DOI: 10.3745/KIPSTC.2009.16C.6.791

정적 애드혹 네트워크 멀티캐스트에서 지연 시간과 에너지 소비의 트레이드오프를 위한 적응 오버레이 트리

모 상 만†

요 약

무선 애드혹 네트워크에서의 멀티캐스팅은 그룹 내 여러 노드의 협력을 필요로 하는 많은 응용 분야에 기본적인 기능이다. 일반적인 접근 방법은 오버레이 트리를 구성하고 멀티캐스트 패킷을 트리 상의 여러 수신 노드에게 전달하는 것이다. 본 논문에서는 정적 노드로 구성된 무선 애드혹 네트워크에서 지연 시간 및 에너지를 고려하는 멀티캐스트를 위한 적응 오버레이 트리(AOT)를 제안한다. 트레이드오프(tradeoff) 함수를 정의하고 AOT 생성을 위한 새로운 알고리즘을 고안한다. 보통 지연 시간과 에너지 소비에 대한 요구 사항은 응용 분야의 종류에 따라 다르다. 트레이드오프 함수에서 파라미터를 조절함으로써, 서로 다른 종류의 응용분야에 따라 다른 AOT를 적응적으로 선택할 수 있게 된다. 각 AOT는 $O(ke)$ 시간에 생성된다. 여기서, e는 네트워크 내의 무선 링크의 수이고 k는 멀티캐스트 그룹 내의 멤버 노드의 수이다. 시뮬레이션 결과에 의하면, AOT는 가장 빠른 트리(지연 시간이 가장 중요한 설계 요소인 경우)와 가장 에너지 효율적인 트리(에너지 소비가 일차적인 관심사인 경우) 사이의 트레이드오프를 적응적으로 제공한다. 즉, 네트워크 운용 환경에 따라 여러 AOT 중의 하나를 적절하게 선택할 수 있게 해준다.

키워드 : 애드혹 네트워크, 멀티캐스트, 오버레이 트리, 지연 시간, 에너지, 트레이드오프

Adaptive Overlay Trees for Tradeoffs between Delay and Energy Consumption in Multicast on Static Ad Hoc Networks

Sangman Moh†

ABSTRACT

Multicasting is fundamental to many ad hoc network applications requiring collaboration of multiple nodes in a group. A general approach is to construct an overlay tree and to deliver a multicast packet to multiple receivers over the tree. This paper proposes *adaptive overlay trees* (*AOTs*) on wireless ad hoc networks of static nodes for delay- and energy-efficient multicast. A tradeoff function is derived, and an algorithm for AOT construction is developed. Note here that the requirements of delay and energy consumption may vary with different classes of applications. By adjusting parameters in the tradeoff function, different AOTs can be adaptively chosen for different classes of applications. An AOT is constructed in $O(ke)$ time where e is the number of wireless links in a network and k is the number of member nodes in a multicast group. The simulation study shows that AOT adaptively provides tradeoffs between the fastest multicast (which is the choice if delay is the most important factor) and the most energy efficient multicast (which is used when energy consumption is the primary concern). In other words, one of AOTs can be appropriately chosen in accordance with the operation requirement.

Keywords : Ad Hoc Network, Multicast, Overlay Tree, Delay, Energy, Tradeoff

1. Introduction

Infrastructure-free *wireless ad hoc networks* [1, 2] have attracted a lot of attention with the advent of inexpensive wireless network solutions [3],[4]. In general, they can be categorized into mobile and static networks according to whether nodes are mobile or not. In this paper, we focus on wireless ad hoc networks of static nodes, a typical domain of which is wireless sensor networks [5].

Wireless ad hoc networks pose many challenging problems. With limited bandwidth and restricted battery capacity, *delay* and *energy efficiency* may be the most

※ A preliminary version of this work was presented at the Fourth International Conference on Ubiquitous Intelligence and Computing (UIC 2007), Hong Kong, July 2007 [22]. This research was supported in part by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute for Information Technology Advancement) (IITA-2009-C1090-0904-0005).
† 종신회원 : 조선대학교 컴퓨터공학부 교수
논문접수 : 2009년 8월 24일
수 정 일 : 1차 2009년 10월 16일
심사완료 : 2009년 10월 21일

important design criteria because the communication delay can be a bottleneck of collaborative tasks and the remaining energy of battery determines the system lifetime. The communication delay is a primary performance metric in many applications. On the other hand, the energy efficient network protocols are important in most scenarios since the energy consumption due to wireless communication may represent more than half of total system energy consumption [6]. However, it is impractical to minimize both delay and energy consumption simultaneously. As an extreme approach, for example, minimum connected dominating set can be considered [7] to save energy, but it may result in impractically poor delay. Therefore, the engineering tradeoff between delay and energy consumption is necessarily required in many practical applications.

This paper exploits the tradeoff of delay and energy consumption in multicasting on wireless ad hoc networks of static nodes. *Multicasting* has been extensively studied for wireless ad hoc networks for many years [8-15] because it is fundamental to many applications requiring collaboration of multiple nodes in a group. However, most works have been devoted to scenarios of mobile nodes [16]. In general, amulticast packet is delivered to multiple receivers through a network structure such as *overlay tree*. In the conventional overlay trees which are based on join messages [8], however, the number of nodes involved (which is associated with energy consumption) as well as the tree height (which is associated with delay) is not controllable and sometimes is given by chance because a join message may traverse different paths according to the different network status such as medium contention and network load.

