

A Dynamic Load Balancing Scheme for VoIP over WLANs

SHIAO-LI TSAO AND CHIH-CHIEN HSU

*Department of Computer Science
National Chiao Tung University
Hsinchu, 300 Taiwan*

Coverage areas of WLAN access points (APs) are usually overlapped so a WLAN station (STA) might be able to find several APs to attach in a WLAN hotspot. Experimental results indicate that a WLAN STA normally associates with an AP with the maximal signal strength and requests the bandwidth of the AP for establishing network connections. However, this kind of STA-centric association and bandwidth request policy may introduce unbalance loads of APs, and the bandwidths of APs in a WLAN hotspot cannot be fully utilized. This unbalance load problem is a critical issue for the commercial deployment of voice over IP (VoIP) over WLAN (VoWLAN) service which has to maximize the number of concurrent VoWLAN sessions with Quality of Service (QoS) guarantees. In this paper, a novel dynamic load balancing scheme is proposed for a VoWLAN system. The network-assisted association policy first advises an STA to request a VoWLAN session through an AP with the minimal load. In case of the APs which the STA can attach are all overloaded, the proposed load balancing scheme further rearranges the serving VoWLAN STAs between APs in order to spare enough resources for accommodating that new request. Simulation results demonstrate that the reject rate of service requests for a VoWLAN system can be considerably reduced by employing the proposed scheme.

Keywords: voice over IP (VoIP), VoIP over WLAN (VoWLAN), radio resource management, load balancing, WLAN

1. INTRODUCTION

The technology development and network deployment of WLANs have grown rapidly in recent several years, and WLAN has become one of the most popular access technologies for mobile Internet services. Among all mobile Internet services and applications, voice over IP (VoIP) over WLAN (VoWLAN) has attracted considerable interest from both academia and industry and is regarded as one of the killer applications for both public and enterprise WLANs [1]. However, VoWLAN applications generate a large amount of small voice packets which degrade the WLAN utilization due to the nature of WLAN medium access control (MAC) mechanism [2], and the service capacity of a WLAN access point (AP) for VoWLAN services, *i.e.* the number of concurrent VoIP sessions that a WLAN AP can support, is very limited [3]. To increase the number of VoWLAN sessions that an AP can serve and to maximize the resource utilizations of APs in a WLAN hotspot are both challenging issues for the commercial deployment of VoWLAN services.

Previous studies have worked on improving the utilization of a single AP for VoWLAN services [4], and have proposed several radio resource management schemes

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for WLANs [5-7]. Considering a WLAN hotspot with multiple APs whose coverage areas are overlapped, the AP association policies for STAs become important since a WLAN STA might be able to find several APs to attach. Conventional AP association policies are usually implemented on STAs and suggest STAs to select and request bandwidth of an AP with the maximal signal strength. However, this STA-centric network association and service request policy may introduce unbalance loads on APs, and the utilizations of APs in a hotspot cannot be maximized [8-10]. To improve the overall utilization of APs in a WLAN hotspot, several approaches have been proposed. These approaches can be classified into three categories. The first category is the AP channel assignment schemes which efficiently assign available channels to the APs to avoid interference. For example, Papanikos and Logothetis [11] suggest APs to exchange the information of their operational channels. A new start-up AP can use this information to decide its camped channel so that the interference from the neighbor APs can be minimized. Another category is called cell breathing presented by Brickley *et al.* [12]. The approach reduces the transmission power of an overloaded AP. Therefore, the coverage area of the AP is shrunken, and the STAs which originally attach to the AP may lose the connection and are enforced to handoff. The third category is the STA association management. These approaches in this category determine the association relationships between STAs and APs to optimize the overall utilization of APs in a hotspot. A number of studies suggest APs to broadcast the additional information such as the number of STAs associated with APs, the average received strength of the STAs, packet error rate etc in beacon or probe response frames [11, 13-15]. STAs thus can use the information to choose the most suitable AP to associate. For instance, Velayos *et al.* [16] differentiate APs to three load levels, *i.e.* underloaded, balanced or overloaded, by comparing their load with the average load of APs. Then, each AP performs admission control based on its load level. If an STA is denied by an AP, the STA is then re-directed to a neighbor AP which is underloaded. Thus, STAs can associate with the underloaded AP such that the overall utilization of APs in a WLAN hotspot is improved. Bejerano *et al.* [17] further consider the fairness between STAs which are contending the bandwidths of APs in a hotspot. They apply the max-min fairness scheme to manage the bandwidth assignment of APs to STAs in a hotspot. Unfortunately, they assume STAs are requesting best effort services and contending WLAN channels with peer STAs. They do not consider the QoS requests. To allocate WLAN resources for QoS sessions such as VoWLAN service, Balachandran *et al.* [18] present a network-assisted mechanism. In this scheme, a centralized server in the backbone network collects the load information of APs and an STA sends a request to the server before establishing a QoS connection. The server performs the admission control and finds a suitable AP for the STA. If more than one AP is found, the AP with the minimal load is recommended. This scheme only statically assigns STAs to APs while the STAs initially request QoS services, but does not consider the dynamical rearrangement of AP loads to optimize the overall utilization.

