High Capacity Mobile Multi-Hop Relay Network for Temporary Traffic Surge

Ju-Ho LEE¹, Nonmember, Goo-Yeon LEE², Member, and Choong-Kyo JEONG†, Nonmember

SUMMARY Mobile Multi-hop Relay (MMR) technology is usually used to increase the transmission rate or to extend communication coverage. In this work, we show that MMR technology can also be used to raise the network capacity. Because Relay Stations (RS) are connected to the Base Station (BS) wirelessly and controlled by the BS, an MMR network can easily be deployed when necessary. High capacity MMR networks thus provide a good candidate solution for coping with temporary traffic surges. For the capacity enhancement of the MMR network, we suggest a novel scheme to parallelize cell transmissions while controlling the interference between transmissions. Using a numerical example for a typical network that is conformant to the IEEE 802.16j, we find that the network capacity increases by 88 percent.

key words: MMR, IEEE 802.16j, sub-cell, parallel transmission, capacity

1. Introduction

MMR technology is usually used to extend a cellular system’s coverage. It is a cost-effective way of reaching out to low-traffic shaded areas because relay stations are functionally simple compared to base stations and connected to the base station wirelessly. In this work, we show that MMR technology can be used to boost network capacity and suggest a novel design method. We believe that MMR technology is a good way to cope with temporary traffic surges because MMR network can be deployed in a short time at low cost. After the traffic returns to normal, the network can be reconfigured to the original state without relay stations.

There have been several studies on the improvement of MMR system throughput. Marza and Navidi [1] proposed a two-player game model to find the optimal relay station via which traffic will be relayed. However, their work lacks the quantitative analysis to show the network capacity. Khan [2] showed that network capacity improvement by relay stations can only be obtained in certain limited cases (such as low SNR). It dealt with simple linear links and did not cover complex two-dimensional networks. Wang et al. [3], [4] calculated the capacity of a cell with various numbers of relay stations in it when the adaptive modulation and coding technique is used. They showed that the cell capacity increases as the number of relay stations rises from one to three. When the number of relay stations is larger than three, the cell capacity improvement is not obvious because of the interference among relay stations.

In this work, we lay out 18 relay stations in a cell and propose a novel multiplexing scheme to maximize parallel transmissions while limiting the interference among relay stations. Numerical analysis shows that cell capacity increases by 88 percent under this scheme. This scheme can be applied to cope with a temporary traffic surge in some locations because it is simple without any complex control such as beam forming [5] or cooperative operation between relay stations [6]. We assume that the system is conformant to the IEEE 802.16j [7] and operates in nontransparent mode.

2. MMR System Design for Capacity Improvement

In Fig. 1, a cell experiencing temporary traffic surge in a cellular communication network is reconfigured as a 19 sub-cell MMR system with the deployment of 18 relay stations. If we let the area of the original cell be equal to the area of the MMR system, \( l_s = l_o / \sqrt{19} \), where \( l_o \) is the cell radius of the original cell and \( l_s \) is sub-cell radius of the MMR system. Sub-cells in the MMR system use the same frequency as the original cell because the change to the MMR system should not affect the neighbor cells. Sub-cells using the same frequency, therefore, cannot transmit all at the same time. Instead they are divided into groups that take turns in transmitting data. Sub-cells in a group transmit data simultaneously. Figure 1 shows a sub-cell grouping proposed in this work. Sub-cells are divided into three groups. Sub-cells in a group are geographically separated to limit the interference between them. The number of groups is critical for system capacity improvement. When there are two sub-cell groups, some sub-cells are adjacent to other sub-cells in the

Fig. 1 A sub-cell grouping: (a) original cell (b) proposed MMR system.
same group. In this case, numerical analysis as described in Sect. 3 shows that the strong interference effect between sub-cells in each group exceeds the parallel transmission advantage, lowering the system capacity. On the other hand, when the number of sub-cell groups is larger than three, parallel transmissions in each group reduce and the frame time allocated to a group decreases, making the system capacity low despite the reduced interference.

