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Traffic Agents for Improving QoS in Mixed Infrastructure and Ad Hoc Modes Wireless LAN

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As an important complement to infrastructured wireless networks, mobile ad hoc networks (MANET) are more flexible in providing wireless access services, but more difficult in meeting different quality of service (QoS) requirements for mobile customers. Both infrastructure and ad hoc network structures are supported in wireless local area networks (WLAN), which can offer high data-rate wireless multimedia services to the mobile stations (MSs) in a limited geographical area. For those out-of-coverage MSs, how to effectively connect them to the access point (AP) and provide QoS support is a challenging issue. By mixing the infrastructure and the ad hoc modes in WLAN, we propose in this paper a new coverage improvement scheme that can identify suitable idle MSs in good service zones as traffic agents (TAs) to relay traffic from those out-of-coverage MSs to the AP. The service coverage area of WLAN is then expanded. The QoS requirements (e.g., bandwidth) of those MSs are considered in the selection process of corresponding TAs. Mathematical analysis, verified by computer simulations, shows that the proposed TA scheme can effectively reduce blocking probability when traffic load is light.

1. INTRODUCTION

As mobile customers, we always want to use cheap and user-friendly wireless devices to enjoy different high-quality multimedia services, such as voice, video, email, and interactive games, at anytime anywhere. This basic but challenging requirement has driven us to develop the first-, second-, and third-generation cellular mobile communication systems, for example, global system for mobile communications (GSM), wideband code division multiple access (WCDMA), CDMA One (IS-95), and CDMA-2000. In addition, as a self-organized and easy-to-deploy complement without a central controller, mobile ad hoc networks (MANET) can provide more flexible wireless access services in the areas not suitable (technically or economically) for deploying those infrastructured wireless networks.

Depending on specific applications, mobile customers may have different quality of service (QoS) requirements in terms of blocking probability, access delay, bandwidth (transmission data rate), and throughput, and so forth. Compared with infrastructured networks, it is much more difficult to provide QoS support in MANET because of the following inherent characteristics of MANET: dynamic network topology, inefficiently distributed network management and control, unreliable and time-varying radio channel conditions, and limited network resources [1]. Specifically, it is very challenging to design efficient QoS-aware medium access control (MAC), routing, resource reservation, and network management protocols for MANET.

In real world, both *infrastructure* and *ad hoc* network structures are supported in the standard of wireless local area networks (WLAN) [2]. As an efficient solution to provide wireless broadband data communications in a limited geographical area, WLAN has become very popular and has been widely deployed in offices, residential apartments, hospitals, and other indoor environments. As shown in Figure 1, an access point (AP) is usually installed on the ceiling of central office area to provide wireless data services for all mobile stations (MS) in its coverage area. The propagation of radio signals heavily depends on office dimensions, obstructions, partitioning materials, and even moving objects. Some MSs may only be able to receive weak signals, or even totally no signal, from the AP. According to the received signal strength from the AP, the whole office area can be divided into five service zones, numbered from 0 to 4 (as shown in Figure 1). Specifically, zone-0 represents the out-of-coverage area, such that it cannot support any data service. While zone-1 to zone-4 can support different access

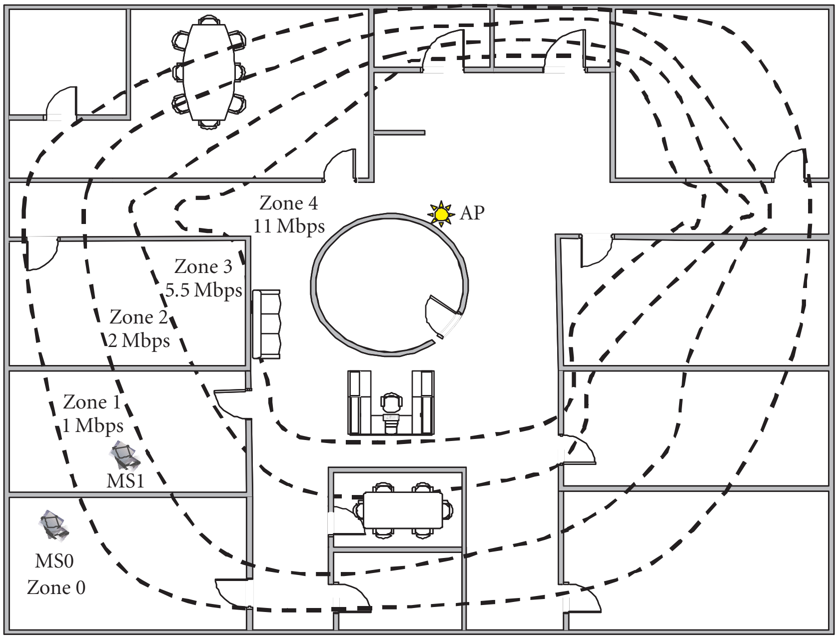

Figure 1: A WLAN deployment example.

