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☐ 期中進度報告

具高效能及服務品質之合作式網路設計-子計畫二：

合作式網路之頻寬管理機制 (2/2)

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中文摘要

為了滿足無線網際網路高頻寬的需求，基於基礎建設網路之多躍中繼（Multihop Relay, MR）技術於近年內被提出。在「合作式網路之頻寬管理機制」中，針對 IEEE 802.16j MR WiMAX 系統，深入研究網路頻寬使用和分配的問題，利用頻寬重新分配（Bandwidth Repacking）和頻寬攜帶（Bandwidth Borrowing）做為基本概念，設計出適合於 IEEE 802.16j 網路的時槽重新分配（Slot Repacking）演算法和時槽攜帶（Slot Borrowing）演算法。提出的頻寬管理機制可有效地降低換手連線拒絕率，進而使網路的頻寬能夠更有效率地被使用。

關鍵詞：合作式網路、多躍中繼、頻寬重新分配、頻寬攜帶、頻寬管理。

Abstract

The IEEE 802.16j standard has been proposed to triumph over the shadow fading and path attenuation problems in IEEE 802.16e networks by employing the multihop relay (MR) technology. Taking path selection and spatial reuse into account, numerous dynamic/heuristic scheduling algorithms have been presented for MR networks. Unfortunately, although these scheduling schemes can achieve high efficiency of resource utilization, almost all of their low time complexities considerably rely on expensive operations and sophisticated data structures. To maintain the simplicity and low time complexity of fixed-assignment scheduling while guaranteeing high resource utilization, this paper proposes a repacking and borrowing-based resource scheduling algorithm, RBRS, for IEEE 802.16j MR networks. In the repacking phase, a connection that is served via a direct path can be handed off to a cooperative path to release a part of its allocated base station (BS) resources. Since BS resources are shared by all connections within the BS coverage, repacking can increase the amount of available BS resources to serve the connection attempts that arrive at relay stations (RSs) currently under resource starvation. To complement repacking and further enhance the performance of RBRS, borrowing is applied. In the borrowing phase, over-loaded RSs are capable of borrowing resources from under-loaded RSs, further improving the resource utilization. Our main contributions are twofold: (1) to the best of our knowledge, this paper is the first effort in the literature to investigate the performance enhancement of repacking and borrowing operations for MR networks (including IEEE 802.16j); (2) both analytic and simulation models are developed to validate against each other and to study the performance of RBRS. The simulation results indicate that RBRS requires a low computational time which is comparable to that of fixed-assignment scheduling. Furthermore, by increasing available BS resources and balancing RS resources, RBRS shows near-optimal system capacity and throughput performance at the same time.

Keywords: Borrowing, IEEE 802.16j, multihop relay (MR), repacking, resource utilization, scheduling algorithm, WiMAX

一、 研究背景與目的

■ 前言

The IEEE 802.16j standard [1] has been proposed to triumph over the shadow fading and path attenuation problems in IEEE 802.16e networks [2] by employing the multihop relay (MR) technology. IEEE 802.16j MR networks deploy low-power relay stations (RSs) between base stations (BSs) and mobile stations (MSs). A BS can communicate with an MS via a direct path (single-hop path between the BS and the MS) or a cooperative path (multihop path through the BS to RSs, and then to the MS). When the short-distance and line-of-sight conditions are met, RSs can be used to forward data for BSs/MSs with better radio quality and higher transmission rates. Moreover, if the radio interference among non-adjacent RSs can be neglected, these RSs can transmit data simultaneously by exploiting spatial reuse [3,4]. With the new issues of multipath selection and spatial-reuse RSs determination, the resource scheduling problem in IEEE 802.16j MR networks is much more complicated than that in IEEE 802.16e networks.

■ 文獻探討

Taking path selection and spatial reuse into account, numerous scheduling algorithms have been presented for MR networks. The simplest and fastest scheduling algorithm is the fixed-assignment scheduling (FAS) [5,6], in which a BS statically allocates each subordinate RS with a fixed amount of bandwidth. However, FAS leads to inflexible and inefficient resource utilization, significantly degrading the system throughput and capacity. To accomplish the maximal system performance, most of the recent approaches allocate bandwidth in a dynamic manner. Note that various performance objectives exist such as delay minimization [7–9], proportional fairness [10–13], QoS guarantee [14–17], and throughput maximization [18–21]. According to specific objectives, the scheduling problems can be formulated as different optimization problems. For example, the scheduling problems were modeled as a graph multicoloring problem in [20] to maximize the sizes of non-adjacent RS sets, a boundary selection problem in [11] to balance the traffic loads among RSs, a user-required-rate problem in [17] to satisfy each user's required rate, a network flow problem in [7] to select an appropriate transmission order, and an interference minimization problem in [16] to discover a less interfering path for each connection. If the above optimization problems can be solved, the corresponding performance objectives can be achieved. However, those optimization problems are either NP-hard or NP-complete. Hence, heuristic algorithms were also proposed in the respective researches to derive near-optimal solutions in polynomial time for the scheduling problems. Unfortunately, although these dynamic/heuristic scheduling schemes can achieve high efficiency of resource utilization, almost all (if not all) of their low time complexities considerably rely on expensive operations (e.g., memory and/or database access) and sophisticated data structures. In accordance with our experience of practical IEEE 802.16 network implementation (with III and ITRI, Taiwan), the period for a scheduler to generate a bandwidth allocation map should typically be less than one millisecond. In this case, if the time constraint

cannot be relaxed, these schemes may still not be applicable.

