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Wireless Mesh Networks for Intelligent Transportation Systems

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Abstract— **The wireless mesh network (WMN) is an economical solution for disseminating broadband wireless information in the intelligent transportation systems (ITS). This paper investigates the issue of deploying access points (APs) in an ITS wireless mesh network, where several adjacent APs form a cluster. Each AP in a cluster operates as a wireless relay to forward neighboring AP's traffic to the central access point connected to the Internet through cables. In general, access points are placed for maximizing cell coverage. However, larger coverage of an AP leads to lower throughput and longer delay in the access link as well as in the relay link. To find the optimal tradeoffs among delay, capacity, and coverage, we develop a physical (PHY)/medium access control (MAC) cross-layer analytical model to evaluate the throughput and delay of the considered ITS wireless mesh network. We consider the carrier sense multiple access (CSMA) protocol and the impact of hop distance on the data rate in the physical layer. Then, we apply the mixed-integer nonlinear programming (MINLP) optimization approach to determine the optimal number of APs in a cluster and the best cell radius of each AP, aiming at maximizing the capacity and coverage of a cluster of APs subject to the delay and fairness requirements.**

I. INTRODUCTION

The wireless mesh network (WMN) is a promising information dissemination technology for the next-generation intelligent transportation systems (ITS) because it can enhance throughput and coverage with less cabling engineering [1], [2]. Figure 1 illustrates the ITS wireless mesh network scenario considered in this paper. In this ITS wireless network, several adjacent access points (APs) form a cluster. In each cluster of APs, only the central access point AP_0 has a wireline connection to the Internet. Other APs communicate with the neighboring APs via wireless link. In addition, each AP operates as a wireless relay to forward neighboring AP's traffic toward the central AP_0. By using this multi-hop network architecture, the ITS wireless networks can be rapidly deployed in large scale with less cabling engineering work.

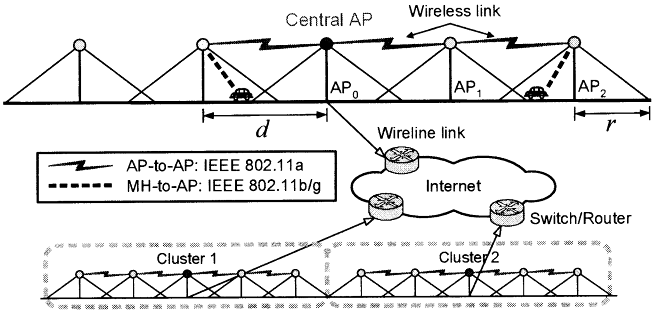

Fig. 1. System architecture for an ITS wireless mesh network.

In a wireless mesh network, coverage extension, throughput enhancement and delay improvement are usually contradictory goals. On the one hand, maximizing the cell coverage of an AP can lower the total infrastructure costs. On the other hand, a larger cell coverage leads to lower throughput and longer access delay due to more collisions from a larger number of contending users. In the meanwhile, the larger separation distance between two APs also decreases the data rates in the wireless relay link. Therefore, achieving the optimal tradeoff among throughput, delay, and coverage for each AP is a key challenge for deploying the ITS wireless mesh networks.

In the literature, the issue of access point placement for outdoor WLANs has been studied in [1] and [3]-[8]. In [3], an integer linear programming (ILP) optimization model was proposed for the access point placement, where the objective function was to maximize the signal level in the service area. In [4], an optimization approach was proposed to minimize the areas with poor signal quality and improve the average signal quality in the service area. The authors in [5] and [6] proposed optimization algorithms to minimize average bit error rate (BER). In [7], the WLAN deployment problem was also formulated as an ILP optimization problem with the objective function of minimizing the maximum of channel utilization to achieve load balancing. However, in [3]-[7] all the access points are connected to the backbone network through cables. Fewer papers have considered both throughput and coverage performance issues when deploying access points in the ITS wireless networks. The work in [1] investigated the relation of throughput and coverage for an ITS WMN in a single user case. In our previous work [8], the tradeoff between throughput and coverage in a multi-user ITS WMN was investigated. In [1] and [8], however, the delay performance issues were not considered.

