Analysis of Traffic Agent Scheme for Coverage Improvement in Wireless Local Area Networks

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Abstract. Wireless Local Area Network (WLAN) can provide high data-rate wireless multimedia applications to end users in a limited geographical area and has been widely deployed in recent years. For indoor WLAN systems, how to efficiently improve service coverage is a challenging problem. In this paper, we propose a coverage improvement scheme that can identify suitable Mobile Stations(MS) in good service zones and use them as Traffic Agents (TA) to relay traffic for those out-of-coverage MS's. The service coverage area of WLAN system is therefore expanded. Mathematical analysis, verified by computer simulations, shows that the scheme can effectively reduce blocking probability when the system is lightly loaded.

1 Introduction

In recent years, the proliferation of mobile devices like laptops and Personal Digital Assistant (PDA) has resulted in the rapid evolution of Wireless Local Area Networks (WLAN). WLAN can provide high-bandwidth wireless data communications in a limited geographical area. WLAN is becoming commonly used in offices, residential apartments, hospitals, and other indoor environments. For indoor WLAN systems, signal dispersion is highly disturbed. The propagation of radio signals heavily depends on office dimensions, obstructions, partitioning materials and even the moving objects. Therefore, how to effectively guarantee the radio signal coverage for complicated indoor wireless areas is a very challenging problem.

Fig. 1 shows a WLAN deployment example for office area. The Access Point (AP), usually installed in the ceiling of central area, provides wireless data service for all Mobile Stations (MS) located in its covered area. According to the received signal strength from the AP, the whole office area can be further divided into five service zones, numbered from 0 to 4. Specifically, zone-0 represents the area out-of-coverage so that cannot support any data services. While zone-1 to zone-4 can support different access data rates, i.e. 1Mbps, 2Mbps, 5.5Mbps, 11Mbps, as specified in the IEEE 802.11b standard [1].

The coverage situation of radio signals is almost fixed when the system is deployed. On the other hand, the required bandwidth from a user or MS is usually application dependent, not relevant to its location. The coverage problem occurs when a zone-0 MS has a service request. In [5] and [6], the coverage extension schemes using different

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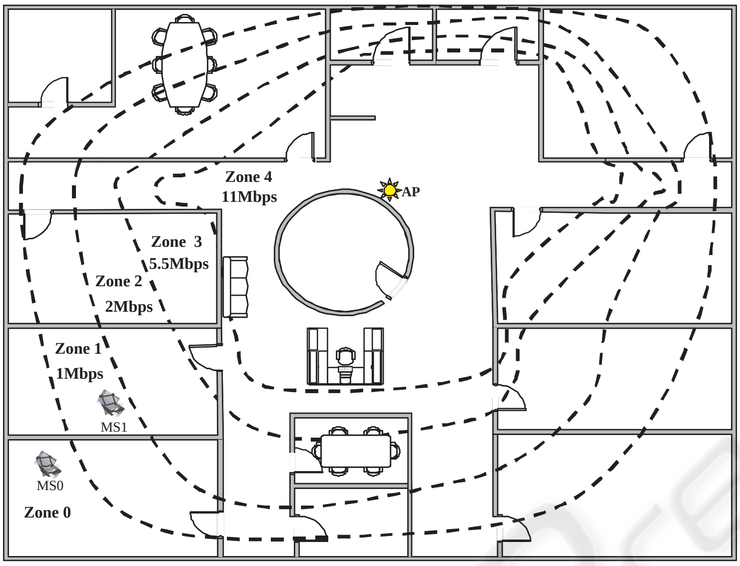

Fig. 1. A WLAN Deployment Example.

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 [7–10]. This kind of solutions is, however, highly environment dependant.

The concept of mixed-mode MS, which can switch between the "infrastructure mode" and the "ad-hoc mode" dynamically, was presented in [2] to improve system efficiency and utilization. Based on this concept, a scheme for relieving congested traffic in hot spots is proposed in [3]. Inspired by these work, we propose in this paper the Traffic Agent (TA) scheme to improve the coverage area of WLAN systems. The TA scheme uses idle high-zone MS's to relay traffic from zone-0 MS's to the AP.

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 are derived in Section 3 and Section 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 high service zones to relay traffic. Take MS0 and MS1 in Fig. 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 Table 1 and Table 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 MS’s within its radio coverage in all available channels. The RFA message contains MS-B’s identification and all idle neighboring MS’s can receive the RFA message. As the response, they will send back positive acknowledgments (ACK) and become candidate TA MS’s (as shown in Table 2). If two or more ACKs are received, MS-B will select the candidate MS with the largest zone number (strongest wireless connection with the AP) as its TA [1]. 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.

