A Novel Network Architecture for Cognitive Wireless Sensor Network

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***Abstract*—Recent advances in wireless communications and electronics have enabled the development of low cost, low power, multi-functional sensor nodes that are small in size. These nodes coordinate to perform distributed sensing in various fields such as health, military, home etc. But these small devices in Wireless Sensor Network (WSN) are still limited with some constrains, and efforts are required to increase the lifetime and other performance measures of the network. On the other hand, with recent advances in Cognitive Radio (CR) technology, it is possible to apply the Dynamic Spectrum Access (DSA) model in WSNs to get better throughput, even in congested spectrum along with better propagation characteristics. This paper proposes a novel architecture for Cognitive-WSN which consists of a Forest of Distributed Minimum Spanning Trees. Paper also shows that this multilevel network provides fault tolerance, admits simple routing, and offers easy extensibility with power efficiency.**

***Index Terms* - Wireless Sensor Network, Cognitive WSN, Architecture, Cognitive Radio, Dynamic Spectrum Access.**

I. INTRODUCTION

A general Wireless Sensor Network (WSN) consists of a set of sensor nodes that are deployed in a field and interconnected with a wireless communication network. Each sensor node is made up of sensing unit, data processing unit, communication unit and power unit. Components of a sensor node are shown in figure 1. Each of these scattered sensor nodes has the capabilities to collect data, and route the data back to the sink/base station [1], [2].

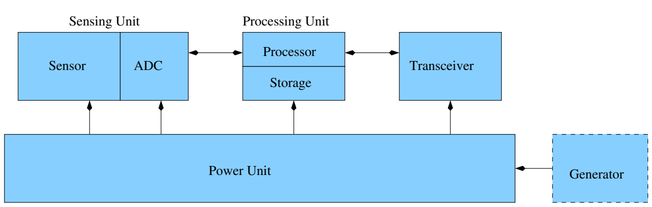

Fig. 1. The Components of a Sensor Node

In many applications, it is impractical to recharge nodes after they are deployed, as WSN nodes do not receive personal human interaction/care and usually get deployed in field at random unknown locations. Thus sensor nodes show strong dependence on battery life. In WSN, each node plays the dual role of data collector and data router, hence malfunctioning of few nodes can cause significant topological changes. It might require rerouting of packets and reorganization of the complete network. Hence, energy efficient communication is very significant constraint in WSN.

Most WSN operate in unlicensed frequency bands which are also used by other wireless applications, such as Wi-Fi and Bluetooth. This makes unlicensed bands overcrowded. To reduce network congestion, Dynamic Spectrum Allocation (DSA) can be used in such scenarios. Since sensors have limited power, we assume that some specialized nodes are responsible for spectrum sensing and they forward the spectrum availability information to the base station [3]–[6]. Base station can later use this information to assign non-overlapping frequencies to neighboring sensor nodes. This paper proposes a novel architecture for Cognitive-WSN and also shows that the proposed network architecture is power efficient.

The rest of this paper is organized as follows. Section II explains the proposed network structure using reference from previously proposed network architectures. Section III discusses the process flow required to define and use the proposed network structure. And finally, Section IV summarizes the work done.

II. PROPOSED NETWORK ARCHITECTURE

This section explains the proposed network structure with reference to other already present in the literature. To reduce complexity of final architecture, neighboring nodes have been clustered together. We have divided the sensor nodes into several clusters in the sensed area. Each cluster chooses a cluster head automatically. Nodes belonging to a cluster send data to their cluster head. After receiving data from all member nodes, the cluster head transmits the data to sink and/or to other cluster heads. Hence the problem of defining the network structure can be divided into two smaller problems. First problem is trying to represent nodes in one cluster as one structure and second is to represent network of clusters as one unified super-structure.

Normally cluster head is at one-hop distance from other member nodes belonging to the same cluster. Cluster head and other member nodes together form a simple, star-like connection as shown in figure 2. In this representation routing is very simple; every sensor node sends data directly to the cluster head. Once cluster head receives data from all the sensor nodes in cluster, fusion algorithms are applied on the received data.