■ 研究目的

To maintain the simplicity and low time complexity of FAS while guaranteeing high resource utilization, this paper proposes a repacking and borrowing-based resource scheduling algorithm, RBRS, for IEEE 802.16j MR networks. In the repacking phase, a connection that is served via a direct path can be handed off to a cooperative path to release a part of its allocated BS resources. Since BS resources are shared by all connections within the BS coverage, repacking can increase the amount of available BS resources to serve the connection attempts that arrive at RSs currently under resource starvation. To complement repacking and further enhance the performance of RBRS, borrowing is applied. In the borrowing phase, over-loaded RSs are capable of borrowing resources from under-loaded RSs, further improving the resource utilization. Note that both the repacking and borrowing processes only invoke the simple selection operation to choose the first candidate from the respective candidate lists maintained in an “off-line” manner. Our main contributions are twofold: (1) to the best of our knowledge, this paper is the first effort in the literature to investigate the performance enhancement of repacking and borrowing operations for MR networks (including IEEE 802.16j); (2) both analytic and simulation models are developed to validate against each other and to study the performance of RBRS. The analytic and simulation models are significantly different from the existing mobile network models owing to the introduction of RS and the consideration of the corresponding MR operations.

二、 研究方法

(1) System model

- IEEE 802.16j MR network architecture

The system we consider is the standard IEEE 802.16j MR network. Fig. 1(a) shows a typical IEEE 802.16j MR network, where a BS is located in the center and surrounded by several RSs. The BS coverage area is overlaid with these RS coverage areas. The BS and RSs are stationary while the MSs are moveable and randomly distributed within the network. An MS can issue the bandwidth request to its corresponding BS for establishing a connection through either a direct path (single-hop path) or a cooperative path (multihop path). Note that we only investigate single-hop direct paths and two-hop cooperative paths in this paper since it has been shown in [22,23] that the system throughput decreases as the number of hop counts increases.

- IEEE 802.16j frame structure

In standard IEEE 802.16jMR networks, the MAC protocol for data transmission is frame-based as illustrated in Fig. 1(b). Each frame is partitioned into a downlink (DL) subframe and an uplink (UL) subframe. To determine the bandwidth allocations, the BS performs the resource scheduling algorithm at the beginning of each frame. Since IEEE 802.16j MR networks adopt orthogonal frequency-division multiple access (OFDMA) as the physical-layer technology, the resource allocation unit of the subframes can be defined as a slot [20]. Each slot is composed of a subchannel in the frequency domain and several symbols in the time domain. The slots are allocated not only for BSs to transmit/receive data to/from RSs and MSs, but also for RSs to transmit/receive data to/from RSs and MSs. Slots are grouped into several bursts, each of which can adopt its own modulation and coding schemes.

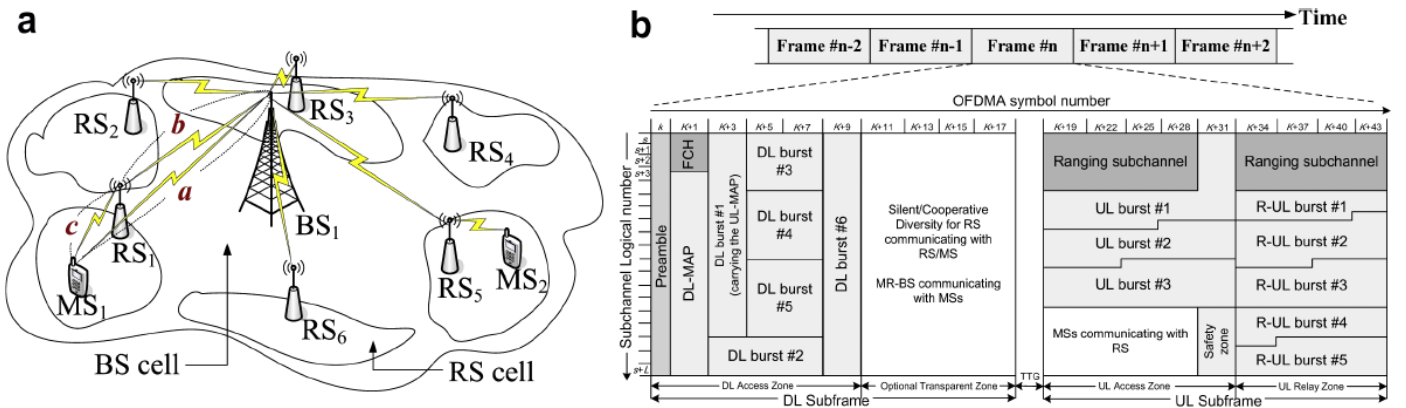


Fig. 1. (a) IEEE 802.16j MR network architecture. (b) IEEE 802.16j frame structure.

