Adaptive Resource Reuse Scheduling for Multihop Relay Wireless Network Based on Multicoloring

Xin Guo, Wenchao Ma, Zihua Guo, Xuemin (Sherman) Shen and Zifeng Hou

***Abstract*— In this paper, an adaptive resource reuse scheduling (ARRS) algorithm is presented with the goal of enhancing the system capacity for relay networks, which supports arbitrary topology and relay stations (RSs) mobility. Since one key step in ARRS is modeled as graph multicoloring, a fast $\lceil \frac{\Delta+1}{2} \rceil$-approximation algorithm named dual sorting greedy (DSG) is provided for the problem. Simulation results show that ARRS achieves high system capacity and hence satisfies the multimedia service QoS requirements of relay networks efficiently.**

***Index Terms*— Relay networks, scheduling, multimedia services, multicoloring, approximation algorithms, NP-hard.**

I. Introduction

Multihop relay wireless network is an attractive solution to B3G and 4G systems [1], which will suffer from smaller than expected coverage and excessive amount of shadowed areas due to the high operating frequencies. Relay networks enhance the coverage as well as the signal quality by utilizing relay stations (RSs) on behalf of base station (BS) to provide radio coverage in areas that out of range or shadowed. In such networks, the relaying of duplicated user data between BS and RSs leads to serious capacity degradation, therefore, an efficient scheduling strategy is necessary.

The most simple scheduling scheme is to allocate each RS with an equal time share (ETS) of the time frame [2]. Without utilizing resource reuse, the above solution is very inefficient. Therefore, spatial independency (SI) has been studied, in attempts to enhance the system capacity [3-4]. In [3] and [4], resource reuse for non-adjacent RSs is performed and different reuse sets are allocated equal share of resources in time and frequency domains, respectively. However, these studies can only be used for fixed and symmetrically planned relay networks. In [5], resource reuse for arbitrary topology based on interference measurements between RSs is proposed for IEEE 802.16j [6], but no practical algorithm is provided.

This letter presents a novel adaptive resource reuse scheduling (ARRS) algorithm to enhance the system throughput for relay networks, which supports arbitrarily located and mobile RSs. Further, one key step in ARRS is modeled as multicoloring of arbitrary graph G with associated weight vector w, which is known to be NP-hard. The traditional transforming of multicoloring into pure graph coloring does not adapt to relay networks where the ongoing bandwidth requests (i.e., the elements of w) may be exceedingly large and change frequently. Therefore, we propose a fast $\lceil \frac{\Delta+1}{2} \rceil$-approximation algorithm dual sorting greedy (DSG) for multicoloring of the pair (G, w) where Δ is the maximum vertex degree of G. Simulation results show that ARRS achieves high system throughput, thus efficiently guaranteeing the multimedia service QoS requirements of relay networks.

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TABLE I
MULTIMEDIA SERVICES AND QOS PARAMETERS

Service	MRR(slot)	MSR(slot)	ML(time unit)	Application
UGS	-	5	20	VoIP
rtPS(ErtPS)	8	12	40	Audio,Video
nrtPS	5	7	80	FTP
BE	0	2	-	Data,Web

II. ARRS Algorithm for Relay Networks

A. Overview of the Solution

Since the throughput decreases with an increasing number of hop-counts [7], this letter investigates a 2-hop system with relaying in the time domain: *relay link* is used for the communications between BS and RSs; *access link* is for BS (RSs) and their directly served mobile stations (MSs). Our system adapts to arbitrarily located BS (RSs) to provide efficient area coverage as well as to support RSs mobility. And our research supports five classes of multimedia services defined in IEEE 802.16j: UGS, rtPS, ErtPS, nrtPS and BE. The services are characterized by three QoS parameters as shown in Table I: maximum sustained traffic rate (MSR) and minimum reserved traffic rate (MRR) are the upper and lower bounds of bandwidth requirements, respectively; maximum latency (ML) is the upper bound of the acceptable delay. Since rtPS and ErtPS have similar QoS requirements, they will be treated as one class in our simulation.

We assume BS and RSs all adopt omni-directional antennas and hence BS can only communicate with each RS respectively in relay link as shown in Fig.1-(b). We exploit access link tier reuse, which is related to two types of information: bandwidth (time slots) requests of BS (RSs) needed by their directly served MSs and co-channel interference between BS (RSs). See access link in Fig.1-(b) where BS (RSs) are represented by the 2-tuples (label, bandwidth request). The communications associated with RSs labelled with R7 and R1 have no interference with each other and thus can share the same time slots. By contrast, the mutually-interferenced RSs R7 and R8 can only be allocated disjoint sets of time slots.

