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An Energy-Efficient Method for Nodes Assignment in Cluster-Based 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. Thus, making good use of energy is a must in ad hoc networks. In this paper, we define as network *lifetime* the time period from the instant when the network starts functioning to the instant when the first network node runs out of energy. Our objective is to devise techniques to maximize the network lifetime in the case of cluster-based systems, which represent a significant sub-set of ad hoc networks. Cluster-based ad hoc networks comprise two types of nodes: cluster-heads and ordinary nodes. Cluster-heads coordinate all transmissions from/to ordinary nodes and forward all traffic in a cluster, either to other nodes in the cluster or to other cluster-heads. In this case, to prolong the network lifetime we must maximize the lifetime of the cluster-heads because they are the critical network element from the energy viewpoint. We propose an original approach to maximize the network lifetime by determining the optimal assignment of nodes to cluster-heads. Given the number of cluster-heads, the complexity of the proposed solution grows linearly with the number of network nodes. The network topology is assumed to be either static or slowly changing. Two working scenarios are considered. In the former, the optimal network configuration from the energy viewpoint is computed only once; in the latter, the network configuration can be periodically updated to adapt to the evolution of the cluster-heads energy status. In both scenarios, the presented solution greatly outperforms the standard assignment of nodes to cluster-heads, based on the minimum transmission power criterion.

Keywords: wireless ad hoc networks, clustering, energy efficiency, modeling

1. Introduction

Ad hoc networks are self-organizing wireless systems that can be easily deployed in a variety of environments, from unknown environments with harsh working conditions to electronic classrooms and convention centers. They are composed of tens to hundreds of battery-powered nodes, which are all alike and are typically able to transmit over limited distance ranges, as compared to the network extension.

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 *lifetime*, i.e., the interval during which the network functions properly, becomes an important performance metric. There are various possible definitions for the network lifetime, depending on the network application. For example, it can be considered the time spanning from the instant when the network starts functioning until a certain percentage of nodes run out of energy, or until the network gets disconnected. In this work, we define the network lifetime as the time spanning from the instant when the network starts functioning to the instant when the first network node dies out, as first proposed in [3].

In order to maximize the system lifetime, the network must be designed to be extremely energy-efficient. In this paper, we deal with system architectures based on a clustering approach [6,7,9], 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 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. Such a system organization presents several advantages: (i) it enables

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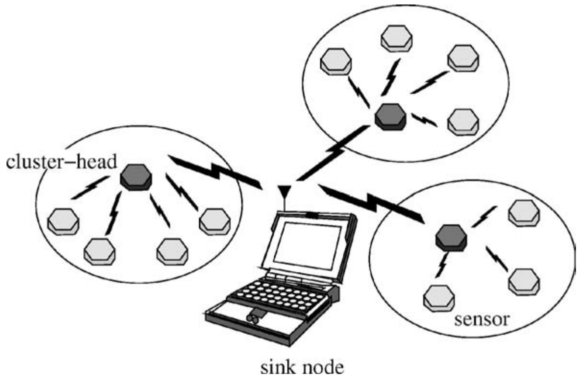

Figure 1. Sensor network organized in clusters.

robust networking with point-to-point connectivity, since only cluster changes have an impact on the network topology; (ii) it allows for bandwidth reuse, by assigning different channels to different clusters, thus resulting in an increased system capacity; (iii) it reduces routing complexity by limiting routing information storage and processing overhead [8]; (iv) it provides an improved power control, since power control schemes typically used in a cellular environment can be used with minor changes [9]; (v) it reduces the complexity of the location management procedures thanks to the node localization performed by the cluster-heads [4].

As an example, a clustering approach can be applied to sensor networks, where RF communication processors with sensing capabilities collect information and pass it to sink nodes [2,13–16]. The sink nodes convey the gathered data to a long-haul communication infrastructure either over the radio channel or through a wired connection. As shown in figure 1, sensors may be organized in clusters, where nodes transmit information to their cluster-heads, which forward the collected data to the sink node. A similar system is represented by the Real Time Location network (RFID Technology) [17], which includes cluster-heads, also called *readers*, and a large number of small, low-cost RF tags. Readers communicate over a shared wireless channel to the tags and then send the received data to a host computer for elaboration.