(2) The concept of the RBRS algorithm

To design an efficient resource scheduling algorithm in our considered system model, we take all the aforementioned potential factors into account. We propose a repacking and borrowing-based resource scheduling algorithm, RBRS, which can be implemented for both DL and UL resource scheduling scenarios. For the demonstration purpose, we only discuss the DL scenarios in the remaining sections. As shown in Fig. 2, RBRS is composed of four phases: pre-configuration phase, fixed-assignment phase, repacking phase and borrowing phase. At the system initialization, the pre-configuration phase determines the assignment of activation sets. Then, at the beginning of each frame, the scheduling procedure, including the fixed-assignment phase, repacking phase and borrowing phase, is executed. According to the pre-configured activation sets, the fixed-assignment phase allocates slots to each connection request in a simplest and fastest manner. If the fixed assignment phase cannot meet all the requirements of the connection attempts, the repacking and borrowing mechanisms will be employed in the following phases. In the repacking phase, a connection served via a high-cost direct path can be handed off to a low-cost cooperative path to enhance the slot utilization. In the borrowing phase, the over-loaded RS cells are capable of borrowing slots from the under-loaded RS cells, and thus the slot utilization can be further improved.

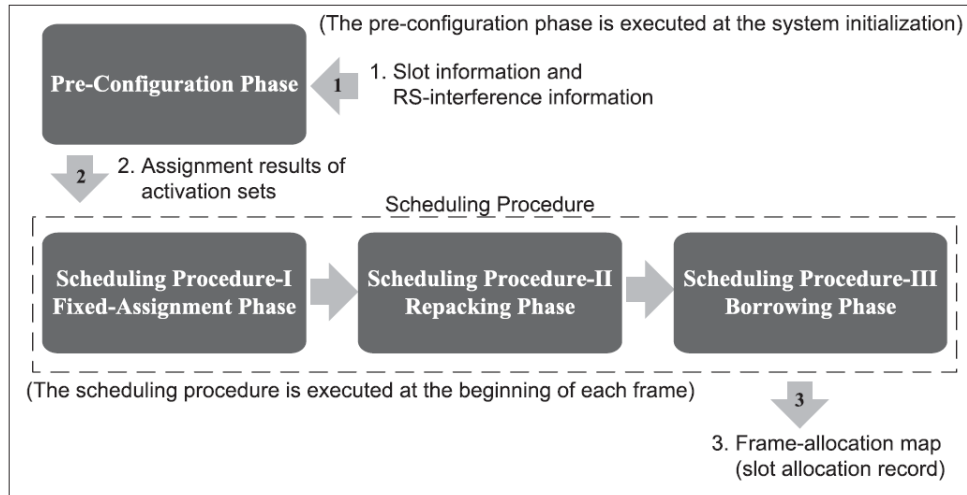


Fig. 2. The concept of the proposed RBRS algorithm.

● Pre-configuration phase

In the pre-configuration phase, we consider the effect of activation set assignment on slot utilization. We use Figs. 1 and 3 as examples. If RS1, RS3 and RS5 in Fig. 1(a) are classified into the same activation set while RS2, RS4 and RS6 are classified into another set, the pre-configuration procedure will allocate these two activation sets with the same amount of slots, as illustrated in Fig. 3(a). With different classifications, more activation sets may be used. As drawn in Fig. 3(b), if the RSs are classified into three activation sets, the slots would be allocated to the three sets. From this example, the importance of minimizing the number of activation sets is highlighted because the less the activation sets

exist, the more the slots can be allocated to each set.

We use Fig. 1(a) as the scenario to discuss how RBRS can properly determine the number of activation sets. For this scenario, the relationship of co-channel interference among the RS cells is assumed to be represented by the undirected graph $G(V,E)$ in Fig. 3(c). In G , the vertex set V represents the RS cells, and the edge set E represents the interference among them. Assume that to color the vertices of G , no two adjacent vertices can share the same color. Based on this rule, each set of the vertices that are assigned the same color is equivalent to an activation set, because the vertices with the same color are interference-free from each other. The problem of minimizing the number of activation sets can be thereby modeled as the minimum coloring problem of G . However, to color G with the minimum number of colors is known as an NP-hard problem. To guarantee the computation time, the well-known greedy coloring algorithm, the Welsh Powell algorithm [24], is used in this paper. In this algorithm, the vertices of higher degrees are assigned the colors with higher priorities. First, the vertices in G are sorted in descending order of vertex degree. Then, following this order, each vertex will be assigned a color that is different from its neighbors. Specifically, when determining the color of a vertex, the vertex will examine, color by color, whether the color is already used by its neighbors, until an unused color occurs. Finally, the Welsh Powell algorithm terminates when all the vertices in G are colored. This algorithm guarantees that the number of colors is at most one more than the maximum degree $D(G)$. That is, the Welsh Powell algorithm determines at most $D(G) + 1$ activation sets. Accordingly, given the co-channel interference graph (provided from the network operator), the Welsh Powell algorithm can appropriately assign each RS to an activation set.