In this paper, *adaptive overlay trees* (*AOTs*) are proposed for wireless ad hoc networks of static nodes. A tradeoff function is derived, and an algorithm for AOT construction is developed. Note here that the requirements of delay and energy consumption may vary with different classes of applications. By adjusting parameters in the tradeoff function, different AOTs can be adaptively chosen for different classes of applications in terms of delay and energy consumption. The proposed function f: $(\alpha, \beta) \rightarrow \text{AOT}(\alpha, \beta)$ provides a wide range of tradeoffs between the most energy efficient overlay tree *(i.e.,* AOT(1, 0)*)* and the fastest overlay tree *(i.e.,* AOT(0, 1)*)* by adjusting parameters α and β. The two parameters α and β are nonnegative integers and correlated with each other such that if $\alpha > 0$ and $\beta > 0$, $\alpha\beta$ is α or β; otherwise, $\alpha + \beta = 1$. AOT(α, β) is a breadth-first spanning tree (BT) with $\min_{i\in[1,k]} E_i^{\alpha} T_i^{\beta}$ among k BTs for a multicast group with k members, where E_i and T_i are the normalized energy consumption and delay for a multicast in BT_i, respectively. Note here that the product of energy consumption and delay is used for tradeoffs between energy consumption and delay. One of various AOTs can be appropriately chosen in accordance with the operation requirement. That is, when delay is more important than energy consumption, AOT(0, 1) can be employed while AOT(1, 0) can be used if energy performance is a critical factor. AOT (1, 1) can be taken into account as a *central tradeoff* when delay and energy consumption are equally important. The proposed *AOT construction algorithm* makes every member of a multicast group construct the same overlay tree in a distributed manner and, thus, no dissemination of the overlay tree is necessary. For a multicast group with k member nodes in a network of e wireless links, an AOT is constructed in $O(ke)$ time. The performance study shows that AOT(0, 1) has about 60 percent shorter delay than AOT(1, 0) while AOT(1, 0) consumes up to 45 percent less energy than AOT(0, 1) in the given simulation environment. It is also shown that AOT(1, 1) is the middle point of AOT(0, 1) and AOT(1, 0) in terms of tradeoff. More sophisticated tradeoffs are possible by adjusting the two parameters α and β.

The rest of the paper is organized as follows: Overlay trees for multicast, power saving mechanism and energy model are briefly described in the following section. Section 3 presents the proposed AOT in detail. After the tradeoff function is derived, the AOT construction algorithm is presented with examples and it is then analyzed in terms of complexity. The performance evaluation using simulation is discussed and the tradeoff effect is validated in Section 4. Finally, the conclusions are covered in Section 5.

2. Preliminaries

This section briefly describes the fundamental overview of overlay tree-based multicast, power saving mechanism and basic energy model for wireless ad hoc networks.

2.1 Overlay Trees for Multicast

As presented in Introduction, a multicast packet is delivered to multiple receivers through a network structure such as *overlay tree* rather than using naïve multiple point-to-point transmissions. The tree-based multicast protocols basically construct an overlay tree structure to deliver multicast messages. In the conventional overlay trees which are based on join messages [8], however, the number of nodes involved (which is associated with energy consumption) as well as the tree height (which is associated with delay) is not controllable and sometimes is given by chance because a join message may traverse different paths according to the different network status such as medium contention and network load. In wireless ad hoc networks of static nodes, every member node in a multicast group can determine an overlay tree at the group creation time and agree on the same overlay tree for the same root node since neither node mobility nor network topology change is assumed. Note here that any node failure during network operation is not taken into account throughout the paper.

Tree-based multicast can be further classified as either *per-source tree multicast* or *shared tree multicast* [17]. In the per-source tree approach, each source has to construct a separate overlay tree rooted at itself. Therefore, there will be as many trees as the number of sources and a significant amount of control overhead is required to maintain them. On the other hand, shared tree multicast has lower control overhead because it maintains only a single tree shared by all sources [18]. A multicast packet is (unicast) delivered to the root node first and then (multicast) delivered to all group members along the tree structure. However, the path is not necessarily optimal, and the root node is easily overloaded due to the sharing of the single tree. The proposed AOTs uses a shared tree as a fundamental structure to derive the delay- and energy-efficient overlay tree.

2.2 Power Saving Mechanism and Energy Model

Recent wireless LAN specifications usually provide power saving mechanisms for energy-constrained applications. For example, Bluetooth network interface operates in time-division multiplexing (TDM), where a master node controls up to seven neighboring slaves. Each slave node has a designated time slot for communication and can sleep in other time slots to conserve energy [19]. In IEEE 802.11 standard, a master node, or called an *access point (AP)*, periodically sends a beacon packet followed by *TIM (Traffic Indication Map)* that indicates the desired receivers. Each slave wakes up when beacons are sent and checks whether it is the intended receiver. If it is not, it sleeps again; otherwise, it stays awake to receive data [4].

IEEE 802.11 ad hoc power saving mechanism operates in a similar fashion but without APs. Any node requiring communication sends beacons to synchronize with nodes in its vicinity. A beacon period starts with *ATIM (ad hoc TIM)*, during which all nodes listen, and the pending traffic is advertised. Each node turns itself on or off depending on the advertised traffic [4]. Unlike the AP-based mechanism, packets are buffered at the sender node and are directly transmitted to the receiver node. This power saving mechanism reduces the available channel capacity because useful traffic cannot be transmitted during the ATIM window. In addition, it also suffers from longer packet delay because each intermediate node needs to buffer the packet until the next beacon period.

The abovementioned power saving mechanisms favor unicast over broadcast communication. For unicast, all other neighbors do not need to wake up and thus can save energy. However, if a sender has more than one receiver, it must resort to broadcast that results in many unnecessary receptions as well as wasted energy.

