Energy Efficient Design of Wireless Ad Hoc Networks

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Abstract. One of the most critical issues in wireless ad hoc networks is represented by the limited availability of energy within network nodes. The time period from the instant when the network starts functioning to the instant when the first network node runs out of energy, the so-called network *life-time*, strictly depends on the system energy efficiency. Our objective is to devise techniques to maximize the network life-time in the case of cluster-based systems, which represent a significant sub-set of ad hoc networks. We propose an original approach to maximize the network life-time by determining the optimal clusters size and the optimal assignment of nodes to cluster-heads. The presented solution greatly outperforms the standard assignment of nodes to cluster-heads, based on the minimum distance criterion.

1 Introduction

One of the major challenges in the design of ad hoc networks is that energy resources are significantly more limited than in wired networks. Recharging or replacing the nodes battery may be inconvenient, or even impossible in disadvantaged working environments. This implies that the time during which all nodes in the ad hoc network are able to transmit, receive and process information is limited; thus, the network *life-time* becomes one of the most critical performance metrics [1, 2].

Here, we define the network life-time as the time spanning from the instant when the network starts functioning to the instant when the first network node runs out of energy. In order to maximize the life-time, the network must be designed to be extremely energy-efficient. Various are the possible network configurations, depending on the application. In this paper, we deal with system architectures based on a clustering approach [3–5], which represent a significant sub-set of ad hoc networks.

In cluster-based systems, network nodes are partitioned into several groups. In each group, one node is elected to be the cluster-head, and act as local controller, while the rest of the nodes become ordinary nodes (hereinafter nodes). The cluster size is controlled by varying the cluster-head's transmission power. The cluster-head coordinates transmissions within the cluster, handles inter-cluster traffic and delivers all packets destined to the cluster; it may also exchange data with nodes that act as gateways to the wired network.

In cluster-based network architectures, the life-time is strongly related to cluster-heads' failure. Indeed, power consumption in radio devices is mainly due to the following components: digital circuitry, radio transceiver, and transmission amplifier. Thus, energy consumption increases with the number of transmitted/received/processed packets and with the device's transmission range. Consider a network scenario where all nodes within a cluster are one-hop away from the cluster-head, as it often occurs in cluster-based systems [5–7], and assume that the traffic load is uniformly distributed among the nodes. Since cluster-heads have to handle all traffic generated by and destined to the cluster, they have to transmit, receive and process a significant amount of packets (much larger than for ordinary nodes), which depends on the number of controlled nodes. In addition, while transmitting the collected traffic to other cluster-heads or to gateway nodes, they have to cover distances that are usually much greater than the nodes' transmission range. Cluster-heads therefore experience high energy consumption and exhaust their energy resources more quickly than ordinary nodes do. The life-time of cluster-based networks thus becomes the time period from the instant when the network starts functioning to the instant at which the first cluster-head runs out of energy. In order to maximize the system life-time, it is imperative to find network design solutions that optimize the cluster-heads' energy consumption.

The procedure of cluster formation consists of two phases: cluster-head election and assignment of nodes to cluster-heads. Although several algorithms have been proposed in the literature, which address the problem of cluster formation [2, 3, 5–9], little work has been done on energy-efficient design of cluster-based networks. In [2], an energy-efficient architecture for sensor networks has been proposed, which involves a randomized rotation of the cluster-heads among all the sensors and an assignment of nodes to clusters based on the minimum distance criterion. Cluster-heads rotation implies that the network energy resources are more evenly drained and may result in an increased network life-time. On the other hand, cluster-heads re-election may require excessive processing and communications overhead, which outweigh its benefit. Thus, having fixed the nodes that act as cluster-heads, it is important to optimize the assignment of nodes to cluster-heads in such a way that cluster-heads' energy efficiency is maximized.

In this paper, we consider a network scenario where cluster-heads are chosen a priori and the network topology is either static, like in sensor networks, or slowly changing. We propose an original solution, called *ANDA (Ad hoc Network Design Algorithm)*, which maximizes the network life-time while providing the total coverage of the nodes in the network. ANDA is based on the concept that cluster-heads can dynamically adjust the size of the clusters through power control, and, hence, the number of controlled nodes per cluster. ANDA takes into account power consumption due to both the transmission amplifier and the transmitting/receiving/processing of data packets, and it levels the energy consumption over the whole network. Energy is evenly drained from the cluster-heads by optimally balancing the cluster traffic loads and regulating the cluster-heads' transmission ranges.

