

# New Clustering Schemes for Energy Conservation in Two-Tiered Mobile Ad Hoc Networks

Jung-hee Ryu, *Member, IEEE*, Sanghwa Song, and Dong-Ho Cho, *Senior Member, IEEE*

**Abstract**—Two distributed heuristic clustering schemes are proposed that will minimize the required transmission power in two-tiered mobile ad hoc networks. Both schemes can be implemented and executed in real time and can be adopted for periodic or event-driven cluster reconfiguration. Scheme performance is simulated and compared with optimum configurations based on the mean transmission power and the call drop rate as performance measures. Numerical results show that the proposed schemes deliver performance similar to optimum results.

**Index Terms**—Ad hoc networks, clustering scheme, energy conservation.

## I. INTRODUCTION

A MOBILE ad hoc network is a multihop wireless network in which mobile hosts communicate over a shared and limited radio channel. It is characterized by lack of a wired backbone or centralized entities. The architecture of an ad hoc network can be either flat or hierarchical [1]. In a hierarchical network, the network elements are partitioned into several groups, called clusters. In each cluster, there is a master node that manages all the other nodes (slave nodes) within the cluster. The depth of the network can vary from a single tier to multiple tiers. However, most hierarchical networks, such as the Bluetooth Scatternet [2], [3], are two-tier networks.

Two-tier mobile ad hoc networks require sophisticated algorithms to perform clustering based on limited resources, such as the energy of each node, to communicate with each other. The cluster area of a node is related to the transmission power. Therefore, a larger cluster area requires more energy. The energy required by a two-tier mobile ad hoc network varies with the clustering configuration (the master node selection of slave nodes) because the transmission power of each node must be set to satisfy the minimum power level at the receiving node. Therefore, there exists an optimum clustering configuration that minimizes the call drop rate and the energy required for the still snapshot of the network. However, the optimum clustering configuration cannot be calculated quickly. A heuristic clustering scheme resulting in energy conservation for the network that can be implemented and executed in a limited time is needed for real-time clustering. We proposed two such heuristic clustering schemes.

Manuscript received September 29, 2000; revised September 6, 2001.

J. Ryu and D.-H. Cho are with the Communication and Information Systems Laboratory, Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, 305-701 Taejon, Korea (e-mail: ryu@ee.kaist.ac.kr; dhcho@ee.kaist.ac.kr).

S. Song is with the Operations Research Laboratory, Department of Industrial Engineering, Korea Advanced Institute of Science and Technology, 305-701 Taejon, Korea.

Digital Object Identifier 10.1109/TVT.2002.804865

Research concerning energy conservation schemes for mobile ad hoc networks is lacking. Shah and Flikkema proposed a power-based leader selection scheme [4] that used a physical layer-based framework in a quasi-static environment. Uplink, downlink, and the overall optimum leader nodes could be selected based on a link loss matrix and an iterative algorithm. Shah *et al.* determined the best node for the leader node in a two-layered mobile ad hoc network when all nodes are eligible to be a master node. However, adoption of this framework is difficult when master nodes are determined in advance. The scheme is not acceptable for real-time configuration applications, such as periodic or event-driven reconfigurations. Results approximating the optimum configuration can be derived when the number of iterations is large.

Rodoplu and Meng proposed a distributed position-based network protocol optimized for minimum energy consumption [5]. The proposed protocol is based on a position-based algorithm with the assumption of mobile terminals containing embedded GPS receivers. This assumption is not suitable for lightweight mobile terminals, such as bluetooth applications. Chang and Tassiulas proposed energy-conserving schemes focusing on maximization of the system lifetime [6], where routing nodes are disconnected based on their energy drain. This protocol is suitable for a static, flat, ad hoc network but is not suitable for a hierarchical network and real-time reconfiguration because communication is established only via master nodes in a hierarchical ad hoc network.

A routing scheme for power-saving in mobile ad hoc networks proposed by Ryu [7] considered an environment with two node types (battery-powered and outlet-plugged). This scheme is difficult to apply in mobile networks where most nodes are battery-powered. Our proposed schemes are distributed, time-limited energy-conserving clustering algorithms for two-tiered mobile ad hoc networks. They are suitable for periodic or event-driven cluster reconfiguration based on new call initiation and call completion.

Section II describes a network model for the proposed schemes. Section III derives equations for the optimum power-saving clustering configuration. The two new clustering schemes are presented in Section IV, and Section V shows numerical examples. Conclusions are presented in Section VI.