Let the total energy consumption per unit multicast packet be denoted as E, which includes the transmission energy (E_{TX}) as well as the energy required to receive the transmission (E_{RX}). This paper only considers data packets for simplicity. According to the first-order radio model [20], $E = E_{TX} + E_{RX} = N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX}$, where N_{TX} and N_{RX} are the number of transmissions and the number of receives, respectively, and e_{TX} and e_{RX} are the energy consumed to transmit and receive a unit multicast message via a wireless link, respectively [1)]

Let Γ_+, Γ_1, and Γ_0 be the set of tree nodes with more than one receiver, with exactly one receiver, and with no receiver, respectively. Thus, the set of all tree nodes is $\Gamma = \Gamma_+ + \Gamma_1 + \Gamma_0$. It is straightforward to show that, in an overlay tree for multicast, N_{TX} is the number of tree nodes except the leaf receiver nodes (*i.e.,* root and intermediate nodes) and N_{RX} is $\sum_{i\in\Gamma_+} f_i + |\Gamma_1|$, where f_i is the number of neighbors of node i.

3. Adaptive Overlay Trees

This section presents the proposed adaptive overlay trees (*AOTs*) for wireless ad hoc networks of static nodes. The function for tradeoffs of delay and energy consumption is derived first and the *AOT construction algorithm* is then discussed with some examples.

1) In reality, e_{TX} and e_{RX} are slightly different. For example, e_{TX} = 300mA and e_{RX} = 250mA for WaveLAN-II from Lucent [3].

3.1 Function for Tradeoffs

Given a multicast group with kmembers, kbreadth-first spanning trees (BTs) can be generated rooted at every member node in a distributed manner and labeled as BT_1, BT_2, ⋯, BT_k. For providing tradeoffs between the most energy efficient tree and the fastest tree, given tradeoff parameters α and β, a *adaptive overlay tree (AOT)* called AOT(α, β) is defined as follows:

Definition 1. AOT(α, β) is a BT with $\min_{i\in[1,k]} E_i^{\alpha} T_i^{\beta}$ among k BTs for a multicast group with k members, where E_i and T_i are the normalized energy consumption and delay for a multicast in BT_i, respectively, and and are nonnegative integers and correlated with each other such that if $\alpha > 0$ and $\beta > 0$, $\alpha\beta$ is α or β; otherwise, $\alpha + \beta = 1$.

The correlation between the two parameters and is summarized in Table I. The following Theorem 1 with proof shows that f:(α, β) → AOT(α, β) is a function providing prudent tradeoffs between the most energy efficient AOT and the fastest AOT.

Theorem 1. f:(α, β) → AOT(α, β) is a function providing tradeoffs between the most energy efficient AOT (*i.e.*, AOT(1, 0)) and the fastest AOT (*i.e.*, AOT(0, 1)), where α and β are nonnegative integers and correlated with each other such that if $\alpha > 0$ and $\beta > 0$, is α or β; otherwise, $\alpha + \beta = 1$.

〈Table I〉 Correlation between two tradeoff parameters α and β.(Selection criteria mean the criteria to choose one of k BTs and further explained in Section 3.2 with some examples.)

Tradeoff parameters		AOT(α, β)	Selection criteria
α	β		
1	0	AOT(1, 0)	E
0	1	AOT(0, 1)	T
1	1	AOT(1, 1)	ET
2	1	AOT(2, 1)	E^2T
3	1	AOT(3, 1)	E^3T
4	1	AOT(4, 1)	E^4T
…	…	…	…
1	2	AOT(1, 2)	ET^2
1	3	AOT(1, 3)	ET^3
1	4	AOT(1, 4)	ET^4
…	…	…	…

Proof. According to the correlation between two nonnegative integer parameters α and β shown in Table I, the most energy efficient AOT, AOT(1, 0), does not consider delay but energy consumption while the fastest AOT, AOT(0, 1), does vice versa. On the other hand, AOT(1, 1) considers both energy consumption and delay equally and, thus, it is a tradeoff between AOT(1, 0) and AOT(0, 1). If $\alpha \geq 2$, then $\beta = 1$ by Definition 1 and possible AOTs are AOT(2, 1), AOT(3, 1), ⋯, which pay more attention to energy consumption with larger and are tradeoffs between AOT(1, 1) and the most energy efficient AOT, AOT(1, 0). On the contrary, if $\beta \geq 2$, then $\alpha = 1$ by Definition 1 and possible AOTs are AOT(1, 2), AOT(1, 3), ⋯, which pay more attention to delay with larger and are tradeoffs between AOT(1, 1) and the fastest AOT, AOT(0, 1). Therefore, f: (α, β) AOT(α, β) is a function providing tradeoffs between AOT(1, 0) and AOT(0, 1). **Q.E.D.**

According to Theorem 1 and the associated Table I, AOT(α_2, β) is more energy efficient than AOT(α_1, β) if $\alpha_1 < \alpha_2$ because it pays more attention to energy consumption. Likewise, AOT(α, β_2) is faster than AOT(α, β_1) if $\beta_1 < \beta_2$ because it pays more attention to delay. As a result, it can be easily inferred that the order of energy efficiency is AOT(1, 0) > AOT(∞, 1) > ⋯ > AOT(3, 1) >AOT(2, 1) > AOT(1, 1) > AOT(1, 2) > AOT(1, 3) > ⋯ AOT(1, ∞) > AOT(0, 1) while that of delay performance is vice versa.

3.2 Algorithm for AOT Construction

Given two parameters and , the primary goal of our study is to construct an adaptive overlay tree, AOT(α, β), with $\min_{i\in[1,k]} E_i^{\alpha} T_i^{\beta}$ among k BTs for a multicast group with k members in a wireless ad hoc network of static nodes. The network can be represented with a graph $G = (V, E)$ in which each vertex in $V(G)$ is a node and each edge in $E(G)$ is a wireless link between nodes. Under the assumption that all the nodes have the same capability such as transmission power and bandwidth over the network, multicast delay and energy consumption can be normalized by the height of the overlay tree and the value of $N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX}$ for a multicast, respectively, if medium collision and traffic congestion are negligible. Given a multicast group of k members, k BTs can be constructed at every member node in a distributed manner. Of them, a tree with $\min_{i\in[1,k]} E_i^{\alpha} T_i^{\beta}$ is selected as the overlay tree.