Prior to our modeling, we review some theoretic definitions.

Definition 1: Given an undirected graph $G(V, E)$ and a weight vector w of nonnegative integers w_v indexed by the vertices $v \in V$. $Multicoloring$ of the pair (G, w) is to assign each vertex v with a set of w_v distinct colors such that adjacent

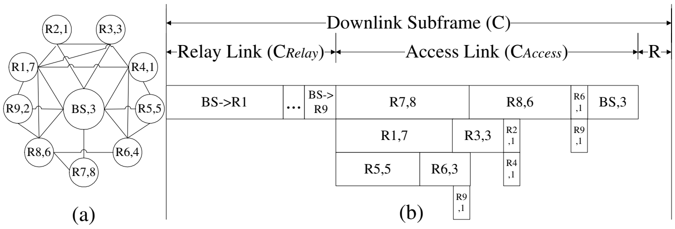


Fig. 1. Example of scheduling model and scheduling result.

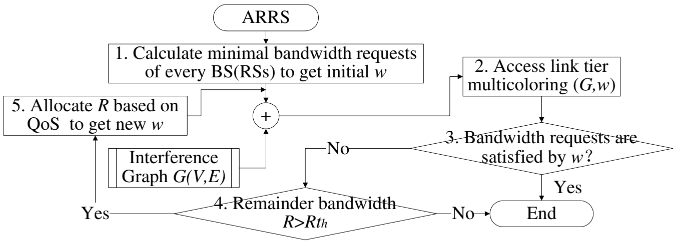


Fig. 2. Flowchart of ARRS algorithm.

vertices receive disjoint sets of colors. The minimum number of colors needed by multicoloring is the *Weighted Chromatic Number* of (G, w), denoted by $\chi^w(G)$.

Definition 2: The *Weighted Clique Number* of the pair (G, w), denoted by $\omega^w(G)$, is defined as $\max_{S\in F}\left(\sum_{v\in S} w_v\right)$ where F represents the set of cliques in the graph G.

Let $G(V, E)$ be an undirected graph, where the vertex set V corresponds to BS (RSs) and the edge set E represents the co-channel interference between them. A vector w denotes the bandwidth requests of BS (RSs). Thus, the access link tier scheduling can be modeled as multicoloring of the pair (G, w). Fig.1-(a) shows an example of the graph model.

B. Detailed Description of ARRS Algorithm

Based on the above model, we design ARRS, as shown in Fig.2. The algorithm is illustrated with downlink scheduling, for uplink pattern can be obtained alike. Let C be the system capacity, C_{relay} and C_{access} the bandwidth granted to relay link and access link respectively, and R the remainder bandwidth defined by $R=C-(C_{relay}+C_{access})$, see Fig.1-(b).

ARRS comprises five steps. Step 1 calculates the minimal bandwidth requests of every BS (RSs) by adding the MRR of their directly served MSs to obtain initial w. The interference graph $G(V, E)$ is determined dynamically based on system measurements. Step 2 is multicoloring of the pair (G, w) to get C_{access}. In step 3, if the bandwidth requests of all services are satisfied, end the algorithm; otherwise go to step 4. We can get R with $C_{relay} = \sum_{v\in V} w_v$. If R is greater than a predefined threshold R_{th}, allocate R in step 5 to get new w; otherwise end the algorithm. Step 5 allocates $\alpha R, \alpha \in [0, 1]$ to multimedia services in the priority sequence of rtPS (ErtPS), nrtPS and BE according to their ML value to satisfy their QoS requirements beyond minimal bandwidth guarantees. α is set to guarantee the constraint of $C_{relay}+C_{access} \leq C$. Then go back to step 2.

III. DSG ALGORITHM FOR GRAPH MULTICOLORING

A. DSG Algorithm Description

The proposed DSG, a polynomial-time approximate solution to multicoloring, comprises three phases as shown in

```
Algorithm. DSG(G(V,E), w)
    /*S1, S2, T, Ui and Vi are ordered vertex sets*/
    /*i, j, mi,, I and J are integer numbers*/
    /*χ^w_D(G) is the result number of colors*/
 Phase1. S1 ← weight_descending_order(V);
 Phase2. S2 ← φ;  i ← 0;
         while(S1 ≠ φ) do
           i ← i + 1; Ui ← maximal_independent_set(G, S1);
           insert Ui into the tail of S2;  S1 ← S1\Ui;
         end while
 Phase3. I ← i;  i ← 0;
         while(S2 ≠ φ) do
           i ← i + 1; Vi ← maximal_independent_set(G, S2);
           mi ← min_{u∈Vi} wu;
           for(j = 0; j < |Vi|; j + +) do
             u ← Vi[j]; wu ← wu − mi;
             if(wu == 0) S2 ← S2\{u};
           end for
         end while
         J ← i;  χ^w_D(G) ← Σ_{1≤i≤J} mi;
         return χ^w_D(G);
End
```

Fig. 3. A formal description of the DSG algorithm.