In cluster-based network architectures, the lifetime 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 output transmit power. 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 [1,9,10], 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 lifetime 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 lifetime, 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 [1,7,9–12,14], little work has been done on energy-efficient design of cluster-based networks. In [14], 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 transmission power criterion. Cluster-heads rotation implies that the network energy resources are more evenly drained and may result in an increased network lifetime. On the other hand, cluster-heads re-election may require excessive processing and communications overhead, which outweighs 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, as in sensor networks, or slowly changing. We propose an original solution, called *ANDA* (Ad hoc Network Design Algorithm), which maximizes the network lifetime 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 output transmit power. Two different working scenarios are considered: static and dynamic. In the former, the energy-optimal network design is computed at the time of network deployment and maintained along the entire system lifetime. In the latter, the network configuration can be periodically updated in order to guarantee a longer lifetime. The performance of ANDA is compared to the performance of the assignment of nodes to cluster-heads based on the minimum transmission power criterion, denoted by *ABC* (Assignment to the Best Cluster-head).

The remainder of the paper is organized as follows. Section 2 introduces the lifetime function in the case of a cluster-based network architecture; section 3 presents the mathematical formulation of the energy-efficient network design problem, and describes the proposed solution. Section 4 shows some results; finally, section 5 concludes the paper.

2. The network lifetime

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 lifetime, while the number of nodes within each cluster is determined by the level of transmission power used by the associated cluster-head.

Three are the major contributions to power consumption in radio devices: (i) the power consumed by the digital part of the circuitry; (ii) the power consumption of the transceiver in transmitting and receiving mode; and (iii) the output transmit power.

Based on the above thoughts and under the assumption that traffic load is uniformly distributed among the network nodes, the time spanning from the instant when the network begins to function until the generic cluster-head i runs out of energy, can be written as

$$L_i = \frac{E_i}{\alpha c_i + f(n_i)}, \tag{1}$$

where E_i is the initial amount of energy available at cluster-head i and the two terms at the denominator represent the contribution to power consumption due to the output transmit power and the cluster-head transmitting/receiving activity, respectively. In the first term at the denominator, c_i represents the transmit power level of cluster-head i such that $P_{\min} \leqslant c_i \leqslant P_{\max}$, with $P_{\min}$ and $P_{\max}$ being the minimum and the maximum output transmit power, respectively; α is a constant weighting factor. In particular, such an expression implies that the contribution to power consumption due to the output transmit power is proportional to the level of power used by the cluster-head, as in [5]. The extension to more general models of power consumption, however, is straightforward. In the second term at the denominator, the power consumption of the cluster-head due to its transmitting and receiving activity is modeled as a function of n_i, where n_i is the number of nodes under the control of cluster-head i. This motivated by the fact that an increase in the number of nodes controlled by the cluster-head corresponds to an increase in the information and control packets exchange within the cluster.

Considering that the limiting factor to the network lifetime is represented by the cluster-heads functioning time, the lifetime can be defined as [3,14]

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

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

As mentioned above, power consumption in a radio device depends on the output transmit power and on the time spent by the device in transmitting and receiving mode. Therefore, an expression similar to (1) can be derived for the node functioning time where c_i is the output transmit power of node i and n_i represents the number of nodes belonging to the same cluster of node i. We notice that by fixing the value of traffic load, the time spent by a node in transmitting mode increases with the number of packet collisions; while, the time spent in receiving mode increases with the number of control messages broadcast by the associated cluster-head. Hence, by maximizing the cluster-heads lifetime, energy saving of the network nodes may be maximized as well.

3. Energy-efficient network design

In this section, we formally describe the problem of maximizing the network lifetime. 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 lifetime. Then, we propose an energy-efficient design algorithm, so-called *ANDA* (Ad hoc Network Design Algorithm), which maximizes the network lifetime by fixing 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:

1. The number of cluster-heads, denoted by C.
2. The number of nodes in the network, denoted by N.
3. The transmit power level enabling a cluster-head to reach a node, for each cluster-head and node pair in the network.
4. The initial value of the energy available at each cluster-head.

For the sake of simplicity, we assume a linear relation between the power consumption of the cluster-head transceiver in transmit and receive mode and the number of covered nodes; however, the proposed solution still holds when a different relation is considered. From (1) and (2), we have

$$L_S = \min_{i \in S_C} \frac{E_i}{\alpha c_i + \beta |n_i|}, \tag{3}$$

where β is a constant weighting factor.