It is worth to note that, because the interference information between RSs is usually static for the stationary RSs, our proposed RBRS only executes the coloring algorithm to determine the assignment of activation sets at the system initialization. Afterward, according to this pre-configured assignment, the scheduling procedure of RBRS is executed at the beginning of each frame. This is different from the majority of the conventional scheduling algorithms because the conventional algorithms usually formulate the scheduling problems as combinational-optimization problems of both the activation-set assignment and bandwidth allocation, which leads to a high-complexity scheduling procedure at each frame.

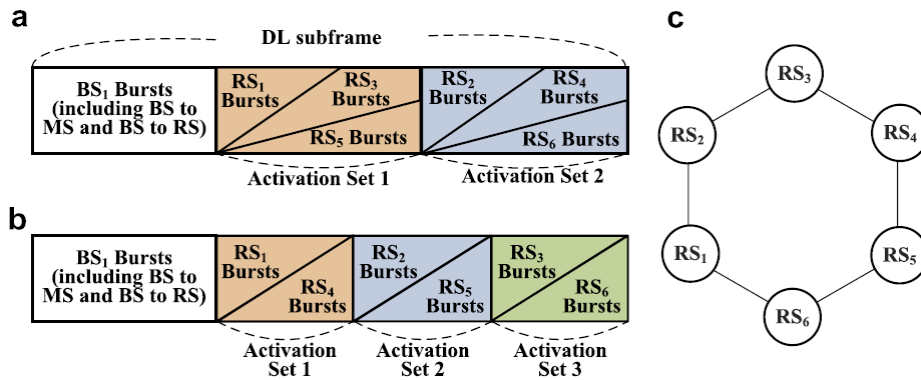


Fig. 3. The slot allocations in the pre-configuration phase and the interference graph of the RSs.

● Scheduling procedure-I: fixed-assignment phase

Algorithm 1: The Scheduling Procedure of RBRS

Input: $I_{BS}, I_{RS_m} \forall m$.

Output: Γ .

Initialization: $i \leftarrow 0$;

Procedure:

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1: while  $Q \neq \phi$  and  $(I_{BS} > 0 \text{ or } I_{RS_m} > 0 \exists m)$  do
2:    $i \leftarrow i + 1$ ;
3:   Pop a connection request  $R_i$  from  $Q$ ;
4:    $m \leftarrow R_i.RS$ ;
5:   if  $I_{BS} \geq R_i.C_{BS}$  and  $I_{RS_m} \geq R_i.C_{RS}$  then
6:      $I_{BS} \leftarrow I_{BS} - R_i.C_{BS}$ ;
7:      $I_{RS_m} \leftarrow I_{RS_m} - R_i.C_{RS}$ ;
8:      $R_i.status \leftarrow Accept_{Coop}$ ;
9:   else if  $I_{BS} \geq R_i.d_{BS}$  then
10:     $I_{BS} \leftarrow I_{BS} - R_i.d_{BS}$ ;
11:     $R_i.status \leftarrow Accept_{Dir}$ ;
12:   else
13:     $R_i.status \leftarrow Reject$ ;
14:   end if
15:   if  $R_i.status = Reject$  then
16:     $R_i.status \leftarrow Repacking(I_{BS}, I_{RS_m}, R_i)$ ;
17:   end if
18:   if  $R_i.status = Reject$  then
19:     $R_i.status \leftarrow Borrowing(I_{BS}, I_{RS_m}, R_i)$ ;
20:   end if
21:   if  $R_i.status = Reject$  then
22:    Block the connection request  $R_i$ ;
23:   else
24:     $\Gamma \leftarrow \Gamma \cup R_i$ ;
25:   end if
26: end while

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The operation of the scheduling procedure of RBRS is depicted in Algorithm 1 and the corresponding notations are listed in Table 1. At line 1, in the beginning of a frame, if the connection-request queue Q is non-empty and available idle slots exist within this frame, the procedure from line 2 to line 25 is repeated for each connection request that is stored in Q .

The procedure for the fixed-assignment phase is executed from line 5 to line 14. At line 5, for the i th connection request R_i , the corresponding current idle slots IBS and IRS_m are first examined as to whether they are sufficient to provide a cooperative service (via a cooperative path). If yes, R_i will be allocated adequate slots at lines 6 and 7 while R_i is accepted at line 8. Otherwise, IBS will be further examined as to whether it is adequate to provide a direct service (via a direct path) at line 9. If IBS is

sufficient, R_i is allocated slots and accepted at lines 10 and 11. Otherwise, R_i is rejected in the fixed-assignment phase at line 13.

In the case that the i th connection request R_i is rejected in the fixed-assignment phase, the repacking phase is executed at line 16. If the repacking phase still cannot provide a service for R_i , the borrowing phase is further employed at line 19. In the worst case, after all the three phases, the available slots are still insufficient, and R_i is thereby blocked at line 22. In the other cases, R_i will be served within this frame, and its slot allocation record is stored in Γ at line 24. When Algorithm 1 terminates, the frame-allocation map Γ of the current frame can thus be obtained.