Table 1. Service-Request MS Algorithm

```
if (Receive a service request) then
  Switch to “ad-hoc mode”;
  Set Channel = 1;
  loop
    if (Channel No. > 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
```

3 Throughput Analysis

Consider a Basic Service Set (BSS) with one AP and a finite number of MS’s randomly distributed in five service zones. Under the Distributed Co-ordination Function (DCF)

[1] We assume in this study the ad-hoc connection between MS-B and its TA has sufficient bandwidth.

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
```

scheme and the ideal channel assumption (i.e. no packet loss, hidden terminal, or capture effect [11]), the throughput performance for the systems without and with the TA scheme are 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 MS's and let n be the total number of MS's. The percentage of zone-i MS's is therefore given by $P_i = n_i/n$. Let τ be the probability that a 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

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

The success probability P_s of a transmission period is therefore

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

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

$$S = \sum_{i=0}^{4} \frac{P_s P_{tr} P_i P}{(1-P_{tr})\sigma + P_s P_{tr}(\frac{P}{R_i} + SIFS + DIFS + ACK) + P_{tr}(1-P_s)(\frac{P}{R_i} + DIFS)} \quad , \tag{3}$$

where P is average payload length in a packet. Symbol σ denotes the slot size and R_i is the channel transmission bit rate in zone-i. $SIFS$, $DIFS$ and ACK denote respectively the Short Inter-Frame Spacing, the DCF Inter-Frame Spacing, and the ACK message transmission time [1].

3.2 Throughput with TA Scheme

Let $\alpha_{i,j}$ be the random variable denoting the number of zone-j MS's 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 MS's is given by

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

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

$$\overline{\gamma_{i,j}} = E[\alpha_{i,j} \cdot \eta_j | \alpha_{i,j} \cdot \eta_j \geqslant 1] = \frac{\overline{\alpha_{i,j}} \cdot \eta_j}{1 - (1 - \eta_i)^{\overline{\alpha_{i,j}}}} \quad . \tag{5}$$

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

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

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

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

Similar, we get

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

and

$$\eta_1 - \tau = \frac{(1 - \eta_1) \cdot \overline{\alpha_{1,0}} \cdot \eta_0 \cdot \eta_4^{\overline{\alpha_{0,4}}} \cdot \eta_3^{\overline{\alpha_{0,3}}} \cdot \eta_2^{\overline{\alpha_{0,2}}}}{1 + (\overline{\beta_{0,1}} - 1)(1 - \eta_1)} \left[1 - \frac{1}{1 + (\overline{\beta_{0,1}} - 1)(1 - \eta_1)}\right]^{\overline{\gamma_{1,0}} - 1} \quad . \tag{9}$$

The probability $P_{tr}^{'}$ that at least one transmission occurs at a specific time slot is given by

$$P_{tr}^{'} = 1 - \prod_{i=1}^{4} (1 - \eta_i)^{n_i} \quad . \tag{10}$$

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

$$P_{s,i} = \frac{n_i \eta_i (1-\eta_i)^{n_i - 1} \prod_{j=1, j\neq i}^{4} (1-\eta_j)^{n_j}}{P_{tr}^{'}}, \quad 1 \leq i \leq 4 \ . \tag{11}$$

The total success probability $P_s^{'}$ is the summation of $P_{s,i}$, i.e.

$$P_s^{'} = \sum_{i=1}^{4} \frac{n_i \eta_i (1-\eta_i)^{n_i - 1} \prod_{j=1, j\neq i}^{4} (1-\eta_j)^{n_j}}{P_{tr}^{'}} \ . \tag{12}$$

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

$$S' = \sum_{i=1}^{4} \frac{P_s' P_{tr}' P_i P}{(1-P_{tr}')\sigma + P_s' P_{tr}' (\frac{P}{R_i} + SIFS + DIFS + ACK) + P_{tr}' (1-P_s')(\frac{P}{R_i} + DIFS)} \ . \tag{13}$$

4 Blocking Probability