Let c_{ik} be the power level needed at cluster-head i to reach node k ($i = 1, \ldots, C$; $k = 1, \ldots, N$); c_{ik} ($k = 1, \ldots, N$) may depend on several propagation effects such as path loss, fading and shadowing. We have that $c_i = c_{ij}$ when j is the node, among those controlled by cluster-head i, requiring the highest transmit power level. Next, let us introduce matrix $\boldsymbol{L} = \{l_{ij}\}$, whose dimension is equal to $|S_C| \times |S_N|$. The generic matrix element l_{ij} represents the lifetime of cluster-head i when its output transmit power is set to $c_i = c_{ij}$, and cluster-head i covers $n_{ij} = \{k \in S_N \mid c_{ik} \leqslant c_{ij}\}$ nodes. We have

$$l_{ij} = \frac{E_i}{\alpha c_{ij} + \beta |n_{ij}|}. \tag{4}$$

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

$$\begin{aligned} &\text{maximize } L_S \\ &\text{subject to} \\ &\quad \sum_i x_{ij} \geqslant 1 && \forall j \in S_N, \\ &\quad L_S \leqslant l_{ij} x_{ij} + M(1 - x_{ij}) && \forall i \in S_C,\ j \in S_N, \\ &\quad x_{ij} \in \{0, 1\},\ L_S \geqslant 0 && \forall i \in S_C,\ j \in S_N. \end{aligned} \tag{5}$$

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.

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. Let us assume that time steps 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 $E_i, c_{ij}, n_{ij}, l_{ij}$ with $E_i^s, c_{ij}^s, n_{ij}^s, l_{ij}^s$ i.e., with the corresponding values computed at time step s. In this case, however, the model is no longer linear, since the model parameters depend on the time step and, thus, on the former nodes assignment.

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 figure 2.

3.2.1. *Static scenario*

The assignment of nodes to cluster-heads is performed through the procedure *Covering*, which associates each node to the cluster-head presenting the longest functioning time. Thus, node j ($j = 1, \ldots, N$) will be covered by cluster-head i if $l_{ij} = \max_{k \in S_C}\{l_{kj}\}$. We highlight that, even if the node assignment is performed sequentially, once the level of output transmit power of the cluster-head is fixed, the corresponding entry of matrix $\boldsymbol{L}$ still takes into account the total number of nodes covered by the cluster when that power level is used (please see (4)).

```
begin Covering
for (every $j \in S_N$)
    set $max = 0$
    for (every $i \in S_C$)
        if ($l_{ij} \geqslant max$)
            set $max = l_{ij}$
            set $sel = i$
        end if
    end for
    Cover node $j$ with cluster-head $sel$
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 $c_{ij}, |n_{ij}|, l_{ij}$
    end for
end for
$L_S^{(new)} = L_S^{(old)} = L_S$
$\Delta = 0$
while ($L_S^{(new)} \leqslant L_S^{(old)} - \Delta$)
    $\Delta = \Delta + 1$
    for (every $i \in S_C$)
        for (every $j \in S_N$)
            Recompute $E_i = E_i - \Delta(\alpha c_i + \beta|n_{ij}|) - H$
            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
```

Figure 2. Pseudo-code of the network design algorithm.

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 lifetime and therefore the configuration would not be optimal.

The ANDA algorithm can be implemented in a centralized as well as in a distributed manner. When a central controller exists, the c_{ij} and n_{ij} values ($i = 1, \ldots, C$; $j = 1, \ldots, N$), and the cluster-heads energy status have to be collected at the central entity, which executes the function *Covering* and notifies the cluster-heads of the node assignment. On their turn, the cluster-heads inform the nodes about the network configuration. A distributed implementation of the algorithm can be obtained in two rounds. First, the generic cluster-head i ($i = 1, \ldots, C$) has to collect the values c_{ij} related to the nodes that are within its maximum transmission range. Then, the cluster-head has to send to each of the reachable nodes the following information: (i) the cluster-head energy level; (ii) the value of transmit power required to communicate with the node (e.g., c_{ij}, where j is the generic node that the cluster-head is able to cover); (iii) the number of nodes, n_{ij}, that the cluster-head covers when it uses a power level equal to c_{ij}. Based on this information, every node can compute the lifetime of its candidate cluster- heads and select the one with the highest value of lifetime.