data rates, that is, 1 Mbps, 2 Mbps, 5.5 Mbps, 11 Mbps, as specified in the IEEE 802.11b standard [2].

The profile of radio signal coverage is almost fixed when the system is deployed, while the QoS requirement (e.g., bandwidth) from an MS is usually application-dependent, rather than location-dependent. When an MS in zone-0 receives a service request, the challenging "coverage problem" occurs, that is, how to connect this out-of-coverage MS to the AP and, at the same time, provide QoS support accordingly. In [3, 4], two coverage extension schemes using different antenna diversity technologies were proposed and studied. To implement these schemes in real systems, extra hardware devices and more signal-processing power are required. Other researchers tried to solve the coverage problem by finding the optimal installment positions for all APs [5–8]. This kind of solutions is, however, highly environment-dependent.

Inspired by the fact that WLAN supports both infrastructure and ad hoc network structures, we propose and study in this paper the traffic agent (TA) scheme as a new solution to the coverage problem. The basic idea is to use some idle MSs in good service zones as agents to relay traffic from zone-0 MSs to the AP. To achieve this purpose, the busy MSs in good service zones are operating in "infrastructure" mode (communicate with the AP), all zone-0 MSs are in "ad hoc" mode (communicate with the TAs) and, most importantly, all TAs should have the capability of switching between "infrastructure" and "ad hoc" modes dynamically (communicate with the AP and zone-0 MSs). This concept of mixing the infrastructure and the ad hoc modes in WLAN has been previously used to improve system efficiency and utilization [9], and to relieve congested traffic in hot spots [10].

The rest of this paper is organized as follows. In Section 2, the TA scheme is proposed and the complete MS working flow is given. Mathematical analysis of throughput and blocking performance is derived in Sections 3 and 4, respectively. In Section 5, analytical results, verified by computer simulations, are compared between the original system and the system using the TA scheme.

2. THE TRAFFIC AGENT SCHEME

On receiving a service request, the MS in zone-0 will switch to "ad hoc" mode and try to find an idle MS in good service zones to relay traffic. Take MS0 and MS1 in Figure 1 as an example. Suppose MS1 is idle and within the coverage of MS0. Instead of blocking its service request, MS0 can use MS1 as an agent to relay its traffic to the AP.

A "Coverage Improvement Algorithm" will be performed to find TAs, when a zone-0 MS, say "MS-B," has a service request. We present in Tables 1 and 2 the algorithms for the service-request MS (i.e., MS-B) and the traffic agent MS, respectively. When the service-request algorithm is triggered, MS-B will first switch to the "ad hoc mode" and mark the initial frequency channel as No. 1 channel. MS-B will then advertise request-for-agent (RFA) messages to all the neighboring MSs within its radio coverage in all available channels. The RFA message contains MS-B's identification and all idle neighboring MSs can receive the RFA message. As the response, they will send back positive acknowledgments (ACKs) and become candidate TA MSs (as shown in Table 2). If two or more ACKs are received from the same channel, MS-B will select the candidate MS with the largest zone

Table 1: Service-request MS algorithm.

```
if (Receive a service request) then
    Switch to “ad hoc mode”;
    Set $Channel = 1$;
    loop
        if ($Channel\ No. > \text{Max}\ Channel$) then
            Block service request;
        else
            Advertise request-for-agent message;
            if (receive positive response) then
                Select an agent & connect;
                Transmit data from traffic agent;
            end if
            Channel++;
        endif
    endloop
endif
```

Table 2: Traffic agent MS algorithm.

```
if (MS is idle) then
    if (Receive traffic agent request) then
            Advertise acknowledge (ACK) message;
        if (receive commission) then
            Date transmission by TA in “ad hoc mode”;
        end if
    end if
else
    Data transmission in “infrastructure mode”;
end if
```

number (strongest wireless connection with the AP) as its TA. (We assume in this study the ad hoc connection between MS-B and its TA has sufficient bandwidth.) Next, MS-B will establish connection and exchange data with the selected TA in the “ad hoc mode.” The TA will subsequently establish connection and exchange data with the AP in the “infrastructure mode.” By this two-hop wireless connection, the requested services from the out-of-coverage zone are accommodated.

