Design of a Large Scale Multi-Cluster Wireless Sensor Network

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Abstract: In this paper we propose a new approach to designing a large scale wireless sensor network (WSN) with a cluster-tree topology. Sensors in each cluster communicate directly with their associated cluster head (CH) through contention-based transmissions, and communications between CHs use contention free transmissions. The objective is to balance the energy consumptions of all the CHs, while providing satisfactory throughput. Given the network coverage and throughput requirement, we find the total number of levels of the cluster tree, number and coverage area of the clusters in each level, and amounts of time for contention-based and contention free transmissions at each CH. Our results show some interesting observations about traffic load distribution among the clusters and the CH timeline allocations.

I. INTRODUCTION

Ubiquitous wireless sensor networks are expected to play an important role in the future society, such as for health care and environmental monitoring. A future wireless sensor network (WSN) is required to cover a wide coverage area with a large number of sensor nodes. For example, in a WSN for health care or environmental monitoring hundreds or thousands of sensor nodes can be distributed in a city wide area. Most of the sensor network devices are designed to be small and low-power for low data-rate transmissions, and therefore energy and power saving is important for extending lifetime of the network devices as well as the network. An essential issue in designing large-scale WSNs is the scalability to a large number of nodes. In this paper we study the design of such a network based on the IEEE 802.15.4 protocol and the ZigBee cluster-tree topology.

The IEEE 802.15.4 standard defines the physical and medium access control (MAC) layers for low-rate, low-power and flexible wireless personal area networks (PANs). It allows two types of contention-based channel access mechanisms: a slotted CSMA/CA used in the beacon enabled network, and an unslotted CSMA/CA used in the non-beacon enabled network. For the former, a superframe is defined to be the period between two successive beacons. Beside the contention-based period, contention free transmissions are also allowed, providing much higher efficiency. ZigBee Alliance defines three network topologies above the IEEE 802.15.4 physical and MAC layers, the cluster-tree topology, the star topology and the mesh topology. Both the star and cluster-tree topologies can use beacon frames to synchronize devices to their parent node, and thus minimize power consumption of the devices by intermittent operations. The cluster-tree topology has a better scalability than the star topology and is more suitable for large-scale sensor networks. As a result, the cluster-tree topology defined by ZigBee Alliance is attracting increasingly more attention recently, e.g.,[1][2][3].

In a network where all nodes are homogeneous, the node serving as the cluster head (CH) consumes more energy than other nodes. Dynamic topology formation using protocols such as LEACH [4] and various modifications based on it can balance the energy consumption of the nodes. The basic idea is to dynamically or periodically update the network topology so that in every update the node with more remaining energy serves as the CH. Recently, there has been some work, e.g., [1][2], considering WSNs with heterogeneous devices, i.e., full function devices (FFDs) and reduced function devices (RFDs) as defined by the IEEE 802.15.4 standard. An FFD can communicate with other FFDs or RFDs, while an RFD can only communicate with an FFD.

In a large network with multiple clusters, energy consumption and traffic load should also be balanced among the CHs. In a WSN with a cluster-tree topology, the clusters are partitioned into different levels and traffic converges at the root. As traffic travels through the tree, CHs closer to the root have to carry more traffic and consume more energy, and therefore become the capacity bottleneck and limit the network lifetime. The problem becomes severer in a WSN with a large number of clusters. How to balance the load, resource utilization and data aggregation among different clusters or CHs in a large size WSN becomes very important and challenging. On the other hand, dynamically changing the network topology can be very difficult due to the large number of devices which can result in very high computational complexity and huge signaling overhead.

In this paper we consider the design of a large scale WSN with a relatively static cluster-tree topology where regular sensor nodes are RFDs and CHs are specially deployed FFDs. The objective is to design a WSN in order to balance and minimize the energy consumptions of all CHs, while providing satisfactory throughput. Given the network coverage and throughput requirement, we find the total number of levels of the cluster tree, number and coverage area of clusters in each level of the tree, and amounts of time allocated for local and forwarded traffic at each CH. The remainder of the paper is organized as follows. In Section II we describe the
system model. The sensor network design problem and design methodologies are given in Section III. In Section IV we provide numerical results to demonstrate the design features. Section V concludes the paper.