## II. NETWORK MODEL

We use a two-tiered mobile ad hoc network that assumes two node types: master and slave. A slave node must be connected to only one master node, and a direct connection between slave nodes is prohibited. Each master node can establish a cluster

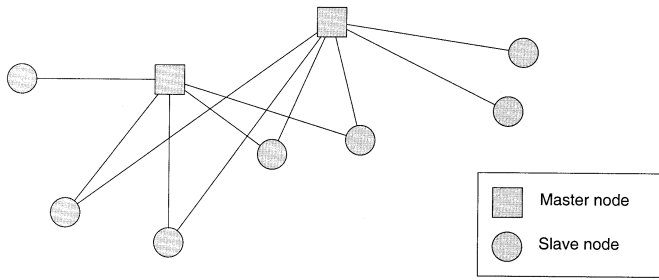


Fig. 1. Graph of the network in the original state.

based on connections to slave nodes. The area of a cluster is determined by the farthest distance between the master node and a slave node in the cluster. When the distance between the master node  $i$  and the slave node  $j$  is equal to  $d(i, j)$ , the relation equation for power transmitted by a master node  $P_t(i, j)$  and power received by a slave node  $P_r(i, j)$  is assumed to be [8]

$$P_r(i, j) = d(i, j)^{-4} \cdot P_t(i, j). \quad (1)$$

We assume that the power received at all slave nodes  $P_r(i, j)$  must be the same value as  $P_r$ . Hence, the transmission power of master nodes  $P_t(i, j)$  can vary based on the following equation:

$$P_t(i, j) = d(i, j)^4 \cdot P_r. \quad (2)$$

When a slave node transmits a signal to a master node, the transmission power of the slave node must also vary in order to adjust the power received at the master node to the same level.

Because the master node has limited energy, the value of  $d(i, j)$  that is able to be serviced is also limited. If the maximum value is  $d_{\max}$ , the maximum radius of a cluster is  $d_{\max}$  and the maximum transmission power of a node is  $d_{\max}^4 \cdot P_r$ .

We also assume that each master node has limited channels for communicating with slave nodes and separate, unlimited channels for communicating with other master nodes. This assumption requires that the number of slaves connected to a master node be limited. We refer to the maximum number of slave nodes that are connected to a master node as the number of channels  $C$ .

### III. OPTIMAL POWER-SAVING CLUSTERING

We derive a binary integer programming (BIP) formulation for the optimum clustering configuration for energy conservation to evaluate the proposed power-saving clustering schemes. Let the graph  $G = (V, E)$ , which is composed of a set of vertices  $V$  and a set of edges  $E$ , represent a network with a set of master nodes  $M$  and a set of slave nodes  $N$ . Then the set of vertices is equal to the set of all nodes; hence  $V = M \cup N$ . Assume that the length of each edge in  $E$  indicates the distance between a master node and a slave node. An illustrative graph of this situation is shown in Fig. 1.

When the distance  $d(i, j)$  between a master node  $i$  and a slave node  $j$  is more than  $d_{\max}$ , the corresponding link is not included in the graph. The objective of the analysis is to find an assignment between master nodes and slave nodes that minimizes the total required system power. This is a generalized assignment problem (GAP). However, the solution to a GAP can be nonfeasible because of capacity. If master nodes do not have enough

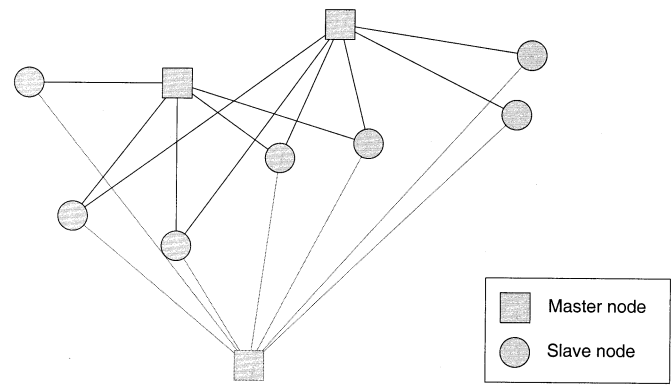


Fig. 2. Graph of the network with a dummy master node.

capacity, GAP optimization results in a nonfeasible solution. Thus, a dummy master node must be added to the original graph so that all the dropped slave nodes are included in the dummy master node cluster. A graph of this situation is shown in Fig. 2.

The dashed line indicates a hypothetical link between slave nodes and a dummy master node. To avoid a dummy master node assignment, an arbitrary large number ( $B$ ) is chosen as the cost of dummy node assignment in the GAP formulation. The associated problem is mathematically expressed as follows.

#### Notation

- |        |  |
|--------|--|
| $i, M$ | $M$ is a set of master nodes $i$ . The index of the dummy master node is zero. Other master nodes are numbered from one to $ M $ . |
| $j, N$ | $N$ is a set of slave nodes $j$ .  |
| $u(i)$ | A set of slave nodes that can be connected to master node $i$ . For the dummy master node, $u(0) = N$ .                            |
| $t$    | Time period $t$ in which the snapshot graph is generated.  |

#### Parameters

- |             |   |
|-------------|---|
| $C$         | Channel capacity of each master node. We assume that all master nodes except the dummy master node have the same capacity. There is no restriction on the dummy master node capacity. |
| $B$         | An arbitrarily chosen large number.   |
| $P_t(i, j)$ | The level of power needed between master node $i$ and slave node $j$ at time period $t$ . For the dummy master node, $P_t(0, j) = B$ .  |

