Performance Analysis of Indoor-Outdoor Wireless Caching Relay System

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***Abstract*—This paper proposes a novel indoor-outdoor caching relay system (CRS) and develops the corresponding caching mechanism, which can improve the utilization of wireless resources. It operates in two phases periodically. In Phase I, spectrum resources of the established links between MBS and user equipment (UE) are extracted to support data caching. In Phase II, caching relay system can directly serve indoor users and the fronthaul resources are released to serve other users. Simulations verify that compared with the conventional relay system (RS) the proposed CRS can improve the system throughput by at most 142% in the reusable data caching cases, only at the cost of temporarily suppressing the traffic rate to establish caching links.**

Keywords—indoor-outdoor wireless relay; caching relay system; performance analysis.

I. Introduction

As the demand for multimedia services increases, it calls for new architectural design, which integrates sophisticated techniques. In [1], it proposed an indoor-outdoor relay network. It employs the wired links between outdoor relays and indoor APs to decrease penetration loss and utilizes large outdoor antenna relays to provide additional antenna gains. However, the effectiveness of this cellular architecture is impaired by the lack of cost-effective backhaul connectivity of these relays to MBSs. Moreover, many users may request the same popular content successively, which consumes large amount of bandwidth due to duplicate downloads [2]. Therefore, caching is adopted to reduce the duplicate transmissions. It is used to achieve a trade-off between the bandwidth cost, which is usually expensive, and the storage cost, which is becoming much cheaper [3].

Existing works mainly focus on the related algorithms, such as selection of caching network topology [4], classification and storage of cache content [5][6], etc. And some works are related to improve performance, such as to promote energy efficiency [7]. Caching technology is applicable to various networks. For instance, [2] and [4] are in wireless relay networks. In [2], it focuses on when and what to cache by relay stations to degrade energy consumption. In [4], it emphasized on the topology of wireless relay caching network. These works uses stochastic process to model user requests and focuses on the selection of locations and content of cache. But they does not pay attention to the process of caching data which can further improve transmission efficiency.

Consequently, this paper improves the indoor-outdoor RS with caching strategies. Different from the existing works, we focus on link resource allocation in the process of caching data. And based on the real volume of user requests, we propose the corresponding data caching mechanism to optimize network performance. The main contributions are as follows.

1) In the paper, we firstly propose an indoor-outdoor CRS which adds cache entities to relays in the conventional indoor-outdoor RS, aiming to improve resource untilization.

2) We formalize the caching relay network optimization problem, i.e. maximum the throughput. The problem is related to user number, positions of users and relays, and so on. Then, we calculate the applicability of the mechanism. And we prove that in a certain scenario the objective function is an inverse proportional funtion with respect to the ratio of caching bandwidth. And it monotonically increases on the interval with constraints. Thus, the optimal bandwidth allocation is derived. Finally, we give out the workflow of caching mechanism which is exected periodly in two phases.

3) On the practical side, we present a simulation. Our main finding is that there are very significant gains when caching mechanism is used.

The rest of the paper is organized as follows. Section II presents the system model; bandwidth allocation and system applicability is then discussed in section III; section IV evaluates the system performance; the last section summarizes the paper.

II. System Model

A. Indoor-outdoor Caching Relay System (CRS)

This paper proposes an indoor-outdoor CRS, as shown in Fig.1. There are relays with large antenna arrays outside each building to connect with MBS only. And the wired links are employed between the large antenna arrays and the indoor wireless access points (APs) which serve indoor users. Caching entities are added to the relays to store data.

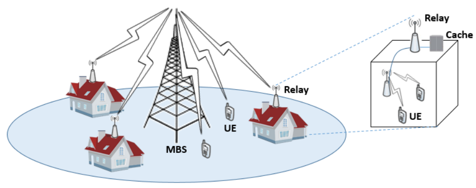

Fig. 1 Indoor-Outdoor Caching Relay System (CRS) Diagram

The advantages include that caching can avoid consuming backhual resource of transmitting duplicate content and decrease the load of MBS. And indoor-outdoor relay is utilized to avoid penetration loss, thereby strengthening indoor coverage.