Table 1

Notation list for the RBRS algorithm.

Notation	Description
$G(V,E)$	The undirected graph representing the relationship of co-channel interference among the RS cells
I_{BS}	Number of current idle slots in the BS
I_{RS_m}	Number of current idle slots in the m th RS
Q	The queue that buffers the connection requests during each frame
R_i	The i th connection request
$R_{i,RS}$	Indicates which RS cell R_i originates from
$R_i.status$	Indicates whether R_i is accepted or not
$R_i.d_{BS}$	Number of required BS slots for a direct service
$R_i.c_{BS}$	Number of required BS slots for a cooperative service
$R_i.c_{RS}$	Number of required RS slots for a cooperative service
T_k	The loading threshold indicating the traffic loading status of each BS cell or RS cell k
Γ	The frame-allocation map that contains the accepted connection requests $\{R_1, R_2, \dots, R_i, \dots\}$
W	Number of slots that are initially allocated to the BS
W_{RS_m}	Number of slots that are initially allocated to the m th RS
W_N	The total number of slots within a frame (i.e., $W_N = W + \sum W_{RS_m}$)

● Scheduling procedure-II: repacking phase

To improve the efficiency of the fixed-assignment phase while avoiding the computation complexity of the optimal and heuristic dynamic scheduling schemes, the slot repacking mechanism can be incorporated with the fixed-assignment phase. The concept of slot-repacking is described as follows. Consider that a connection i arrives at an RS cell m subordinated to a BS cell n . Assume that RS_m does not have sufficient slots to provide a cooperative service and thus connection i is served by BS_n via a direct path. If there are enough slots in RS_m later, connection i can be switched to RS_m again for cooperative transmission. This operation increases the number of idle slots in BS_n so that more slots of

BSn can be shared by its blocked RS cells. The above repacking action can be exercised at different time points. In always repacking (AR), a direct connection (if exists) in the BS cell is moved to the corresponding RS cell for a cooperative service whenever a cooperative connection is completed at that RS cell. On the other hand, in repacking on demand (RoD), repacking is performed only

Criterion 1: The connection j is served by BS1 through a direct path (see Fig. 4(a)).

Criterion 2: The connection j can be served by BS1 and the corresponding RS5 through a new cooperative path. Assume that the new path requires y and z slots of BS1 and RS5, respectively. If RS5 possesses f idle slots and connection j originally occupies x BS1 slots for direct communication (as depicted in Fig. 4(b)), this criterion indicates that f should be no less than z , and $x-y$ additional BS1 slots can be reclaimed (as illustrated in Fig. 4(c)).

The ongoing connection j that satisfies the above criteria can be selected (randomly or according to a specific policy) to exercise slot-repacking. After repacking, the ongoing connection (i.e., repacking candidate) is handed off from a direct path to a cooperative path. The reclaimed $x-y$ BS1 slots can be used to serve the connection attempt in RS1 for direct or cooperative transmission (see Fig. 4(d) and (e), respectively). The repacking operation is repeated until the connection attempt can be served or until no repacking candidate can be processed.