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

3.2.2. Dynamic scenario

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 its output transmit power. By scheduling periodical node re-assignments based on the recomputed values of E_i $(i = 1, \dots, C)$, we can level the system energy consumption.

At each configuration update, the new value of the available energy at cluster-head i $(i = 1, \dots, C)$ is computed as

$$E_i^{(\text{new})} = E_i^{(\text{old})} - \Delta\big(\alpha c_i + \beta|n_i|\big) - H, \tag{6}$$

where Δ is the time interval elapsed from the last update of the network configuration, and H is the cost of the update procedure in terms of protocol overhead. Let us consider, for the sake of simplicity, a centralized implementation of the ANDA scheme. Every time a reconfiguration procedure takes place, the central controller has to advertise to the cluster-heads the procedure start. The cluster-heads then send to the controller their current energy status, and receive the nodes assignment from the controller. Such an information is propagated to the network nodes by the cluster-heads. At each network reconfiguration, a cluster-head has to receive and transmit in total four messages; hence, while deriving the numerical results, we take H to be equal to 4β.

We compute $E_i^{(\text{new})}$ and update matrix $\boldsymbol{L}$ by using the function *Reconfigure*, then, through 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.

4. Numerical results

The performance of ANDA is derived in terms of network lifetime, and mean and variance of the residual energy at the cluster-heads measured at the time instant at which the first cluster-head runs out of energy. Results are plotted as functions of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity, denoted by K. Looking at the denominator in (3), we derive K as a function of α and β as

$$K = \frac{\alpha c_i}{\beta|n_i|}. \tag{7}$$

We consider that all cluster-heads in the network are fixed and have initial energy $E_i = 1$ with $i = 1, \dots, C$. Unless is differently specified, we assume that cluster-heads and nodes are uniformly distributed over a rectangular network area. 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. We set $P_{\max}$ equal to 0.25 and $P_{\min} = P_{\max}/10$, and assume that the variables c_{ij} $(i = 1, \dots, C,\ j = 1, \dots, N)$ are uniformly distributed in the range $[P_{\min}, 1]$. The nodes, which a cluster-head can possibly cover, are those that can be reached by using a transmit power level less than $P_{\max}$.

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 transmission power criterion (denoted by label *ABC* (Assignment to the Best Cluster-head) in the plots), which simply assigns each node to the cluster-head requiring the minimum output transmit power to communicate with the node. Figure 3 shows the network lifetime as a function of the number of cluster-heads, C. Curves are obtained for $N = 1000$ and varying

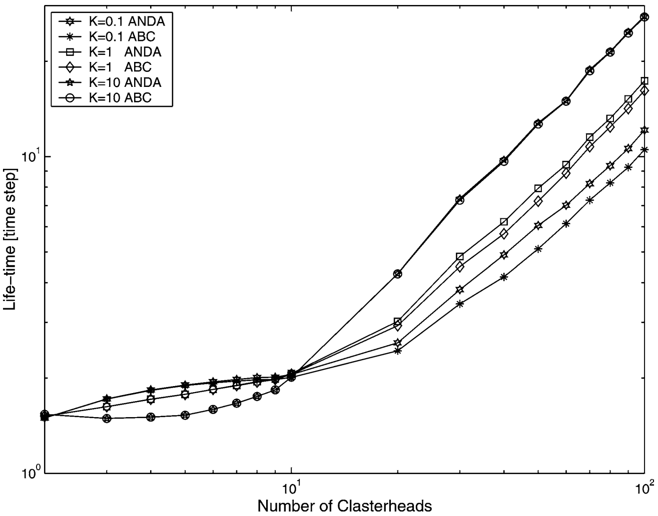

Figure 3. Static scenario: lifetime as a function of the number of cluster-heads, for a number of nodes equal to 1000 and different values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). Results obtained through ANDA and the ABC scheme are compared.