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Moreover, it facilitates indoor users to reuse popular content, thereby improving throughput in the system.

B. System Model

Since duplicate requests only exist in downlink, this paper only considers the downlink. Assumed that K cells distribute uniformly, with a MBS in the cell center. There are one MBS i and N relays connected by fixed links through wireless backhaul. Each relay j has a cache. In order to simplify the analysis, we do not pay attention to the capacity of cache. The outdoor users are assumed to be uniformly distributed with the number of U_i^{out}. Each relay serves U_j indoor users, thus the total user number is $U_i = U_i^{out} + \sum_{j=1}^{N} U_j$. We denote by $\mathcal{U}$ the set of all users u, $\mathcal{U}^{out}$ the set of outdoor users, and $\mathcal{U}^{in}$ the set of indoor users.

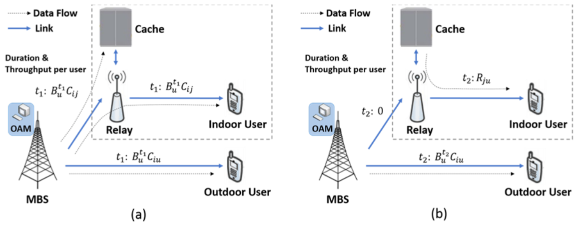

Fig. 2 Illustration of transmission phases: a) Data Caching Phase (Phase I); b) Data Retrieving Phase (Phase II)

Each period T is divided into data caching phase t_1 and data retrieving phase t_2. In Fig. 2, solid lines represent physical links and dotted lines represent data flows. In Phase I, indoor users communicate with MBS via relay, at the same time relays cache data for Phase II. Therefore, the two data flows are from MBS via relay to indoor users and from MBS via relay to cache, respectively. In Phase II, indoor users get data from caches which are written during t_1. Thus, the data flows go from caches via relays to indoor users and from MBS to outdoor users.

Assumed that the data rate from MBS to relay is R_{ij}, and the data rate from relays to indoor users is R_{ju}, it can be derived that the received data rate of indoor users is $\min(R_{ij}, R_{ju})$. Since indoor communication can operate in novel frequency bands with sufficient resources, e.g. millimeter wave, it can assume that $R_{ju} > R_{ij}$. Therefore, the received data rate of indoor users only relate to the data rate between MBS and relays, namely R_{ij}.

During data caching phase, the achievable rate can be denoted as c_{iu}. According to Shannon formula, c_{iu} can be represented by a logarithmic function of SINR.

$$C_{iu} = \log_2(1 + SINR_{iu}) = \log_2\left(1 + \frac{P_i \cdot g_{iu}}{\mathrm{I} + \sigma^2}\right), \qquad (1)$$

where P_i denotes the transmit power of MBS i, g_{iu} denotes the channel gain between user u to MBS i, I denotes the co-channel interference from neighbor cells which is assumed as a constant in this paper, and σ^2 denotes the noise power level.

In LTE, spectrum is divided into resource blocks (RBs). Thus, we assume that the number of available RBs is B. The bandwidth of each RB is W. During data caching phase, MBS allocates α_jB RBs to each relay j to cache. Based on [8], the optimal bandwidth allocation is equal allocation. The achievable bandwidth of each user $B_u^{t_1}$ is

$$B_u^{t_1} = \frac{(1 - \sum_N \alpha_j)}{U_i} BW \ . \qquad (2)$$

During data retrieving phase, as shown in Fig. 2(b), cache serves indoor users individually, and the data rate R_{ju} is constant. Similarly, the bandwidth of each outdoor user $B_u^{t_2}$ can be:

$$B_u^{t_2} = \frac{BW}{U_i^{out}} \ . \qquad (3)$$

C. Problem Description

The received data volume in Phase I should be equal to the total data volume transmitted to indoor users in Phase II.