Fig.3. Phase 1 sorts the vertices of V in decreasing order of weight and the vertices of the same weight in increasing order of degree to get an ordered vertex set S_1. Phase 2 partitions S_1 into serials of ordered maximal independent sets, and then sorts the vertices such that the ones in the same independent set are in consecutive positions in a new ordered vertex set S_2. The referred *maximal independent set* procedure detects vertex sequentially based on its position in S_1. Phase 3 selects vertices in S_2 sequentially to generate a maximal independent set V_i, allocates to V_i its minimal vertex weight of time slots, updates S_2 and iterates until S_2 is null. The $V_1,\ V_2, \ldots, V_J$ form the scheduling sequence and they are assigned $m_1,\ m_2, \ldots, m_J$ number of first available time slots in turn. Access link in Fig.1-(b) shows the scheduling results corresponding to Fig.1-(a) produced by DSG.

B. DSG Algorithm Analysis

From the definitions mentioned above in section II-A, the following is immediate.

Lemma 1: For any graph G with an associated weight vector w, $\chi^w(G) \geq \omega^w(G)$.

Since any edge in a graph represents a clique of two vertices, by Lemma 1 we have

Corollary 1: For any pair $(G(V, E), w)$,

$$\chi^w(G) \geq max_{u,v\in V, uv\in E}(w_u + w_v).$$

Theorem 1: DSG approximates the multicoloring for any pair $(G(V, E), w)$ within a ratio of $\lceil \frac{\Delta+1}{2} \rceil$ where Δ is the maximum vertex degree of graph G.

Proof: Let $\chi^w_D(G)$ denote the colors of multicoloring produced by algorithm DSG on G. Due to the greedy characteristic of the procedure *maximal independent set* of DSG, in phase 2 we can obtain at most Δ+1 independent sets, namely, $1 \leq I \leq \Delta+1$. Consider two separate cases.

Case 1: $\Delta = 0$.

Hence, $I = 1$. Here, DGS can obtain the optimal result. Thus,

$$\frac{\chi^w_D(G)}{\chi^w(G)} = 1 = \left\lceil \frac{0+1}{2} \right\rceil = \left\lceil \frac{\Delta+1}{2} \right\rceil. \quad (1)$$

Case 2: $\Delta \geq 1$.

Suppose graph G has K connected components denoted by B_k, $1 \leq k \leq K$. For DSG, in phase 3, a vertex $u = S_2[i]$ has impact on the coloring of $v = S_2[j]$, if and only if $u, v \in B_k$ and $i < j$. Thus, we focus on B_k. Let $\chi^w_D(B_k)$ be the colors assigned to B_k, $B_{k,i}$ denote $B_k \cap U_i, 1 \le i \le I$ and f_v^D represent the largest color assigned to v according to DSG. Meanwhile, $f_{k,i}^D$ is defined by

$$f_{k,i}^D = \begin{cases} 0 & ,i=0, \\ \max(0, \max_{u \in B_{k,2i-1} \cup B_{k,2i}} f_u^D - f_{k,i-1}^D), 1 \le i \le \lfloor \frac{I}{2} \rfloor, \\ \max(0, \max_{u \in B_{k,I}} f_u^D - f_{k,i-1}^D) & , \lfloor \frac{I}{2} \rfloor < i \le \lceil \frac{I}{2} \rceil. \end{cases} \quad (2)$$

Observe that $u \in B_{k,2i-1}$ is adjacent to some $v \in B_{k,2i}$. Since $u \in B_{k,j}$ has no impact on the coloring of $v \in B_{k,i}$ if $i < j$, by Corollary 1 we have that

$$\begin{aligned} f_{k,i}^D &\le \max_{u \in B_{k,2i-1}, v \in B_{k,2i}, uv \in E} (w_u + w_v) \\ &\le \max_{u,v \in V, uv \in E} (w_u + w_v) \le \chi^w(G). \end{aligned} \quad (3)$$