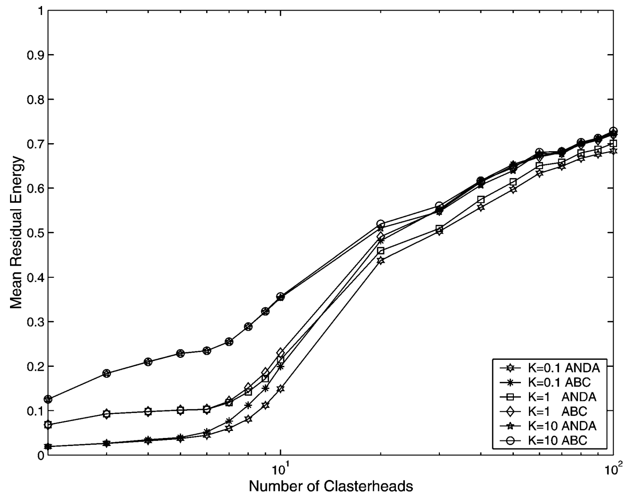

Figure 4. Static scenario: mean residual energy at the cluster-heads as a function of the number of cluster-heads. Curves are plotted for a number of nodes equal to 1000 and for varying values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). Results obtained through ANDA and the ABC scheme are compared.

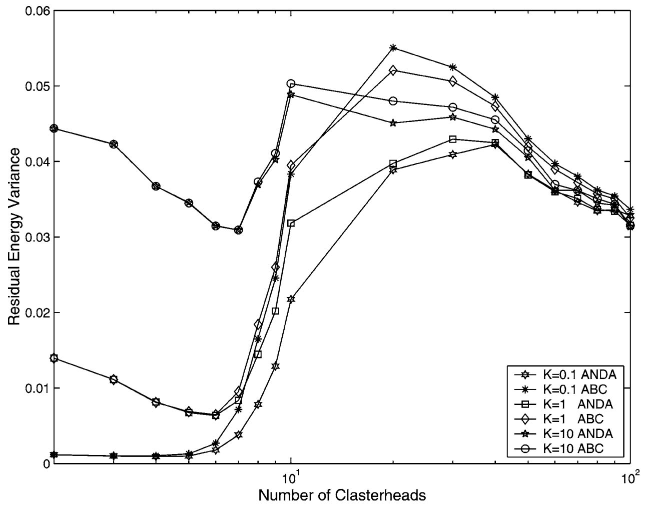

Figure 5. Static scenario: variance of the residual energy at the cluster-heads as a function of the number of cluster-heads. Curves are plotted for a number of nodes equal to 1000 and for varying values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). Results obtained through ANDA and the ABC scheme when nodes are not uniformly distributed in the network area are compared.

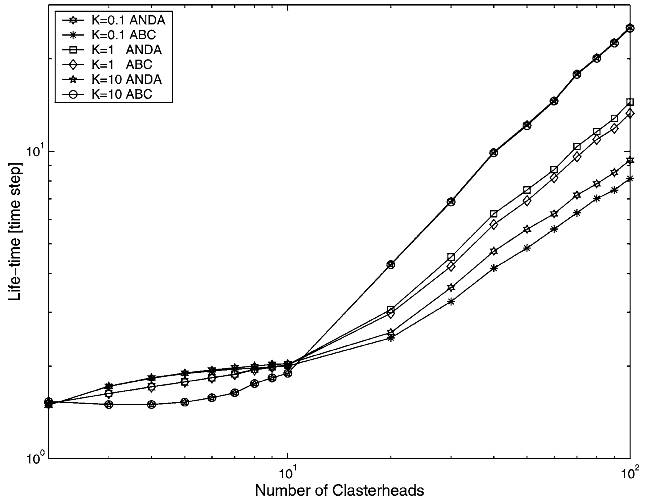

Figure 6. Static scenario: lifetime as a function of the number of cluster-heads, for a number of nodes equal to 1000 and different values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). A non-uniform distribution of the nodes in the network area is assumed.

values of K. As expected, the lifetime increases with the increase of the number of cluster-heads. From the comparison with the performance of the ABC 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 transmit power contribution dominates. For both the ABC scheme and ANDA, when the number of cluster-heads is less than 10, a longer lifetime is obtained when the major contribution to power consumption is due to the transmitting and receiving activity ($K = 0.1$). On the contrary, for a number of cluster-heads greater than 10, the performance gets better as K increases. This is because, when there are few cluster-heads with respect to the number of nodes, the distribution of the nodes among the clusters appears to be fairly even. Thus, if power consumption mainly depends on the number of nodes per cluster (i.e., $K = 0.1$), we obtain a longer network lifetime. As more cluster-heads are available, the number of nodes per cluster decreases and the differences in the number of nodes assigned to the cluster-heads become significant. Since both the ANDA and the ABC scheme level better the output transmit power consumption than the nodes distribution among the clusters, a longer lifetime is obtained for $K = 10$.

