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Enhancing Survivability, Lifetime, and Energy Efficiency of Wireless Networks

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Abstract

In this paper, we focus on improving wireless networks survivability in terms of increasing network lifetime and its energy efficiency via clustering the network in an efficient way. Clustering the network is the procedure of partitioning it into groups, where each of them is known as a cluster. Each cluster elects the station with the highest power to be a cluster head. The remaining stations follow the nearest cluster head. Instead of having each station sends its packets to a remote receiver, the cluster head receives packets from all stations within its cluster, aggregates them, and forwards the resulting packets to the remote receiver. The most significant benefit of clustering the network that we focus on is to decrease distances between sending and receiving stations, which in turn reduces the transmission energy. This reduction in the energy yields an increase in the network lifetime and its survivability.

Keywords- Wireless networks, energy, survivability, lifetime, clustering.

I. INTRODUCTION

Wireless local area networks (WLANs) are flexible data-communications systems implemented as an extension to, or as an alternative for, wired LANs that use radio frequency (RF) technology to transmit and receive data in order to minimize the need for wired connections.

Thus, wireless LANs combine data connectivity with user mobility [1]. Wireless LANs have gained strong popularity in a number of vertical markets, including the health-care, retail, manufacturing, warehousing, and academia. These industries have profited from the productivity gains of using hand-held terminals and notebook computers to transmit real-time information to centralized hosts for processing. In contrast with wired LANs, not every participant may be able to reach each other due to several reasons, including low signal strength, blocked propagation by walls [2].

In this paper, we focus on enhancing survivability of wireless LANs in terms of increasing network lifetime and improving energy efficiency using an efficient clustering protocol that is applicable in wide areas, such as sensor networks, which are typically operated with batteries, whose replacement, when possible, is very difficult and expensive.

Regarding clustering, there are several definitions that can be found in the literature from simple to elaborate. A simple definition of clustering that is shared among most of papers can be found in [3,4,5], which shows a fundamental concept of grouping several nodes together into clusters that may or may not have similar data.

There are several researches who have proposed clustering approaches for wireless networks and have studied the effect of increasing the number of users(e.g. mobile-phone networks). However, they did not analyze the benefits of clustering in enhancing network's lifetime and energy efficiency.

Recently, clustering has been applied to a wide range of research and practical areas, which make clustering a technique that merges several approaches from different disciplines, such as mathematics, physics, programming, statistics, computer science, artificial intelligence, etc.

Clustering can actually be implemented at different levels of the system, including hardware, middle-ware, systems management and applications, and operating systems. It should be noted that the more layers that incorporate clustering, the more reliable, scalable, and manageable the cluster will be.

The authors in [6] considered radio applications in sensor networks to minimize the energy consumption while satisfying given throughput and delay requirements. The authors compared the energy efficiency of several systems under Rayleigh fading channels via numerical analysis. However, they did not study the impact of energy efficiency on network lifetime, which we study in this paper by using a clustering approach and examining it.

To study localization in clustered sensor networks, the authors in [7] presented an approach that can satisfy all desired properties of localization via assigning geographic coordinates to each node in the sensor network along with applying clustering as a basis for determining the position information of sensor nodes. Recent developments in clustering algorithms have led to distributed algorithms that produce highly regular clusters, which are proposed by the authors in [7] to make use of this regularity in forming localization algorithms. However, we use in this paper a clustering approach that aims at enhancing network's lifetime and its survivability.

In this paper, we consider a wireless network (e.g. sensors network), in which the stations are given initial powers (battery). Such stations are typically operated with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must survive without battery replacement for many years. Consequently, minimizing the energy consumption is an important design consideration in sensor networks. This situation enforces researchers to carefully design energy-efficient schemes for transmitting data packets to the receiver that could be a connection device, e.g. a bridge or a control station.

The rest of the paper is organized as follows. In section II we introduce the problem statement. The system model is explained in section III. The performance of the network is evaluated via simulations in section IV. Section V summarizes our main findings.

II. PROBLEM STATEMENT

In this paper, we consider the problem of maximizing the lifetime of a network that consists of energy-constrained (battery-operated) stations (e.g. wireless sensors). The network lifetime depends mainly on its stations lifetime. In our model, we consider the station's power as the main parameter to be used in measuring its lifetime. Once the initial given power of a station reaches zero, its lifetime finishes. Thus, a non-clustered network stays alive until any of its stations consumes all its initial power.