Fig. 1 describes the detailed steps of the AOT

// AOT (Adaptive Overlay Tree) at every member node

/* Let $G = (V, E)$ be a wireless ad hoc network of static nodes represented as a graph of node set $V(G)$ and link set $E(G)$, $M = \{m_0, m_1, \ldots, m_{k-1}\}$ be the set of k member nodes, and α and β be tradeoff parameters constrained by Definition 1.
*/

1: $S = \{\}$; // keep track of selected BTs (initially, $|S| = 0$)

2: Generate k BTs (i.e., $BT_1, BT_2, \ldots, BT_k$) rooted at every member node for M over G, and insert them into S; // $|S| = k$

3: Select BTs with $\min_{i \in [1,k]} E_i^{\alpha} T_i^{\beta}$ as AOT(α, β), where E_i and T_i are the normalized energy consumption ($N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX}$) and delay (tree height) for a multicast in BT_i, respectively, and α and β are nonnegative integers and correlated with each other such that if $\alpha > 0$ and $\beta > 0$, $\alpha\beta$ is α or β; otherwise, $\alpha + \beta = 1$;

4: Delete the remaining BTs from S;

5: If ($|S| > 1$) { // in case there is a tie

6: Select BTs with the minimum number of transmissions;

7: Delete the remaining BTs from S;

8: If ($|S| > 1$) { // in case there is still a tie

9: Select the BT with the root node of the lowest id;

10: Delete the remaining BTs from S;

11: }

12: }

13: Return the selected BT in S; // $|S| = 1$

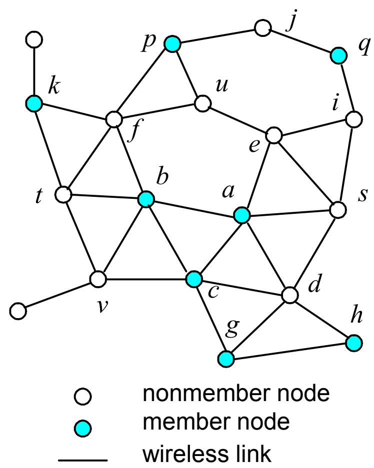
(Fig. 1) The AOT construction algorithm. (Multicast group identifier is not shown for simplicity.)

construction algorithm. The proposed algorithm makes every member node of a multicast group construct the same overlay tree in a distributed manner since no node mobility is assumed and network topology is known at the initial network configuration time and, thus, no network-wide dissemination of the tree is necessary. In other words, every member node runs the algorithm at the group creation time and agrees on the same overlay tree for the same root node. That is, each member node generates k BTs rooted at every member node (line 2 in Fig. 1) and selects BTs with the minimum value of selection criterion given by Definition 1 and Table I and (line 3). If there exist one or more BTs selected, BTs with the minimum number of transmissions (N_{TX}) are selected (lines 5-6) in order to minimize medium collision and network traffic. If there is still a tie, the BT with the root node of the lowest identifier is finally selected (lines 8-9). Note that any node failure during network operation is not taken into account throughout the paper.

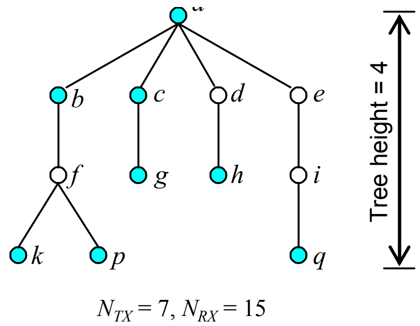
The tradeoff parameters $\alpha$and β can be appropriately chosen in accordance with the operation requirement. For example, when delay is more important than energy consumption, $\alpha = 0$ and $\beta = 1$ can be employed. On the other hand, if energy performance is a critical factor, $\alpha = 1$ and $\beta = 0$ can be used. As a performance tradeoff between delay and energy consumption, $\alpha = 1$ and $\beta = 1$ can be taken into consideration when both delay and energy consumption are equallyimportant. Note that more sophisticated tradeoffs are possible by adjusting the two parameters α and β appropriately as shown in Table I.

3.3 Different Trees for an Example Network

1) Fastest Tree AOT(0, 1): Fig. 2 shows an example wireless ad hoc network consisting of 19 static nodes, where eight shaded nodes are randomly spread member nodes belonging to a multicast group. Fig. 3 shows AOT(0, 1) constructed from the example network in Fig. 2 by the AOT algorithm shown in Fig. 1. Note that AOT(0, 1) is an AOT with the minimum delay for the given multicast group. As shown in Fig. 3, tree height is 4, and N_{TX} and N_{RX} are 7 and 15, respectively. Note here that since the network interface typically accepts only unicast and broadcast addresses, nodes a and f must use broadcast address (resulting in N_{RX} of 15 in total) because they have more than one receiver. Using the overlay tree constructed by the AOT algorithm, four out of 15 receives ($a \rightarrow s$, $f \rightarrow b$, $f \rightarrow t$ and $f \rightarrow u$) are redundantly required. AOT(0, 1) considers the multicast delay first and thus may consume more energy compared to the others.



(Fig. 2) An example of a wireless ad hoc network. (8 members out of 19 nodes are randomly spread over the network.)