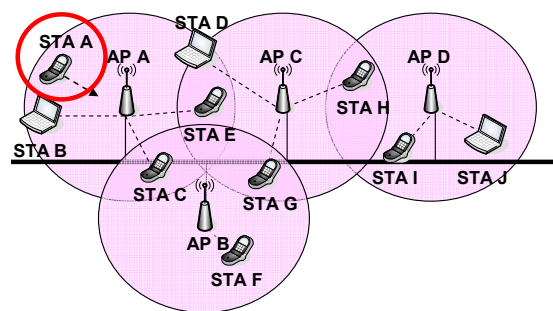
In this work, a novel dynamic load balancing scheme is proposed for a VoWLAN system which offers guaranteed QoS services. The network-assisted mechanism first advises an STA to associate with an AP with the maximal available resources. In case of the APs that the STA can attach are all overloaded, the proposed load balancing scheme is activated to adjust the loads between APs in order to accommodate that new VoWLAN request. The rest of the paper is organized as follows. The concept and procedures of the

proposed dynamic load balancing scheme for a VoWLAN system are presented in section 2. Simulation results are discussed in section 3, and finally section 4 concludes this work.

2. DYNAMIC LOAD BALANCING SCHEME

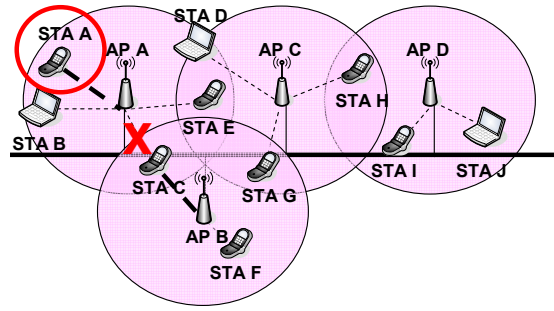
2.1 Dynamic Load Balancing Example

An STA, say STA A, is able to associate with a WLAN AP, say AP A, only. While AP A is overloaded, the STA A cannot obtain enough resources from AP A and the service request from STA A is thus rejected by AP A. Considering AP A is currently serving another STA, say STA B, and STA B can find and associate with another AP, say AP B, which is under-loaded. STA B can change its serving AP from AP A to AP B, and then the resources occupied by STA B on AP A can be released. Therefore, the resources on AP A now become available to serve the new STA A. The load adjustment procedure can be done between two APs, and it can be also applied to a chain of multiple APs. Fig. 1 (a) shows an example where circles represent the coverage areas of APs and the adjoined APs occupy different WLAN channels. In this example, each AP is assumed to support at most three VoIP sessions. STAs B, C, D, E, F, G, H, I and J associate with APs A, A, C, A, B, C, C, D and D respectively. While STA A that can only associate with AP A attaches to the network and requests VoWLAN services, AP A which is overloaded cannot provide the service. A dynamic load balancing scheme is thus applied to the situation. The scheme changes the serving AP of STA C from AP A to AP B, and then the resources on AP A become available to be allocated to STA A. Therefore, the service request from STA A can be accepted by AP A. Fig. 1 (b) illustrates the example shown in Fig. 1 (a) after applying the proposed dynamic load balancing scheme. Fig. 1 (c) shows another example that a dynamic load adjustment can be applied to a chain of multiple APs. While STA A requests a VoIP session to AP A, and AP A is overloaded. STA H can change its AP from AP C which is also overloaded to AP D which is under-loaded. AP C has available resources to serve new requests, and then STA E can change its serving AP from AP A to AP C. Therefore, the resources on AP A become available to be allocated to STA A.