In this paper, we investigate the AP deployment issue in the ITS wireless mesh network, as shown in Fig. 1. In this ITS wireless mesh network, access points are connected through wireless relays to ease deployment. To find the optimal tradeoffs among throughput, coverage, and delay, we develop a physical (PHY)/medium access control (MAC)

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cross-layer analytical model to evaluate the throughput and delay for this ITS WMN, by incorporating the carrier sense multiple access (CSMA) MAC protocol and the impact of hop distance on the data rate in the physical layer. On top of the analytical model, we apply the mixed-integer nonlinear programming (MINLP) optimization approach to determine the optimal number of APs in a cluster and the best cell radius for each AP. The objective is to maximize the capacity and coverage of a cluster of APs with delay and delay fairness requirements.

The rest of this paper is organized as follows. Section II describes the system architecture of the considered ITS wireless mesh network. In Section III, we formulate an optimization problem to maximize the capacity and coverage of the ITS WMN subject to the delay and fairness constraints. Section IV discusses the channel activity in the considered ITS wireless network. In Section V, based on the channel activity concept, we develop a cross-layer analytical throughput and delay model for this ITS WMN. Numerical examples are shown in Section VI. The concluding remarks are given in SectionVII.

II. SYSTEM ARCHITECTURE AND ASSUMPTIONS

Figure 1 shows the considered ITS wireless mesh network. In each cluster, only the central access point AP_0 connects to the backbone network through cables. Any two neighboring APs communicate with each other via wireless link. Therefore, each AP also operates as a wireless relay to forward neighboring AP's traffic to the central access point AP_0. By doing so, the cabling engineering work for deploying APs in the ITS wireless mesh network is reduced.

In this ITS wireless network, we suggest utilizing the IEEE 802.11a WLAN standard for data forwarding between APs, while the IEEE 802.11b/g for data access between APs and user terminals. Recall that the IEEE 802.11a WLAN are assigned with eight non-overlapping channels for outdoor applications in the spectrum of 5.25 to 5.35 GHz and 5.725 to 5.825 GHz, while the IEEE 802.11b/g WLAN has three non-overlapping channels in the spectrum of 2.4 to 2.4835 GHz. To avoid the co-channel interference and improve throughput, frequency planning is also applied to ensure two buffer cells between the two co-channel APs.

III. OPTIMAL ACCESS POINT PLACEMENT

A. Problem Formulation

All the performance issues of throughput, coverage, and delay are essential factors in the design of the ITS wireless mesh network. From the coverage viewpoint, the larger cell can lower infrastructure cost due to fewer APs. From the throughput standpoint, however, a smaller cell is better since fewer users contend for the spectrum. In addition, the small-sized cell also leads to higher throughput in the wireless relay link between APs. The main focus of this paper is on the frame delay consisting of contention delay and queuing delay in each relay node. From the queueing delay perspective, a longer separation distance between two APs may be better due to fewer hops. From the contention delay viewpoint, however, a smaller cell coverage is preferred due to fewer contending users. In the following, we formulate an optimization problem to determine the best number of APs in a cluster and the optimal cell radius of each AP subject to the constraints on delay, throughput, and coverage.

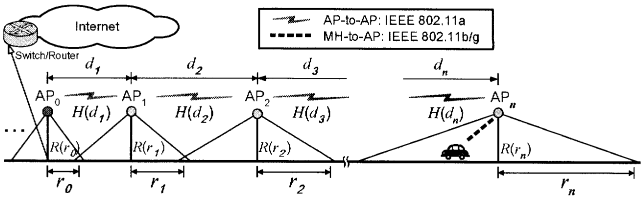

Fig. 2. A cluster of APs in the ITS wireless mesh network, where only the single side of a cluster is shown since the APs in the other side are deployed symmetrically.