Recall that, DGS colors vertices in S_2 sequentially. Therefore, by definition of $f_{k,i}^D$ we have

$$\chi_D^w(B_k) = \sum_{i=1}^{\lceil \frac{I}{2} \rceil} f_{k,i}^D \le \chi^w(G) \left\lceil \frac{I}{2} \right\rceil \le \chi^w(G) \left\lceil \frac{\Delta+1}{2} \right\rceil. \quad (4)$$

As mentioned above, multicolorings of different components B_k have no impact on each other. Thus,

$$\frac{\chi_D^w(G)}{\chi^w(G)} = \frac{\max_{1 \le k \le K} \chi_D^w(B_k)}{\chi^w(G)} \le \left\lceil \frac{\Delta+1}{2} \right\rceil. \quad (5)$$

From Equations (1) and (5), we get the approximation ratio as required. This completes the proof. □

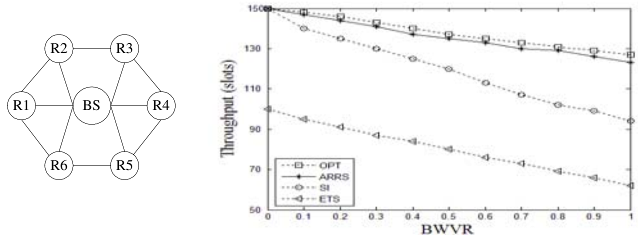
IV. Simulation Results

We provide an experimental performance analysis of our ARRS in comparison with OPT (optimal), SI (only for symmetric topology) and ETS for the downlink scheduling. Therein, SI and ETS are introduced in section I. The only difference between OPT and ARRS is that the former applies optimal value in access link multicoloring. Thus, results of OPT can not be obtained in polynomial time.

The simulator implemented using NS-2 for relay networks takes as input the system bandwidth of 200 time slots, interference graph, and average QoS parameters of services shown in Table I. The actual QoS requirements are uniformly distributed in the range of $(1 \pm 20\%)$average. Since the proposed ARRS can be applied to a class of problems that adhere to the constrictions alike, without loss of generality, our experiments have been constructed under the assumption of a noiseless network with uniform condition for each channel.

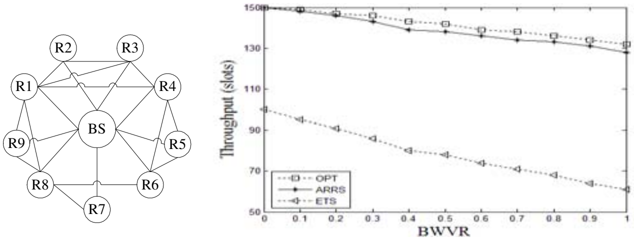
For the estimation of relation between bandwidth requests distribution and the overall system capacity, we introduce a new variable BandWidth Variance Ratio (BWVR) defined by $BWVR = \frac{\sqrt{Var(BW)}}{E(BW)}$ where variable BW is bandwidth request of BS (RSs), $E(BW)$ and $\sqrt{Var(BW)}$ are the expectation and the standard variance of BW, respectively.

In Fig.4, the system throughput of a symmetrically planned six RSs relay network between ARRS, OPT, SI and ETS are compared according to BWVR. Fig.4-(a) is the interference graph. See Fig.4-(b), the ARRS achieves a higher system throughput than both SI and ETS. In particular, the throughput of ARRS decreases very slowly compared to SI and ETS with the increase of BWVR. This means ARRS is efficient even when bandwidth requests among BS (RSs) vary dramatically. The throughput of ARRS is very close to the OPT's, while



(a) (b)

Fig. 4. Throughput vs. BWVR of six RSs scenario.



(a) (b)

Fig. 5. Throughput vs. BWVR of nine RSs scenario.

the time complexity of the polynomial-time algorithm ARRS is far below that of OPT.

Fig.5 shows the system throughput of an asymmetrically planned nine RSs relay network between ARRS, OPT and ETS according to BWVR. ARRS has the advantages as it does in symmetrical scenario. Thus, the graph model based ARRS is effectively adaptive to arbitrary topology and can dynamically adjust according to the change of bandwidth requests.

V. Conclusion

In this paper, a scheduling scheme named ARRS, in which a key step is modeled as graph multicoloring problem, has been developed for relay networks. To ensure efficiency, a fast $\lceil \frac{\Delta+1}{2} \rceil$-approximation algorithm DSG has been proposed for the multicoloring problem. Simulation demonstrates that the graph model based ARRS achieves high system capacity in arbitrarily planned relay networks and thus permits better services QoS and supports RSs mobility.

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