2 The Network Life-time

We consider a generic ad hoc network architecture based on a clustering approach. The network topology is assumed to be either static, like in sensor networks, or slowly changing. Let $S_C = \{1, \ldots, C\}$ be the set of cluster-heads and $S_N = \{1, \ldots, N\}$ be the set of ordinary nodes to be assigned to the clusters. Cluster-heads are chosen a priori and are fixed throughout the network life-time, while the coverage area of the clusters is determined by the level of transmission power used by the cluster-heads.

Three are the major contributions to power consumption in radio devices: *i)* power consumed by the digital part of the circuitry; *ii)* power consumption of the transceiver in transmitting and receiving mode; *iii)* output transmission power. Clearly, the output transmission power depends on the devices' transmission range and the total power consumption depends on the number of transmitted and received packets. Under the assumption that the traffic load is uniformly distributed among the network nodes, the time interval that spans from the time instant when the network begins to function until the generic cluster-head i runs out of energy, can be written as

$$L_i = \frac{E_i}{\alpha r_i^2 + \beta |n_i|} , \tag{1}$$

where E_i is the initial amount of energy available at cluster-head i, r_i is the coverage radius of cluster-head i, n_i is the number of nodes under the control of cluster-head i, and α and β are constant weighting factors. In (1), the two terms at the denominator represent the dependency of power consumption on the transmission range and on the cluster-head transmitting/receiving activity, respectively. Notice that, for the sake of simplicity, the relation between the cluster-head power consumption and the number of controlled nodes is assumed to be linear; however, any other type of relation could have been considered as well, with minor complexity increase.

Considering that the limiting factor to the network life-time is represented by the cluster-heads' functioning time, the lifetime can be defined as [1, 2]

$$L_S = \min_{i \in S_C} \{L_i\} . \tag{2}$$

Our objective is to maximize L_S while guaranteeing the coverage of all nodes in the network.

3 Energy-efficient Network Design

In this section, we formally describe the problem of maximizing the network life-time. Two different working scenarios are analyzed: static and dynamic. In the former, the assignment of the nodes to the cluster-heads is made only once and maintained along the all duration of the system. In the latter, the network configuration can be periodically updated in order to provide a longer network life-time. Then, we propose an energy-efficient design algorithm, so-called *ANDA (Ad hoc Network Design Algorithm)*, which maximizes the network life-time by fixing the optimal radius of each cluster and the optimal assignment of the nodes to the clusters. ANDA is optimum in the case of the static scenario and can be extended to the dynamic scenario by using a heuristic rule to determine whether at a given checking time the network needs to be reconfigured.

3.1 Problem Formalization

We assume that the following system parameters are known: number of cluster-heads (C), number of nodes in the network (N), location of all cluster-heads and nodes, and initial value of the energy available at each cluster-head[3].

Let d_{ik} be the Euclidean distance between cluster-head i and node k ($i = 1, \ldots, C$; $k = 1, \ldots, N$); we have that $r_i = d_{ij}$ when j is the farthest node controlled by cluster-head i. Next, let us introduce matrix $\boldsymbol{L}=\{l_{ij}\}$, whose dimension is equal to $|S_C| \times |S_N|$ and where each entry l_{ij} represents the life-time of cluster-head i when its radius is set to $r_i = d_{ij}$ and it covers $n_{ij} = \{\, k \in S_N \mid d_{ik} \leq d_{ij}\}$ nodes. We have

$$l_{ij} = \frac{E_i}{\alpha d_{ij}^2 + \beta |n_{ij}|} \; . \tag{3}$$

Once matrix $\boldsymbol{L}$ is computed, the optimal assignment of nodes to cluster-heads is described by the binary variable x_{ij}. x_{ij} is equal to 1 if cluster-head i covers node j and equal to 0 otherwise. We derive the value of x_{ij} ($i = 1, \ldots, C$; $j = 1, \ldots, N$) by solving the following *max/min* problem

$$\begin{array}{lll} \textit{maximize} & L_S & \\ \textit{subject to} & \sum_i x_{ij} \geq 1 & \forall j \in S_N \\ & L_S \leq l_{ij}x_{ij} + M(1 - x_{ij}) & \forall i \in S_C,\, j \in S_N \\ & x_{ij} \in \{0,1\}, L_S \geq 0 & \forall i \in S_C,\, j \in S_N \; . \end{array} \tag{4}$$

The first constraint in the problem requires that each node is covered by one cluster-head at least; the second constraint says that if node j is assigned to cluster-head i, the system can not hope to live more than l_{ij}. When node j is not assigned to cluster-head i, this constraint is relaxed by taking a sufficiently large M.