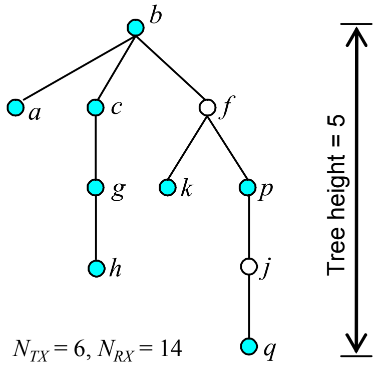


(Fig. 3) AOT(0, 1) constructed from Fig. 2. (12 nodes including 4 nonmember nodes are involved in the overlay tree.)

2) Most Energy Efficient Tree AOT(1, 0): Fig. 4 shows an AOT(1, 0) constructed from the example network in Fig. 2 by the AOT algorithm. Note that AOT(1, 0) is an AOT with the minimum energy consumption for the given multicast group. As shown in Fig. 4, tree height is 5, and N_{TX} and N_{RX} are 6 and 14, respectively. Since the network interface typically accepts only unicast and broadcast addresses, nodes b and f must use broadcast address (resulting in N_{RX} of 14 in total) because they have more than one receiver. Using AOT(1, 0), five out of 14 receives ($b \rightarrow t$, $b \rightarrow v$, $f \rightarrow b$, $f \rightarrow t$ and $f \rightarrow u$) are redundantly required. Since the algorithm considers only energy consumption for AOT(1, 0), it may cause longer multicast delay compared to the others. Obviously, AOT(1,0) consumes less energy than the others and, thus, it may be a useful choice when energy is the primary concern.

As described in Section 2.2, in order to minimize N_{TX}, the number of intermediate nodes should be minimized and, thus, the number of leaf nodes should be maximized. So, a BT is necessarily required while depth-first spanning tree on the other hand is not taken into consideration because it requires more number of transmissions. To minimize N_{RX}, the number of tree nodes with one receiver as well as the number of neighbors of tree nodes with more than one receiver shouldbe minimized. In an overlay tree, the total number of nodes is the sum of the number of member nodes and the number of intermediate nonmember nodes. Thus, the number of intermediate nonmember nodes should be minimized since the number of members is predetermined.

3) Central Tradeoff Tree AOT(1, 1): As the central tradeoff between the fastest tree AOT(0, 1) and the most energy efficient tree AOT(1, 0), AOT(1, 1) is an AOT with the minimum '*energy × time*' (*ET*) value for the given multicast group. The minimum value of ET means



(Fig. 4) AOT(1, 0) constructed from Fig. 2. (10 nodes including 2 nonmember nodes are involved in the overlay tree.)

the minimum value of $(N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX})$×(tree height) for a multicast on the corresponding overlay tree. Of the k BTs rooted at each member node, a tree with the minimum value of $(N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX})$×(tree height) is selectedas the overlay tree. Unlike AOT(0, 1) and AOT(1, 0), AOT(1, 1) uses both energy consumption and multicast delay equally as tradeoff metrics to choose a tree from k candidates.

AOT(1, 1) constructed from the example network in Fig. 2 by the AOT algorithm is the same as Fig. 3, where the value of $(N_{TX} \cdot e_{TX} + N_{RX} \cdot e_{RX})$×(tree height) is 23.4 (= (7 × 0.3 + 15 × 0.25) × 4), because the example network is too small to demonstrate the tradeoff effect of AOT(1, 1). For practically large networks, however, AOT(1, 1) would be different from AOT(0, 1) and AOT(1, 0) and show the tradeoff result as expected. In other words, as a performance tradeoff of energy consumption and multicast delay, AOT(1, 1) may consume less energy than AOT(0, 1) but more energy than AOT(1, 0) while it may result in longer delay than AOT(0, 1) but shorter delay than AOT(1, 0). This will be proved through the simulation later.

3.4 Complexity Analysis

In this subsection, the proposed AOT construction algorithm is analyzed in terms of computational complexity. We assume that the network topology is represented using *adjacency list* [21]. After initialization, each member node generates k BTs rooted at every member node (line 2 in Fig. 1), where k is the number of member nodes in a multicast group, and selects BTs with the minimum value of selection criterion given by Definition 1 and Table I and (line 3 in Fig. 1). Both the lines consume $O(ke)$ time, respectively, where e is the number of wireless linksin the network. Note here that a breadth-first spanning tree is constructed in $O(e)$ time using adjacency list [21]. In case of tie, BTs with the minimum number of transmissions (N_{TX}) are selected (lines 5-6 in Fig. 1) in order to minimize medium collision and network traffic. This step needs just $O(k)$ time because N_{TX} has been calculated above (line 3 in Fig. 1). For the last tie break, the BT with the root node of the lowest identifier is finally selected (lines 8-9 in Fig. 1). It can be completed in $O(k)$ time as well. In summary, an AOT is constructed in $O(ke)$ time.

4. Performance Evaluation

In this section, the performance of the proposed

AOT(α, β) is evaluated via simulation and the tradeoff effect is validated. This paper is motivated by the necessity of tradeoffs between delay and energy consumption and the purpose of the performance evaluation is to verify the tradeoffs in terms of delay and energy consumption. This is because we do not include the simulation of conventional trees in this paper. The network environment, communication model, multicast traffic model, and simulation parameters are described first, and then simulation results are discussed in Section 4.2.

4.1 Simulation Environment

Our performance study simulates and compares the proposed AOT(α, β) in terms of *average multicast delay* (i.e., average end-to-end delay for multicast packets), *total energy consumption*, and *multicast traffic* (i.e., network traffic incurred by multicast packets). For measuring the multicast traffic, each hop-wise transmission of a multicast packet is counted as one transmission.