3. THROUGHPUT ANALYSIS

Consider a basic service set (BSS) with one AP and a finite number of MSs randomly distributed in five service zones. Under the distributed coordination function (DCF) scheme and the ideal channel assumption (i.e., without packet loss, hidden terminal or capture effect [11]), the throughput performance for the systems without and with the TA scheme is analyzed in the following two sections, respectively.

3.1. Throughput without TA scheme

Let n_i $(0 \leq i \leq 4)$ be the number of zone-i MSs and let n be the total number of MSs. The percentage of zone-i MSs is therefore given by $P_i = n_i/n$. Let τ be the probability that an MS has packets to transmit at a specific time slot. The probability P_{tr} that at least one transmission occurs at a specific time slot is derived as

$$P_{\text{tr}} = 1 - (1-\tau)^{n-n_0}. \tag{1}$$

The success probability P_s of a transmission period is therefore

$$P_s = \frac{(n-n_0)\tau(1-\tau)^{(n-n_0-1)}}{P_{\text{tr}}}. \tag{2}$$

Based on the approach given in [12, 13], system throughput S is derived as

$$S = \sum_{i=1}^{4} \frac{P_s P_{\text{tr}} P_i L}{(1-P_{\text{tr}})\sigma + P_s P_{\text{tr}}(L/R_i + \text{SIFS} + \text{DIFS} + \text{ACK}) + P_{\text{tr}}(1-P_s)(L/R_i + \text{DIFS})}, \tag{3}$$

where L is average payload length in a packet. Symbol σ denotes the slot size and R_i is the channel transmission bitrate in zone-i. SIFS, DIFS, and ACK denote short interframe spacing, DCF interframe spacing, and ACK message transmission time [2], respectively.

3.2. Throughput with TA scheme

Let $\alpha_{i,j}$ be the random variable denoting the number of zone-j MSs that are within the coverage area of a typical zone-i MS. Given $\alpha_{i,j} \geq 1$, the conditional expected number $\beta_{i,j}$ of the neighboring MSs is given by

$$\overline{\beta_{i,j}} = E[\alpha_{i,j} \mid \alpha_{i,j} \geq 1] = \frac{\overline{\alpha_{i,j}}}{1 - P\{\alpha_{i,j} = 0\}}. \tag{4}$$

Under the TA scheme, some idle zone-i $(1 \leq i \leq 4)$ MSs are used to relay traffic for the active zone-0 MSs, if any. Let η_i $(1 \leq i \leq 4)$ be the active probability of a zone-i MS, that is, the probability that a zone-i MS has packets to transmit or relay at a specific time slot. Recall that an MS has probability

τ to generate new packets for transmission, and thus we get $(\eta_i - \tau)$ to be probability that a zone-i MS is serving as a TA. For the special case $i = 0$, we have $\eta_0 = \tau$. Given $\alpha_{i,j} \cdot \eta_j \geq 1$, the conditional expected number $\overline{\gamma_{i,j}}$ of the active neighboring MSs is derived as

$$\overline{\gamma_{i,j}} = E\left[\alpha_{i,j} \cdot \eta_j \mid \alpha_{i,j} \cdot \eta_j \geq 1\right] = \frac{\overline{\alpha_{i,j}} \cdot \eta_j}{1 - (1 - \eta_i)^{\overline{\alpha_{i,j}}}}. \tag{5}$$

The probability $(\eta_4 - \tau)$ that a zone-4 MS can be used as a TA is given by

$$\begin{aligned}\eta_4 - \tau &= (1 - \eta_4)\binom{\overline{\gamma_{4,0}}}{1}\frac{1}{\left[1 + (\overline{\beta_{0,4}} - 1)(1 - \eta_4)\right]}\\ &\quad \cdot \left[1 - \frac{1}{1 + (\overline{\beta_{0,4}} - 1)(1 - \eta_4)}\right]^{\overline{\gamma_{4,0}} - 1}\\ &\quad \cdot P_r\{\alpha_{4,0} \cdot \eta_0 \geq 1\}\\ &= \frac{(1 - \eta_4) \cdot \overline{\alpha_{4,0}} \cdot \eta_0}{1 + (\overline{\beta_{0,4}} - 1)(1 - \eta_4)}\\ &\quad \times \left[1 - \frac{1}{1 + (\overline{\beta_{0,4}} - 1)(1 - \eta_4)}\right]^{\overline{\gamma_{4,0}} - 1}.\end{aligned} \tag{6}$$