#### Decision Variable

- |           |   |
|-----------|---|
| $x_{i,j}$ | A binary variable that indicates the connectivity between master nodes and slave nodes. If master node $i$ and slave node $j$ are connected, $x_{i,j} = 1$ . Otherwise, $x_{i,j} = 0$ . |
|-----------|---|

#### Formulation (P)

$$\begin{aligned} \text{minimize} \quad & \sum_{i \in M} \sum_{j \in u(i)} P_t(i, j) \cdot x_{i,j} \\ & = \sum_{i \in M \setminus \{0\}} \sum_{j \in u(i)} P_t(i, j) \cdot x_{i,j} + \sum_{j \in N} P_t(0, j) \cdot x_{0,j} \end{aligned} \quad (3)$$

subject to

$$\sum_{i \in M} x_{i,j} = 1 \quad \forall j \quad (4)$$

$$\sum_{j \in u(i)} x_{i,j} \leq C \quad \forall i \in M \setminus \{0\} \quad (5)$$

$$x_{i,j} \in \{0, 1\} \quad \forall i, j. \quad (6)$$

An objective function (3) indicates that the primary goal is to find a minimum power assignment. However, in the case of nonfeasibility, dummy master node assignments are necessary. Constraints (4) indicate that each slave node must be connected to only one master node and constraints (5) indicate that each master node, except the dummy master node, has  $C$  channels for connections to slave nodes. This modified GAP is referred to as an NP-hard [9], which implies that it is impossible to achieve a practical, optimum solution. An efficient heuristic method is needed that provides a near optimum solution at a low cost in computing time. Thus, we propose two power-saving clustering schemes and compare their solutions with optimum solutions to evaluate the effectiveness of the proposed schemes.

#### IV. PROPOSED CLUSTERING SCHEMES

To provide pseudooptimum power-saving clustering solutions that can be implemented and executed in real time, two heuristic schemes are proposed. These are referred to as the single-phase and double-phase clustering schemes.

The single-phase clustering scheme only requires one page from master nodes and one acknowledgment from slave nodes [10]. Therefore, the power optimization time can be relatively short. Each master node pages at the same maximum power level, and each slave node sends one acknowledgment to the master node from which the highest power was received, which is assumed to be the nearest master. Hence, transmission power can be conserved when the slave node selects the master node that provides the highest received power level. Master nodes allocate a communication channel to the slave nodes when slave nodes send acknowledgment signals to master nodes. To prevent call dropping, each master node first allocates a channel to the slave nodes that received only one paging signal from the master node. If remaining channels exist at the master node, other slave nodes are allocated a channel in the order of the paging signal power level received from the master node.

A flowchart of the proposed single-phase clustering scheme is shown in Figs. 3 and 4.  $N\_ACK$  and  $N\_ONE$  indicate the number of acknowledged slave nodes and the number of slave nodes paged by only one master, respectively.

The double-phase clustering scheme is an extension of the single-phased scheme. It is constructed with the single-phased clustering scheme and an additional channel reallocation phase, which is added to lower the call drop rate of slave nodes. Dropped slave nodes in the first phase retry channel allocation with reacknowledgment to the master nodes that have remaining channels. If a master node has remaining channels after the first phase, that information is paged before reacknowledgment of slave nodes. The slave node sends a reacknowledgment signal only to the master node that paged with the highest received power level, as in the first phase. The