II. SYSTEM DESCRIPTION

We consider a cluster-tree topology network as shown in Fig. 1, where the root and the CHs form a multi-level wireless backbone. CHs are FFDs and sensors are RFDs. Sensors can only communicate with their associated CH. Each CH periodically broadcasts beacons which sensors and lower level CHs use to establish the associations with it and acquire its time line arrangement. Sensors and lower level CHs receive beacons from the CHs and decide when to transmit.

Sensors scan the beacons and associate to the CH with the strongest beacon. The transmission power of the beacons from each CH determines its coverage area. We assume that a frequency reuse plan is in place and there is no interference between transmissions in different clusters. Both the CHs and the sensors are powered by batteries which provide a limited amount of energy. This work focuses on the energy consumptions of the CHs as they are important for forming the backbone of the network. Design of a cluster-tree-based large scale WSN by considering energy consumption of both CHs and sensor nodes will be studied in a separate work.

According to IEEE 802.15.4, each superframe of the root and CHs starts with a beacon packet, followed by an active part and an inactive part. The active part is further divided into a contention access period (CAP), where the access to the channel is managed by a slotted CSMA/CA protocol, and the contention free period (CFP), in which a maximum number of seven guaranteed time slots (GTSs) can be allocated to specific nodes. Communications between sensor nodes and CHs using CAP, and those between CHs use CFP. The contention free transmissions ensure that data collected from sensors can be reliably and efficiently forwarded to the root.

We define local traffic as the traffic between the sensors and their associated CHs. All local traffic should be forwarded by their CHs to higher levels and eventually to the root CH. As a result, the root CH and higher level CHs carry more forwarded traffic than the lower level CHs. In order to balance the energy consumptions of the CHs, a higher level CH should carry less local traffic than a lower level one. A special case is the root CH, which should carry the minimum amount of local traffic. Below that is the timeline of CH 3 at level-1, which has a short CAP period for local traffic, one GTS period for receiving from CH4 at level-2, and another GTS period for forwarding traffic to the root. The figure also shows the timeline for CH 4 at level-2. CH 5 at level-3 does not have child CHs. It has a CAP period for local traffic and a GTS period for forwarding traffic to its parent.

The intention of this work is to provide a simple and effective solution for a large size WSN design. For preliminary research, we consider a homogeneous network, where all clusters in the same level of the tree topology have the same number of associated active sensors, the same number of child CHs, and the same CAP and GTS durations. Our design can be further extended to a more general case by removing one or more of these constraints at a price of increased complexity.

We use $f(N)$ to denote the normalized throughput of the IEEE 802.15.4 CAP with $N$ the total number of sensor nodes competing for the same CH. The normalized throughput is defined as the ratio of the amount of time successfully used for data transmissions to the total amount of CAP time. The relationship between $f(N)/N$ and $N$ is shown in Fig. 3 based on the analytical model developed in [5]. In generating the figure, we used the non-saturation model described in the same reference with transmission delay of 100ms. The figure shows that the IEEE 802.15.4 contention-based transmissions have very low efficiency.

III. DESIGN SOLUTION

We use $M_k$ to represent the number of clusters at level-$k$, and $N_k$ the number of sensors associated to each level-$k$ CH, where $k = 0, 1, \ldots, K$ and $K$ is the total number of levels in the cluster-tree. For special cases, $M_0 = 1$, meaning there is only one root in the cluster tree; $N_0 = 0$ as no sensor is associated directly to the root. We also require that $M_k$ is an
receiving, and sleeping, the power consumption of the CH when it is transmitting, the active period is $T_{L,k}$, since the root does not have a parent cluster.