At first, referring to Fig. 2, we discuss the constraints in the optimization problem for the considered ITS WMN:

- The access link capacity $R(r_i)$ for one user communicating with AP_i should be greater than the demanded traffic R_D of each user. That is, $R(r_i) \geq R_D$, where r_i is the cell radius of AP_i, as shown in Fig. 2. This constraint guarantees the minimum throughput for each user.
- The relay link capacity $H(d_i)$ between AP_i and AP_{i-1} should be larger enough to accommodate the carried traffic load $H_{r,i}$ of AP_i, i.e., $H(d_i) \geq H_{r,i}$, where d_i is the separation distance between AP_i and AP_{i-1}.
- The overall frame delay $D_T(i)$ for the user in the cell of AP_i should meet the delay requirement D_{req}, i.e., $D_T(i) \leq D_{req}$.
- In a multi-hop wireless network, the further the user from the central AP_0, the longer the overall frame delay. To ensure the delay fairness in the considered ITS wireless mesh network, it is required that $DFI \geq DF_{req}$, where DFI is a delay fairness index and DF_{req} stands for the delay-fairness requirement in this ITS WMN.
- The cell radius r_i of an access point should be designed from two folds. The cell radius should be less than r_{MAX} to maintain an acceptable data rate in the access link, while it should be larger than r_{MIN} to lower the handoff probability. Accordingly, $r_{MIN} \leq r_i \leq r_{MAX}$.
- The separation distance $d_i = r_i + r_{i-1}$ between APs should be less than the maximal reception range d_{MAX} of the employed wireless system, i.e., $d_i \leq d_{MAX}$.

B. MINLP Optimization Approach

According to the above considerations, the AP placement issue for an ITS WMN can be formulated as a mixed-integer nonlinear programming (MINLP) problem with the following decisions variables n (the number of APs in the single side of one cluster) and r_1, r_2, …, r_n (the cell radii of APs). The objective function is maximizing the capacity of a cluster of APs as follows.

$$\begin{aligned}&\underset{n,r_0,r_1,\ldots,r_n}{\mathbf{MAX}}\ (\text{Total throughput of a cluster of APs})\\&= \underset{n,r_0,r_1,\ldots,r_n}{\mathbf{MAX}}\ 2\left[r_0+2\sum_{i=1}^{n} r_i\right] D_M R_D \qquad (1)\end{aligned}$$

subject to

$$R(r_i) \geq R_D, \qquad (2)$$

$$H(d_i) \geq H_{r,i}, \qquad (3)$$

$$D_T(i) \leq D_{req}, \qquad (4)$$

$$DFI \geq DF_{req}, \qquad (5)$$

$$r_{MIN} \leq r_i \leq r_{MAX}, \qquad (6)$$

$$d_i \leq d_{MAX}, \qquad (7)$$

where assume that the users are uniformly distributed on the road with density D_M (users/m); $R(r_i)$, $H(d_i)$, $D_T(i)$, and DFI are detailed in Sections V-B and V-C.

IV. CHANNEL ACTIVITY IN THE ITS WIRELESS MESH NETWORK

From the viewpoint of a particular node (access point or user terminal), there are five types of channel activities in the considered ITS wireless network:

(1) Successful frame transmission;
(2) Unsuccessful frame transmission;
(3) Empty slot, where all nodes are backlogged or idle;
(4) Successful frame transmission from other nodes;
(5) Unsuccessful frame transmission from other nodes.

For clarity, radio channel activities can be logically described as a sequence of *effective time slots* [9]-[10]. Subject to the backoff procedures, their durations are defined as $T_1 = T_4 = T_S$, $T_2 = T_5 = T_C$, $T_3 = \sigma$, where σ is the duration of an empty slot, T_S and T_C are the successful transmission time and collision duration, respectively. Therefore, the average duration T_v of an effective time slot can be written as

$$T_v = \sum_{j=1}^{5} \nu_j T_j \ . \qquad (8)$$

Here, ν_j is the corresponding probability for the channel activity type and is calculated in the following.

A. Successful/Unsuccessful Transmission

One node can successfully deliver data frame only if no other node is transmitting in the same cell. Consider a cell of radius r_i with k_i nodes. Suppose that τ is the transmission probability of an active node, and P_0 is the average probability of a node being idle due to empty queue. Then, the unsuccessful transmission probability p_u of a data frame can be computed by

$$p_u = 1 - [1 - \tau(1 - P_0)]^{k_i - 1}, \qquad (9)$$

where the last term represents the probability that all other nodes are backlogged or idle. Consequently, given that the considered node has a non-empty queue, the probability that this node successfully/unsuccessfully sends a data frame in an effective time slot can be expressed as

$$\begin{aligned}\nu_1 &= \tau(1 - p_u) \qquad (10)\\ \nu_2 &= \tau p_u \ . \qquad (11)\end{aligned}$$

B. Empty Slot

One node observes an empty slot when all the nodes in the cell are silent. Therefore, from the viewpoint of the considered node, the empty-slot probability is

$$\nu_3 = (1 - \tau)[1 - \tau(1 - P_0)]^{k_i - 1}, \qquad (12)$$

where the first term means the probability of the considered node being backlogged, and the second term is the probability that all the other nodes are backlogged or idle.