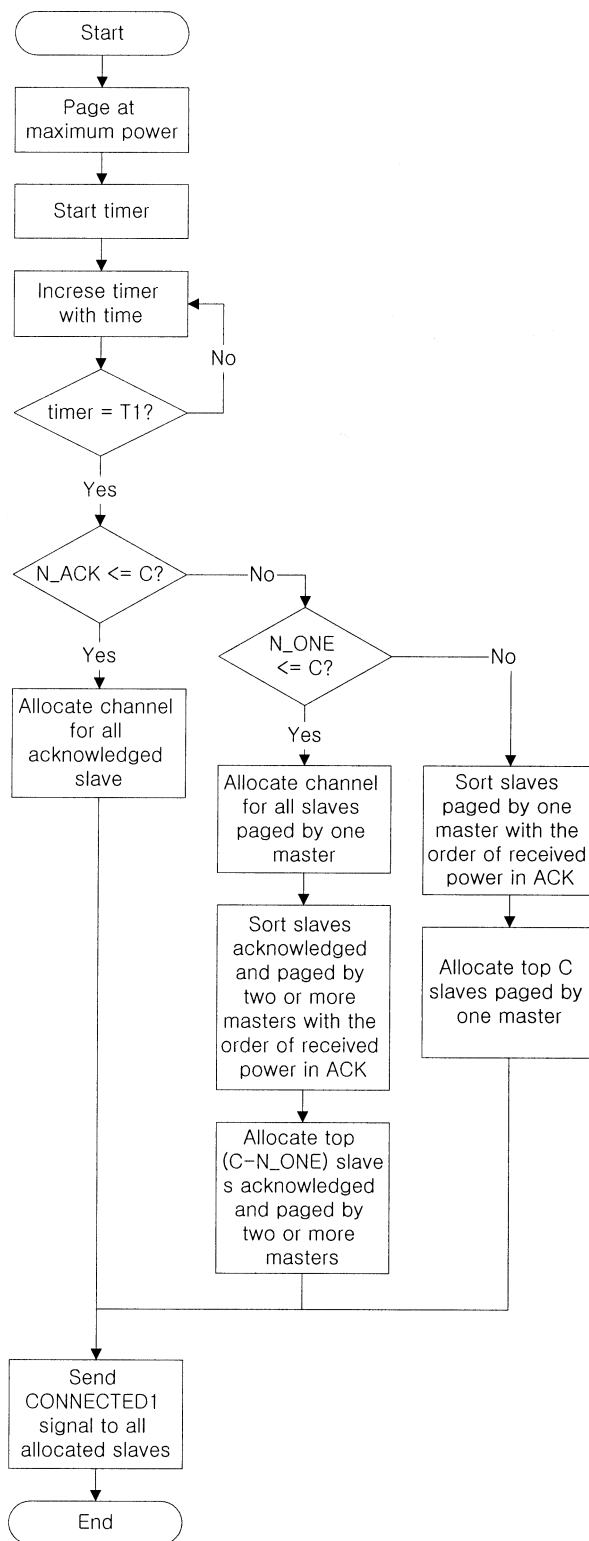


Fig. 3. Flowchart of the proposed single-phase clustering scheme: master node.

master node also allocates remaining channels to slave nodes in the order of the power level of the received paging signal from the master node.

A flowchart of the proposed double-phase clustering scheme is shown in Figs. 5 and 6.  $N\_reACK$  indicates the number of reacknowledged slave nodes.