$N_k$ is the number of sensors per unit area, we have $N_k = wA_k$, where $A_k$ is the coverage area of a level-$k$ cluster, $\sum_{k=1}^{K} M_kA_k = A_{\text{total}}$. $A_{\text{total}}$ is the total coverage area of the network, and the total number of sensors is $N_{\text{total}} = wA_{\text{total}}$. For a level-$k$ CH, we use $X_k$ to represent the CAP period for local traffic, $T_{L,k}$ the GTS period for receiving from one of the child CHs, and $T_{U,k}$ the GTS period for transmitting to the parent CH. We can find that $T_{L,k} = \frac{M_k}{X_{k+1}} T_{U,k+1}$. Note that $X_0 = 0$ since the root does not have local traffic, $T_{L,0} = 0$ since a cluster at the lowest level does not have a child cluster, and $T_{U,0} = 0$ since the root does not have a parent cluster.

Let $\eta_0$ represent the average required throughput for each sensor. That is, on average every sensor should successfully transmit for $\eta_0$ amount of time in each superframe. This is equivalent to a total throughput of $\eta_0 N_k$ in each cluster. Given $N_k$, a sufficient amount of CAP period is required in order to guarantee the local throughput, i.e.,

$$f(N_k) X_k \geq N_k \eta_0.$$  \hspace{1cm} (1)

The local traffic, together with the traffic received from all child CHs, is forwarded to the parent CH. Therefore, $T_{U,k} = T_{L,k} + f(N_k) X_k$. For each of the CHs, the total amount of active period is $(X_k + T_{L,k} + T_{U,k})$, or $X_k + 2T_{L,k} + f(N_k) X_k$, and the difference between the superframe duration, $T_{SF}$, and the active period is the time available for the CH to sleep. Based on power consumption in each period, the total amount of energy consumption of a CH in each superframe is given by

$$E_k = (X_k + T_{L,k}) P_r + [T_{L,k} + f(N_k) X_k] P_{t,k}$$

$$+ [T_{SF} - X_k - 2T_{L,k} - f(N_k) X_k] P_s$$  \hspace{1cm} (2)

for all $k \geq 1$, where $P_{t,k}$, $P_r$, and $P_s$, respectively, are the power consumption of the CH when it is transmitting, receiving, and sleeping. $P_{t,k} = P_0 d_k^\alpha$, $P_0$ is a constant, $d_k$ is the distance between the level-$k$ CH and its parent CH, and $\alpha$ is the path loss exponent. The total energy consumption of the root in a superframe is given by

$$E_0 = T_{L,0} P_r = N_{\text{total}} \eta_0 P_r + (T_{SF} - T_{L,0}) P_s,$$  \hspace{1cm} (3)

where $T_{L,0} = N_{\text{total}} \eta_0$ is the total throughput of the network. For a WSN with a cluster-tree topology, $E_0$ is the minimum energy consumption of the root for the given throughput requirement. Our design objective is to distribute the traffic load so that the energy consumptions of all the CHs are as close to $E_0$ as possible. That is to minimize $|E_k - E_0|$, $k = 1, 2, \ldots, K$. In this way, the energy consumptions of all other CHs are also minimized.

The network design can be done level-by-level from the root to the lowest level. Given $N_{k-1}$, $M_{k-1}$, $X_{k-1}$, $R_{k-1}$ and $T_{L,k-1}$, the design of the level-$k$ clusters can be formulated by the optimization problem below:

$$\min \left| E_k - E_0 \right|$$  \hspace{1cm} (4)

s.t. $$E_k = (X_k + T_{L,k}) P_r + [T_{L,k} + f(N_k) X_k] P_{t,k}$$

$$+ [T_{SF} - X_k - 2T_{L,k} - f(N_k) X_k] P_s,$$  \hspace{1cm} (5)

$$f(N_k) X_k \geq N_k \eta_0,$$  \hspace{1cm} (6)

$$X_k + 2T_{L,k} + f(N_k) X_k \leq T_{SF},$$  \hspace{1cm} (7)

$$N_k, X_k, T_{L,k} \geq 0,$$  \hspace{1cm} (8)

In the optimization problem, the value of $d_k$ depends on locations of the CHs, which further are related to the coverage area of the clusters and the number of sensors in each cluster. Below we find relationships among these parameters for a WSN with circular coverage area. We consider a specific case as shown in Fig. 4, where the black dots are locations of the CHs, and dashed lines represent the parent-child associations. The root is located at the center of the network. Let $R_{k}$ be the radius of a level-$k$ cluster coverage area. The “coverage area” of a CH here is the area where sensor nodes are associated to the same CH. In this sense, a level-$(k+1)$ CH is not in the “coverage area” of its parent level-$k$ CH. This avoids
significant overlapping between the coverage areas of parent and child clusters. The distance between a CH and its child CH can be larger than that between the CH and associated sensor, since the transmission power of the (child) CH can be higher than that of a sensor node. This is reasonable since a CH is a specially designed device and generally has much higher energy than a sensor node.