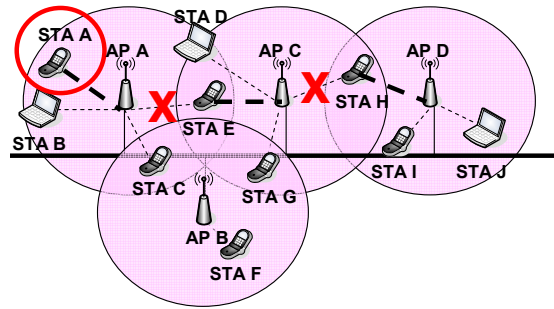


(a) Before load adjustment, STA A cannot obtain the resources.

Fig. 1. Dynamic load balancing examples.



(b) After migrating STA C from AP A to AP B, STA A can obtain the resources.



(c) After migrating STA H from AP C to AP D, STA E from AP A to AP C, STA A can obtain the resources.

Fig. 1. (Cont'd) Dynamic load balancing examples.

2.2 Modeling the Relationships Between APs and STAs

Before the dynamic load balancing scheme is presented, the relationships between STAs and APs in a WLAN hotspot are first modeled. A WLAN hotspot totally contains N WLAN APs, and all APs in the hotspot are assumed identical. The current resource utilization of i^{th} AP, say A_i , is denoted as C_i which is a value between 0 and 1. C_i is defined as the percentage of transmission time occupied by all serving STAs over the total operation time of A_i . Therefore, $C_i = 1$ implies all resources on A_i are occupied by the STAs and there is no resource available to serve any new service. The j^{th} STA, denoted as S_j , associates with a WLAN AP, say A_i , at R_{ij} speed in Kbps. For example, the IEEE 802.11b offers 1 Mbps, 2 Mbps, 5 Mbps, and 11 Mbps speeds for STAs, and the association speed which is determined by the modulation and coding scheme between an AP and an STA depends on the distance and channel quality between them. Assume that an STA requests a VoWLAN session at r Kbps, and then the AP has to allocate r/R_{ij} resources for the VoWLAN session if A_i admits S_j . Here, r is the total bandwidth consumed by the STA, and it can be derived from the factors such as voice data payload, MAC headers, MAC overheads and physical layer overheads. The length of the voice payload is determined by the voice codec. The MAC overheads may include RTS/CTS frames, retransmission and contention overheads. The physical layer overheads are inter-frame

spaces and preambles. The above equations use a simple model to evaluate the resource consumed by an STA which associates with an AP at R_{ij} Kbps and requests r Kbps for its VoIP session. To precisely calculate the resources occupied by an STA for the AP, studies have proposed a number of models. For example, IEEE 802.11e [19] suggests a resource consumption model while performing the call admission control for hybrid coordination function (HCF) controlled channel access (HCCA) mechanism. In this mechanism, an STA, say S_j , must send a request message (ADDTS) to its serving AP, say A_i , for establishing a VoIP session. The request message contains a traffic specification (TSPEC) which describes the traffic characteristics and the QoS requirements of the VoIP session. After the serving AP receives the request, it evaluates its available resources and decides to accept this request or not. If the request is accepted, the AP replies the STA with a transmission opportunity (TXOP) duration among a scheduled service interval (SI). In other words, if the new request is admitted, the AP has to allocate $\frac{TXOP}{SI}$ resources to that new request. Different from the simple resource model described above, IEEE 802.11e [19] provides more accurate resource models to calculate TXOP. More precise and accurate resource models and admission control schemes can be incorporated with and applied to the proposal dynamic load balance approach. Without loss of generality, the simple model is used to present the basic idea behind the proposed load adjustment scheme.