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[3] Notice that in the case of static nodes, this information needs to be collected only once when the network starts functioning; therefore, we neglect the cost of such an operation.

This model can be easily extended to the dynamic scenario by dividing the time scale into time steps corresponding to the time instants at which the network configuration is recomputed. Time steps are assumed to have unit duration. Then, we replace x_{ij} with x_{ij}^s, where x_{ij}^s is equal to 1 if and only if cluster-head i covers node j at time step s and 0 otherwise, and E_i, d_{ij}, n_{ij}, l_{ij} with E_i^s, d_{ij}^s, n_{ij}^s, l_{ij}^s, i.e., with the corresponding values computed at time step s. Note, however, that in this case the model is no longer linear, since the model parameters depend on the time step and, thus, on the former nodes assignment.

```
begin Covering
 for($every\ j \in S_N$)
  set $max = 0$
  for($every\ i \in S_C$)
   if($l_{ij} \geq max$)
    set $max = l_{ij}$
    set $sel = i$
   end if
   Cover node $j$ with cluster-head $sel$
  end for
 end for
end Covering

begin Reconfigure
 for($every\ i \in S_C$)
  set $E_i$ = initial energy of cluster-head $i$
  for($every\ j \in S_N$)
   Compute $d_{ij}$, $|n_{ij}|$, $l_{ij}$
  end for
 end for
 $L_S^{(new)} = L_S^{(old)} = L_S$
 $\Delta = 0$
 while($L_S^{(new)} <= L_S^{(old)} - \Delta$)
  $\Delta = \Delta + 1$
  for($every\ i \in S_C$)
   for($every\ j \in S_N$)
    Recompute $E_i = E_i - \Delta(\alpha r_i^2 + \beta|n_{ij}|)$
    Update $l_{ij}\ \forall i \in S_C, j \in S_N$
   end for
  end for
  Call $Covering$ and update $L_S$
  $L_S^{(new)} = L_S$
 end while
end Reconfigure
```

Fig. 1. Pseudo-code of the network design algorithm.

3.2 ANDA: The Ad Hoc Network Design Algorithm

In order to solve the *max/min* problem described in the previous section, we introduce an algorithm, named *ANDA*, based on a novel node assignment strategy. ANDA solves to optimality the *max/min* problem in the case of the static scenario and guarantees good performance in the case of the dynamic scenario. The algorithm is composed of two main functions: the *Covering* and the *Reconfigure* procedures, where *Reconfigure* is used in the dynamic scenario only. The pseudo-code of the two functions is reported in Fig. 1.

The procedure *Covering* performs the assignment of nodes to cluster-heads by associating each node to the cluster-head that presents the longest functioning time. Thus, node j ($j = 1, \ldots, N$) will be covered by cluster-head i if $l_{ij} = \max_{k \in S_C}\{l_{kj}\}$. The resulting network configuration guarantees that energy consumption is minimized; optimality of the *Covering* procedure can be easily proved from the following consideration. Suppose that in an optimal network configuration, node j is covered by cluster-head i and that $l_{ij} < l_{hj}$ with $l_{hj} = \max_k\{l_{kj}\}$. By assigning node j to cluster-head i instead of assigning the node to h, we would obtain a shorter life-time and therefore the configuration would not be optimal.