C. Successful/Unsuccessful Transmission from Other Node

When the considered node is backlogged at the current effective time slot, the probability that at least one node sends its data frame is equal to $p_{otr} = 1 - [1 - \tau(1 - P_0)]^{k_i - 1}$. Therefore, given that at least one frame is transmitted from other node, the conditional probability that the frame transmission is successful can be written as

$$p_{os} = \frac{\binom{k_i - 1}{1} \tau(1 - P_0)[1 - \tau(1 - P_0)]^{k_i - 2}}{p_{otr}} . \qquad (13)$$

Then, from the viewpoint of the considered node, the probability of an effective time slot containing a successful/unsuccessful frame transmission from other node can be given as

$$\begin{aligned}\nu_4 &= (1 - \tau) p_{otr} p_{os} \qquad (14)\\ \nu_5 &= (1 - \tau) p_{otr} (1 - p_{os}). \qquad (15)\end{aligned}$$

V. CROSS-LAYER THROUGHPUT AND DELAY ANALYSIS

A. Background

Now we calculate the durations of a successful frame transmission and a collision. Recall that the data forwarding in the wireless relay link between two APs follows the IEEE 802.11a WLAN standard. Let l be the payload size of data frame, m_a and m_c be the transmission PHY mode for data frame and that for control frame, respectively. In the wireless relay link between two APs, the successful frame transmission time T_S and collision duration T_C can be calculated by

$$\begin{aligned}T_S &= T_{DATA}(l, m_a) + \delta + SIFS\\ &\quad + T_{ACK}(m_c) + \delta + DIFS, \qquad (16)\\ T_C &= T_{DATA}(l, m_a) + \delta + EIFS, \qquad (17)\end{aligned}$$

where δ is the propagation delay; the durations of short interframe space ($SIFS$), distributed interframe space ($DIFS$), and extended interframe space ($EIFS = SIFS + T_{ACK}(m_c) + DIFS$) are defined in IEEE 802.11a/b WLAN standard. In addition, $T_{DATA}(l, m_a)$ is the transmission time for a data frame with payload size l using PHY mode m_a, and $T_{ACK}(m_c)$ is the transmission time of an acknowledgement (ACK) control frame using PHY mode m_c. The values of $T_{DATA}(l, m_a)$ and $T_{ACK}(m_c)$ can be specified according to the IEEE 802.11a WLAN standard.

In the wireless relay link between two APs, the data rate and the transmission PHY mode m_a will be affected by the hop distance, i.e., the separation distance d_i between APs. In general, the radio signal suffers from path loss, shadowing as well as multipath fading. Considering these radio channel effects along with a proper fading margin, we assume that the average reception ranges for eight PHY modes in the IEEE 802.11a WLAN are D_j, $j = 1, 2, \ldots, 8$, where $D_1 > D_2 > \ldots > D_8$. In principle, two APs with a shorter separation distance can transmit at a higher data rate. Therefore, the transmission PHY mode m_a will be determined according to the separation distance d_i between two APs, i.e.,

$$m_a = j, \text{ if } D_{j+1} < d_i \leq D_j \ . \tag{18}$$

In the wireless access link between AP and user terminal, the IEEE 802.11b WLAN is used. Therefore, the successful frame transmission time T_S and collision duration T_C are expressed as

$$\begin{aligned} T_S &= T_{DATA}(l) + \delta + SIFS \\ &\quad + T_{ACK} + \delta + DIFS, \qquad (19) \\ T_C &= T_{DATA}(l) + \delta + EIFS. \qquad (20) \end{aligned}$$