$$\alpha_j BW c_{ij} t_1 = R_{ju} U_j t_2, \ j = 1, 2, \cdots, N, \ u \in U_j \qquad (4)$$

We assume that each relay in a cell has equal data caching duration. Based on our analysis, this factor is proportional to indoor user number U_j and data rate between relay and user R_{ju}, and is inversely proportional to distance between MBS and relay d_{ij}. Thus the ratio of α_j among different relays can be expressed as $\frac{R_{1u}U_1}{c_{i1}} : \frac{R_{2u}U_2}{c_{i2}} : \ldots : \frac{R_{ju}U_j}{c_{ij}}$, where c_{ij} is related to d_{ij}.

According to (4) and the ratio of α_j, we can obtain that

$$t_1 = \frac{R_{ju}U_j}{\alpha_j BW c_{ij} + R_{ju}U_j} T = \frac{\sum_N \frac{R_{ju}U_j}{c_{ij}}}{\alpha BW + \sum_N \frac{R_{ju}U_j}{c_{ij}}} T \qquad (5)$$

$$t_2 = \frac{\alpha W}{\alpha W + \sum_N \frac{R_{ju}U_j}{c_{ij}}} T \qquad (6)$$

In this paper, our target is to maximize the throughput S_i. To ensure service quality, we set a data rate threshold R^{th}. Thus, the objective function can be expressed as:

$$\begin{aligned} &\arg \max_{\alpha} S_i(\boldsymbol{\alpha}, \mathbf{c}, \mathbf{R}) \\ &\quad = \frac{1}{T} \cdot \Big(\sum_{k \in \mathcal{U}} B_k^{t_1} c_{ik} t_1 + \sum_{k \in \mathcal{U}^{out}} B_k^{t_2} c_{ik} t_2 + \sum_{k \in \mathcal{U}^{in}} R_{jk} t_2\Big) \qquad (7) \\ &\text{s.t.} \quad \alpha_j BW c_{ij} t_1 = R_{ju} U_j t_2, \ j = 1, 2, \cdots, N, \ u \in U_j \\ &\qquad t_1 + t_2 = T, \ T > 0. \end{aligned}$$

This formula consists of three parts. The first part is the sum of rate of all users in Phase I. The second part is the sum of rate of outdoor users connected with MBS in Phase II. The last part is the sum of rate of indoor users which is served by cache in Phase II. The constraints are for data volume and time as mentioned above. Note that situations above are for first requests. But because of repeatability, users may request data stored in cache. The effect of reusing data is verified in Section IV.

III. Caching Relay Mechanism

A. Applicability Analysis

In conventional RS, since relay is used to broadcast and amplify signals, we can ignore its impact on data rate. Then all users in a cell can simply be regarded as connected with MBS i. Thus, the system throughput can be written as follows.

$$S_i^{'} = \sum_{k \in \mathcal{U}} \frac{BW}{U_i} c_{ik} \tag{8}$$

Then, this paper analyses the mechanism applicability by comparing throughput of the caching relay and the conventional RS. Let

$$S_i - S_i^{'} > 0 \tag{9}$$

Then it can be derived that

$$BW \frac{\sum_{k \in \mathcal{U}^{out}} c_{ik}}{U_i^{out}} + \sum_{k \in \mathcal{U}^{in}} R_{jk} - \frac{\sum_{k \in \mathcal{U}} c_{ik}}{U_i} \sum_{j=1}^{N} \frac{R_j U_j}{c_{ij}} - BW \frac{\sum_{k \in \mathcal{U}} c_{ik}}{U_i} > 0 \tag{10}$$

It means that the input parameters user number array $\mathbf{U}$, distance array between user and MBS $\mathbf{d}$, and data rate array from relay to user $\mathbf{R}$ should satisfy the above formula. Since if a scenario is given, i.e. $(\mathbf{R}, \mathbf{d}, \mathbf{U})$ is fixed, we define (10) as $\mathrm{Metric}(\mathbf{R}, \mathbf{d}, \mathbf{U})$. Thus, caching relay mechanism is applicable if the parameters $(\mathbf{R}, \mathbf{d}, \mathbf{U}) \in \{(\mathbf{R}, \mathbf{d}, \mathbf{U}) | \mathrm{Metric}(\mathbf{R}, \mathbf{d}, \mathbf{U}) > 0\}$.

