Throughput per Cell of a Cognitive Radio based Mobile Multi-hop Relay Network

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요 약

본 논문에서는 주파수 자원을 효율적으로 활용하는 알고리즘을 갖는 이동 멀티홉 릴레이를 제안하고 그의 throughput 용량 모델링에 대하여 제안하였다. 이동 렐레이 기지국은 주기지국과 통신에서 저속인 단말에게 가능한 고속의 데이터 서비스를 가능하게 하기 위하여 사용한다. 본 논문에서 이동 멀티홉 릴레이가 cognitive radio (CR) 기능을 수행할 수 있고 spectrum agile 기술을 사용하여 주사용자가 사용하지 않는 유효 스펙트럼을 측정하여 효율적으로 트래픽을 전송하는 시스템을 제안하였다. 이러한 제안된 시스템에 대하여 새로운 throughput 용량 모델을 제안하였다. 제안된 CR 이동 멀티홉 릴레이 시스템의 경우 우수한 성능 향상을 보였으며 또한 비이동 멀티홉 릴레이 시스템에 비하여 우수한 성능을 관찰하였다.

ABSTRACT

In this paper, firstly, we introduced the mobile multi-hop relay (MMR) network in a suitable network model scenario and calculated the throughput capacity for the same. A mobile relay station (MRS) is used in the sense that there will be a MRS which comes closer to the sender terminal at some instant of time and is able to receive the traffic with the highest possible data rate. The MRS then relays the traffic when it arrives in the vicinity of the destination terminal at a later time. Later, cognitive radio (CR) capabilities were introduced in mobile terminals and in MRSs by using the opportunistic spectrum utilization technique called spectrum agility. Finally, CR implementation in our proposed MMR system shows significant improvement in throughput capacity of the system compared to general fixed relay system.

I. Introduction

The purpose of enabling relay is to enhance coverage, range, and throughput and possibly capacity of a mobile multi-hop relay (MMR) base station (BS) and to enable very low power devices to participate in the network.

Since it is possible to have simultaneous transmission by both the BS and relays, throughput gains may also be achieved by either exploiting spectrum efficiency or spatial diversity. Cognitive radio (CR) is a new technology that can improve the efficiency of spectrum usage. CR is a technology that may be used to implement opportunistic sharing. Opportunistic spectrum utilization which is called spectrum agility, can find available spectrum in a crowded network, leading to gains in capacity. Since the cognitive (unlicensed) users are utilizing the licensed band, they must detect the presence of licensed (primary) users in a very short time and must vacate the band for the primary users. The solution to the above mention problem is spectrum agile radio. Agile radios address the important problem of spectrum sharing not only with primary radio systems, but also among other non-primary radio systems, thereby improving overall spectrum utilization.

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 MMR is of paramount importance therefore which requires attention. Hence, this papers details the scheduling scheme of the proposed CR based MMR system and shows significant gain in throughput by comparing with a fixed relay MMR system. A suitable network model was considered for the MMR system development firstly and the influence of mobility was calculated using probabilistic approach. Then, MMR system model was developed including CR capabilities through combining the mobility equations. Finally, based on the throughput equation developed, simulation results were generated for the proposed model and were compared with the fixed relay multi-hop case.

II. Network Model

The hypothesis in our network model that mobility increases capacity is in the sense that there will be a MRS which comes closer to the sender terminal at some instant of time and is able to receive the traffic with the highest possible data rate. The mobile terminal then relays the traffic when it arrives in the vicinity of the destination terminal at a later time. A single-relay-hop cellular network with terminals capable of moving within the cell is considered for the network model of our system for simplistic observation as shown in Fig. 1.