B. Throughput

The MAC throughput is influenced by the backoff time. Consider a binary exponential backoff procedure with the initial backoff window size of W. Let p_u be the unsuccessful transmission probability detailed in (9), and m_{bk} be the maximum backoff stage. The average backoff time can be calculated by

$$\begin{aligned} \overline{B_k} &= (1 - p_u)\frac{W-1}{2} + p_u(1-p_u)\frac{2W-1}{2} + \cdots \\ &\quad + {p_u}^{m_{bk}}(1-p_u)\frac{2^{m_{bk}}W - 1}{2} \\ &\quad + {p_u}^{(m_{bk}+1)}(1-p_u)\frac{2^{m_{bk}}W-1}{2} + \cdots \\ &= \frac{[1 - p_u - p_u(2p_u)^{m_{bk}}]W - (1-2p_u)}{2(1-2p_u)} \ . \qquad (21) \end{aligned}$$

Since a node transmits data frames every $(\overline{B_k} + 1)$ slots on average [11], the transmission probability τ for a node can be written as

$$\tau = \frac{1}{\overline{B_k} + 1} = \frac{2}{1 + W + p_u W \sum_{i=0}^{m_{bk}-1}(2p_u)^i} \ . \tag{22}$$

From (9) and (22), we can obtain the unique solution of τ and p_u for a given idle probability P_0 of a node. The idle probability P_0 will be derived by the following queueing model.

Figure 3 illustrates the proposed discrete-time queueing model for a node (access point or user terminal), where the state variable s represents the number of frames queued in the node. As defined in Section IV-A, in each effective time slot one node can successfully transmit its data frame with probability ν_1. Accordingly, the total contention delay spent for a frame (i.e., the frame service time) will be a geometric random variable with the mean of $1/\nu_1$ effective time slots. In a multi-hop network, this phenomenon means that the arrival process of relayed traffic is also Markovian since the inter-arrival time of relayed traffic is geometrically distributed. Let l be the payload size of a data frame. It is reasonable to assume that the frame arrivals at one node follow a Poisson process with a rate of $\lambda = R_C/l$ frames/s. Here, R_C is the total carried traffic load of the considered node, which will be detailed as follows.

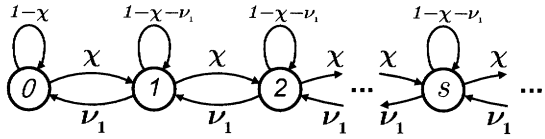

Fig. 3. State transition diagram for a node (access point or user terminal), where the state variable s is the number of frames queued at the node.

Specifically, in the wireless access link between AP and user terminal, the carried traffic load of a user equals the demanded traffic, i.e., $R_C = R_D$. Moreover, since all the data traffic will be forwarded toward the central access point via wireless relays, the carried traffic load of each AP will include the local traffic from users within the cell and the forwarding traffic from other APs. Thus, in the wireless relay link between AP_i and AP_{i-1}, the carried traffic load $H_{r,i}$ of AP_i is equal to the aggregated traffic from AP_i, AP_{i+1}, $\ldots$, and AP_n. That is,

$$H_{r,i} = \sum_{j=i}^{n} k_j R_D = \sum_{j=i}^{n} 2 r_j D_M R_D, \tag{23}$$

where $k_j = 2r_j D_M$ is the total number of users in the cell of AP_j and D_M is user density.

From above considerations, the state-transition probabilities for the queue model can be defined as

$$\begin{aligned} p_{s,s+1} &= \chi = \lambda T_v, \\ p_{s,s-1} &= \nu_1, \\ p_{s,s} &= 1 - \chi - \nu_1. \end{aligned} \tag{24}$$

Then, we can obtain the state probability $P_s = \rho_c^s(1 - \rho_c)$, where $\rho_c = \chi/\nu_1$ and the idle probability of a node can be given as $P_0 = (1 - \rho_c)$.

With the effective time slot concept, the relay link capacity $H(d_i)$ between two APs and the access link capacity $R(r_i)$ between AP and one user terminal can be respectively calculated by

$$\frac{\nu_1 T_1}{T_v} \cdot \frac{l}{T_S} = \frac{\nu_1 l}{T_v} \ , \tag{25}$$

where ν_1 is the probability that one node successfully sends a frame in an effective slot, l is the frame payload size, $T_1 = T_S$ is the time duration for successful frame transmission, and T_v is the average duration of an effective slot. From (8), and (10)-(15), ν_1, T_v, and P_s can be calculated by using an iterative method.