Figure 2 shows the temporal division of the downlink frame. The downlink frame comprises of the access zone and the relay zone. During the access zone, the base station and the relay stations communicate with the mobile stations. Data are relayed from the base station to the relay stations during the relay zone. The access zone is divided into three sub-zones, which are assigned to each sub-cell group. The relay zone is also divided into three sub-zones. Data to be delivered to the mobile stations in each group are relayed from the base station to the relay stations during the corresponding relay sub-zone. During the relay zone, the base station transmits data with sufficient power to send data to all relay stations at a predefined speed, while transmitting data needed to cover its own sub-cell during the access zone with small power.

Sub-zones in the access zone and the relay zone are adjusted according to the traffic in each group. We assume that the mobile stations are geographically evenly distributed across the cell and generate the same amount of traffic. Thus, sub-zones are all set to be equal.

3. System Capacity

In this section, the network capacity improvement resulting from the change from a single cell system to an MMR system is investigated quantitatively.

First, we calculate the cell capacity of the original cellular system as a reference. Let the minimum data rate required at the cell boundary be $r_{\text{min}}$, and find out the minimum transmission power of the base station. The system capacity is obtained by summing up all data rates of the mobile stations, which are determined by their distances from the base station and the transmission power of the base station.

Next, we calculate the capacity of the MMR system. Let the six sub-cells around the center sub-cell be tier-1 sub-cells and the 12 sub-cells at the boundary of the original cell be tier-2 sub-cells. The transmission power of the tier-2 relay stations are set, so that the signal power at the outer boundary of the tier-2 sub-cells is the same as that of the original single cell. The transmission power of the tier-1 relay stations and the base station can be set arbitrarily. As the transmission power of the tier-1 relays and the base station goes high, the signal power at the receiving mobile stations becomes stronger, but the interference between the sub-cells belonging to the same group increases as well. Once the transmission powers of the base station and the relay stations are determined, the data rate at each mobile station is calculated from the signal-to-interference-plus-noise ratio (SINR) at its location.

The capacity of an MMR system is affected by the ratio of the access zone and the relay zone in Fig. 2. Let the average data rate of the mobile stations in the $j$th sub-cell of the $i$th group be $r_{ij}$ $(1 \leq i \leq 3, 1 \leq j \leq 6)$ and the data rate at the relay link between the base station and the relay station be $r_r$. The system capacity peaks when the amount of data transferable from the base station to the relay stations during the relay zone is the same as the amount of data transferable from the relay stations to the mobile stations during the access zone. This can be expressed as

$$
\sum_{i=1}^{3} \sum_{j=1}^{6} r_{ij} t_{ai} = \sum_{i=1}^{3} r_r t_{rij},
$$

where $t_{ai}$ and $t_{rij}$ are frame times allocated to the $i$th sub-cell group in the access zone and the relay zone, respectively.

The system capacity, defined by the sum of the maximum of the average data rates of all the mobile stations, is given by

$$
r = \frac{\alpha_0 t_{a1} + \sum_{i=1}^{3} \sum_{j=1}^{6} r_{ij} t_{ai}}{\sum_{i=1}^{3} (t_{ai} + t_{r})},
$$

where $\alpha_0$ is the average data rate of the mobile stations in the center sub-cell.

4. Numerical Example

In this section, we provide a numerical example of the network capacity improvement for typical parameters and environment. Let the cell radius be 1,500 meters and assume that the mobile stations are three meters apart from one another in rectangular grids. It is assumed that signal attenuation follows the free-space path loss model [8]. The data rate at a given SINR is determined by the standard modulation and coding scheme (MCS) [9]. 64QAM/2 is assumed for the link between the base station and the relay station. The minimum MCS required at the cell boundary is set to QPSK/2.