B. Optimal Bandwidth Allocation

During data caching phase, bandwidth of MBS can be divided into two parts, namely bandwidth to cache data and bandwidth to serve users. Assumed that the ratio of MBS bandwidth for cache α equals to $\sum_{j=1}^{N} \alpha_j$, we can obtain that

$$\alpha^* = \arg \max_{\alpha} f(c, R, U) \tag{11}$$

According to the above results, we can rewrite the formula as (12) in the next page.

Obviously, S_i is an inverse proportional function with respect to α. Furthermore, this formula can be simplified into normal form as $\mathrm{A} + \mathrm{E} \cdot \frac{1}{\mathrm{C}x + \mathrm{D}}$ in which $\left(-\frac{\mathrm{D}}{\mathrm{C}}, \mathrm{A}\right)$ is its symmetry point and E determines its monotonicity.

Thus we can obtain the parameters as follows.

$$-\frac{\mathrm{D}}{\mathrm{C}} = -\frac{\sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}}{BW} < 0 \tag{13}$$

$$\begin{aligned} \mathrm{E} &= \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} \left(\frac{BW}{U_i^{out}} \sum_{k \in \mathcal{U}} c_{ik} - \frac{BW}{U_i^{out}} \sum_{k \in \mathcal{U}^{out}} c_{ik} - \sum_{k \in \mathcal{U}^{in}} R_{jk} + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} \frac{\sum_{k \in \mathcal{U}} c_{ik}}{U_i} \right) \\ &= \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} \cdot (-1) \cdot \mathrm{Metric}(\mathbf{R}, \mathbf{d}, \mathbf{U}) < 0 \end{aligned} \tag{14}$$

From the above we know, $S_i(\alpha)$ monotonically increases on $[0,1]$. Therefore, on the premise that user service quality is ensured, when α reaches its maximum, the overall system throughput would reach the maximum value.

Since we set R^{th} as minimum data rate threshold, each users can get $\frac{R^{th}}{\min(c_{iu})}$ bandwidth. Thus the maximum of α can be written as:

$$\alpha_{\max} = 1 - \frac{R^{th} U_i}{\min(c_{iu}) BW} \tag{15}$$

C. Caching Relay Mechanism

The flowchart of the mechanism is illustrated in Fig. 3.

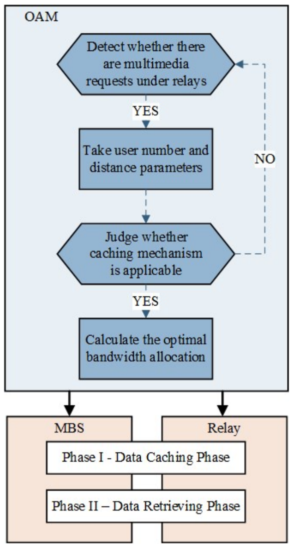

Fig. 3 the Flowchart of System Operation

Step 1: OAM at MBS detects all user requests. If it detects that any relay receives multimedia requests, then enter Step 2.

Step 2: OAM takes scenario parameters, including distance between MBS and relay d_{ij}, average distance between MBS and outdoor users $\sum_{u \in \mathcal{U}^{out}} d_{iu} / U_i^{out}$, number of indoor users $\sum_{j=1}^{N} U_j$, and number of outdoor users U_i.