It should be noted that the significance of achieving high survivability via clustering is seen when one node fails, where another node in the cluster can resume the work load of the failed node, and therefore the users notice no interruption of access. Another advantage of clustering is scalability, which results in an improved application's performance and a greater number of supported users. Therefore, a cluster of servers can be seen as if the servers are single and unified computing resource. In such a case, with the total redundancy of multiple servers, the cluster can help achieve greater system uptime.

III. SYSTEM MODEL

Clustering is the procedure of partitioning a network topology into groups called clusters. In this work, each cluster elects the station with the highest power to be a cluster head. The remaining stations follow the nearest cluster head. Instead of having each station sends its packets to a remote receiver, the cluster head receives, aggregates, and forwards the packets of all stations within its cluster to a remote receiver.

In this paper, we take into account both the transmission and circuit parts of the energy consumption. The power consumed for each packet to be transmitted is given by [8]:

$$P_t = (1+\alpha)\gamma(M_t, M_r)N_0 B N_f G_0 M_l d^n$$

where α is a factor that depends on the drain efficiency of the power amplifier and the underlying modulation scheme [9], $\gamma(M_t, M_r)$ is the required signal to noise ratio (SNR) at the receiver when a specific number of antennas is used for transmission and reception, N_0 is the single-sided thermal noise power spectral density (PSD), B is the pass-band bandwidth, N_f is the receiver noise figure, G_0 is a constant that depends on the transmitter and receiver antenna gains, M_l is a link margin that compensates for hardware variations and other sources of interference, n is the path-loss exponent, and d is the transmitter-receiver distance. It should be noted that the main factor in determining the transmission power is the distance between the transmitting and receiving stations, which are directly related to each other, i.e., the power consumed for each packet transmission increases as the separation distance between the stations increases.

Notice that in clustered networks, the factors that affect the power consumed by a station in order to send a packet to the cluster head are similar to those in non-clustered networks. However, the main factor (d) indicates the distance between the transmitter and the cluster head in clustered networks rather than the distance between any two stations in non-clustered networks. Therefore, this reduction in the distance between clustered and non-clustered networks results in decreasing the required packet transmission power.

The other main part of the total required power consumption is the circuit power, which is given by [8]:

$$P_r = P_{DAC} + 2P_{mix} + P_t^{filter} + 2P_{sym} + P_{LNA} + 2P_{IFA} + P_r^{filter} + P_{ADC}$$

where P_{DAC}, P_{mix}, P_t^{filter}, P_r^{filter}, P_{sym}, P_{LNA}, P_{IFA}, and P_{ADC} are the power consumption values for the digital-to-analog converter, the mixer, the active filters at the transmitter and the receiver sides, the frequency synthesizer, the low-noise amplifier, the intermediate-frequency amplifier, and the analog-to-digital converter, respectively.

Accordingly, the total energy consumption per bit is given by [8]:

$$Total\ Enrgy\ Per\ Bit = \left(P_t + P_r\right) / R$$

where R is the bit rate (for the binary phase shift keying (BPSK) modulation scheme $R \approx B$ bits/sec).

It should be noted that the main achievable benefit of network clustering is to decrease the distances between sending and receiving stations, which in turn reduces the transmission energy. This reduction in the energy yields an increase in the network lifetime and an enhancement in the survivability of the network. Therefore, our three main goals of this work are achieved, i.e., enhancing the survivability, lifetime, and energy efficiency of wireless networks.

IV. PERFORMANCE EVALUATION

In order to demonstrate how clustering the network enhances its survivability, lifetime, and energy efficiency, we simulate different network models, which are explained later. We compare the results for clustered and non-clustered networks. Our simulation setup considers randomly distributed stations that have random initial powers.

In our simulations, we refer to the station's remaining power after each transmission as the "current power," which can be computed as follows:

$$Current\ Power = Power - Transmitting\ Power\ \left(P_t\right)$$

where *power* is the initial power value given to the station.

In clustered networks, the cluster heads spend power in both transmitting and receiving packets. Thus, the *current power* value for such stations is computed as follows:

$$Current\ Power = Power - \left(Transmitting\ Power\ \left(P_t\right) + Receiving\ Power\ \left(P_r\right)\right)$$

To calculate the total energy consumption, the following formula is used [8,10]:

$$Total\ Enrgy = Packet\ Size \times Total\ Enrgy\ Per\ Bit$$

where the *Total Energy Per Bit* can be found as illustrated in section III. Accumulating the values of the total energy consumption for all network's stations results in the overall energy consumed in the whole network, which is shown in the simulation figures.