All level- \( k \) CHs are equally spaced and located in the circle centered at the root and with radius of \( R_{k-1} + R_k \), where \( R_k = \sum_{k'=1}^{k} 2R_{k'} \) for \( k \geq 1 \) and \( R_0 = 0 \). In this way, all the level- \( k \) CHs should cover a ring between radius \( R_{k-1} \) and radius \( R_k \) with the root CH at the center. In order to have circular coverage areas of the CHs cover the entire network area, neighboring CHs in the same level should have some overlapping. Let \( r_k \) be the ratio of the overlapping area between the coverage areas of two neighboring level- \( k \) clusters to the coverage area of one of the clusters. A larger value (closer to 1) of \( r_k \) reduces coverage holes, but increases \( R_k \) as well as the transmission power of the CH. The number of sensor nodes in a level- \( k \) cluster is

\[
N_k = w\pi (R_k)^2 (1 - r_k).
\]  

The total area of coverage of all \( M_k \) level- \( k \) clusters is given by

\[
\pi (R_k)^2 (1 - r_k) M_k = \pi (R_k)^2 - \pi (R_{k-1})^2,
\]

and \( M_k \) can be found as

\[
M_k = \left[ \frac{(R_k)^2 - (R_{k-1})^2}{(R_k)^2 (1 - r_k)} \right].
\]  

We can then find the relationship between \( d_k \) and \( R_k \). When the root is in the coverage edge of all level-1 clusters as shown in Fig. 4, \( d_1 = R_1 \). In general, \( d_k \) depends on \( R_k \), \( R_{k-1} \) and locations of the level- \( k \) and level- \( (k-1) \) CHs. In Fig. 5 we consider a worst case where \( F \) is the root, \( B \) and \( C \) are two neighboring CHs at the level- \( k \), and \( D \) is the reference CH at the level- \( (k-1) \). The maximum \( d_k \) is obtained when the level- \( (k-1) \) CH is located in the bisector of the angle \( BFC \). In Fig. 5 the length of \( BF \) is equal to that of \( CF \) and given by \( R_{k-1} + R_k \), the length of \( DF \) is given by \( R_{k-2} + R_{k-1} \), and the angle between \( BF \) and \( DF \) is \( \pi/M_k \). Then \( d_k \) can be found from (11):

\[
(d_k)^2 = (R_{k-2} + R_{k-1})^2 + (R_{k-1} + R_k)^2 - 2 (R_{k-2} + R_{k-1})(R_{k-1} + R_k) \cos \left( \frac{\pi}{M_k} \right).
\]  

With the relationships (9)-(11), the optimization problem in (4) is nonlinear, but the design parameters can be found easily using the exhaustive search method. Given the throughput requirement \( \eta_0 \) per sensor node, \( N_{\text{max}} \), the maximum number of sensors competing for the same CH can be found using the throughput model in [5] or graphically from Fig. 3. Given the design parameters of all higher level clusters, the design parameters of level- \( k \) can be found as follows.

1. for \( N_k = 1 \) : \( N_{\text{max}} \) do
2. Find \( R_k \), \( M_k \) and \( d_k \) using (9), (10) and (11), respectively.
3. Find \( X_k \) using the equality in (6), and find \( E_k \) using (5).
4. end for
5. Find the final value of \( N_k \) as \( N_k^* = \arg \min_{N_k} |E_k - E_0| \).
6. Find the final value of \( R_k \), \( M_k \), \( X_k \) and \( E_k \) as in Lines 2 and 3.