In the dynamic scenario, the rule adopted to determine the time instants at which the network needs to be reconfigured is of crucial importance. We assume that at the time of network deployment all cluster-heads are equipped with the same amount of energy. The initial node assignment is obtained from the *Covering* procedure, which gives the optimal network configuration. However, while the system is running, each cluster-head experiences a different energy consumption depending on the number of controlled nodes and on the coverage area. By scheduling periodical node re-assignments based on the recomputed values of E_i ($i = 1, \ldots, C$), we can level the system energy consumption. Through function *Reconfigure*, we compute the new value of the available energy at cluster-head i ($i = 1, \ldots, C$) as

$$E_i^{(new)} = E_i^{(old)} - \Delta(\alpha r_i^2 + \beta|n_i|) \;, \tag{5}$$

where Δ is the time interval elapsed from the last update of the network configuration. By using $E_i^{(new)}$ and recomputing matrix $\boldsymbol{L}$, from the procedure *Configure* we obtain a new nodes assignment and a new maximized value for L_S. If the difference between the old value and the new value of L_S is greater than Δ, it is worthwhile updating the network configuration and therefore the nodes re-assignment is performed.

We point out that in ANDA the assignment of nodes to cluster-heads is obtained by determining for every node i ($i = 1, \ldots, N$) the maximum value among entries l_{ij} ($j = 1, \ldots, C$). Therefore, the complexity of the assignment procedure is $O(C \cdot N)$.

4 Numerical Results

The performance of ANDA is derived in terms of network life-time and variance of the residual energy at the cluster-heads measured at the time instant at which

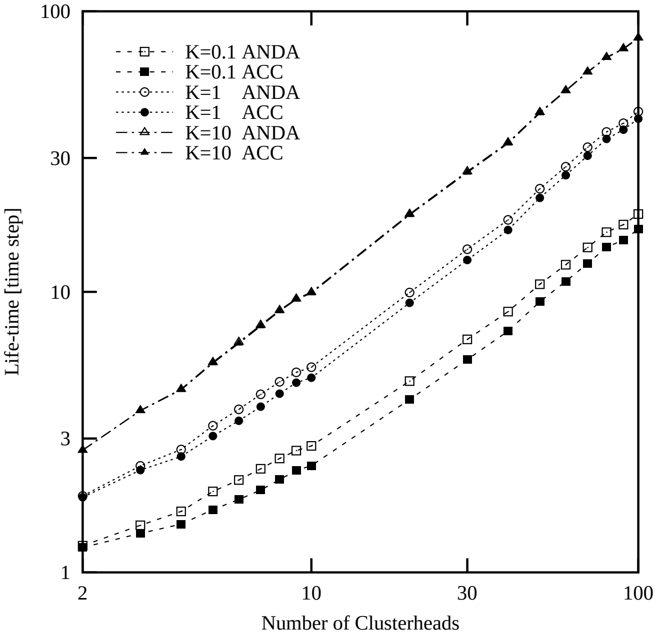

Fig. 2. Static scenario: Life-time as a function of the number of cluster-heads, for a number of nodes equal to 1000 and different values of K. Results obtained through ANDA and the ACC scheme are compared.

the first cluster-head runs out of energy. Results are plotted as functions of the ratio of the output transmission power to the power consumption due to the transmitting/receiving activity, denoted by K. We consider that all the nodes in the network are fixed and have initial energy $E_i = 1$ with $i = 1, ..., N$. We assume that the cluster-heads are uniformly distributed over the network area and are known a priori. Results were derived also in the case of a slowly changing network topology; however, they do not significantly differ from those obtained in the case of a network with fixed nodes.

First, we consider the static scenario, where only one network configuration is allowed. We compare the performance of ANDA with the results obtained by using a simple network design algorithm based on the minimum distance criterion (in the plots denoted by label *ACC (Assignment to Closest Cluster-head)*), which simply assigns each node to the nearest cluster-head. Fig. 2 shows the network life-time as a function of the number of cluster-heads, C. Curves are obtained for $N = 1000$, varying values of K, and nodes uniformly distributed over the network area. As expected, the life-time increases with the increase of the number of cluster-heads. From the comparison with the performance of the ACC scheme, we observe that the improvement achieved through ANDA is equal to 15% for $K = 0.1$, while it becomes negligible for $K = 10$, i.e., when the output transmission power contribution dominates. For both the ACC scheme