An idle zone-3 MS can serve as a TA only when all the zone-4 MSs are busy. Therefore, we obtain

$$\begin{aligned}\eta_3 - \tau &= \frac{(1 - \eta_3) \cdot \overline{\alpha_{3,0}} \cdot \eta_0 \cdot {\eta_4}^{\overline{\alpha_{0,4}}}}{1 + (\overline{\beta_{0,3}} - 1)(1 - \eta_3)}\\ &\quad \times \left[1 - \frac{1}{1 + (\overline{\beta_{0,3}} - 1)(1 - \eta_3)}\right]^{\overline{\gamma_{3,0}} - 1}.\end{aligned} \tag{7}$$

Similarly, we get

$$\begin{aligned}\eta_2 - \tau &= \frac{(1 - \eta_2) \cdot \overline{\alpha_{2,0}} \cdot \eta_0 \cdot {\eta_4}^{\overline{\alpha_{0,4}}} \cdot {\eta_3}^{\overline{\alpha_{0,3}}}}{1 + (\overline{\beta_{0,2}} - 1)(1 - \eta_2)}\\ &\quad \times \left[1 - \frac{1}{1 + (\overline{\beta_{0,2}} - 1)(1 - \eta_2)}\right]^{\overline{\gamma_{2,0}} - 1},\\ \eta_1 - \tau &= \frac{(1 - \eta_1) \cdot \overline{\alpha_{1,0}} \cdot \eta_0 \cdot {\eta_4}^{\overline{\alpha_{0,4}}} \cdot {\eta_3}^{\overline{\alpha_{0,3}}} \cdot {\eta_2}^{\overline{\alpha_{0,2}}}}{1 + (\overline{\beta_{0,1}} - 1)(1 - \eta_1)}\\ &\quad \times \left[1 - \frac{1}{1 + (\overline{\beta_{0,1}} - 1)(1 - \eta_1)}\right]^{\overline{\gamma_{1,0}} - 1}.\end{aligned} \tag{8}$$

The probability P'_{tr} that at least one transmission occurs at a specific time slot is given by

$$P'_{\text{tr}} = 1 - \prod_{i=1}^{4}(1 - \eta_i)^{n_i}. \tag{9}$$

The success probability $P_{s,i}$ of a transmission or relay period for a zone-i MS is given by

$$P_{s,i} = \frac{n_i\eta_i(1 - \eta_i)^{n_i - 1}\prod_{j=1,\, j\neq i}^{4}(1 - \eta_j)^{n_j}}{P'_{\text{tr}}}, \quad 1 \leq i \leq 4. \tag{10}$$

The total success probability P'_s is the summation of $P_{s,i}$, or

$$P'_s = \sum_{i=1}^{4}\frac{n_i\eta_i(1 - \eta_i)^{n_i - 1}\prod_{j=1,\, j\neq i}^{4}(1 - \eta_j)^{n_j}}{P'_{\text{tr}}}. \tag{11}$$

Finally, system throughput under the TA scheme is derived to be

$$S' = \sum_{i=1}^{4}\frac{P'_sP'_{\text{tr}}P_iL}{(1 - P'_{\text{tr}})\sigma + P'_sP'_{\text{tr}}(L/R_i + \text{SIFS} + \text{DIFS} + \text{ACK}) + P'_{\text{tr}}(1 - P'_s)(L/R_i + \text{DIFS})}. \tag{12}$$

4. BLOCKING PROBABILITY

When the TA scheme is not used, all zone-0 MSs cannot get access to the AP so that their service requests will be blocked. The corresponding blocking probability is $P_{b,0} = 1$. For the MSs in other zones, they have the same blocking probability

$$P_{b,i} = 1 - (1 - \tau)^{n - n_0 - 1}, \quad 1 \leq i \leq 4. \tag{13}$$

The overall blocking probability P_b is simply the weighted summation of $P_{b,i}$, that is,

$$P_b = \sum_{i=0}^{4}P_i \cdot P_{b,i} = P_0 + \left[1 - (1 - \tau)^{n - n_0 - 1}\right] \cdot (1 - P_0). \tag{14}$$