It should be noted that in our simulations, after choosing the network-clustering state in the simulations interface, the stations with the highest power values are elected as cluster heads of the network, where each of them creates later its corresponding cluster. The criterion for any station to follow a specific cluster is the distance between that station and all cluster heads, where every station associates itself with the nearest cluster head among all cluster heads.

The simulation platform is MATLAB. The system parameters that are used in our simulations are tabulated in Table 1.

Table 1: System Parameters

Parameter	Value
α	0.3
$\gamma(M_t, M_r)$	24.4 dB = 275.42
N_0	1.38 * 10^{-23} W
R	1 Mbps
B	1 MHz
P_{DAC}	15 mW
P_{ADC}	15 mW
P_t^{filter}	2.5 mW
P_r^{filter}	2.5 mW
P_{LNA}	20 mW
N_f	10 dB
G_0	1 m^{-4}
M_l	10 dB
n	4
P_{mix}	30.3 mW
P_{sym}	50 mW
P_{IFA}	2 mW
Packet size	64 bits

We performed our simulations based on the previously mentioned setup. We now compare the results for clustered and non-clustered networks. The following simulation figures verify that applying the clustering algorithm into a network increases the network's lifetime by an average of three times compared with non-clustered networks, which results in reducing network's consumed energy and improving its survivability. Our results prove these achievements for several numbers of stations (i.e., 200, 250, 300, and 400 stations).

IV.A 200-Station Network

In this section, we compare the performance of ten different 200-station clustered and non-clustered networks in terms of their lifetime and total energy consumption (which includes both transmission and circuit parts). We refer to the ten different network topologies as network numbers (one to ten), where the main difference in these topologies is thedistribution of the stations in the network area. Figure 1 shows the resultant network's lifetime for the ten different 200-station networks. We conclude from this figure that the average lifetime for a non-clustered 200-station network is always 2 time units, whereas it is (on average) for clustered 200-station network 3.7 time units. This achievement is due to the fact that the transmitter-receiver distances in clustered networks are smaller than those in non-clustered networks. As a result, it is clear that clustering the network improves the network's lifetime, and thus its survivability.

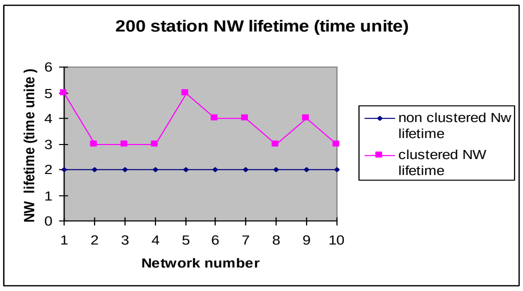

Figure 1. 200-station network's lifetime

The other compared parameter between clustered and non-clustered 200-station networks is the resultant total energy consumption (including both transmission and circuit parts), which is provided in Figure 2. It can be noted from this figure that the total energy consumption has been decreased by about 0.8 mJ for clustered networks (2.5 mJ) compared with non-clustered networks (3.3 mJ). As a conclusion, clustered networks are more energy efficient than non-clustered networks.

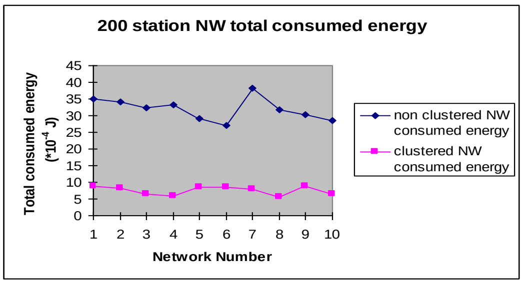

Figure 2. 200-station network's total energy consumption

IV.B 250-Station Network

In this section, we study the effect ofchanging the number of stations in the network (from 200 to 250 stations) on its lifetime and total energy consumption. This experiment has also been conducted for ten different clustered and non-clustered networks. Figure 3 ensures the result revealed by Figure 1 (i.e., clustering the network improves the network's lifetime, and thus its survivability). From Figure 3, it can be seen that the average network's lifetime has improved from 1 time unit for non-clustered 250-station networks to 3.2 time units (on average) for clustered 250-station networks. This result is caused by the same reason mention for Figure 1 regarding the transmitter-receiver distances.