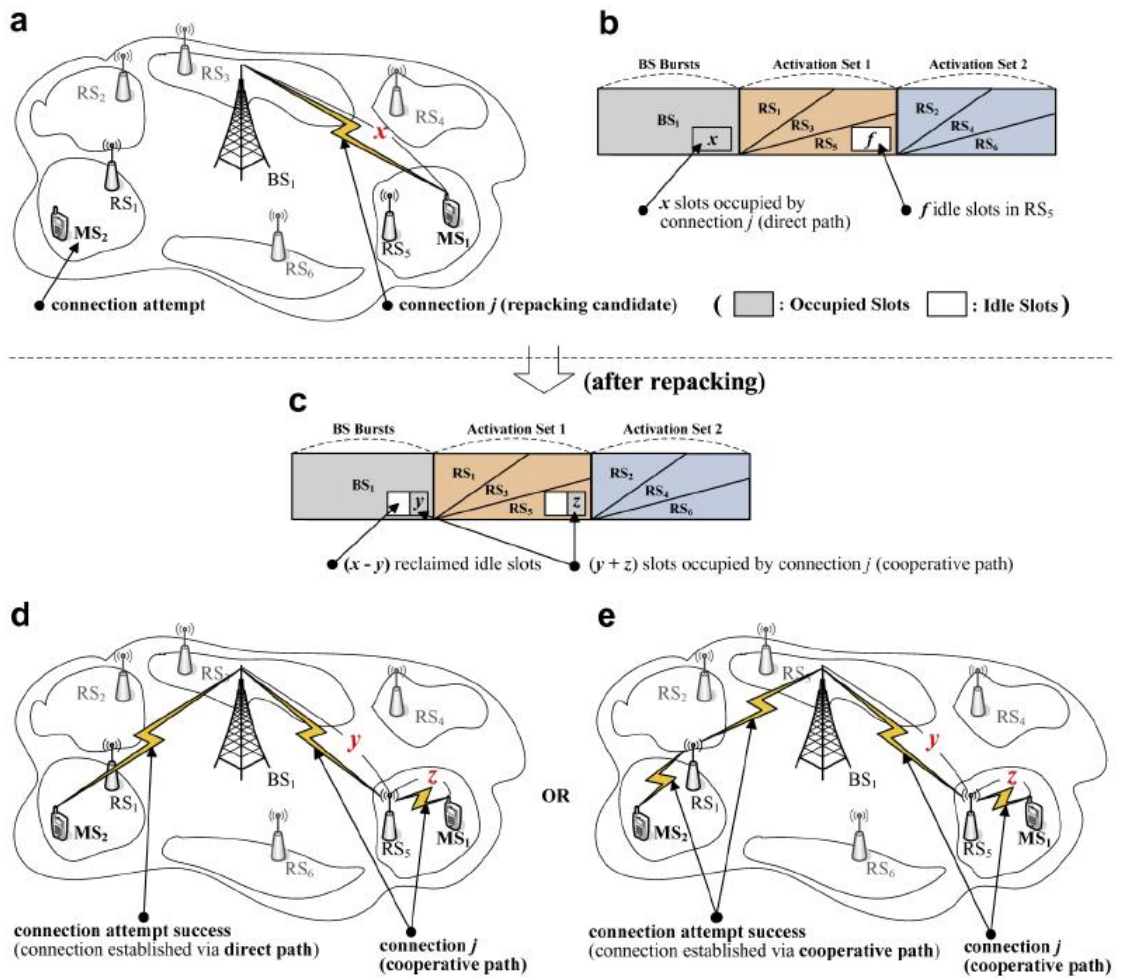


Fig. 4. The concept of slot-repacking for IEEE 802.16j MR networks.

● Scheduling procedure-III: borrowing phase

Although slot-repacking can improve the efficiency of slot allocation, the waste and starvation problems due to fixed slot assignment cannot be completely solved. The limitation of slot-repacking is that repacking candidates do not always exist. Consider the scenario in Fig. 5(a) for illustration. RS1, RS3 and RS5 possess several idle slots while the slots of all the other RSs are fully occupied. If no ongoing connections in RS1, RS3 and RS5 are served through direct paths, slot-repacking cannot be performed, and any connection attempt i at the blocked RS6 is rejected even though RS1, RS3 and RS5 have idle slots. To resolve this weakness of slot-repacking, the slot-borrowing mechanism can be incorporated for further enhancement of the utilization of scarce slot resources. Slot-borrowing allows a cell that suffers from slot starvation to borrow slots from another cell that possesses redundant idle slots. Note that although slot-borrowing can serve as a standalone scheduling scheme to dynamically allocate resources for IEEE 802.16j MR networks, it introduces extra scheduling complexity at the same time. In our proposed scheduling architecture, slot-borrowing is employed to complement the slot repacking mechanism. By integrating the merits of both mechanisms, we enhance the efficiency of slot utilization and simultaneously mitigate the computation complexity of scheduling operations.

Before slot-borrowing can be exercised, a loading threshold T_k should be defined first to indicate the traffic loading status of each BS cell or RS cell k . If the number of idle slots in cell k is less than T_k , cell k is classified as an over-loaded cell. Otherwise, cell k is an under-loaded cell. Note that these thresholds T_k s can be determined in a static or dynamic manner, depending on the system performance requirement of each individual cell. Then, based on T_k s, borrowing-candidate cells can be identified. A cell m is a borrowing candidate if it satisfies the following criterion:

Borrowing criterion: Cell m and all of its co-slot cells (e.g., RS3 and RS5 for RS1 in Fig. 5) are under-loaded. This criterion prevents a starving cell from borrowing slots from over-loaded cells where idle slots are already inadequate.

Each of the borrowing-candidate cells can be selected as a slot lender (randomly or following a pre-defined selection policy). Every chosen lender loans as many slots as it can to assist borrower cells to establish a (less slot-consuming) cooperative path for the connection attempt. Notice that the co-slot cells of the lender are prohibited to use the borrowed slots in order to avoid increased interference. This borrowing-lending procedure is repeated until the bandwidth requirement of the connection attempt is met or until no more borrowing candidates can be found.

During a slot-borrowing operation, according to whether the borrower or lender is a BS or an RS, the borrowing scenarios can be classified into three categories: (1) an RS borrows slots from a BS; (2) a BS borrows slots from an RS; (3) an RS borrows slots from another RS. These different borrowing scenarios merit further discussions as follows.

(1) An RS borrows slots from a BS: In Fig. 5(a), if connection attempt i occurs in RS6 when RS6 possesses no sufficient slots for providing a transmission service, RS6 may attempt to borrow slots from BS1. If BS1 can lend slots to RS6, BS1 must be under-loaded, i.e., the number of idle slots in BS1 is no

less than the loading threshold T . However, when BS1 is underloaded, connection attempt i should be able to be directly served by BS1 through a direct path unless connection attempt i 's slot requirement for direct transmission is extremely high compared to that for cooperative transmission, or the loading threshold T is extremely low such that even T slots are not adequate for direct transmission. Therefore, under reasonable system parameter configurations, RSs would never borrow slots from BSs.