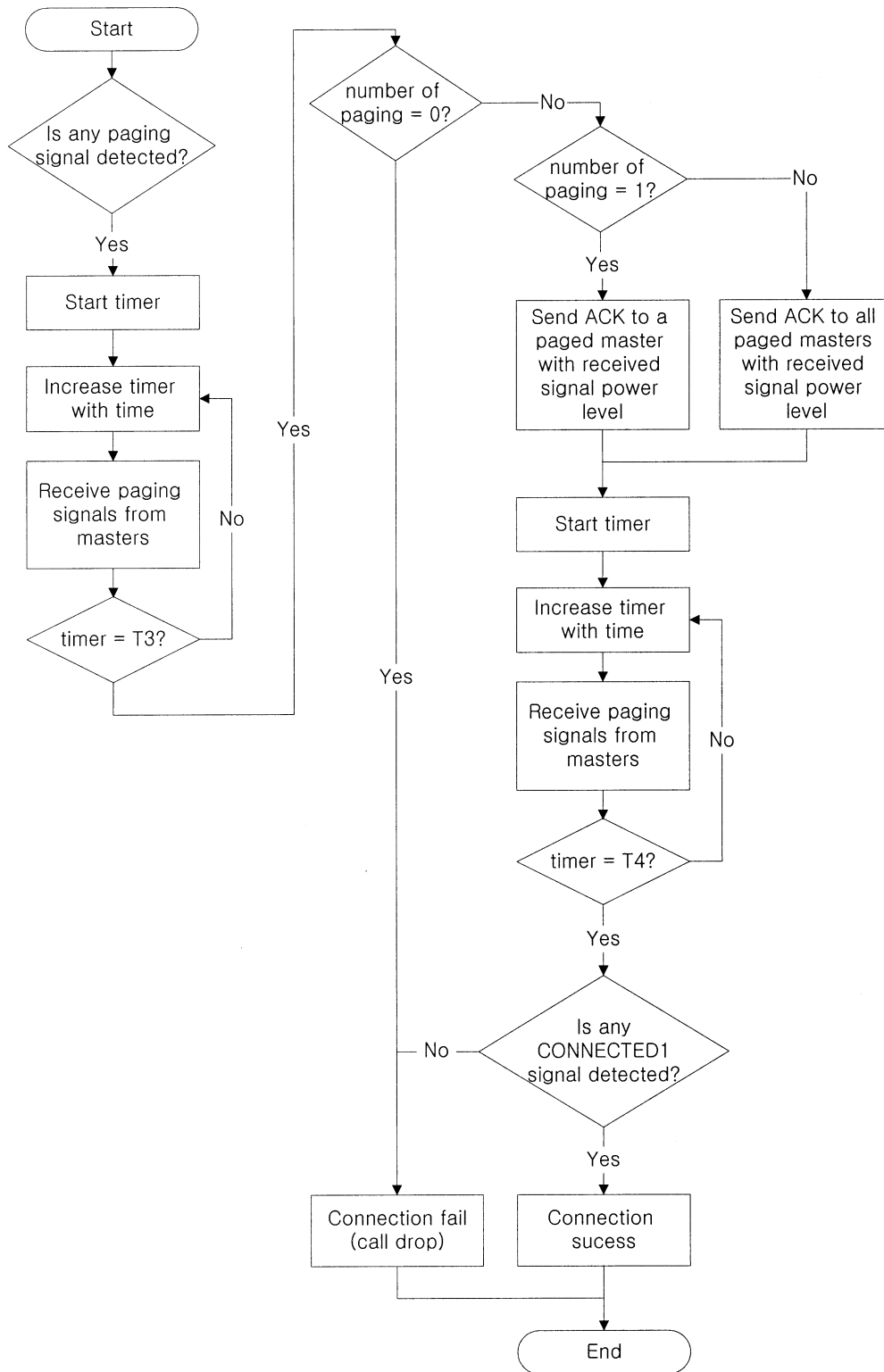


Fig. 4. Flowchart of the proposed single-phase clustering scheme: slave node.

## V. NUMERICAL EXAMPLES

Our simulated network consists of 10, 20, and 30 mobile nodes in an area of 10 by 10 m<sup>2</sup>. The number of master nodes varies from one to five. All other mobile nodes are slave nodes. For example, when the number of mobile nodes is 20 and the number of master nodes is three, the number of slave nodes is

17. Each mobile node is uniformly randomly distributed in the simulation area. The numerical examples are statistic results, which are the mean values of 1000 random configurations of the mobile nodes.

Simulation of the proposed scheme is based on the assumption that the network topology remains fixed during the clustering process. We also assume that there is no MAC

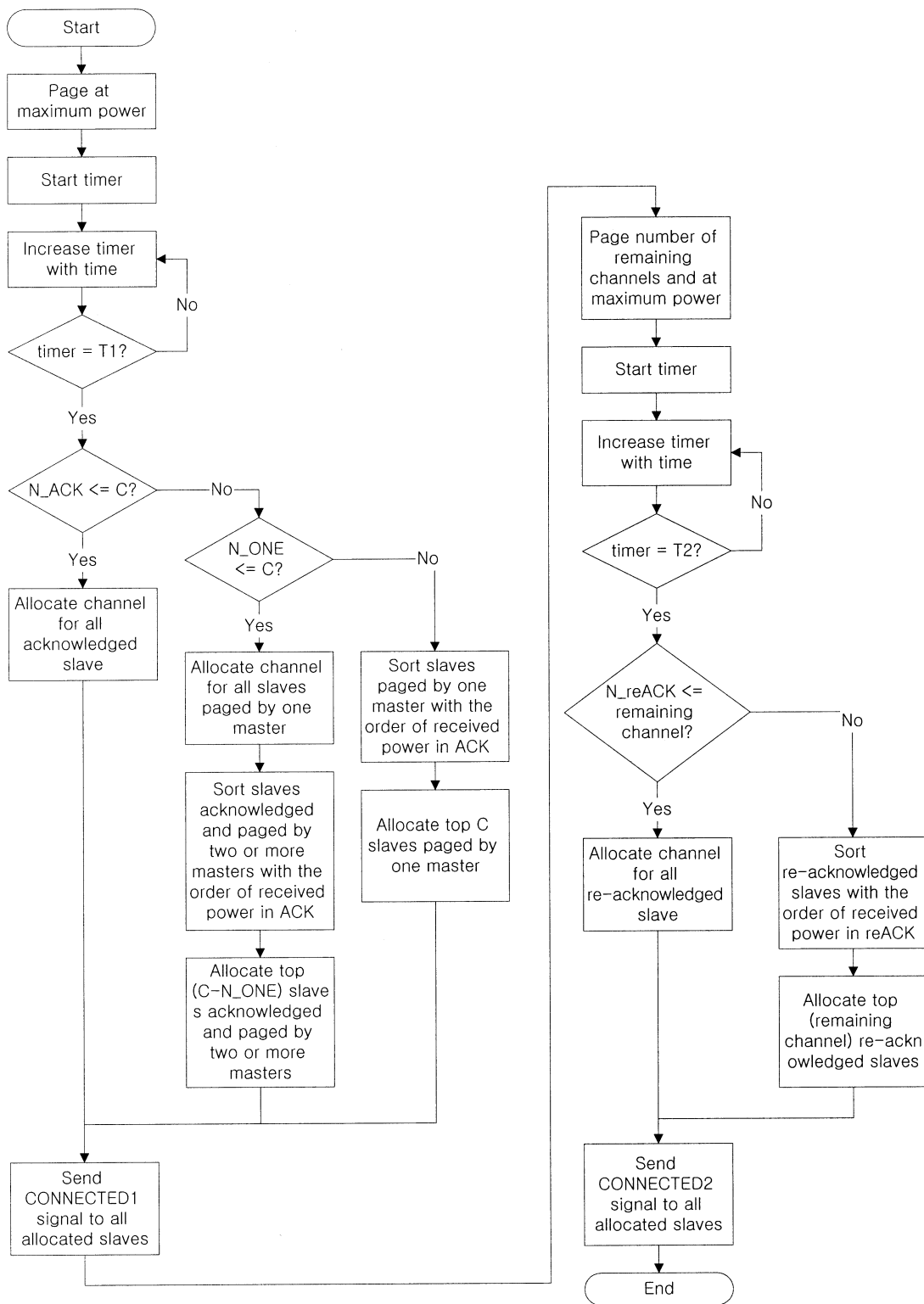


Fig. 5. Flowchart of the proposed double-phase clustering scheme: master node.

layer channel contention and that packets are received under error-free conditions only within the maximum radius of the paging area  $d_{max}$  from the transmitter. We set  $d_{max}$  equal to 5 m. Results from the optimum configuration are calculated with CPLEX, based on the BIP equations of (3)–(6).