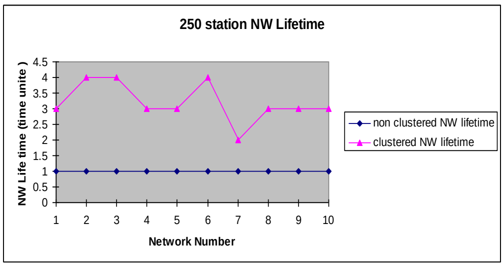

Figure 3. 250-station network's lifetime

Figure 4 shows the resultant total energy consumption for clustered and non-clustered 250-station networks. The figure indicates that the energy values are 0.8 mJ and 2 mJ for clustered and non-clustered networks, respectively, which supports the fact that clustering the network results in an improved network's energy efficiency.

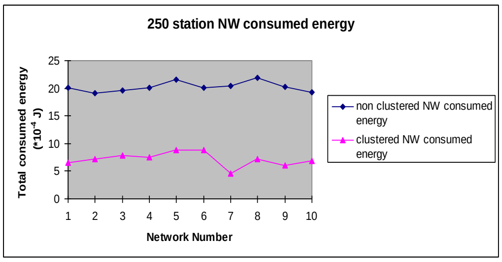

Figure 4. 250-station network's total energy consumption

IV.C 300-Station Network

We now change the number of stations in the network from 250 to 300 stations, and study the effect of this change on thenetwork's lifetime and total energy consumption for clustered and non-clustered networks. Figure 5 shows that the lifetime of the non-clustered 300-station networks is 1.3 time units, whereas it has increased for the clustered 300-station networks to 3.2 time units.

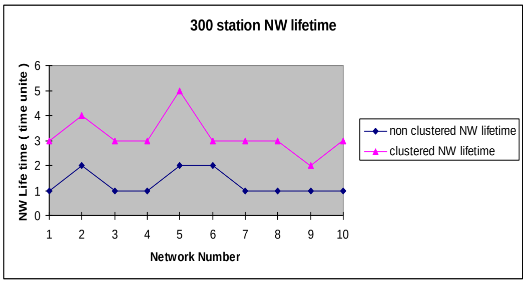

Figure 5. 300-station network's lifetime

Figure 6 shows the total energy consumption for clustered and non-clustered 300-station networks. This figure reveals that the energy values are 0.8 mJ and 4 mJ for the clustered and non-clustered networks, respectively.

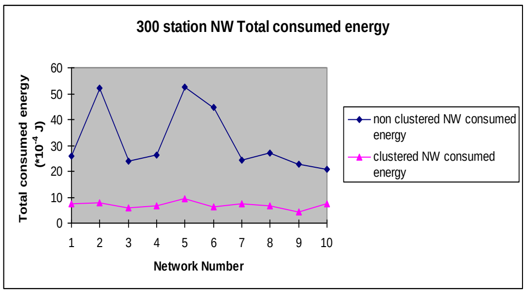

Figure 6. 300-station network's total energy consumption

IV.D 400-Station Networks

In this section, we study the effect of changing the number of stations in the network from 300 to 400 stations on its lifetime and total energy consumption for ten different clustered and non-clustered networks. Figure 7 ensures the results revealed by Figures 1, 3, and 5 regarding the network's lifetime and survivability.

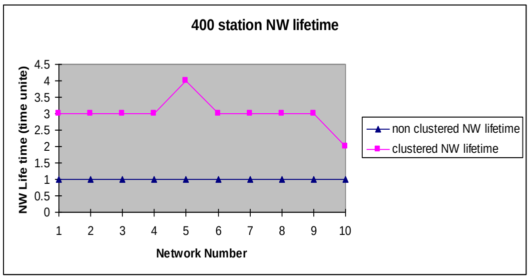

Figure 7. 400-station network's lifetime

Figure 7 depicts that the network's lifetime has improved from 1 time unit for non-clustered 400-station networks to 3 time units (on average) for clustered 400-station networks.

Figure 8 shows the resultant total energy consumption for clustered and non-clustered 400-station networks. The figure indicates that the energy value for the clustered networks is 0.7 mJ, whereas it is 3.3 mJ for the non-clustered networks.