Step 3: OAM at MBS judges whether caching mechanism is applicable. If $(\mathbf{R}, \mathbf{d}, \mathbf{U}) \in \{(\mathbf{R}, \mathbf{d}, \mathbf{U}) | \mathrm{Metric}(\mathbf{R}, \mathbf{d}, \mathbf{U}) > 0\}$, enter Step 4; if not, go back to Step 1. That is, OAM continues to detect whether there are multimedia requests under relays.

Step 4: OAM calculates the optimal bandwidth allocation. Use $(1 - \frac{R^{th} U_i}{\min(c_{iu}) BW})$ to determine the ratio of bandwidth allocation. Then it sends control signals to MBS and relays in the cell.

Step 5: MBS and relays execute the caching mechanism, including caching data and retrieving data, as described in Section II.

$$\begin{aligned} S_i &= \frac{1}{T} \cdot \left(\sum_{k \in \mathcal{U}} B_k^{t_1} c_{ik} t_1 + \sum_{k \in \mathcal{U}^{out}} B_k^{t_2} c_{ik} t_2 + \sum_{k \in \mathcal{U}^{in}} R_{jk} t_2 \right) \\ &= \frac{(1-\alpha) BW}{U_i} \sum_{k \in \mathcal{U}} c_{ik} \cdot \frac{\sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}}{\alpha BW + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}} + \frac{BW}{U_i^{out}} \sum_{k \in \mathcal{U}^{out}} c_{ik} \cdot \frac{\alpha BW}{\alpha BW + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}} + \sum_{k \in \mathcal{U}^{in}} R_{jk} \cdot \frac{\alpha BW}{\alpha BW + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}} \\ &= \frac{1}{U_i} \sum_{k \in \mathcal{U}} c_{ik} \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} \left(\frac{BW}{U_i} \sum_{k \in \mathcal{U}} c_{ik} - \frac{BW}{U_i^{out}} \sum_{k \in \mathcal{U}^{out}} c_{ik} - \sum_{k \in \mathcal{U}^{in}} R_{jk} + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}} \frac{\sum_{k \in \mathcal{U}} c_{ik}}{U_i} \right) \cdot \frac{1}{BW \alpha + \sum_{j=1}^{N} \frac{R_{ju} U_j}{c_{ij}}} \end{aligned} \tag{12}$$

IV. RESULTS AND ANALYSIS

A. Simulation Scenario

Each cell consists one MBS and three relays which are 150m, 100m and 50m away from MBS. The number of outdoor users is 30, with a mean distance of 200m apart from MBS. The number of indoor users is 8, 14, and 8 respectively. The total user number is 60. Path loss is set as $34 + 40\log_{10} d\ (\mathrm{m})$ dB. And the penetration loss is set as 10dB. Other parameters are in Table I.

TABLE I. SIMULATION PARAMETERS

Parameters	Value
Transmit power of MBS P_i	46 dBm
Data rate from relay to user R_{ju}	[5 10 15] Mbps
Bandwidth of MBS W	20MHz
Thermal noise σ^2	-118 dBm
Co-channel interference I	-104 dBm
Period T	50 s

B. Results Analysis

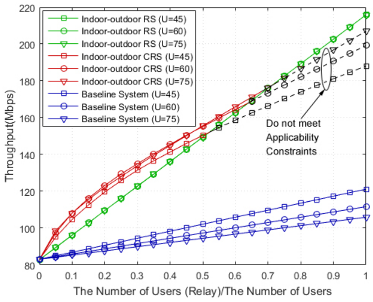

Fig. 4 System throughput related to the ratio of indoor and outdoor users

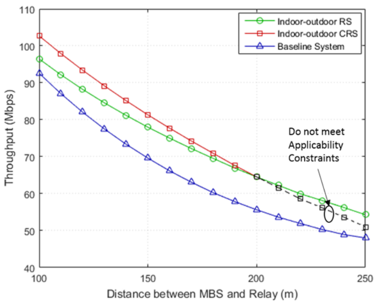

Fig. 5 System throughput related to distance between MBS and relay

Here the baseline system is the network in which only MBS serves users. Fig. 4 shows that with the ratio of indoor users increasing, the system throughput increases. That is because relays can amplify signals and enhance coverage. Then, Fig. 4 shows that when the ratio of relay users is relatively large, the throughput of no caching relay system is a little larger, which leads to inapplicability of caching mechanism.