Besides the resource models, the relationships between APs and STAs are also defined. While an STA, say S_j , performs WLAN channel scan and finds an AP, say A_i , S_j then inserts A_i into the candidate list. Here, $n_{i,j}$ defines the coverage relationships between APs and STAs as:

$$n_{i,j} = \begin{cases} 1, & \text{if } A_i \text{ is in } S_j' \text{ candidate list.} \\ 0, & \text{otherwise.} \end{cases}$$

After scan procedures, S_j decides to associate with A_i , and requests a VoWLAN service, $m_{i,j}$ defines the serving relationships between APs and STAs as:

$$m_{i,j} = \begin{cases} 1, & n_{i,j} = 1 \text{ and } A_i \text{ is serving } S_j. \\ 0, & \text{otherwise.} \end{cases}$$

For example, for STA E in Fig. 1 (a), $n_{A,E} = 1$, $n_{C,E} = 1$ and $m_{A,E} = 1$, $m_{C,E} = 0$.

2.3 Dynamic Load Adjustment

To achieve a better network utilization, a network-assisted policy assigns the AP with the minimal load to serve a new VoWLAN STA. That is, a new VoWLAN STA, say S_j , is asked to associate with A_i that is in S_j 's candidate list, *i.e.* $n_{i,j} = 1$, and A_i has the maximal available resources after serving S_j , *i.e.* A_i with the minimal $C_i + r/R_{ij}$. If the serving AP of a VoWLAN STA does not have enough resources, the traditional network-assisted approaches reject this VoWLAN request. In our design, the second step procedure, *i.e.* the dynamic load balancing procedure, is activated to adjust loads between APs to accommodate that new request. A direct graph is newly proposed in this paper to rep-

represent the current loads and the relationships between APs and STAs. The directed graph, called resource-allocation graph G , illustrates the resource-allocated status between APs and STAs. Vertices V in graph G could be STAs or APs. An edge E denotes the relationship between vertices. An edge only appears between one AP and one STA, but does not exist between two APs or two STAs. An edge from A_i to S_j denotes as (A_i, S_j) means AP A_i is serving STA S_j , called an assignment edge. An STA can be only served by one AP and an edge represents all connections between the STA and the serving AP. That is $n_{ij} = 1$ and $m_{ij} = 1$. If there is an edge from S_j to A_i , denoted as (S_j, A_i) , implies A_i is in S_j 's candidate list but A_i is not serving S_j , called a claim edge. In other words, $n_{ij} = 1$ and $m_{ij} = 0$. Fig. 2 shows an example of the resource-allocation graph for Fig. 1 (a). The relationship between APs and STAs can be easily obtained from the resource-allocation graph, and the dynamic load balancing scheme can use the graph to determine the load adjustments between APs.

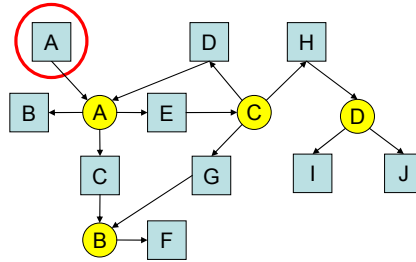


Fig. 2. The resource-allocation graph of Fig. 1 (a).

It can be seen from Fig. 2 that STA A can be only served by AP A but unfortunately AP A is overloaded. The next step of the load balancing procedure is to find a directed path without an STA visited twice in the resource-allocation graph from STA A to any other AP with available resources. A feasible path P in G for S_j is defined as $\{(S_j, A_i), (A_i, S_j'), (S_j', A_i'), \dots, (S_j^{(n)}, A_i^{(n)})\}$. In this path, A_i to $A_i^{(n-1)}$ could be overloaded and only $A_i^{(n)}$ must be under-loaded and can serve $S_j^{(n)}$. A path represents a list of load adjustment operations. For example, S_j' can change its current serving AP from A_i to A_i' , and then A_i has available resources to serve S_j . Before the migration of S_j' , S_j'' can change its serving AP from A_i' to A_i'' . Since $A_i^{(n)}$ is under-loaded, STAs S_j' to $S_j^{(n)}$ can perform migrations for the old serving APs to the new serving APs. Therefore, the new STA S_j can be admitted and served by A_i . It is important to note that for an STA which has existing connections with another AP, the STA handoffs all existing connections to the new AP. A VoWLAN request might have multiple feasible paths, *i.e.* $\{(STA A, AP A), (AP A, STA C), (STA C, AP B)\}$ and $\{(STA A, AP A), (AP A, STA E), (STA E, AP C), (AP C, STA H), (STA H, AP D)\}$. If more than one path is found, the shortest path which implies the minimal migration overheads is selected. Once the path is decided, the direction of edges of the path should be reversed. That is, assignment edges become claim edges and claim edges become assignment edges. Fig. 3 illustrates the resource-allocation graph of Fig. 1 (c) after the load adjustment is performed. While STA A cannot get the resources from AP A, the dynamic load balancing mechanism is to find a load adjustment path P from STA A to