When the TA scheme is used, the average total number of service requests generated by all-zone MSs is kept unchanged, that is, $\sum_{j=0}^{4} n_j \cdot \tau$. The percentage P'_0 of the zone-0 requests that cannot identify any TAs is derived as

$$\begin{aligned}&P'_0\\ &\quad = \frac{n_0 \cdot \eta_0 - \sum_{i=1}^{4} n_i \cdot (\eta_i - \tau) \cdot (1 - \eta_i)^{n_i - 1}\prod_{j=1,\, j\neq i}^{4}(1 - \eta_j)^{n_j}}{\sum_{j=0}^{4} n_j \cdot \tau}.\end{aligned} \tag{15}$$

So the corresponding blocking probability is $P'_{b,0} = 1$. The percentage P'_i $(1 \leq i \leq 4)$ of the new and relay transmissions

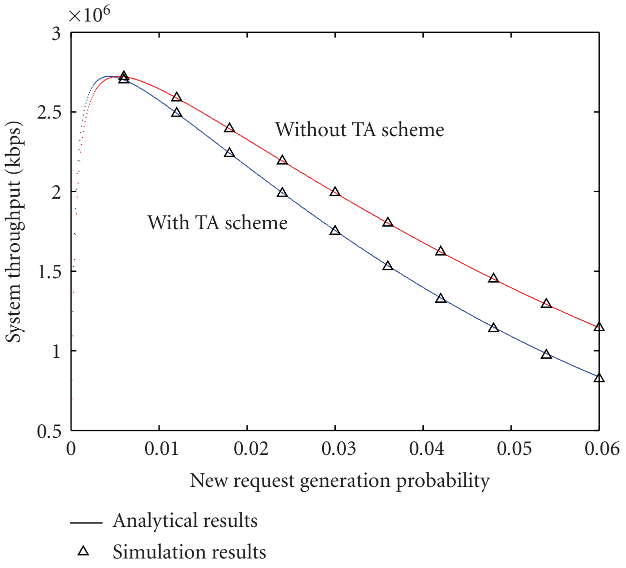

Figure 2: System throughput.

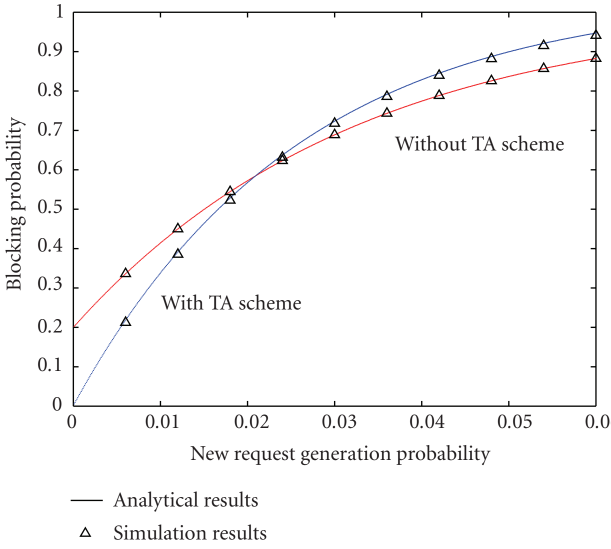

Figure 3: Overall blocking probability.

from the zone-i MSs is

$$P'_i = \frac{n_i \cdot \eta_i}{\sum_{j=0}^{4} n_j \cdot \tau}, \quad 1 \le i \le 4. \tag{16}$$

The corresponding blocking probability $P'_{b,i}$ for the MSs in zone-1 to zone-4 is given by

$$P'_{b,i} = 1 - (1-\eta_i)^{n_i - 1} \prod_{j=1,\, j\neq i}^{4} (1-\eta_j)^{n_j}, \quad 1 \le i \le 4. \tag{17}$$

Therefore, the overall blocking probability for the systems using the TA scheme is

$$\begin{aligned} P'_b &= \sum_{i=0}^{4} P'_i \cdot P'_{b,i} \\ &= P'_0 + \sum_{i=1}^{4} \left[1 - (1-\eta_i)^{n_i-1} \prod_{j=1,\, j\neq i}^{4} (1-\eta_j)^{n_j} \right] \cdot P'_i. \end{aligned} \tag{18}$$