(2) A BS borrows slots from an RS: As drawn in Fig. 5(c) and (d), BS1 borrows a slots from RS1 to serve connection attempt i in RS6. In this case, the number of BS1 slots is increased by a . However, the number of BS1 slots is never decreased since no RSs could borrow slots from BS1 (see the first borrowing scenario above). Therefore, when BS1 borrows slots from an RS, these borrowed slots should be returned later to prevent the number of BS1 slots from unilateral increment. In our slot-borrowing scheme, BS1 returns the borrowed a slots to RS1 when these slots are released from connection i .

(3) An RS borrows slots from another RS: As illustrated in Fig. 5(c) and (d), to serve connection attempt i in RS6, RS6 borrows b slots from RS1. In this case, slot returning is unnecessary since by dynamically borrowing/lending slots without returning, our scheduling algorithm could adapt to the real-time traffic condition. More specifically, over-loaded cells can be allocated with more slots while under-loaded cells can be allocated with fewer slots.

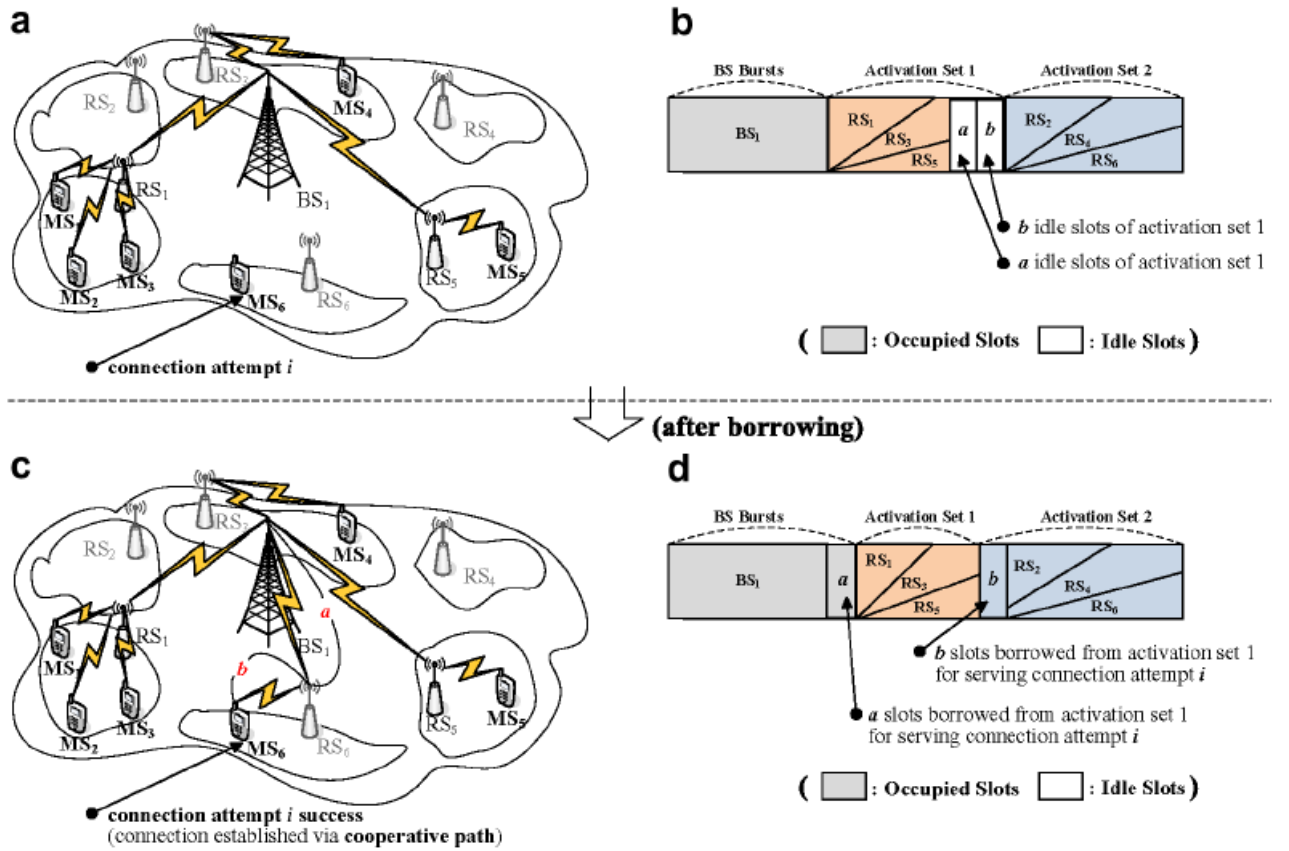


Fig. 5. The concept of slot-borrowing for IEEE 802.16j MR networks.