We used the average drop rate and the average consumed power per slave node as performance measures. The average

drop rate is defined as the probability that call dropping occurs when 1) a slave node belongs to none of the maximum paging areas of the master nodes or 2) the communication channels of the master node that received the acknowledge/reacknowledge signal from the slave node are all occupied.

The average consumed power per slave node  $\bar{P}_t$  is the normalized value of the total power consumed by the system in

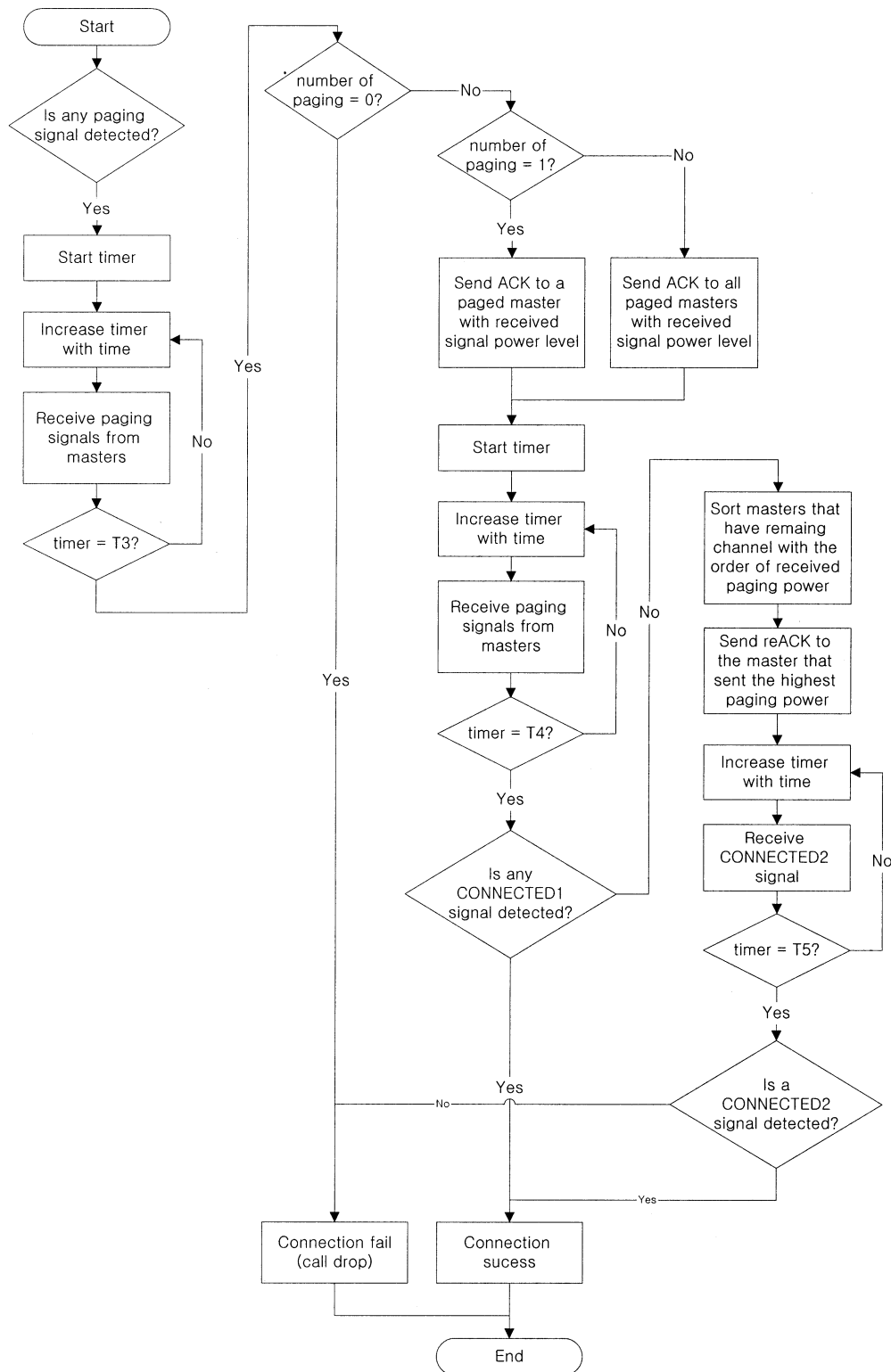


Fig. 6. Flowchart of the proposed double-phase clustering scheme: slave node.