Our simulation is based on the simulation of static nodes spread over a square area of $1200 \times 1200m^2$ for 15 minutes of simulation time. The radio transmission range is assumed to be $250m$ and a free space propagation channel is assumed with a data rate of 2 Mbps. Note that omni-directional antennas and symmetric radio links are assumed in conjunction with the same transmission power. That is, all the nodes have the same capability over the network. Note here that, given network area A and radio transmission range R, the radio coverage C is $\pi R^2/A$ and the average node connectivity[2] Υ is given by $nC = \pi nR^2/A$, where n is the total number of nodes. For example, if n=20 and R=250 meters in the above network environment, $\Upsilon = \pi \times 20 \times 250^2/1200^2 = 2.7$.

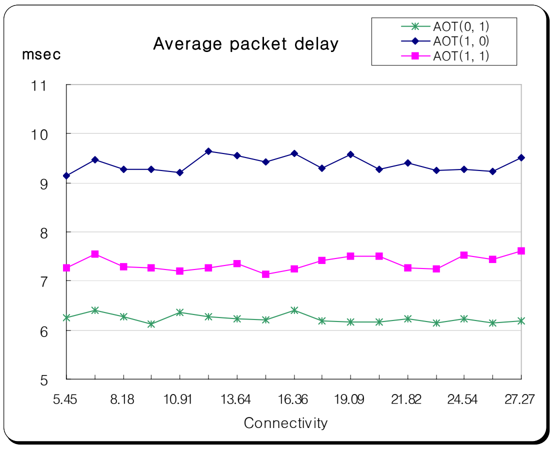
In our simulation, a constant bit rate (CBR) source and its multiple destinations are randomly selected among the nodes. A CBR source sends a 512-byte multicast packet every 100 *msec* during the simulation. For simplicity, we assume a multicast message consists of one data packet. The hop propagation delay including node processing time is assumed to be 2 msec on average in the condition where no congestion is encountered. Packet queueing delay is added as well.

For measuring the three performance metrics of average multicast delay, total energy consumption, and multicast traffic, two simulation factors of *average node connectivity* and *group size* (i.e., the number of member nodes in a multicast group) are varied in a meaningful range; i.e., the average node connectivity from 5.5 (40 nodes) to 27.3 (200 nodes) and the group size from 20 to 200 are applied. The default values are as follows: the group size of 20 and the total number of nodes of 200 (which is equivalent to node connectivity of 27.3).

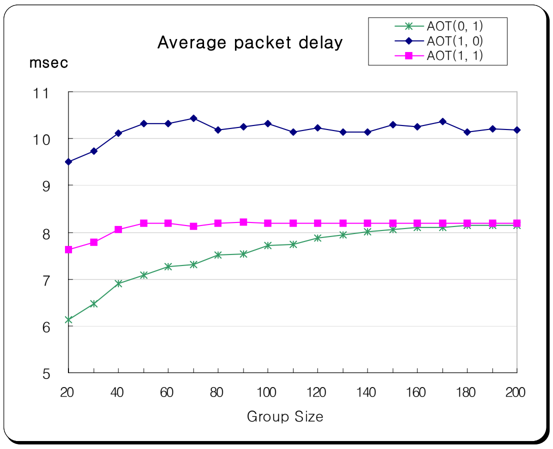
4.2 Simulation Results and Discussion

The following six graphs show the performance impact of the proposed AOT on the node connectivity and the group size of multicast. Comparative discussion based on the simulation results is given in this subsection.

Fig. 5 *shows average multicast delay* for various node connectivity and group size. Note that the multicast delay is end-to-end delay for multicast packets. Varying node connectivity, AOT(0, 1) reveals about 60 percent shorter



(a) Varying node connectivity (Group size: 20)



(b) Varying group size (Node connectivity: 27.3)

(Fig. 5.) Average multicast delay

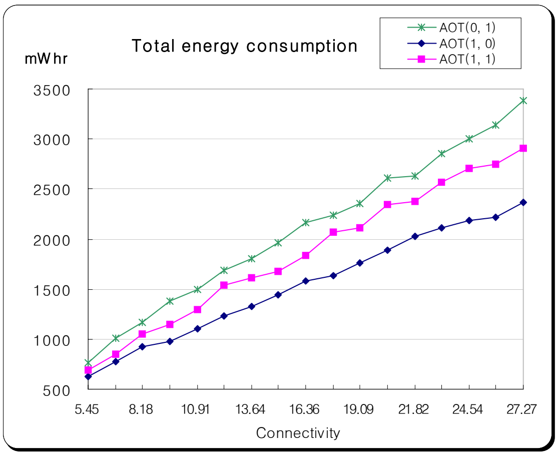
---

2) Node density, defined as the number of nodes per unit area, does not indicate the connectivity between wireless nodes. Node connectivity is a relative measure of the node density compared to the radio transmission range of underlying wireless network interface; *i.e.*, it is the number of neighboring nodes a node can communicate.

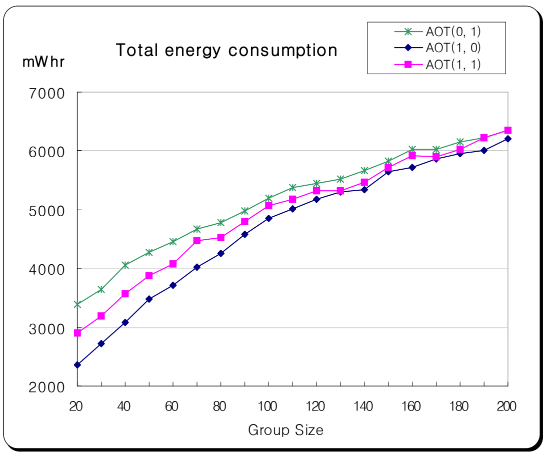
delay than AOT(1, 0) while AOT(1, 1) does about 25 percent longer delay than AOT(0, 1). The multicast delay is almost constant and out of influence on the increased node connectivity since the member nodes in a multicast group are randomly spread over the whole network. It is shown that AOT(1, 1) is a tradeoff of AOT(0, 1) and AOT(1, 0) in terms of multicast delay. Varying group size, the multicast delay is increased with relatively small groups but it is almost saturated with large groups. An interesting point here is that the multicast delay of AOT(1, 1) is almost the same as that of AOT(0, 1) after saturation in Fig. 5(b). This effect is mainly due to the fact that, for large groups, most nodes are involved in a BT and, as a result, the tree height is almost the same and AOT(1, 1) becomes similar to AOT(0, 1).