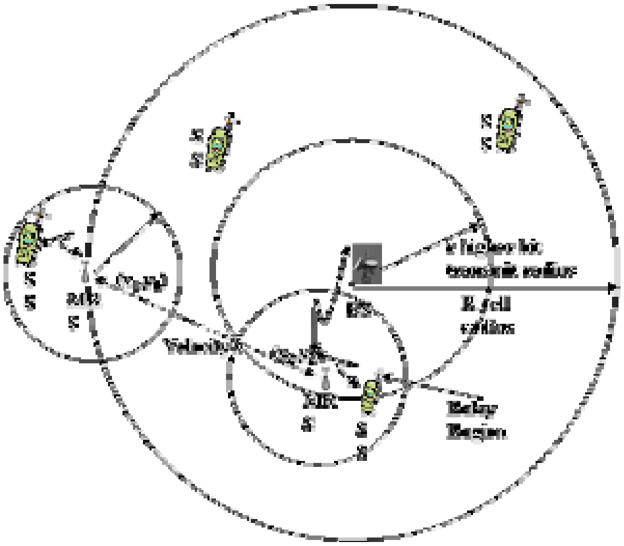

Fig.1. Simple single-relay-hop network with relay region

The network consists of a Base Station (BS), a far Subscriber Station (SS) and a MRS. The SS and MRS are assumed to be in the radio coverage of the cell. R is the radius of the cell and r is the radius of higher transmission rate range. We assumed uniform omni-directional radio propagation and the derivations shown here are strictly geometric.

Let us assume that the far Subscriber Station SS has traffic to send to the BS but it can only send with the maximum transmission power and slowest data rate. Otherwise SS needs to use an intermediate relay station to send its traffic with higher transmission rate. The aim now is to determine the probability of finding a mobile multi-hop relay station MRS within the higher transmission range of station SS at time $\boldsymbol{t_1}$ such that this relay station moves in the direction of the BS and reaches within the higher transmission range of the BS at time $\boldsymbol{t_2}$ for $\boldsymbol{t_2 - t_1 \leq T_D}$, where $\boldsymbol{T_D}$ is some delay threshold time. Let the BS is located at (0, 0) and the subscriber station SS at (x_{ss}, y_{ss}). A single-relay-hop with a higher transmission rate is possible if the following conditions are met:

i. The distance between SS and MRS at time $\boldsymbol{t_1}$ is less than $\boldsymbol{r}$.

ii. The time needed for MRS to reach within the transmission radius $\boldsymbol{r}$ of BS (in the relay region) from its initial state should not exceed the delay threshold, i.e., $\boldsymbol{t_2 - t_1 \leq T_D}$.

iii. The distance between the BS and MRS at time $\boldsymbol{t_2}$ is less than $\boldsymbol{r}$.

Assume that the mobile relay station MRS moves within the cell with random mobility and to see the extent to which the mobility further improves the system capacity, we need to determine the probability of finding such terminals in the network. Thus we should consider the following terms for mobile multi-hop relay case:

i. determine the probability of finding a mobile relay station MRS with subscriber station SS at time $\boldsymbol{t_1}$ and this mobile relay station relays the traffic to the BS when it comes closer to the higher transmission range of the BS at time $\boldsymbol{t_2}$ such that $\boldsymbol{t_2 - t_1 \leq T_D}$, where $\boldsymbol{T_D}$ is some threshold delay time.

ii. Determine the expected proportion of mobile relay station that satisfies the condition in i, which will not be calculated in this paper.

Assume that the transmission range of mobile relay station MRS be in $A(S, r)$, area with radius $\boldsymbol{r}$ and center at $\boldsymbol{S}$ and let $A\ (O, R)$ be the coverage area of the cell centered at O with radius R. Let there exist N mobile relays uniformly distributed in the cell and independent of each other. Let ζ be the event that there is a mobile terminal in $A(S, r)$. At time $t=0$, the probability that at least one of the N-1 terminals is with in $A(S, r)$ is given by:

$$\Pr(\zeta) = 1 - (1 - \frac{\lambda(A(S,r))}{\lambda(A(O,R))})^{N-1}, \qquad (1)$$

where $\lambda(\cdot)$ is the surface of the transmission coverage. If the event ζ is not satisfied, the sender terminal A either sends its traffic with the slowest data rate or waits for some time until the event ζ is true.