AP D: {(STA A, AP A), (AP A, STA E), (STA E, AP C), (AP C, STA H), (STA H, AP D)}. Then, the directions of the edges in the path should be reversed. Fig. 4 illustrates the flow chart for the admission control and the procedures for the proposed dynamic load balancing scheme. The blocks with different colors illustrate the procedures that the STA and APs should perform. Fig. 5 shows the algorithm for the admission control and dynamic load balance scheme.

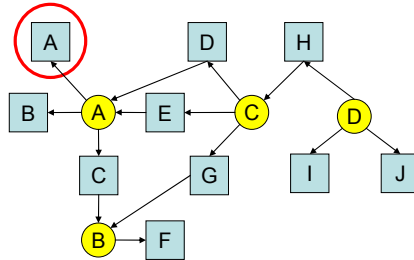


Fig. 3. The resource-allocation graph of Fig. 2 after performing load adjustments.

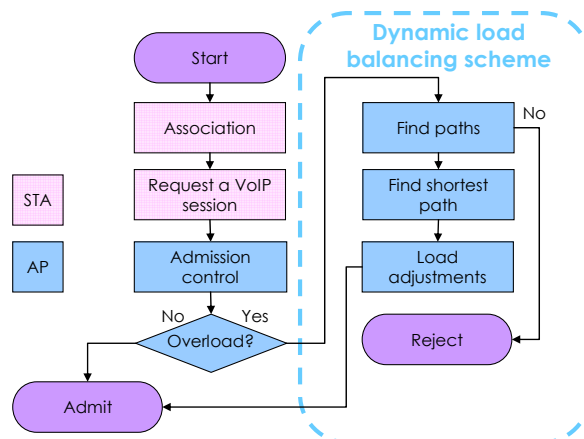


Fig. 4. The proposed admission control and the dynamic load balancing scheme.

To implement the proposed dynamic load balancing scheme, one possible approach is to setup a centralized server for admitting service requests and initiating the load adjustments between APs. A distributed approach which exchanges the load conditions of APs and performs the load adjustments is also possible. These load information of APs and the control messages for performing load adjustments between APs are exchanged over the backbone network. To implement the STA migration between APs, IEEE 802.11f [20] which can transfer the context of an STA between APs, IEEE 802.11k [21] which advises an STA to attach to a specific AP, and IEEE 802.11r [22] which assists APs and STAs to perform seamless handovers can be utilized. The proposed approach can be implemented in WLAN hotspots by integrating the current IEEE 802.11 standards and draft standards.

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CP: set of feasible paths
P: a feasible path
SP: the shortest feasible path
V: set of vertices have been visited

Admission Control(Sj)
{ if (Overload(Sj) = false)
  { if ((CP = Find Path(Sj, Ri,j)) = true)
    { SP = Find Shortest Path(CP); // return the shortest path
      Load Adjustment(SP); // reverse the directions of the edges in the path
    }
    else // can not find any feasible path
      Reject the request;
  }
  else // APs with available resources found
    Accept the request;
}

Overload(Sj) // checks if all APs that STA can find are overloaded
{ min_C = 1;
  for i where ni,j = 1 // calculate resources
    { if Ci + r/Ri,j <= 1 and Ci + r/Ri,j < min_C
      min_C = Ci + r/Ri,j and min_A = i
    }
  if min_C = 1
    return false // all APs the STA can hear are overloaded
  else
    return min_A // return AP with the minimal load
}