a snapshot with the sum of the received powers at communicating slave nodes. The total power consumed by the system is defined as the sum of all power that is needed to make connections between each master node and each slave node. We assume that the power required to make a connection is propor-

tional to the fourth power of the distance between two nodes [8]. Thus, the fourth power of the distance between two nodes is a measure of the power that is needed to make a connection. The average power required per slave node in the numerical examples is the normalized sum of the fourth power of the distance

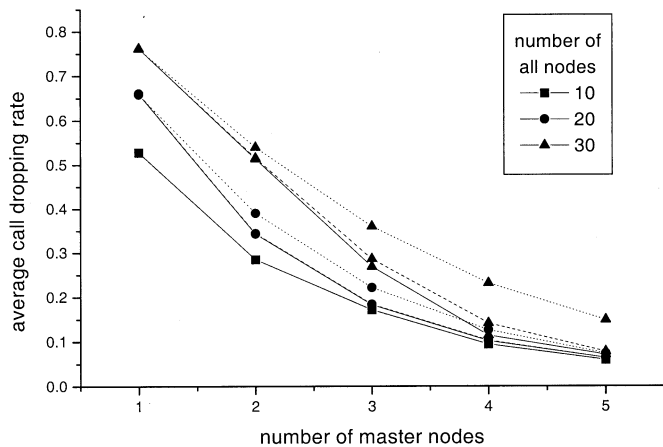


Fig. 7. Average call drop rate versus the number of master nodes (solid line: optimum case; dashed line: double-phase scheme; dotted line: single-phase).

between each master node and each allocated slave node with the number of communicating slave terminals. This relationship can be expressed as

$$\bar{P}_t = \frac{\sum_{i \in M} \sum_{j \in u(i)} P_t(i, j)^4 \cdot x_{i,j}}{\sum_{i \in M} \sum_{j \in u(i)} P_r \cdot x_{i,j}} = \frac{\sum_{i \in M} \sum_{j \in u(i)} d(i, j)^4 \cdot x_{i,j}}{\sum_{i \in M} \sum_{j \in u(i)} x_{i,j}} \quad (7)$$

The numerical results of these two measures are shown in Figs. 7 and 8. The average call drop rates in two-tiered mobile ad hoc systems consisting of 10, 20, and 30 mobile nodes are shown in Fig. 7. The difference between the average call drop rate for systems based on the optimum clustering configuration with GAP and the proposed double-phased clustering scheme was less than 23.8% of the average call drop rate for the optimum configuration. The average difference in all cases was 2.89%, and the average difference for ten mobile nodes was 0.192%.

For the proposed single-phase clustering scheme, the average call drop rate was relatively higher than for the double-phase scheme. The difference between the average call drop rate for systems based on the optimum clustering configuration and the single-phase scheme was less than 111% of the average call drop rate (when the number of master nodes is five) for the optimum configuration. The mean of the difference for all cases was 21.9%.

The differences between systems based on the optimum clustering configuration and the proposed clustering schemes increased with the number of nodes. The differences were small where the number of master nodes was either extremely small or large. However, the difference was relatively large in other cases because a large number of slave nodes are dropped when a small number of master and slave nodes are allocated to channels in the master nodes. The number of channels in the master nodes also probably increases when a large number of master and slave nodes are allocated to the channels.

The double-phase scheme, which exhibits only a small difference from the optimum configuration, is recommended for decreasing the call drop rate. However, when the number of nodes is relatively small, the single-phase scheme can be more

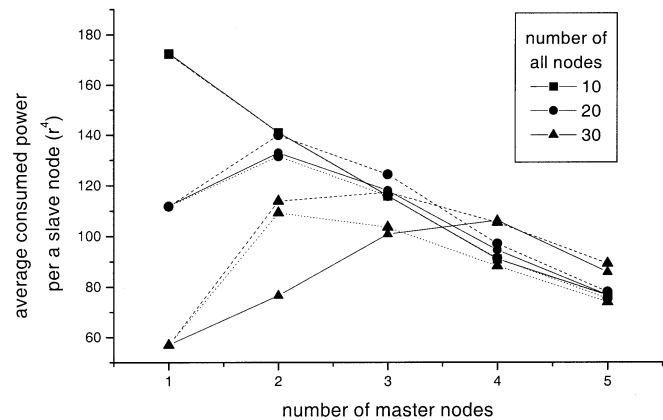


Fig. 8. Average power required per slave node versus number of master nodes (solid line: optimum case; dashed line: double-phase scheme; dotted line: single-phase scheme).

advantageous considering computational power and speed because the difference between the average call drop rate for the single-phase and the double-phase schemes is small. The mean difference between the single-phase and the double-phase average call drop rates was 7.23% when the number of nodes for the double-phased scheme was less than 20.