After the level- \( k \) cluster parameters are found, the total coverage area is updated as \( A = \sum_{k'=1}^{k} \pi (R_{k'}^2) (1 - r_k) M_k \). If this area is less than \( A_{\text{total}} \), then we proceed the design for level \( (k+1) \). Otherwise, the design process is complete and the value of current \( k \) is the total number of levels \( K \). Note that it may happen that the lowest level CHs only carry traffic for a small number of sensors, then the decision is up to the designer whether to keep this level of CHs or have the sensor nodes associate to the next higher level CHs. In the former case, the network is ready to be extended to a larger coverage area. In the latter case, a fewer number of CHs are needed but the lowest level CHs need to increase their coverage area and transmission power. It is also possible to redesign all previous level clusters by increasing the coverage of CHs in each level so that the energy consumptions of CHs at all levels are balanced, but this increases the design complexity and is not considered in this work.

IV. NUMERICAL RESULTS

We design a WSN with circular coverage area using the proposed approach. As circular coverage areas of the CHs can result in coverage holes. Sensors located in the holes are associated to the CH with strongest CH. Default parameters are listed in Table I. Based on the parameters we can find that the root energy consumption per superframe is \( E_0 = 0.64 \) Joules. The design solution is given in Table II. There are 4 levels in the cluster tree excluding the root and coverage areas of the first three levels are shown in Fig. 4. There are
5 level-1 CHs, each has 3 ($M_2/M_1 = 3$) level-2 child CHs, each of which further has 1 ($M_3/M_2 = 1$) level-3 child CH, and each level-3 CH has 2 ($M_4/M_3 = 2$) level-4 (not shown) child CHs.

From Table II we can have some observations. First, the energy consumptions of all the CHs at different levels are quite close. The differences are mainly due to the fact that $M_k$’s and $N_k$’s can only take integer values. Second, a higher level CH carries less local traffic than a lower level one. This is indicated by the increase of values of both $X_k$’s and $N_k$’s with $k$. Meanwhile, a higher level CH carries more forwarded traffic than a lower level CH. That is, $T_{L,k}$ decreases with $k$. The coverage area of the CHs is affected by two factors. First, as more local traffic is carried by lower level CHs, the total coverage area at level $k$ may increase with $k$ in order to accommodate the larger number of sensors. Second, the number of CHs, or $M_k$, may also increase with $k$ as each CH has at least one child CH. As a result, the coverage areas of CHs at different levels have only slight difference.

When the per sensor throughput requirement, $\eta_0$, changes, the total throughput requirement is changed, if the number of sensors is the same. As shown in Tables II and III, the energy consumptions of the CHs in the first 3 levels increase from approximately 0.64 Joules ($\eta_0 = 0.01$) to approximately 1.28 Joules ($\eta_0 = 0.02$) and then to approximately 2.56 Joules ($\eta_0 = 0.04$). That is, the energy consumptions of the CHs increase linearly with $\eta_0$. Meanwhile, $X_k$’s and $T_{L,k}$’s also increase linearly with $\eta_0$, while $N_k$, $M_k$ and $R_k$ are not affected.

We then compare the results by changing values of both $\eta_0$ and $N_{\text{total}}$ but keeping the product of the two the same so that the total required throughput is kept the same. The network topology is changed as shown in Table IV. First, with larger $N_{\text{total}}$ (smaller $\eta_0$), more levels are required, since the coverage area is also increased. Second, other design parameters are also changed due to the fact that the relationship between the throughput $f(N)$ and number of nodes $N$ is non-linear, and $f(N)/N$ decreases with $N$.

We then change to a dense network with $w = 4$ nodes per unit area and $\eta_0 = 0.02$. In this case, $E_0 = 1.280$ Joules. The results in Table V show that the energy consumption of lower level CHs is much smaller than the root energy consumption. This is the bottleneck effect at the root. In this case, the solution is to have multiple root nodes or a single but more powerful root node.

V. CONCLUSIONS

We have proposed an approach to designing a large scale wireless sensor network with a cluster-tree topology. Our results show that the design can effectively balance energy consumptions of CHs in the network. Local and forwarded traffic loads are effectively distributed among CHs at different levels.

ACKNOWLEDGMENT

This work is supported by Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Projects.

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