Find Path(Sj, Ri,j) // depth first traversal
{ Add Sj to V;
  for i where ni,j = 1 and mi,j = 0 AND Ai ∉ V
    { Add Ai to V;
      Add (Sj, Ai) to P;
      // Search for STA Sk from the graph where mi,k = 1
      if (Ci + r/Ri,j <= 1)
        Add P to CP; // path is found
      else if (Sk ∉ V and Ci + r/Ri,j - r/Ri,k <= 1) {
        { Add (Ai, Sk) to P;
          Find Path(Sk, Ri,k);
          Delete (Ai, Sk) from P;
        }
      }
      Delete Ai from V;
      Delete (Sj, Ai) from P;
    }
  Delete Sj from V;
}

```

Fig. 5. The admission control and proposed dynamic load balancing scheme.

3. SIMULATION RESULTS AND ANALYSIS

Simulations are conducted to evaluate the performance by applying the conventional STA-centric approach, the network-assisted approach and the proposed dynamic load balancing scheme. For the conventional STA-centric approach, an STA always sends its request to the AP with the maximal signal strength. If the AP cannot accept this request, the request is rejected. For the network-assisted approach, the AP actively broadcasts the loads of APs, and advises the STA to request its QoS session to the APs with the minimal load. If all APs that the STA can attach are fully occupied, the service request is rejected. For the proposed dynamic load balancing scheme, an STA first sends its request to the AP with the minimal load. If the request is rejected, the dynamic load balancing scheme is activated to find a feasible load adjustment in order to accommodate the new request. If there is no load adjustment can be performed, the service request is rejected. The reject rate of the new service requests and the overhead which is introduced by employing the proposed method are both investigated. The reject rate of the new service requests is the percentage of new requests which are rejected by APs. The overhead here is defined as the numbers of STAs which are forced to change their serving APs in order to accommodate new requests.

In a simulation, a deployment scenario of a WLAN hotspot is first generated. A deployment scenario means a particular number of WLAN APs which are randomly deployed in a fixed-size hotspot. To simplify the simulations, an AP only offers one association speed, *i.e.* 11Mbps, within the coverage area of an AP, which is a 30-meter-radius range. A WLAN hotspot is a 300 meters by 300 meters square area. In our simulations, three different network densities D which are $D = 1.5$, $D = 3.0$ and $D = 6.0$ of WLAN hotspots are considered. The network density D here is defined as the average number of APs that an STA can detect at any location of a WLAN hotspot. For example, IEEE 802.11b/g has three non-overlapped channels, and operators may install IEEE 802.11b/g APs in a hotspot where STAs can hear APs in the three non-overlapped channels, *i.e.*, Channel 1, Channel 6 and Channel 11. In such a deployment, the network density D could be approximately three. For IEEE 802.11a, there are twelve non-overlapped channels, the network density D could be twelve. If a WLAN hotspot installs both IEEE 802.11b/g and IEEE 802.11a APs, the network density D could be up to 15.

After a deployment scenario of a WLAN hotspot is settled, STAs that appear at random locations within a WLAN hotspot and send service requests to APs for establishing QoS connections are generated. An STA requests only one G.711 VoIP session which consumes 80Kbps downlink and 80Kbps uplink bandwidth of a WLAN AP. The length of a VoIP session is randomly generated between one to 30 minutes, and the call occupies the resources for the entire VoIP session. The arrival of the service requests is assumed a Poisson process. Different arrival rates of the service requests are generated in order to simulate different loads of APs in the hotspot. The QoSs of service requests from STAs are all identical. Therefore, each AP can support up to eight VoIP sessions concurrently. All simulations are based on the average results which are collected from a total of 100 randomly deployed scenarios of WLAN hotspots.