Since shortening the distance between MBS and relays can improve the indoor transmission rate in Phase I, from Fig. 5, we can see that as distance increases, the throughput decreases. Here when distance between MBS and relay is less than 200m, throughput in CRS is larger than that in conventional RS. It follows that under suitable scenarios, indoor-outdoor CRS can promote throughput efficiently compared with the conventional indoor-outdoor RS.

Due to the repeatability of multimedia requests, caching mechanism can save backhaul bandwidth. As shown in Fig. 6, under indoor-outdoor CRS, caching function can decrease the waste of bandwidth to transmit repeated data. Thus, as ratio of repeated requested increases, system throughput increases obviously (nearly 142%), from 156Mbps to 377Mbps.

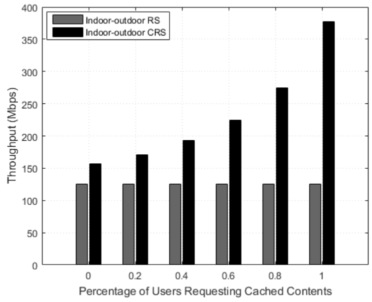

Fig. 6 System throughput related to the ratio of requesting cached contents

V. CONCLUSIONS

This paper innovatively proposes an indoor-outdoor CRS, which adds caching entities to indoor-outdoor RS, thereby substantially promoting the utilization of bandwidth and system throughput. This paper mainly puts forward a caching mechanism which is executed periodically in two phases and analyses the optimal allocation of bandwidth and applicable scenarios. In simulation part, we confirm the efficacy of this system in consideration of effect of parameters varying with comparison to other systems. The numerical results suggest under the best situation, the performance of proposed CRS can be improved approximately 142% if indoor users reuse the caching data. There are still some details to be discussed, such as the limitation of cache capacity and cleaning cache content. These problems will be considered in our further study.

REFERENCES

[1] Wang C. X., Haider F., Gao X., You X. H., Yang Y., and Yuan D., "Cellular architecture and key technologies for 5G wireless communication networks," in Communications Magazine, 2014, 52(2): 122-130.

[2] Wang X., Bao Y., Liu X., and Niu Z., "On the design of relay caching in cellular networks for energy efficiency," in Computer Communications Workshops, 2011, pp.259-264.

[3] Xiaofei W., Min C., Taleb T., Ksentini A., and Leung V., "Cache in the air: exploiting content caching and delivery techniques for 5G systems," in Communications Magazine, 2014, 52(2): 131-139.

[4] Xie F., and Hua K.A., "A caching-based video-on-demand service in wireless relay networks," in Wireless Communications & Signal Processing, 2009, pp.1-5.

[5] Thomos C., Stamos K., Pallis G., Vakali A., and Andreadis G. Pallis G., "Content Classification for Caching under CDNs," in Innovations in Information Technology, 2007, pp.586-590.

[6] Han W., Liu A., and Lau V. K. N., "Degrees of Freedom in Cached MIMO Relay Networks," in IEEE Transactions on Signal Processing, 2015, 63(15): 3986-3997.

[7] Gao Y., Li Y., Yu H., Wang X. F., and Gao S. H., "Energy efficient content aware cache and forward operation in 3GPP LTE-Advanced base stations," in Computer Science and Network Technology, 2013, pp.816-820.

[8] Ye Q., Rong B., Chen Y., Al-Shalash M., Caramanis C., and Andrews J. G., "User Association for Load Balancing in Heterogeneous Cellular Networks," in IEEE Transactions on Wireless Communications, 2013, 12(6): 2706-2716.