Now let us assume that ζ is true and choose a single random mobile relay at position Y_0 from $A(S, r)$ in time $t=0$. At any time t, the mobile relay moves at a randomly chosen direction and speed $\boldsymbol{v}$ as:

$$Y_t = Y_0 + vt.A_\alpha e_1 \tag{2}$$

where $\boldsymbol{Y_0}$ is uniformly distributed in $A(S,r)$, e_1 is a direction vector and $\boldsymbol{A_\alpha}$ is a random angle with uniform distribution given by,

$$A_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ \sin\alpha & -\cos\alpha \end{pmatrix} \tag{3}$$

According to the random direction shown, a mobile station *x* can either reach the higher transmission range of the BS for a finite time $\boldsymbol{\tau}$ or it will never come close to the BS transmission range in one step. In other words:

$$\tau = \inf\{t : Y_t \in A(BS, r)\}$$

Thus the probability that a mobile terminal is within *A(S, r)* moves at a speed $\boldsymbol{v}$ and reaches in *A (O, r),* higher transmit radius $\boldsymbol{r}$ range of the BS, within a finite time is:

$$\Pr[\tau < t] = \frac{1}{A(S,r)} \int_{A(S,r)} \Pr(\tau < t \mid Y_0 = x)dx \tag{4}$$

which is given as:

$$\Pr[\tau<t]$$
$$= \begin{cases} 0 & vt \leq |x-O| - r \\ \dfrac{1}{\pi}\arccos\left(\dfrac{(vt)^2 + |x-O|^2 - r^2}{2vt|x-O|}\right) & |x-O| - r \leq vt < \sqrt{|x-O|^2 - r^2} \\ \dfrac{1}{\pi}\arcsin\left(\dfrac{r}{|x-O|}\right) & \sqrt{|x-O|^2 - r^2} \leq vt \end{cases} \tag{5}$$

Let the BS is at located *(0, 0)* and the sender mobile relay *S* is at *(s,0)* as in the coordinate shown in following figure. The probability is then:

$$\Pr[\tau < t] = \frac{1}{A(S,r)} \int_{A(S,r)} \Pr(\tau < t \mid Y_0 = x)dx \tag{6}$$
$$= \frac{1}{A(S,r)} \int_{A_I} \frac{1}{\pi} \arcsin\left(\frac{r}{|BS - x|}\right) d\alpha$$
$$+ \frac{1}{A(S,r)} \int_{A_{II}} \frac{1}{\pi} \arcsin\left(\frac{(vt)^2 + |BS - x|^2 - r^2}{2vt\,|BS - x|}\right) d\alpha$$

Changing in the coordinate to polar as shown in following figure we get

$$= \frac{1}{A(S,r)} \int_{A_I} \rho \frac{1}{\pi} \arcsin\left(\frac{r}{\rho}\right) l(\rho)d\rho \tag{7}$$
$$+ \frac{1}{A(S,r)} \int_{A_{II}} \rho \frac{1}{\pi} \arcsin\left(\frac{(vt)^2 + \rho^2 - r^2}{2vt\rho}\right) l(\rho)d\rho$$

From the equation, *l (ρ)* is given by,

$$\alpha = \left(\frac{s^2 + \rho^2 - r^2}{2s\rho}\right) \quad \text{and} \quad l(\rho) = 2\rho \arcsin\left(\frac{s^2 + \rho^2 - r^2}{2s\rho}\right)$$

Rewriting the probability expressions we get:

$$= \frac{1}{A(S,r)} \int_{\min\left(s-r, \sqrt{(vt)^2 + r^2}\right)}^{\min\left(\sqrt{(vt)^2 + r^2}, s+r\right)} \rho \frac{1}{\pi} \arcsin\left(\frac{r}{\rho}\right) l(\rho)d\rho \tag{8}$$
$$+ \frac{1}{A(S,r)} \int_{\min\left(\sqrt{(vt)^2 + r^2}, s-r\right)}^{\min(r+s, vt+r)} \rho \frac{1}{\pi} \arcsin\left(\frac{(vt)^2 + \rho^2 - r^2}{2vt\rho}\right) l(\rho)d\rho$$

Finally the probability that at least one of the *N-1* relays is with in *A(S,r)* and reaches in the higher transmission range of the BS is:

$$\frac{1}{A(S,r)} \int_{A(s,r)} \Pr\left(\tau < t \mid Y_0 = x\right) dx. \left(1 - \left(1 - \frac{\lambda(A(S,r))}{\lambda(A(O,R))}\right)^{N-1}\right)$$

which is:

$$P_{mobile} = \frac{1}{A(S,r)} \int_{\min\left(s-r, \sqrt{(vt)^2 + r^2}\right)}^{\min\left(\sqrt{(vt)^2 + r^2}, s+r\right)} \rho \frac{1}{\pi} \arcsin\left(\frac{r}{\rho}\right) l(\rho)d\rho +$$
$$\frac{1}{A(S,r)} \int_{\min\left(\sqrt{(vt)^2 + r^2}, s-r\right)}^{\min(r+s, vt+r)} \rho \frac{1}{\pi} \arcsin\left(\frac{(vt)^2 + \rho^2 - r^2}{2vt\rho}\right) l(\rho)d\rho \tag{9}$$
$$.\left(1 - \left(1 - \frac{\lambda(A(S,r))}{\lambda(A(BS,R))}\right)^{N-1}\right)$$