Figures 4 and 5 show the mean and the variance of the residual energy at the cluster-heads, respectively, as functions of the number of cluster-heads. The number of nodes in the network is set to 1000. As expected, in figure 4 the mean value of the residual energy increases with the number of cluster-heads. A more interesting behavior is obtained for the variance of the residual energy, as shown in figure 5. For $K \leqslant 1$ and small values of the number of cluster-heads, 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. We notice that, for any value of K, ANDA outperforms the ABC scheme both in terms of mean and variance of the residual energy.

Figure 6 presents curves derived in presence of a large spatial variation of the nodes density, as we have in sensor networks. We assume $N = 1000$ and that the network area is divided into ten sub-areas; in each sub-area nodes are uniformly distributed but with different density. We consider that 40% of the nodes is concentrated in two sub-areas, while the remaining 60% is evenly distributed in the other eight sub-areas. As in the case where nodes are uniformly distributed over the network area, up to 15% improvement in lifetime is obtained with respect to the ABC scheme.

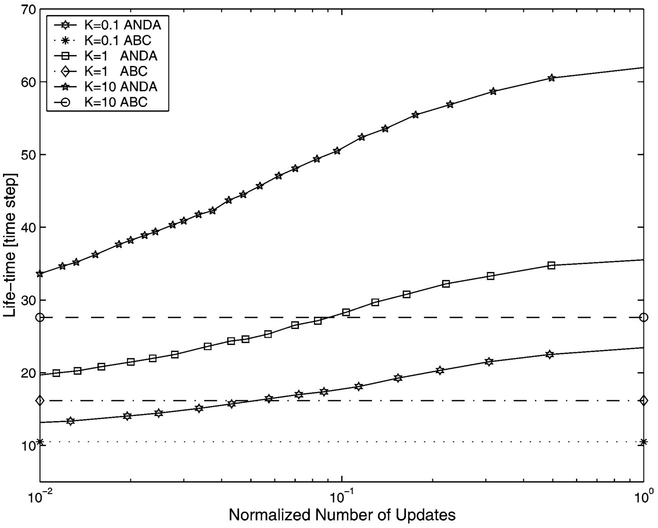

Figure 7. Dynamic scenario: lifetime versus the normalized number of configuration updates, for a number of nodes $N = 1000$, a number of cluster-head $C = 100$, and different values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). Nodes are uniformly distributed in the network area.

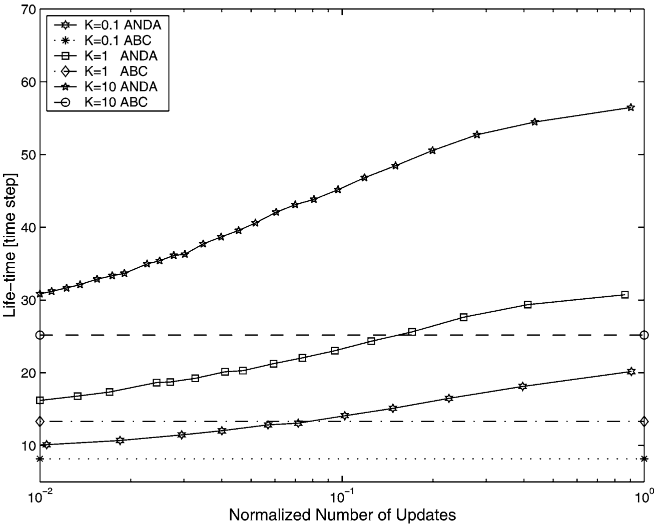

Figure 9. Dynamic scenario: network lifetime versus the normalized number of network configuration updates as the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). We have: $N = 1000$ and $C = 100$. A non-uniform distribution of the nodes in the network area is assumed.

