Throughput Capacity of a Cognitive Radio Based Multi-hop Relay Network

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Abstract: The purpose of enabling relay is to enhance coverage, range, and throughput and possibly capacity of a multi-hop relay network and to enable very low power devices to participate in the network. Since it is possible to have simultaneous transmission by both the base station (BS) and relay station (RS), throughput gains may also be achieved by either exploiting spectrum efficiency or spatial diversity. Cognitive radio (CR) is another promising technology that can improve the efficiency of spectrum usage by finding available spectrum in a crowded network, leading to gains in capacity. In cellular networks, integration of CR techniques with the multi-hop relays can enhance the performance significantly. In this paper, we investigate the throughput capacity of a multi-hop relay network with CR enabled RS. 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: Multi-hop relay, cognitive radio, throughput capacity.

1. Introduction

In cellular networks, integration of multi-hop capability is considered one of the most prominent technologies. Relaying can extend the coverage of the cell to provide high data rate service to a greater distance and in the shadowed regions. 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.

Besides multi-hop techniques, the concept of the CR is also very promising. The CR has the possibility to drastically change the conventional frequency assignment policy. In the conventional frequency assignment policy, the frequency band is fixedly assigned to the operator. On the other hand, in the CR case, the frequency band that is not used by the other communication systems can be used for any users, so the fixed frequency assignment may not be required.

Previous studies involved CR based multi-hop wireless networks in [1] where simple and efficient distributed heuristic for MAC-layer scheduling was proposed. Frequency sharing system with adaptive route selection according to the surrounding radio environment was narrated in [2] to avoid transmission in interference area of a multi-hop ad-hoc CR. However, throughput enhancement using CR based multi-hop relay is of paramount importance therefore which requires attention.

Hence, in this paper, we propose a system model of a multi-hop relay network with CR enabled RS to utilize the above mentioned features. We suggest a TDMA/FDMA based communication scheme where RSs dynamically select unused channels to communicate with the 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.

2. 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 Figure 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 through multiple frequency bands as shown in the figure. To clarify the relaying scheme, we consider three cases. Case 1 deals with the direct path communication between BS to MS1 using f0 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 f2 and f1 bands. Case 3 shows three hop communication where RS1 relays BS packets to RS2 and finally RS2 serves MS3.

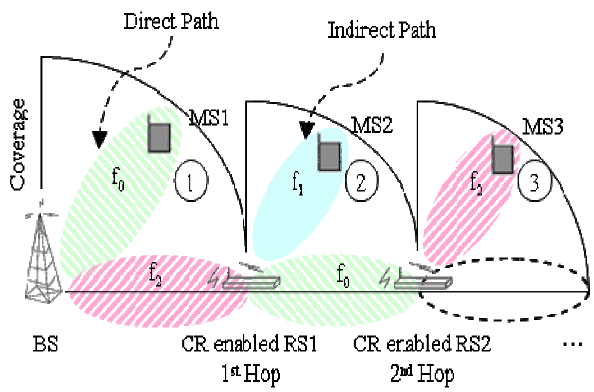

Figure 1. CR based multi-hop cell architecture

3. Results and Discussion

We analyze the throughput capacity of a multi-rate multi-hop relay network similar to the work in [3]. Then we incorporate CR relays with that model and calculate the overall throughput capacity. Now let there be L RSs each of which is forming relay cell of radius r. Also, let us define a_r as the area of a relay cell and ρ be the density of active MSs. Therefore, the expected number of MSs that fall within the L relay cells are $\rho a_r L$. These $\rho a_r L$ active MSs 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 MSs belong to relay cells where N is the total number of active MSs. The remaining $(N - \rho a_r L)$ active MSs 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,

$$T_{RS} = \frac{\rho a_r L C \tau + \sum_{j=1}^{N-\rho a_r L} C_j \tau}{N} \quad , \qquad (1)$$

where τ is the duration of each slot, C is the highest data rate at which the RSs are transmitting, C_j is the data rates received by the MSs which are not covered by the RSs and N is the number of active users in a cell. Now, the utilization of the CR can be given as [4]

$$U_{CR} = \sum_{K=0}^{N} \min(M, K) \binom{N}{K} (1-u)^K u^{N-K} / M \quad , \qquad (2)$$

where M is the number of CRs and u is the primary user utilization. Therefore, throughput model for the RSs with enhanced capacity for the CRs is

$$T_{RS,CR} = \frac{\rho a_r L C \tau + \sum_{j=1}^{N-\rho a_r L} C_j \tau}{N} \left(1 + \frac{M U_{CR}}{N}\right) \quad . \qquad (3)$$

Figure 2 represents the throughput capacity of our proposed system model for different number of RSs. In Figure 2, a significant improvement is found in throughput capacity when primary utilization factor is low.

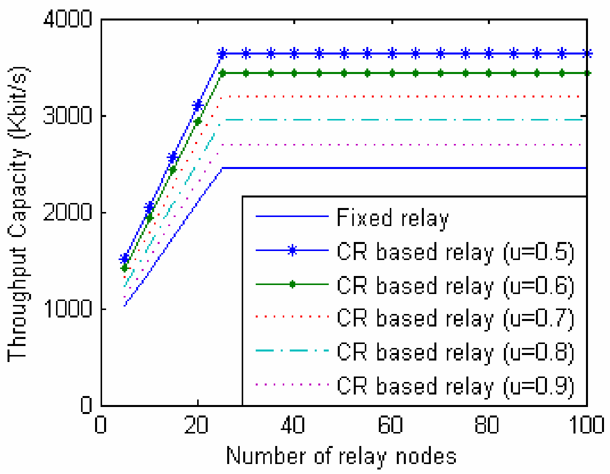

Figure 2. The throughput capacity of the proposed system varying utilization factor

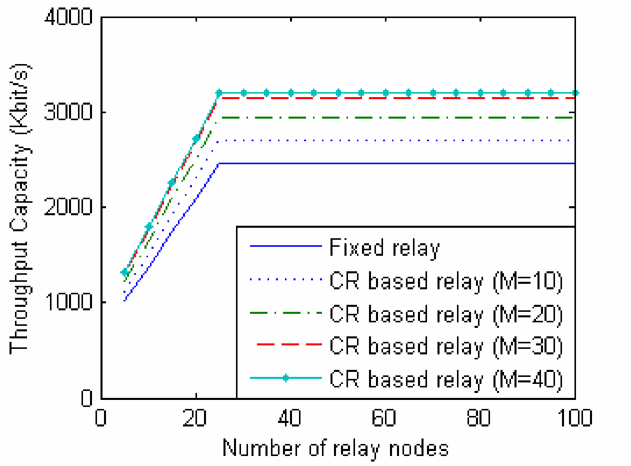

Figure 3. The throughput capacity of the proposed system varying number of CRs

Figure 3 shows the throughput capacity of our system using varying number of CRs. In this case utilization factor is chosen to be $u = 0.7$ and $N = 100$. It can be seen that with the increase in the number of CRs 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.

4. Conclusion

In this paper, we investigated the throughput capacity of a new architecture for CR enabled multi-hop relay network. We suggested a 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 CR capabilities are assumed in terms of the system throughput capacity of a multi-hop relay networks as well as reducing interference between RSs.

References

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