III. Results and Discussion

According to the fixed relay throughput model expressed in [3] we can write

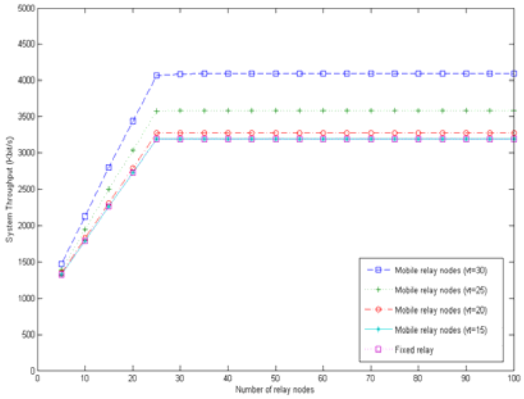

Fig. 2. System throughput for CR based MMR varying mobility factors

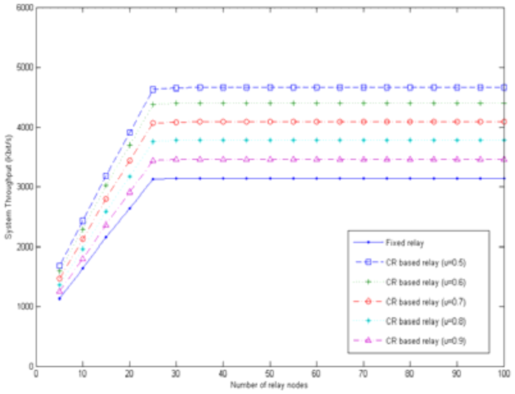

Fig. 3. System throughput for CR based MMR varying utilization factor

$$T_{RS} = \frac{\rho a_r L C \tau + \sum_{j=1}^{N-\rho a_r L} C_j \tau}{N}, \qquad (10)$$

where the expected number of users that fall within the L relay cells is $\rho a_r L$, τ is the duration of each slot, C is the highest data rate at which the relay nodes are transmitting, C_j is the data rates received by the MTs which are not covered by the relay nodes and N is the number of active users in a cell. The utilization of the spectral agile can be given as [4]

$$U_{agile} = \sum_{k=0}^{N} \min(M,k) \binom{N}{k} (1-u)^k u^{N-k} / M, \qquad (11)$$

where N is the number of primary radios, M is the number of spectral agile radios and u is the primary user utilization. Therefore, the mobility equation as in (9) can be integrated with (10) and (11) to finally develop a throughput model for the proposed system as follows

$$T_{MMR-system} = \frac{\rho a_r L C \tau + \sum_{j=1}^{N-\rho a_r L} C_j \tau}{N} \qquad (12)$$

$$\cdot \left(1 + \frac{U_{agile} \cdot M}{N}\right) \cdot \left(1 + P_{Mobile}\right)$$

Fig. 2 shows the system throughput of CR based MMR system varying mobility factors. It can be seen that with the increase in *vt* causes throughput to increase. Also, total throughput is even more increased as CR based technique is employed and throughput becomes constant for relay nodes minimum 25.

Fig. 3 shows the system throughput CR based MMR system using different utilization factor. The overall system performance improves as the number of secondary users increases and the primary user utilization factor decreases.

IV. Conclusion

In this work, we developed the MMR system model with CR capabilities to define the throughput performance compared to the fixed relay case. Also, the scheduling scheme for the proposed model is narrated and finally employed in the system to find out the throughput enhancement. Our system successfully performed well in terms of throughput compared to other cases and spectral agile radio techniques were efficiently employed to figure out better performance. The developed system will therefore provide significant directions in the deployment of CR capabilities in mobile multi-hop relay networks.

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