A graph of the average power required per slave node versus the number of nodes is shown in Fig. 8. It is difficult to interpret the numerical results of the average power required per slave node because the power can be less than the indicated values with a low call drop rate. This can happen when closer slave nodes are allocated with a relatively high call drop rate.

An example is shown with 30 nodes. The average power required per slave node in the single-phase scheme, which has a higher call drop rate, is less than those in both the double-phase scheme and the optimum configuration when the number of master nodes is over three.

Based on these numerical examples, the average power required per slave node has a maximum value at a specific number of master nodes and generally decreases with both fewer and more nodes. The above specific numbers of master nodes are one, two, and four when the total number of nodes is ten, 20, and 30, respectively. This tendency is based on a reduction of the mean distance between master and slave nodes when the number of master nodes is larger than this specific number. Slave nodes farther removed from the master nodes are dropped with a rise in the call drop rate when the number of master nodes is less than this specific number. The optimum number of master nodes per total number of nodes, considering energy conservation, can be determined based on this relationship. However, we leave this for further study.

The values of average power required per slave node for both the single and the double-phase schemes are similar to the optimum configuration. However, the values of average power required in the proposed schemes are relatively higher when the number of nodes is 30 and the number of master nodes is less than three. An increase in the number of master nodes is required for the proposed schemes in this case.

With only a small difference in the call drop rate from the optimum configuration and a relatively low level of power

consumption, the proposed double-phase clustering scheme is as useful as the pseudooptimum heuristic solutions for power-saving clustering in two-tiered mobile ad hoc networks.

The proposed single-phase clustering scheme can be useful in situations where the performance difference between the single-phase and the double-phase schemes is relatively small. For example, when the number of nodes is less than 20, the heuristic scheme can be executed with less computing power at high speed using the single-phased scheme.

## VI. CONCLUSION

We propose two distributed heuristic clustering schemes for energy conservation in two-tiered mobile ad hoc networks. The proposed schemes can be implemented and executed in real time. The mean transmission power and the call drop rate for the proposed schemes approximate optimum results. Hence, the proposed schemes are suitable for periodic or event-driven cluster reconfiguration. The proposed double-phase scheme is useful when energy conservation and call completion are more important than computing power and the speed of the scheme. In the opposite case, the proposed single-phase scheme can be adopted.

## REFERENCES

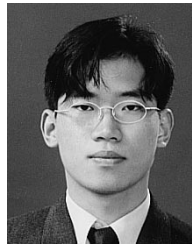
- [1] Z. J. Hass and S. Tabrizi, "On some challenges and design choices in ad-hoc communications," in *Proc. MILCOM'98*, Oct. 1998.
- [2] P. Johansson *et al.*, "Short range based ad-hoc networking: Performance and properties," in *Proc. of ICC'99*, June 1999.
- [3] *Specification of the Bluetooth System*, v1.0 B ed., vol. 1, Core, TBluetooth Special Interest Group, 1999.
- [4] M. J. Shah and P. G. Flikkema, "Power-based leader selection in ad-hoc wireless networks," in *Proc. IPCCC'99*, Feb. 1999.
- [5] V. Rodoplu and T. H. Meng, "Minimum energy mobile wireless networks," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1333–1344, Aug. 1999.
- [6] J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proc. INFOCOMM 2000*, Mar. 2000.
- [7] J. Ryu and D.-H. Cho, "A new routing scheme concerning power-saving in mobile ad-hoc networks," in *Proc. ICC 2000*, June 2000.
- [8] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Englewood Cliffs, NJ: Prentice-Hall, 1996.
- [9] M. Savelsbergh, "A branch-and-price algorithm for the generalized assignment problem," *Oper. Res.*, vol. 45, no. 6, pp. 831–841, 1997.
- [10] J. Ryu, S. Song, and D.-H. Cho, "Clustering scheme for energy conservation in two-tiered mobile ad-hoc networks," *Electron. Lett.*, vol. 37, no. 11, May 2001.



**Jung-hee Ryu** (S'98–M'02) received the B.S. and M.S. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1996 and 1998 and Ph.D. degree in Electrical Engineering and Computer Science from KAIST in 2002, respectively.

His interests include mobile ad hoc network and ubiquitous/pervasive computing.

Dr. Ryu is a Member of the IEEE Communications Society and the IEEE Vehicular Technology Society.



**Sanghwa Song** received the B.S. and M.S. degrees in industrial engineering from the Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1997 and 1999, respectively, where he is currently pursuing the Ph.D degree in industrial engineering.

His interests include design of virtual private networks and resource management in wireless networks.



**Dong-Ho Cho** (M'85–SM'00) received the B.S. degree from Seoul National University, Seoul, Korea, in 1979 and the M.S. and Ph.D. degrees from the Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1981 and 1985, respectively, all in electrical engineering.

From 1987 to 1997, he was a Professor of computer engineering at Kyunghee University. Since 1998, he has been a Professor of electrical engineering and computer science at KAIST. His professional interests include wired and wireless communication network, protocol, and services.

Prof. Cho is a Member of the IEEE Communications Society and the IEEE Vehicular Technology Society.