TABLE I

SYSTEM PARAMETERS FOR NUMERICAL EXAMPLES.

Symbol	Item	Nominal value
l	Frame payload size,	1500 bytes
D_M	User density	0.05 users/m
R_D	Traffic demand of each user	0.4 Mbps
r_{MIN}	Min. of cell radius	75 m
r_{MAX}	Max. of cell radius	300 m
d_{MAX}	Max. distance between APs	300 m

C. Delay and Delay Fairness

By Little's formula, the average frame delay (i.e., the sojourn time for a frame spent in a node) can be expressed as

$$\frac{\sum_{s=0}^{\infty} sP_s}{\chi} = \frac{1}{\nu_1(1-\rho_c)}, \qquad (26)$$

where $\rho_c = \chi/\nu_1$. In (26), note that both the access contention delay and queueing delay at the node are included.

In a multi-hop network, the overall frame delay is defined as the elapsed time from the frame generated at the source node to the successful reception by the central AP_0. Let $D_d(i)$ be the frame delay in the wireless access link from user to AP_i; and $D_r(i)$ be the frame delay in the wireless relay link between AP_i and AP_{i-1}. Both $D_d(i)$ and $D_r(i)$ are calculated by (26). Then, the overall frame delay for the user in the cell of AP_i can be expressed as

$$D_T(i) \;=\; D_d(i) + \sum_{j=1}^{i} D_r(j). \qquad (27)$$

Then, we evaluate the delay fairness for the considered ITS wireless mesh network. Let x_j be the overall frame delay experienced by the jth user and N be the total number of users in a cluster of APs. Referring to [12], we define the delay fairness index DFI for this ITS WMN as

$$\begin{aligned} DFI &= \frac{(\sum_{j=1}^{N} x_j)^2}{N\sum_{j=1}^{N} x_j^2} \\ &= \frac{[k_0 D_T(0) + 2\sum_{i=1}^{n} k_i D_T(i)]^2}{N[k_0(D_T(0))^2 + 2\sum_{i=1}^{n} k_i (D_T(i))^2]}, \end{aligned} \qquad (28)$$

where $k_i = 2r_i D_M$ is the number of users in the cell of AP_i, D_M is the user density, and n is the number of APs in the single side of the cluster. Clearly, the total number of user in a cluster of APs is $N = k_0 + 2\sum_{i=1}^{n} k_i$. By (28), $DFI = 1$ is achieved for perfect fairness, while $DFI = 1/N$ for absolute unfairness.

VI. NUMERICAL RESULTS

In this section, we investigate the interactions among delay, capacity, and coverage in the ITS wireless mesh network. This paper considers a simple case where all the cell radii for APs are the same, i.e., $r_i = r$, and then $d_i = d = 2r$. The system parameters are summarized in Table I. The user density is assumed to be $D_M = 0.05$ (users/m). The maximum of cell radius of each AP is limited to $r_{MAX} = 300$ (m), and thus all the users can communicate with the APs at the data rate of 11 Mbps. In the wireless relay link between two APs using the IEEE 802.11a WLAN, the ACK frames are transmitted with PHY mode $m_c = 1$ for reliability. Referring to the measured results in [13], the corresponding average reception ranges for eight PHY modes in the IEEE 802.11a WLAN are $D_j = \{300, 263, 224, 183, 146, 107, 68, 30\}$ (m). It is true that these reception ranges vary for different environments. Nevertheless, the proposed optimization approach is general enough to evaluate the performances for different ITS wireless mesh networks by adopting various reception ranges.