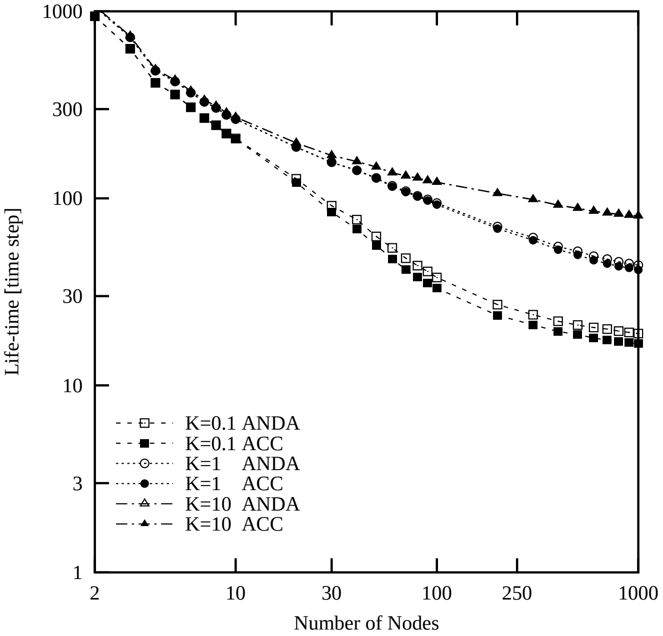

Fig. 3. Static scenario: Life-time as a function of the number of nodes, for a number of cluster-heads equal to 100 and different values of K. Results obtained through ANDA and the ACC scheme are compared.

and ANDA, a longer life-time is obtained when the major contribution to power consumption is due to the output transmission power ($K = 10$). In fact, both the schemes are able to level the output transmission power consumption among the cluster-heads; while, it is difficult to achieve an even distribution of the nodes among the clusters.

Fig. 3 shows the network life-time as the number of nodes changes, for a number of cluster-heads $C = 100$ and a uniform distribution of the network nodes. The life-time decreases as the number of nodes grows; however, for a number of nodes greater than 100, the life-time remains almost constant as the number of nodes increases.

Fig. 4 shows the variance of the residual energy at the cluster-heads as a function of the number of cluster-heads. The number of nodes in the network is set equal to 1000. For small values of C, we have a low variance since all cluster-heads have to control a large number of nodes. Increasing C, some cluster-heads may have to cover few nodes while others may experience a significant energy consumption, thus resulting in higher values of variance. For values of C greater than 25, the variance drops below 0.07 suggesting that all cluster-heads are evenly drained. Also, we notice that for small values of C and $K < 1$ we have lower variance than for $K \geq 1$ since, as mentioned above, it is hard to achieve an

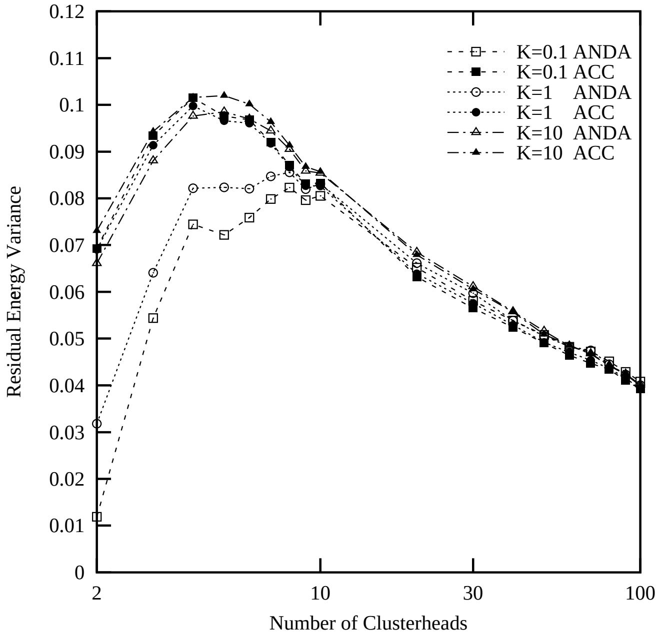

Fig. 4. Static scenario: Variance of the residual energy at the cluster-heads as a function of the number of cluster-heads. Curves are plotted for a number of nodes equal to 1000 and for varying values of K. Results obtained through ANDA and the ACC scheme are compared.

equal distribution of the nodes among the clusters. For any value of K ANDA outperforms the ACC scheme.

Next, we consider the dynamic scenario with $C = 100$ and $N = 1000$. In this case, periodical updates of the network configuration are executed; the more frequently the network configuration is updated, the greater the network life-time and the system complexity. Thus, results showing the trade-off between network life-time and number of executed configuration updates are presented.