5. ANALYTICAL AND SIMULATION RESULTS

Based on the MATLAB$^{\text{TM}}$ software package, we use a discrete event simulation approach to develop the simulation platform for system performance evaluation. The system parameters for deriving the numerical and simulation results are summarized in Table 3. In addition, we assume the random variables $\alpha_{i,j}$ $(0 \le i,\ j \le 4)$ have the same uniform distribution in the range $[0,4]$. So, we obtain $\overline{\alpha_{i,j}} = 2$ and $\overline{\beta_{i,j}} = 2.5$.

Figure 2 shows the system throughput as a function of the probability τ that a new service request is generated by an MS in each time slot. The analytical results shown in solid lines match perfectly to the simulation results in markers. As seen, although the TA scheme increases the active probability of in-coverage MSs from τ to η_i $(1 \le i \le 4)$ and decreases the success probability of a busy period from P_s in (2) to P'_s in (11), it can still offer the same maximum throughput performance as the system without using the TA scheme. Specifically, when the system is lightly loaded, say $\tau \le 0.005$, the use of TA scheme can slightly improve the system throughput because a small amount of zone-0 traffic is relayed to the AP through some two-hop connections. When the probability τ becomes large, most MSs are busy and cannot serve as TA. In addition, due to more frequent packet collisions, the success probability of a busy period becomes smaller and the throughput curve under the TA scheme is lower.

Figure 3 shows the overall blocking probability as a function of τ. As expected, the TA scheme can offer much better blocking performance when the system is lightly loaded. In this case, the TA scheme can accommodate most zone-0 service requests by identifying suitable TAs to relay their traffic to the AP. When τ is large, few in-coverage MSs are suitable for serving the zone-0 MSs as TAs. If any, they will further increase the active probability of in-coverage MSs and produce more collisions in packet transmission. The resulting overall blocking probability, calculated by (18), is therefore larger than that of the system without using the TA scheme.

6. CONCLUSIONS

As a very popular wireless system for broadband data communications, WLAN takes the advantages of both infrastructure and ad hoc network structures to fulfil different wireless access and QoS requirements for mobile users. Due to unreliable radio channel condition and limited transmission power, the service coverage area of WLAN is limited. It is a very challenging problem to extend data communication services to those out-of-coverage MSs and provide them QoS support as well. In this paper, we used the concept of mixing the infrastructure and the ad hoc modes in WLAN and proposed the TA scheme to identify suitable MSs in good service

Table 3: System parameters.

R_i	$(1, 2, 5.5, 11) \times 10^6$ bps, $i = 1, 2, 3, 4$
n	40
L	1024 bytes
P_i	$0.2, 0.2, 0.2, 0.2, 0.2$, $i = 0, 1, 2, 3, 4$
SIFS	10 μs
DIFS	50 μs
ACK	19.2 μs
σ	20 μs

zones as agents to relay traffic for those out-of-coverage MSs. The QoS requirements (e.g., bandwidth) of those MSs are considered in the selection process of corresponding TAs. Analytical results, verified by simulation results, have shown that the TA scheme can reduce system blocking probability by establishing two-hop traffic connections between out-of-coverage MSs and the AP when the system is lightly loaded. The service coverage area of WLAN is therefore expanded. However, when traffic load is heavy, the use of idle MSs as TAs will degrade system performance, for example, throughput and blocking probability, due to extra packet collisions.

The performance of TA scheme can be improved by deploying multiple APs in the same service area, whereby the total traffic load is distributed into many separated channels so that packet collisions are effectively mitigated. An extension of our analytical approach to this multiple-AP scenario is straightforward. The extra energy consumption due to the overhead of radio signaling and traffic relaying at the intermediate MSs (serving as TAs) is not analyzed in this paper and, therefore, deserves a further in-depth study.

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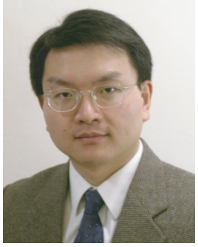

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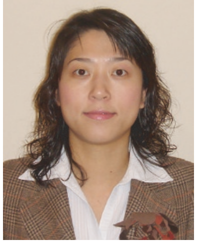

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