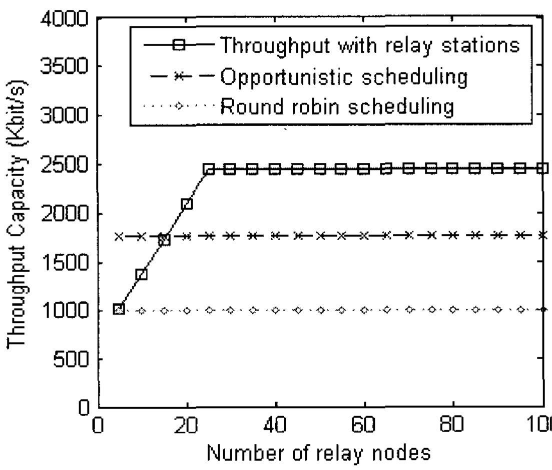

그림 6. 전형적인 무선 fixed 멀티홉 릴레이 네트워크의 시스템 throughput 용량

Fig. 6. System throughput capacity of wireless fixed multi-hop relay network.

number of primary channels, the capacity of the CR system approaches the theoretical limit of Shannon's capacity for large utilizations of primaries.

Fig. 4 and Fig. 5 shows the spectrum utilization of the CRs for $M=9$ and $N=12$ and two types of non-agile radios and a relative comparison. In coordinated non-agile scheme the radios can coordinate among themselves so that one channel is not being used by two radios simultaneously. However, in random scheme no coordination is required, as a result conflict occurs when two radios try to use the same channel. From Fig. 4 and Fig. 5 we see that as the primary user's spectrum utilization increases, the CRs find it more and more difficult to acquire any spectrum holes. This is because now, the primary users are using the spectrum more efficiently. However, in low utilization case ($U_{primary}$ < 30 %), the secondary users can achieve near to maximum utilization.

The results obtained from Equation (10) are compared with the existing (without relay stations) system throughputs which is throughput capacity per cell as shown in Fig. 6. The figure shows us clearly that after a certain number of relay stations the system throughput is much better than the existing system. It also demonstrates how the optimal number

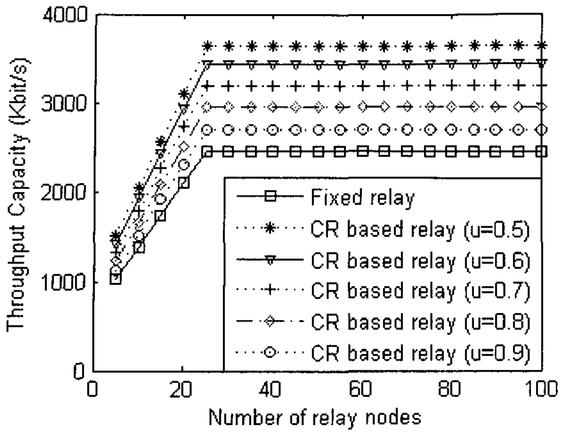

그림 7. Utilization factor에 따른 제안 시스템의 throughput 용량

Fig. 7. The throughput capacity of the proposed system varying utilization factor.

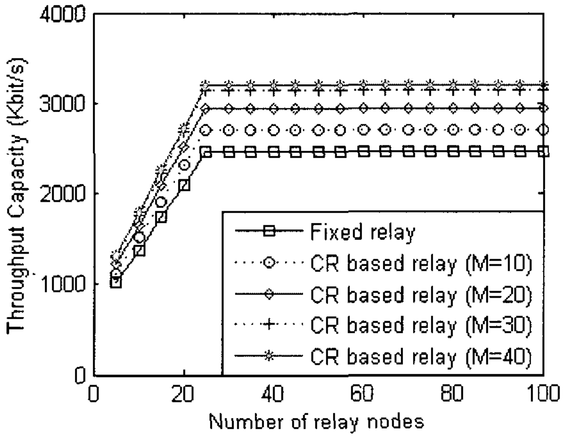

그림 8. Secondary user에 따른 제안 시스템의 throughput 용량

Fig. 8. The throughput capacity of the proposed system varying secondary users.

of relay nodes is obtained. With the increase in number of relay nodes, system throughput also increases continuously, till a certain value of L is reached, where the maximum value of throughput is obtained. In an ideal situation, this value of L is the saturation point after which the throughput does not increase since all the users are accommodated by the relay nodes.

Fig. 7 represents the throughput capacity of our proposed system model for different number of relay nodes. As can be seen from this figure, as the relay nodes reach to approximately 25, system throughput capacity becomes constant to a certain value even though number of relay nodes is increased. Also, a significant improvement is found in throughput if CR based technique is used as proposed in our system.

For example, for 50 relay nodes and 100 nodes all together, using fixed relay provides 2500 kbps throughput while CR based technique with a utilization factor $U_{primary}$=0.5 allows more than 3500 kbps throughput. If the utilization factor for the primary users increases to $U_{primary}$=0.9, throughput decreases to approximately 2600 kbps which is still more than using fixed relay without CR capabilities.

Fig. 8 shows the throughput capacity of our system using varying number of secondary users in CR based technique. In this case utilization factor is chosen to be $U_{primary}$=0.7 and $N=100$. It can be seen that with the increase in the number of secondary users throughput increases. But, after $M=30$, throughput enhancement is not that high as compared to the $M=10$ or $M=20$ case. This can be explained from the fact that after a saturation point, there is no spectrum opportunities left for the additional secondary users.

V. Conclusion

In this paper, we investigated the throughput capacity of a new architecture for cognitive radio enabled multi-hop relay network. We suggested an TDMA/FDMA based frame structure and also cognitive radio based frequency band selection method. We derived a new throughput capacity model for the proposed architecture. The results show that our proposed system performs better than traditional fixed relay based systems where no cognitive radio capabilities are assumed in terms of the system throughput capacity of a multi-hop relay networks as well as reducing interference between RSs.

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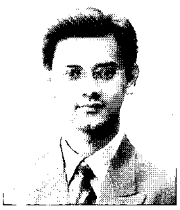

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