Figure 4 illustrates the capacity (total throughput) and coverage for a cluster of $(2n+1)$ APs under different delay requirements. In the figure, $n = 5$ can achieve the optimal capacity of 35 (Mbps) and coverage of 1748 (m) if without delay requirement. If setting the delay fairness requirement $DF_{req} = 0.9$, the optimal capacity and coverage for a cluster remain unchanged for $n = 5$, while for $n = 4$ the optimal capacity decreases from 32 to 31.8 (Mbps). In addition, one can observe that the delay requirement $D_{req} = 0.2$ (s) can be fulfilled at the expense that the optimal capacity for a cluster decreases to 33.7 (Mbps) with a coverage of 1683 (m) at $n = 5$. In this figure, it is obvious that the more the number n of APs, the better the capacity and coverage of a cluster. However, the optimal solution is determined by the constraints on the link capacity, reception ranges, and delay requirements.

In Fig. 5, the overall frame delay $D_T(n)$ for the user in the cell of AP_n versus the cell radius r is shown. This figure shows that the frame delay can be ensured by appropriately shortening the cell radius r. For example, the frame delay can be dramatically reduced from hundreds of seconds to 0.1 (s), while the cell radius r merely decreases from 79.4 to 79.1 (m) at $n = 5$. In this ITS WMN, the phenomenon of excessive delay is due to the fact that the wireless relay link is fully utilized (especially for the link between AP_1 and AP_0), if without any delay constraint. In the meanwhile, for $\rho_c \approx 1$, the frame delay grows toward a very large value [14], as shown in (26). However, by shrinking the cell radius and then the separation distance between APs to raise link capacity, the delay performance can be improved at the cost of lower capacity and coverage of a cluster as shown in Fig. 4.

In Fig. 5, it is also shown that the maximum cell radius r of each AP decreases if the number of n increases. In this ITS wireless mesh network, the total throughput for a cluster also increases while n increases, as illustrated in Fig. 4. For handling the increment of forwarding traffic as n increases, the separation distance d between APs (and then the cell radius r) should be reduced to improve the relay link capacity. Due to the constraint on the cell radius as in (6), i.e., $r = d/2 \geq r_{MIN}$, there will exist a maximum value of n. In this example, the maximum allowable number of APs

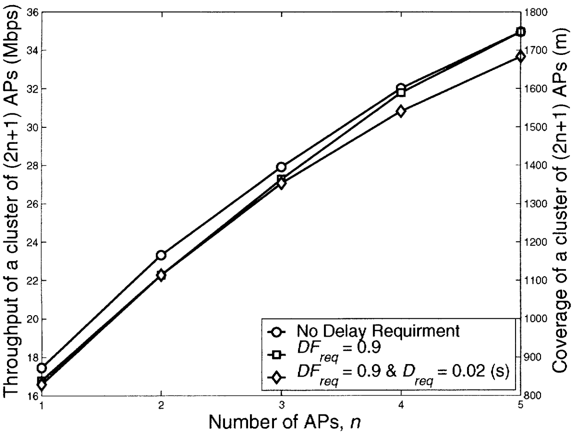

Fig. 4. Capacity (total throughput) and Coverage for a cluster of $(2n+1)$ APs, under different delay requirement.

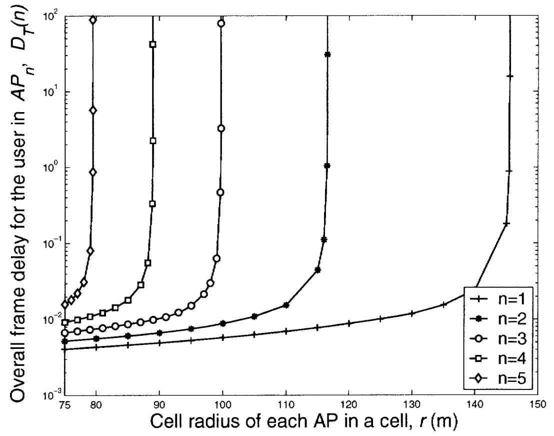

Fig. 5. Overall frame delay $D_T(n)$ for the user in the cell of AP_n versus the cell radius r.

in a cluster is $n = 5$.

Figure 6 shows that the achieved delay fairness index DFI versus the cell radius r of each AP. On can observe that the delay fairness degrades as the cell radius r or the number n of APs in a cluster increases. In this ITS WMN, given the cell radius r, the larger n will cause higher traffic load and longer delay in the relay link between APs as shown in Figs. 4 and 5. Accordingly, the frame delay for the users in AP_1, $AP_2, \ldots$, and AP_n increase, while that for the users in AP_0 remain unchanged. Therefore, the delay fairness downgrades as n is increasing. In the same manner, the increment of r will also lead to higher delay in the relay link between APs, thereby degrading the delay fairness.