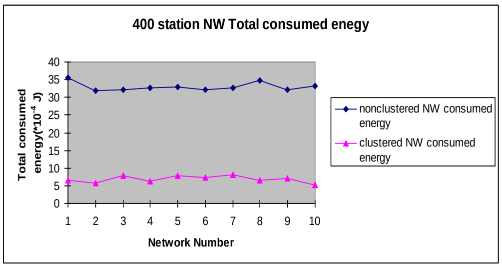

Figure 8. 400-station network's total energy consumption

IV.E Summary of Simulation Results

To summarize the effectiveness of clustering a network based on the three main metrics of our simulations (enhancing the network's survivability, lifetime, and energy efficiency), we provide two figures (Figures 9 and 10) that compare clustered networks with non-clustered networks in terms of network's average lifetime and average energy consumption as a function of the network's number of stations. Figure 9 shows the behavior of the average energy consumption for clustered and non-clustered networks under four different topologies, i.e., for networks with 200, 250, 300, and 400 stations.

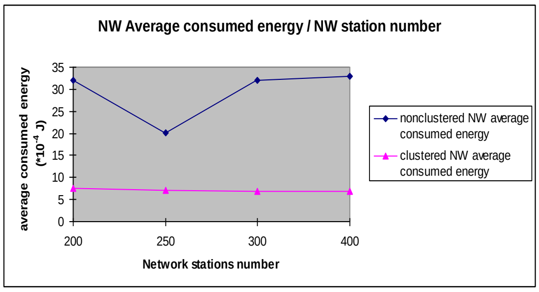

Figure 9. Average energy consumption versus number of stations

It can be easily shown from Figure 9 thatthe energy can be significantly conserved via clustering the network for all tested numbers of stations. This conclusion leads to a consequent result regarding improving the network's survivability.

Figure 10 depicts the average network's lifetime for clustered and non-clustered networks with 200, 250, 300, and 400 stations. Comparing the two curves (for clustered and non-clustered networks) of this figure ensures that clustering the network improves the network's lifetime under all numbers of network's stations.

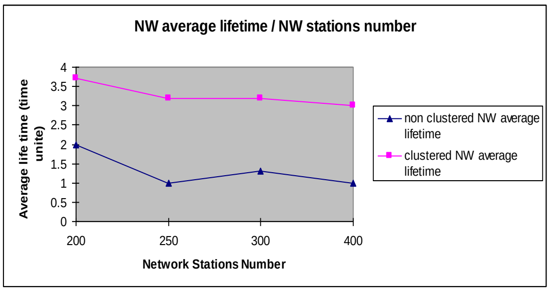

Figure 10. Average network's lifetime versus number of stations

V. CONCLUSIONS AND FUTURE WORK

In this paper, we enhanced the survivability, lifetime, and energy efficiency of wireless networks via clustering them in an efficient way. The clustering algorithm can be summarized as follows. Each cluster elects the station with the highest power among them to be a cluster head. The remaining stations associate themselves with the nearest cluster head. Each station within a cluster sends its packets to the cluster head, which aggregates and forwards the packets from all the stations within its cluster to a remote receiver. The main achievable benefit of this clustering algorithm is to decrease the distances between the sending and receiving stations, which in turn reduces the required transmission energy. This reduction in the energy yields an increase in the network lifetime and survivability.

To demonstrate how clustering the network achieves those goals, we conducted several simulation experiments to compare the performance of clustered and non-clustered networks. The simulation results showed that the lifetime of clustered networks reaches three times that of non-clustered networks, which results in an improvement in the network survivability. Also, the results revealed that the total energy consumption in clustered networks is enhanced over non-clustered networks. Those results are based on simulating several networks with different topologies (i.e., different numbers of stations). For instance, in clustered 200-station networks, the lifetime is about two times that of non-clustered 200-station networks. Moreover, under the same topology, the average energy consumption in clustered networks is 0.7132 mJ, whereas it is 2.0242 mJ for non-clustered networks.

As a future extension of this work, we plan on proposing a clustering technique that employs the scalability issue in wireless networks. We also plan on maximizing a utility function that depends on the network survivability, lifetime, and energy efficiency together so that the network performance is optimized. Another issue that is left for future work is suggesting new clustering algorithms that improve the network performance over the algorithm that is used in this paper.

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