Fig. 6 shows the network-wide *total energy consumption* for different node connectivity and group size. AOT(1, 0) consumes up to 45 percent less energy than AOT(0, 1). It is also shown that AOT(1, 1) is a tradeoff tree of AOT(0, 1) and AOT(1, 0) in terms of energy consumption. The total energy consumption is almost linearly proportional to group size as well as node connectivity since more nodes are involved directly or indirectly in a multicast. As group size increases, the energy difference of the three AOTs becomes smaller and smaller. This is due to the fact that more and more nodes are involved in multicast operation; e.g., in an extreme case, all the nodes are the member nodes of a multicast group and little difference is shown as expected.

Fig. 7 shows the *multicast traffic* with respect to node connectivity and group size. Note that the multicast traffic is the network traffic incurred by multicast packets and each hop-wise transmission of a multicast packet is counted as one transmission. Varying node connectivity, AOT(0, 1) and AOT(1, 1) reveal about 40 and 20 percent less traffic, respectively, compared to AOT(1, 0). The traffic is somewhat increased with the node connectivity, and it is proportional to relatively small group sizes but

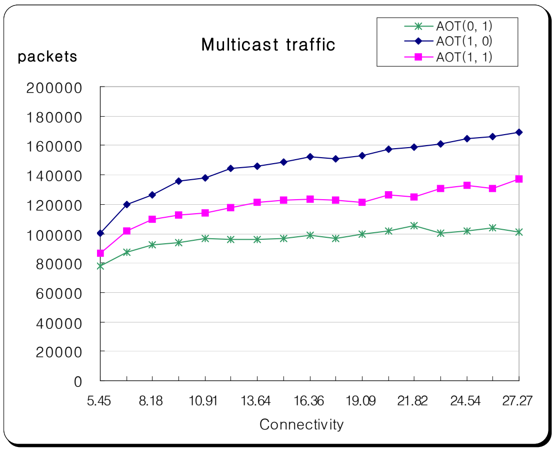


(a) Varying node connectivity (Group size: 20)

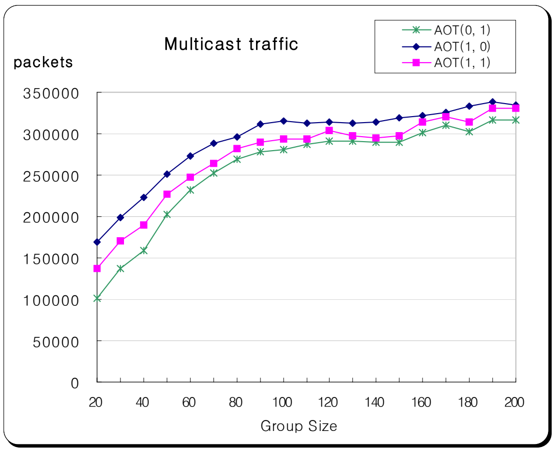


(b) Varying group size (Node connectivity: 27.3)

(Fig. 6) Total energy consumption



(a) Varying node connectivity (Group size: 20)



(b) Varying group size (Node connectivity: 27.3)

(Fig. 7) Multicast traffic

saturated with large ones. As group size increases, the traffic difference of the three AOTs is gradually decreased because there is little difference between BTs and most nodes are involved in multicast operation.

From the simulation results, it is easily inferred that the overlay tree can be constructed in accordance with what the primary concern of multicast operation is. That is, if the multicast delay is the most important factor, AOT(0, 1) should be the choice while AOT(1, 0) is most efficient when energy consumption is the primary concern. Since AOT(1, 1) is a tradeoff between AOT(0, 1) and AOT(1, 0), it is preferable when both multicast delay and energy consumption are moderately taken into consideration. Note that adjusting the two parameters α and β allows more sophisticated tradeoffs between AOT(0, 1) and AOT(1, 0).

5. Conclusions

In this paper, adaptive *overlay trees (AOTs)* on wireless ad hoc networks of static nodes have been proposed as tradeoffs between delay and energy consumption. The proposed function f: $(\alpha, \beta) \rightarrow \mathrm{AOT}(\alpha, \beta)$ provides prudent tradeoffs between the most energy efficient AOT and the fastest AOT by adjusting two parameters α and β. The proposed AOT algorithm makes every member node of a multicast group construct the same overlay tree in a distributed manner and, thus, no dissemination of the overlay tree is necessary. For a multicast group with k member nodes in a network of e wireless links, an AOT is constructed in $O(ke)$ time. According to the performance study, AOT(0, 1) reveals about 60 percent shorter delay than AOT(1, 0) while AOT(1, 0) consumes up to 45 percent less energy than AOT(0, 1). When delay is more important than energy consumption, AOT(0, 1) can be employed while AOT(1, 0) can be used if energy consumption is a critical factor. As a performance tradeoff, AOT(1, 1) is preferable when both multicast delay and energy consumption are equally important. Furthermore, more sophisticated tradeoffs are possible by adjusting the two tradeoff parameters α and β.

As a future work, we are investigating a mixed network environment in which static and mobile nodes exist together and a multicast source may be either static or mobile. Such a dynamic network situation makes group communications more complicated and, thus, more factors should be taken into account in terms of performance and quality of service.