The capacity improvement of the MMR system over the original single cell is shown in Fig. 3. This figure shows the capacity improvement for varying transmission power of the base station and the relay stations. The x-axis represents the transmission distance of the base station normalized by
the sub-cell radius $l_s$, where the transmission distance means the maximum distance, at which point the mobile stations can decode the signal from the base station or from the relay station using QPSK$^{1/2}$. The y-axis represents the transmission distance of the tier-1 relay station normalized by the sub-cell radius $l_s$. The transmission distances of the tier-2 relay stations are fixed to be equal to the sub-cell radius $l_s$.

The MMR system capacity change caused by the variations in transmission distance is determined by the trade-off between the received signal strength at the mobile station and the interference among sub-cells in the same group. As the transmission distance of the base station increases, data rates in the center sub-cell increase and the data rates in the six sub-cells in group-1 decrease. As the transmission distance of the tier-1 relay stations gets large, the data rates of three tier-1 sub-cells in group-2 and group-3 increase, but the data rates of the tier-2 sub-cells in each group decrease. The original single cell capacity is calculated to be 5.312 Mbps and the MMR system capacity is at maximum 9.99 Mbps when the transmission distance of the base station and the relay stations are 396 meters ($1.15l_s$) and 516 meters ($1.5l_s$), respectively.

The average data rates of the sub-cells in two hypothetical cases are shown in Fig. 4; in one the transmission distance of the base station and the tier-1 relay stations are $l_s$ and $l_r$, and the in the other they are $1.15l_s$ and $1.5l_r$. G1, G2, and G3 in the figure signify transmission groups. The data rate of a sub-cell is high when the number of simultaneously transmitting sub-cells is small and they are far apart from one another. For example, the signals from the mobile stations in the center cell are interference noise to all the six relay stations in group-1.

This example shows that the MMR technology can boost the capacity of a single cell by 88 percent. We found significant network capacity improvements in other parameter settings and environments which are not shown in this letter. The MMR design scheme proposed in this letter is simple enough to be easily deployed and effective for capacity improvement. It can thus be used effectively to cope with temporary traffic surges occurring at unspecified places.

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**References**

[1] V. Marza and H. Navidi, “Enhancing capacity of IEEE 802.16j mobile multi-hop networks by two-player game theory model,” J. Computing, vol.3, no.3, pp.36–39, March 2011.

[2] F. Khan, “Capacity and range analysis of multi-hop relay wireless networks,” Proc. 64th IEEE Vehicular Technology Conference, VTC-2006 Fall, pp.2524–2528, Montreal, Canada, Sept. 2006.

[3] H. Wang, C. Xiong, and V.B. Iversen, “Uplink capacity of multi-class IEEE 802.16j relay networks with adaptive modulation and coding,” Proc. IEEE International Conference on Communications, ICC 2009, pp.4746–4751, Dresden, Germany, June 2009.

[4] H. Wang, J.G. Andrews, and V.B. Iversen, “Uplink capacity of 802.16j mobile multihop relay networks with transparent relays,” Proc. 28th IEEE Global Telecommunications Conference, GLOBECOM ’09, pp.5179–5184, Honolulu, USA, Nov. 2009.

[5] S.W. Kim, W. Sung, and J.W. Jang, “Enhanced throughput and QoS fairness for two-hop IEEE 802.16j relay networks,” J. Communications and Networks, vol.13, no.1, pp.32–42, Feb. 2011.

[6] H.S. Ryu, H.S. Lee, J.Y. Ahn, and C.G. Kang, “Achieving maximum system throughput with cooperative relaying: A case study of IEEE 802.16j multi-hop relay,” J. Communications and Networks, vol.13, no.5, pp.466–474, Oct. 2010.

[7] “IEEE Standard for local and metropolitan area networks part 16: Air interface for broadband wireless access systems amendment 1: Multiple relay specification,” IEEE Std 802.16j-2009 (Amendment to IEEE Std 802.16-2009), June 2009.

[8] T.S. Rappaport, Wireless Communications Principles and Practice, Prentice Hall, 1996.

[9] "IEEE Standard for air interface for broadband wireless access systems,“ IEEE Std 802.16-2012 (Revision of IEEE Std 802.16-2009), Aug. 2012.