First, the percentage of service requests which are rejected by APs are evaluated under different loads of APs in a WLAN hotspot and different network densities. Fig. 6 shows the reject rate of the service requests under different loads of WLAN APs and

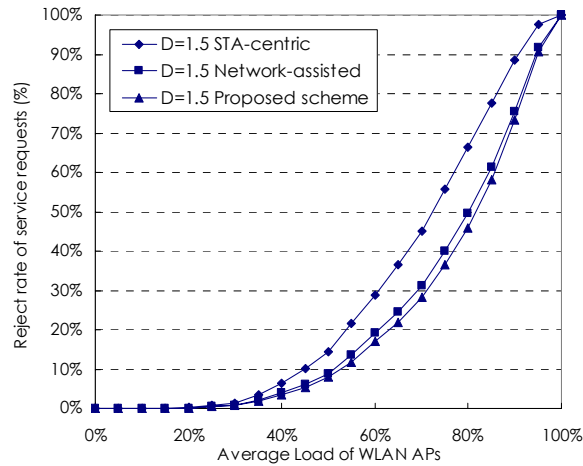


Fig. 6. Reject rate of service requests which are rejected under different load conditions and a WLAN hotspot with $D = 1.5$.

$D = 1.5$. It can be learned from the figure while the loads of APs are low, *e.g.* less than 30%, the reject rates of a system by applying the three approaches are similar and all service requests can be accepted. When the system load increases, the network-assisted approach and the proposed approach can reduce the reject rate of the service requests. Although, the network-assisted approach and the proposed approach both reduce the reject rate of the service requests, the improvements are marginal. That is because in these deployment scenarios with $D = 1.5$, an STA can detect only one or two APs. It is very difficult for STAs to find many alternative APs to attach. The reject rate of the service requests cannot be improved too much by applying the network-assisted approach. Moreover, the proposed approach has to find STAs which can attach to more than one AP and then the algorithm can find load rearrangements between APs. Without enough network densities, the benefit that the proposed approach can gain is very limited. Thus, we change the network density from $D = 1.5$ to $D = 3.0$. Fig. 7 shows the simulation results. It can be seen from the figure that both the network-assisted approach and the proposed approach reduce the reject rates of the service requests. The performance is significantly improved while the system is heavily loaded, *i.e.* 60% to 90%. For the network assisted approach, to select an AP with the minimal load can reduce the service reject rate. The proposed scheme further achieves lower service reject rates than that of the network-assisted approach by rearranging the loads between APs. Simulation results show that 10% improvement compared to the network-assisted approach can be achieved by employing the proposed scheme under the system load is 80%. For STAs can find more APs to attach, the proposed scheme can find more feasible load adjustment paths so that more new service requests can be accommodated when the system load is heavy. If the network density increases to six, the proposed method can further reduce the reject rate of the service requests than the network-assisted approach by 30% under the system load is 90%. Fig. 8 illustrates the simulation results. We can conclude that for the hotspots with high network densities and heavy loads, *i.e.* 60% to 90%, the proposed mechanism significantly minimizes the reject rate of the service requests.

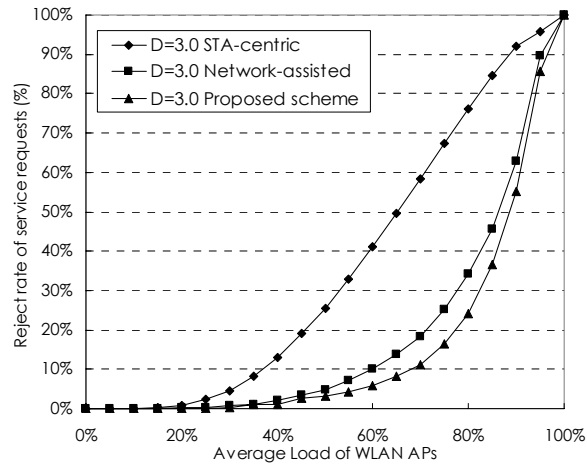


Fig. 7. Reject rate of service requests which are rejected under different load conditions and a WLAN hotspot with $D = 3.0$.

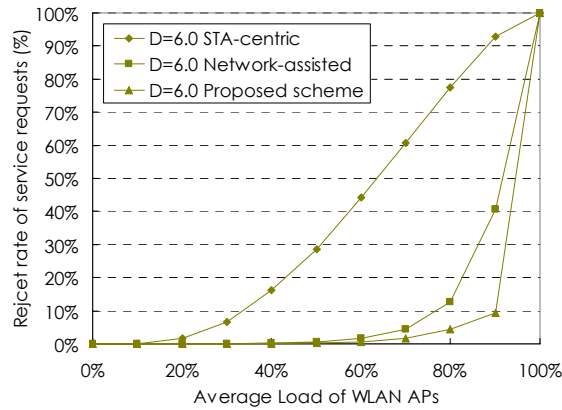


Fig. 8. Reject rate of service requests which are rejected under different load conditions and a WLAN hotspot with $D = 6.0$.

Then, the overhead by employing the proposed scheme is evaluated. Fig. 9 demonstrates the overheads of the proposed scheme in terms of roamed STAs under different network densities. The number of roamed STAs means that the number of existing STAs which have to roam from one AP to another AP in order to accommodate the new requests. It can be seen from Fig. 9 that the numbers of roamed STAs increase while the network density and workload increase. This is because the proposed method is especially useful while network load and density are both high. For the system is almost fully loaded, *i.e.* more than 90%, the proposed method can not improve anymore since all requests are rejected. Simulation results demonstrate when the system load is 60% to 90%, only 1.5 to 2.5 STAs are influenced for accommodating a new request under $D = 3.0$, and only 2.5 to 4 STAs have to roam from their current APs to other APs under $D = 6.0$.