References

[1] C. E. Perkins, *Ad Hoc Networking*, Addison-Wesley Pub. Co., Upper Saddle River, NJ, 2001.

[2] C. Siva Ram Murthy and B. S. Manoj, *Ad Hoc Wireless Networks*, Prentice Hall, Upper Saddle River, NJ, 2004.

[3] A. Kamerman and L. Monteban, "WaveLAN-II: A High-Performance Wireless LAN for the Unlicensed Band," *Bell Labs Technical Journal*, Summer 1997, pp.118-133.

[4] H. Woesner, J. Ebert, M. Schlager, and A. Wolisz, "Power-Saving Mechanisms in Emerging Standards for Wireless LANs: The MAC Level Perspective," *IEEE Personal Communications*, Vol.5, Issue 3, Jun., 1998, pp. 40-48.

[5] A. Hac, *Wireless Sensor Network Designs*, John Wiley & Sons, West Sussex, England, 2003.

[6] R. Kravets and P. Krishnan, "Power Management Techniques for Mobile Communication," *Proc. of Int. Conf. on Mobile Computing and Networking* (*MobiCom*), Oct., 1998, pp.157-168.

[7] T. Acharya and R. Roy, "Distributed Algorithm for Power Aware Minimum Connected Dominating Set for Routing in Wireless Ad Hoc Network," *Proc. of ICPP 2005 Workshop on Wireless and Sensor Networks*, Jun., 2005, pp.387-394.

[8] S.-J. Lee, W. Su, J. Hsu, M. Gerla, and R. Bagrodia, "A Performance Comparison Study of Ad Hoc Wireless Multicast Protocols,"*Proc. of the IEEE Infocom 2000*, Vol.2, Mar., 2000, pp.565-574.

[9] B. Wang and S. K. S. Gupta, "On Maximizing Lifetime of Multicast Trees in Wireless Ad Hoc Networks," *Proc. of 2003 Int. Conf. on Parallel Processing* (*ICPP*), Oct., 2003.

[10] W. Wei and A. Zakhor, "Connectivity for Multiple Multicast Trees Schemes in Ad Hoc Networks," *Proc. of Int. Workshop on Wireless Ad Hoc Networks* (*IWWAN*), Jun., 2004.

[11] P.-J. Wan, G. Calinescu, and C.-W. Yi, "Minimum-Power Multicast Routing in Static Ad Hoc Wireless Networks," *IEEE/ACM Trans. on Networking*, Vol.12, No.3, June, 2004, pp.507-514.

[12] P. Floreen, P. Kaski, J. Kohonen, and P. Orponen, "Lifetime Maximization for Multicasting in Energy-Constrained Wireless Networks," *IEEE Journal on Selected Areas in Communications*, Vol.23, No.1, Jan., 2005, pp.117-126.

[13] Y. Choi, E. Lee, D. Lee, S. Park, F. Yu, and S.-H. Kim, "An Implicit Cluster-Based Overlay Multicast Protocol for Mobile Ad Hoc Networks," *Proc. of IEEE Wireless Communications and Networking Conference* (*WCNC 2007*), Mar., 2007, pp.3507-3512.

[14] Y. Li, S. Peng, and W. Chu, "K-Tree Trunk and a Distributed Algorithm for Effective Overlay Multicast on Mobile Ad Hoc Networks," *Proc. of Int. Symp. on Parallel Architectures, Algorithms, and Networks* (*I-SPAN 2008*), May 2008, pp.

53-58.
[15] S. Moh, C. Yu, B. Lee, and H. Y. Youn, "Energy Efficient Two-Tree Multicast for Mobile Ad Hoc Networks," *Advances in Wireless Ad Hoc and Sensor Networks*, Edited by Maggie Xiaoyan Cheng and Deying Li, Chapter 10, pp. 235~259, Springer, Berlin, Germany, 2008.
[16] S. Moh, S. J. Lee, and C. Yu, "Adaptive Multicast on Mobile Ad Hoc Networks Using Tree-Based Meshes with Variable Density of Redundant Paths," to appear in *Wireless Networks*, 2009.
[17] G. Xylomenos and G. C. Polyzos, "IP Multicast for Mobile Hosts," *IEEE Communications Magazine*, Jan., 1997, pp. 54-58.
[18] C.-C. Chiang, M. Gerla, and L. Zhang, "Adaptive Shared Tree Multicast in Mobile Wireless Networks," *Proc. of IEEE Global Telecomm. Conference* (*GlobeCom*), Vol.3, Nov., 1998, pp.1817-1822.
[19] M. Frodigh, P. Johansson and P. Larsson, "Wireless Ad Hoc Networking - The Art of Networking without a Network," *Ericsson Review*, No.4, 2000, pp.248-263.
[20] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocols for Wireless Microsensor Networks," *Proc. of HawaiiInt. Conf. on System Sciences*, Jan., 2000, pp.3005-3014.
[21] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms*, 2nd Ed., MIT Press, 2001.
[22] S. Moh, "Adaptive Multicast Trees on Static Ad Hoc Networks: Tradeoffs between Delay and Energy Consumption," *Proc. of 4th Int. Conf. on Ubiquitous Intelligence and Computing (UIC-2007)*, Hong Kong, July 2007, pp.267-275.

모 상 만

e-mail : smmoh@chosun.ac.kr
2002년 한국과학기술원(KAIST)(박사)
1991년~2002년 한국전자통신연구원(ETRI) 컴퓨터소프트웨어연구소(팀장)
2002년~현 재 조선대학교 컴퓨터공학부 교수
관심분야 : 모바일컴퓨팅, 애드혹네트워크, 센서네트워크, 병렬분산컴퓨팅 등