VII. CONCLUSIONS

In this paper, we have investigated the access point placement problem for the ITS wireless mesh network. The presented mesh network architecture is appealing for the ITS applications due to less cabling engineering work and lower infrastructure cost. An optimization approach to maximize the capacity and coverage for the considered ITS WMN has been also presented.

In the presented ITS WMN, the frequency planning has been employed to effectively utilize the available multiple channels. We have also proposed a PHY/MAC cross-layer analytical mode to evaluate the delay and throughput of this ITS WMN. On top of the cross-layer model, the MINLP optimization approach helps to analytically determine the optimal number of APs in a cluster and the associated cell radius for each AP subject to the tradeoffs among delay, throughput, and coverage.

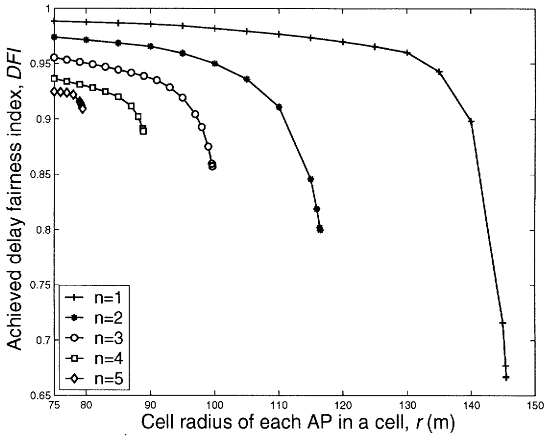

Fig. 6. Achieved delay fairness index DFI versus the cell radius r of each AP.

REFERENCES

[1] R. Pabst *et al.*, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Commun. Mag.*, vol. 42, no. 9, pp. 80–89, Sept. 2004.

[2] *MeshDynamics website*, http://www.meshdynamics.com.

[3] R. C. Rogrigues, G. R. Mateus, and A. A. F. Loureiro, "On the design and capacity planning of a wireless local area network," in *Proc. IEEE/IFIP NOMS'00*, pp. 335–348, Apr. 2000.

[4] M. Amenetsky and M. Unbehaun, "Coverage planning for outdoor wireless LAN systems," in *Proc. IEEE Zurich Seminar on Broadband Communications*, pp. 49–1–6, Feb. 2002.

[5] M. Kobayashi *et al.*, "Optimal access point placement in simultaneous broadcast system using OFDM for indoor wireless LAN," in *Proc. IEEE PIMRC'00*, pp. 200–204, Sept. 2000.

[6] T. Jiang and G. Zhu, "Uniform design simulated annealing for optimal access point placement of high data rate indoor wireless LAN using OFDM," in *Proc. IEEE PIMRC'03*, pp. 2302–2306, Sept. 2003.

[7] Y. Lee, K. Kim, and Y. Choi, "Optimization of AP placement and channel assignment in wireless LANs," in *Proc. IEEE LCN'02*, pp. 831–836, Nov. 2002.

[8] J.-H. Huang, L.-C. Wang, and C.-J. Chang, "Deployment strategies of access points for outdoor wireless local area networks," in *Proc. IEEE VTC'05*, May 2005.

[9] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Select. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[10] X. J. Dong and P. Variya, "Saturation throughput analysis of IEEE 802.11 wireless LANs for a lossy channel," *IEEE Commun. Lett.*, vol. 9, no. 2, pp. 100–102, Feb. 2005.

[11] Y. C. Yay and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol," *Wireless Network*, pp. 159–171, Jul. 2001.

[12] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," *Technical Report DEC-TR-301, Digital Equipment Corporation*, Sept. 1984.

[13] CISCO, *Cisco Aironet 1200 Series access point.* [Online]. Available: http://www.cisco.com/en/US/products/hw/wireless/ps430/index.html

[14] D. Gross and C. M. Harris, *Fundamentals of Queueing Theory*, 3rd ed. New York: John Wiley & Sons, Inc, 1998.