When the TA scheme is not used, all zone-0 MS's 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 MS's in other zones, they have the same blocking probability

$$P_{b,i} = 1 - (1-\tau)^{n-n_0-1}, \quad 1 \leq i \leq 4 \ . \tag{14}$$

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

$$P_b = \sum_{i=0}^{4} P_i \cdot P_{b,i} \quad = P_0 + \left[1 - (1-\tau)^{n-n_0-1}\right] \cdot (1-P_0) \ . \tag{15}$$

When the TA scheme is used, the average total number of service requests generated by all-zone MS's is kept unchanged, i.e. $\sum_{j=0}^{4} n_j \cdot \tau$. The percentage $P_0^{'}$ of the zone-0 requests that cannot identify any TAs is derived as

$$P_0^{'} = \frac{n_0 \cdot \eta_0 - \sum_{i=1}^{4} n_i \cdot (\eta_i - \tau) \cdot (1-\eta_i)^{n_i - 1} \prod_{j=1, j\neq i}^{4} (1-\eta_j)^{n_j}}{\sum_{j=0}^{4} n_j \cdot \tau} \ . \tag{16}$$

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 from the zone-i MS's is

$$P_i^{'} = \frac{n_i \cdot \eta_i}{\sum_{j=0}^{4} n_j \cdot \tau}, \quad 1 \leq i \leq 4 \ . \tag{17}$$

The corresponding blocking probability $P_{b,i}^{'}$ for the MS's in zone-1 to zone-4 is given by

$$P_{b,i}^{'} = 1 - (1-\eta_i)^{n_i - 1} \prod_{j=1, j \neq i}^{4} (1-\eta_j)^{n_j}, \quad 1 \leq i \leq 4 \ . \tag{18}$$

The overall blocking probability for the systems using the TA scheme is therefore

$$\begin{aligned} P_b^{'} &= \sum_{i=0}^{4} P_i^{'} \cdot P_{b,i}^{'} \\ &= P_0^{'} + \sum_{i=1}^{4} \left[1 - (1-\eta_i)^{n_i - 1} \prod_{j=1, j \neq i}^{4} (1-\eta_j)^{n_j} \right] \cdot P_i^{'} \ . \end{aligned} \tag{19}$$

5 Analytical and Simulation Results

The system parameters for deriving the numerical and simulation results are summarized in Table 3. In addition, we assume the random variables $\alpha_{i,j}$ ($0 \leq i, j \leq 4$) have the same uniform distribution in the range $[0, 4]$. So, we obtain $\overline{\alpha_{i,j}} = 2$ and $\overline{\beta_{i,j}} = 2.5$.

Table 3. System Parameters

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

Fig. 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 are perfectly verified by the simulation results in markers. As seen, although the TA scheme increases the active probability of in-coverage MS's from τ to η_i ($1 \leq i \leq 4$) and decreases the success probability of a busy period from P_s in (2) to $P_s^{'}$ in (12), 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 $\tau \leq 0.005$, 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 MS's 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.

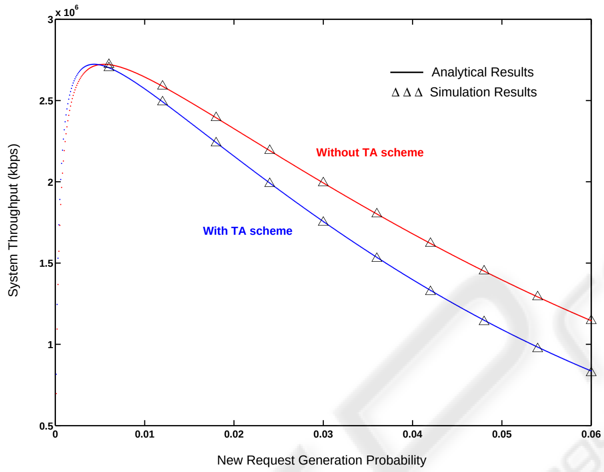

Fig. 2. System throughput.

Fig. 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 MS's are suitable for serving the zone-0 MS's as TAs. If any, they will further increase the active probability of in-coverage MS's and incur more collisions in packet transmission. The resulting overall blocking probability, calculated by (19), is therefore larger than that of the system without using the TA scheme.

6 Conclusions

For indoor WLAN systems, how to efficiently improve service coverage is a challenging problem. The Traffic Agent scheme proposed in this paper can identify suitable MS's in good service zones as agents to relay traffic for those out-of-coverage MS's. Analytical results, verified by simulation results, show that the TA scheme can reduce the system blocking probability by establishing the two-hop traffic connections between the out-of-coverage MS's and the AP when the system is lightly loaded. The service coverage of indoor WLAN systems is therefore enhanced.

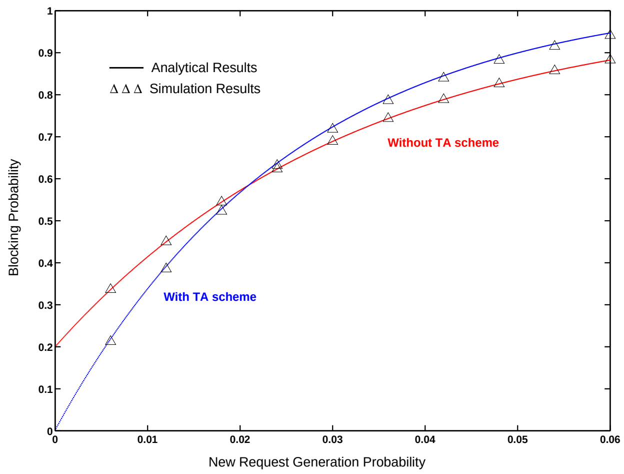

Fig. 3. Overall blocking probability.

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