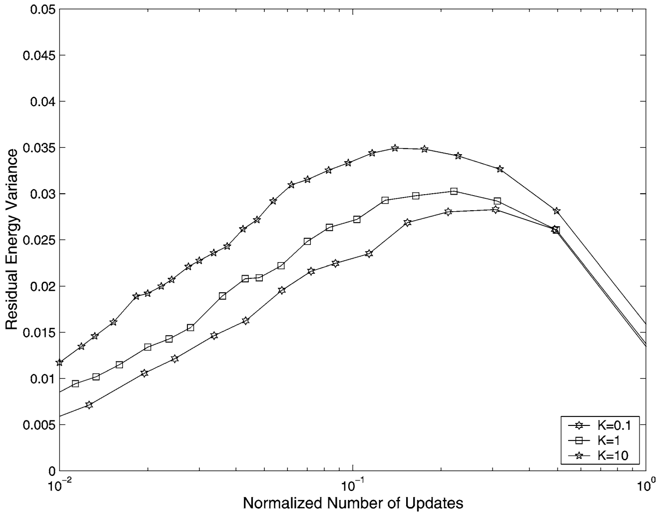

Figure 8. Dynamic scenario: variance of the residual energy at the cluster-heads versus the normalized number of configuration updates, for a number of nodes $N = 1000$, a number of cluster-head $C = 100$, and different values of the ratio of the output transmit power to the power consumption due to the transmitting and receiving activity (K). Nodes are uniformly distributed in the network area.

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 lifetime and the system complexity. Thus, results showing the trade-off between network lifetime and number of executed configuration updates are presented. Figures 7–9 report in abscissa the number of performed configuration updates normalized to the observation time expressed in time steps.

Figure 7 presents the network lifetime for different values of K and nodes uniformly distributed in the network area. Results obtained through the ANDA scheme are compared with the performance of the ABC algorithm, that does not involve network reconfigurations. Looking at the performance of ANDA, the lifetime 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 90% with respect to the case where ANDA is applied to the static scenario is achieved. Comparing the performance of ANDA, with the lifetime obtained by using the ABC scheme, we obtain an improvement of about 120%.

Figure 8 shows the variance of the residual energy as K varies and for a uniform distribution of the network nodes. We observe that the ANDA scheme provides a very low variance, for any value of K and of normalized number of configuration updates. The behavior of the curves obtained by using ANDA can be explained as follows. For a low number of configuration updates, the variance is quite small since most of the cluster-heads will enjoy a fairly limited energy consumption. As the number of updates grows, more cluster-heads may experience a high energy consumption, thus resulting in larger values of variance. Then, for a normalized number of updates greater than 0.2, the variance starts decreasing suggesting that all cluster-heads are evenly drained.

Figure 9 shows the network lifetime obtained for $C = 100$, $N = 1000$, and a non-uniform distribution of the nodes over the network area. Both the performance of the ANDA and of the ABC scheme are plotted. By comparing these results with those in figure 7, we observe that similar values of the network lifetime are obtained. This suggests that the proposed algorithm is able to create an energy-efficient configuration even when the network is characterized by a large spatial variation of the nodes density. As in the case where nodes are uniformly distributed, we achieve improvements in network lifetime equal to about 90% with respect to the case where ANDA is used in the static scenario and equal to 120% with respect to the ABC scheme.

Finally, we highlight that when a rotation of the cluster-heads among the various network nodes is possible [14], a significant increase in lifetime can be obtained. However, cluster-heads rotation involves an election procedure during which all nodes must be synchronized, thus resulting in an increased system complexity as well. A thorough study would be necessary to investigate the trade-offs that exist between the improvement in network lifetime and the additional system complexity due to a cluster-heads rotation procedure.

5. Conclusions

We addressed the problem of maximizing the lifetime 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 lifetime by determining the optimal assignment of nodes to cluster-heads. We considered two working scenarios: static and dynamic. In the former, the network configuration is computed only once; in the latter, the network configuration can be periodically updated. We compared the proposed nodes assignment algorithm with earlier methods which assign each node to the cluster-head associated with the minimum value of transmission power. Results showed that our method provides up to 15% improvement in the network lifetime in the case of the static scenario, and up to 120% improvement in the case of the dynamic scenario. We expect that by combining the proposed assignment scheme with cluster-heads rotation, the system performance will further improve.

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