三、 結果與討論

(1) Analytic Results and Simulation Results

We have developed a discrete-event simulation model to validate against our analytic analysis. Following the simulation approach used in [32], the model simulates the connection traffic and mobility behaviors of MSs, and the scheduling details of RBRS. In the simulation experiments, we consider a 2-layer BS/RS cell layout (will be elaborated in the next section). To simulate only the repacking phase of RBRS, we set the loading threshold T_k as a significantly large value so as to deactivate the borrowing phase. Table 2 compares the analytic results with the simulation results in the stationary and mobile scenarios. The table indicates that the error rates between the analytic analysis and simulation are less than 0.07% in the stationary cases and 4.9% in the mobile cases. This concludes that both the analytic and simulation models are accurate.

Table 2. Comparison of the analytic and simulation results

stationary scenario ($1/\eta = 1.0 \times 10^{10}$ frames)						
$1/\lambda_o$ (unit: frame)	500	600	700	800	900	1000
P_{nc} (Analytic)	0.8066	0.7684	0.7306	0.6931	0.6561	0.6195
P_{nc} (Simulation)	0.8061	0.7682	0.7309	0.6933	0.6561	0.6191
Error	-0.0620%	-0.0260%	0.0411%	0.0289%	0.0000%	-0.0646%
mobile scenario ($1/\eta = 11000$ frames)						
$1/\lambda_o$ (unit: frame)	500	600	700	800	900	1000
P_{nc} (Analytic)	0.7809	0.7430	0.7063	0.6706	0.6358	0.6019
P_{nc} (Simulation)	0.8092	0.7726	0.7367	0.7018	0.6665	0.6311
Error	3.6240%	3.9838%	4.3041%	4.6525%	4.8286%	4.8513%

(2) Conclusions

To maintain the simplicity and low time complexity of FAS while guaranteeing high resource utilization, this paper proposed a repacking and borrowing-based resource scheduling algorithm, RBRS, for IEEE 802.16j MR networks. In the repacking phase, a connection that is served via a direct path can be handed off to a cooperative path to release a part of its allocated BS resources. To complement repacking and further enhance the performance of RBRS, borrowing is applied. In the borrowing phase, over-loaded RSs are capable of borrowing resources from under-loaded RSs, further improving the resource utilization. Both analytic and simulation models were developed to validate against each other and to study the performance of repacking and borrowing mechanisms.

Based on the validated simulation model, we first investigated the appropriate loading threshold T_k for the borrowing mechanism of RBRS to achieve the desired performance. Then, we studied the effects of traffic loading and user mobility on the P_{nc} , TP and CT performance. For the input parameter settings considered in this paper, our study further indicates the following. In comparison with FAS, RBRS accomplishes much higher capacity and throughput, while RBRS is at most 2.1 times slower than FAS. On the other hand, in

comparison with the state-of-the-art dynamic scheduling algorithm, the capacity and throughput of RBRS closely approximate those of ARRS, while RBRS is at least 8.91 and 9.96 times faster than ARRS in the symmetric and asymmetric environments, respectively. From these results, we conclude that repacking and borrowing mechanisms for multihop relay systems can effectively strike a balance between increasing the system capacity/throughput and decreasing the scheduling computation time.

四、 成果自評

1. 完成之工作項目
 - 設計 IEEE 802.16j 網路之時槽重新分配演算法
 - 設計 IEEE 802.16j 網路之時槽攜帶演算法
 - 設計 IEEE 802.16j 網路之頻寬管理分析模型
 - 設計 IEEE 802.16j 網路之頻寬管理模擬模型
2. 對於學術研究、國家發展及其他應用方面之貢獻
 - 本計畫的研究成果已被國際期刊[A1]接受
 - 提出數學分析模型以研究“合作式通訊網路之系統效能”
 - 提出電腦模擬模型以研究“合作式通訊網路之系統效能”
 - 這個計畫的結果可提供給工業界參考，我們很樂意將研發的技術技轉給工業界
3. 對於參與之工作人員，獲得以下訓練
 - 在研究的過程中瞭解並學習 Cooperative Communication Networks 的相關知識
 - 熟識 IEEE 802.16e、IEEE 802.16j 等相關業界標準
 - 學習“Discrete-Event System Simulation”之電腦模擬模型技巧

我們主要的貢獻可分為兩部分：(1)據我們所知，這項研究計畫是在文獻中第一個針對合作式多躍中繼網路(包含 IEEE 802.16j 網路)進行頻寬重新分配機制 (Bandwidth Repacking) 和頻寬攜帶機制 (Bandwidth Borrowing) 之效能分析的研究。(2)我們設計了數學分析模型與程式模擬模型，兩者之間可相互驗證，並幫助我們研究時槽重新分配演算法與時槽攜帶演算法之效能。由於合作式中繼站(Relay Station)的採用和多躍中繼網路運作的考量，使得我們所提出的數學分析模型與程式模擬模型有別於現有的非合作式行動網路模型。除此之外，我們的研究成果也已經發表於國際知名期刊[A1]。

Appendix:

[A1] Chien-Chi Kao, Shun-Ren Yang, and Tung-Lin Tsai, “Performance Enhancement of Repacking and Borrowing Mechanisms for IEEE 802.16j Multihop Resource Scheduling,” Accepted for Publication in *Elsevier Computer Networks*.

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