Fig. 5 presents the network life-time for different values of K and nodes uniformly distributed in the network area. In abscissa, it is reported the number of performed configuration updates normalized to the observation time expressed in time steps. The life-time significantly increases as the number of reconfigurations grows since the energy available in the system is better exploited. For all values of K and a normalized number of updates equal to 1, an improvement of about 50% with respect to the case where ANDA is applied to the static scenario is obtained.

Finally, we expect that by combining the proposed assignment scheme with cluster-heads rotation [2], the network life-time will further increase. However, cluster-heads rotation involves an election procedure during which all nodes must be synchronized, thus resulting in an increased system complexity as well.

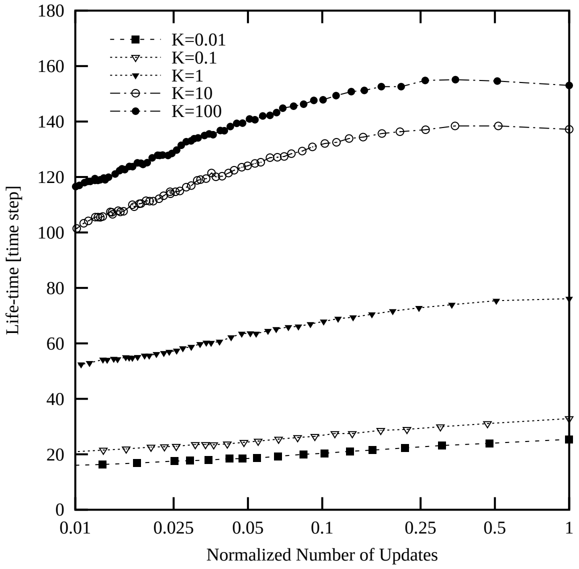

Fig. 5. Dynamic scenario: Life-time versus the normalized number of configuration updates, for a number of nodes equal to 1000, for a number of cluster-heads equal to 100 and different values of K. Nodes are uniformly distributed in the network area.

5 Conclusions

We addressed the problem of maximizing the life-time of a wireless ad hoc network, i.e., the time period during which the network is fully working. We focused on cluster-based networks and presented an original solution that maximizes the network life-time by determining the optimal clusters size and assignment of nodes to cluster-heads. We considered two working scenarios: in the former, the network configuration is computed only once; in the latter, the network configuration can be periodically updated. We obtained improvements in the network life-time equal to 15% in the case of the static scenario, and up to 74% in the case of the dynamic scenario.

References

1. Chang, J.H., Tassiulas, L., "Energy conserving routing in wireless ad hoc networks," *Proc. INFOCOM 2000,* Tel-Aviv, Israel, Mar. 2000.
2. Rabiner Heinzelman, W., Chandrakasan, A., Balakrishnan, H., "Energy-Efficient Communication Protocols for Wireless Microsensor Networks," *Proc. HICSS,* Maui, Hawaii, Jan. 2000.
3. Haker, D.J., Ephremides, A., "The Architectural Organization of a Mobile Radio Network via a Distributed Algorithm," *IEEE Trans. on Comm.,* Vol. 29, No. 11, Nov. 1981, 1694–1701.

4. Gerla, M., Tsai, T.-C., "Multicluster, Mobile, Multimedia Radio Network," *ACM/Baltzer Journal of Wireless Networks,* Vol. 1 , No. 3, 1995, 255–265.
5. Kwon, T., Gerla, M., "Clustering with Power Control," *Proc. MILCOM'99,* Nov. 1999.
6. Lin, C.R., Gerla, M., "Adaptive Clustering for Mobile Wireless Networks," *IEEE JSAC,* Vol. 15, No. 7, Sep. 1997, pp. 1265–1275.
7. Basagni, S., "Distributed and Mobility-Adaptive Clustering for Multimedia Support in Multi-Hop Wireless Networks," *IEEE VTC'99,* 889–893.
8. McDonald, A.B., "A Mobility-Based Framework for Adaptive Clustering in Wireless Ad-Hoc Networks," *IEEE JSAC,* Vol. 17, No. 8, Aug. 1999, 1466–1487.
9. Pearlman, M.R., Haas, Z.J., "Determining the Optimal Configuration for the Zone Routing Protocol," *IEEE JSAC,* Vol. 17, No. 8, Aug. 1999, 1395-1414.