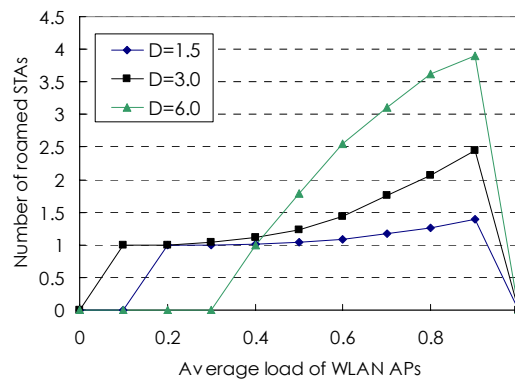


Fig. 9. The overheads by employing the proposed scheme for a WLAN hotspot with $D = 1.5, 3.0$ and 6.0 .

4. CONCLUSIONS

In this study, a novel dynamic load balancing scheme was proposed for a VoWLAN system. The network-assisted policy balances the loads of APs, and the dynamic load balancing scheme further reduces service reject rates when the system is heavily loaded. The proposed scheme rearranges the serving STAs between APs in a WLAN hotspot in order to accommodate the service requests. Simulation results demonstrate that the proposed approach can reduce the service reject rate of the conventional STA-centric approach by 20% to 54% under different load conditions. Comparing with the network-assisted approach, the proposal scheme further reduces 10% and 30% service reject rates while the loads of a WLAN hotspot are 80% and 90% and the network densities are 3.0 and 6.0, respectively.

The proposed scheme not only can be used in a VoWLAN system, but also can be applied to a heterogeneous wireless overlay network. In a heterogeneous wireless overlay network, the coverage areas of base stations of heterogeneous wireless systems may overlap, and the network density of a heterogeneous wireless overlay network becomes higher than that of a single WLAN system. Considering that the proposed scheme can achieve a better performance for a WLAN hotspot with high WLAN densities, the proposed scheme is also an efficient approach in managing radio resources of a heterogeneous wireless overlay network.

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Shiao-Li Tsao (曹孝傑) received B.S., M.S., and Ph.D. degrees in Engineering Science from National Cheng Kung University, Taiwan, in 1995, 1996 and 1999, respectively. His research interests include mobile communication and wireless network, embedded software and system, and multimedia system. From 1996 to 1997, he was a research assistant of Institute of Information Science, Academia Sinica. He visited Bell Labs, Lucent technologies, NJ, USA, in the summer of 1998. From 1999 to 2003, Dr. Tsao joined Computers and Communications Research Labs (CCL) of Industrial Technology Research Institute (ITRI) as a researcher and a section manager. Dr. Tsao is currently an assistant professor of Computer Science of National Chiao Tung University. Prof. Tsao has published more than 60 international journal and conference papers, and has held or applied 16 US, 3 Germany, 17 R.O.C. patents. Prof. Tsao received the Research Achievement Awards of ITRI in 2000 and 2004, the Outstanding Project Award of Ministry of Economic Affairs (MOEA) of R.O.C. in 2003, the Advanced Technologies Award of MOEA of R.O.C. in 2003, and the Research Paper Award of ITRI in 2002. He also received the Teaching Award of National Chiao Tung University and Young Researchers Award of Pan Wen-Yuan Foundation in 2007. He is a member of IEEE and IEEE ComSoc.



Chih-Chien Hsu (徐誌謙) received the double B.S. degrees in Management Science and Computer Science and Information Engineering from National Chiao Tung University of Taiwan in 2005, and M.S. degree in Computer Science from the same university in 2007. His research interests include wireless networks and mobile communications, embedded software and system on chip. He is currently a Ph.D. student of Computer Science of National Chiao Tung University.