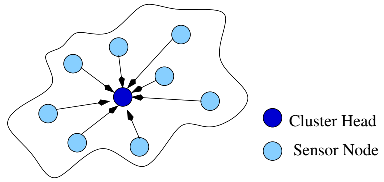

Fig. 2. Cluster Representation with Star Topology

Now only problem of fusion and routing of information between clusters (or specifically cluster heads) remains. Here each cluster is considered as one node, as only cluster heads participate in the process of data transmission. The representation of clusters and base-station in the field are shown in figure 3. Traditionally, flooding was used to forward data from

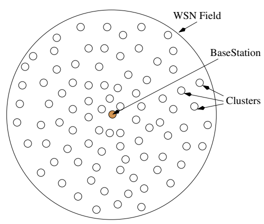

Fig. 3. WSN with the Group of Clusters

the cluster to the base station [7]. During flooding cluster-heads forward data in all directions. We can use undirected graph to represent connections among cluster-heads in case of flooding. To construct graph between sensors, we assume that the transmission range of a sensor node is 'd'. So the nodes that have geographical distance less then d will be connected to each other as represented in figure 4.

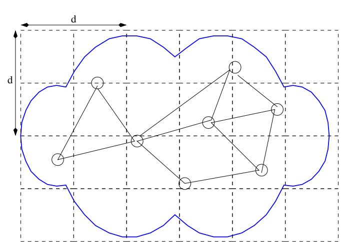

Fig. 4. Graph Representation

The main drawback of flooding was inefficient use of resources (esp. energy) as lot more than necessary messages are sent during flooding. [8]. To overcome this issue, Tree-based Efficient Protocol for Sensor Information (TREEPSI) was proposed [9]. TREEPSI constructs a tree-like hierarchical path of the nodes. Only one spanning tree is created with TREEPSI which connects all nodes. Since this tree is very big, it is harder to manage.

To reduce the size of tree that gets created with TREEPSI, we propose this architecture in which, we divide the complete area into sectors of 30 degrees with base station as origin. Then spanning trees are constructed to represent sensor nodes within a sector as shown in figure 5.

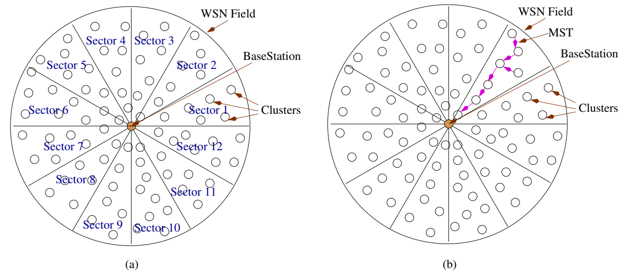

Fig. 5. Sector Representation and Spanning-Tree for a Sector

In this new structure every cluster can forward the packet to only one other neighboring cluster and thus avoids flooding. This improves energy efficiency as now redundant messages are avoided. The spanning tree for graph shown in figure 4 is shown in figure 6.

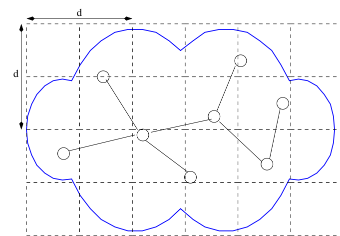

Fig. 6. Spanning Tree Representation

If we assign weights to the edges based on the power required to transmit signal between the nodes connected through the edge, then the solution can be further improved by using Minimum Spanning Tree (MST). MSTs can be created within the sectors considering base station as a root node of the tree. MST improves energy efficiency as either less number of packets needs to be transmitted or packets are transmitted to smaller distance or both. Base station assigns different frequency bands dynamically to different clusters and sectors based on the spectrum availability to improve utilization.

This is the very power efficient solution for routing in Cognitive-WSN. But the solution has serious draw-back that all nodes become single point of failure. If any internal node of MST fails then remaining nodes get divided into two disconnected MSTs. Hence to make this network more fault tolerant we connect these MSTs with each other. The nodes which are near sector boundaries are connected to other MSTs as shown in figure 7.

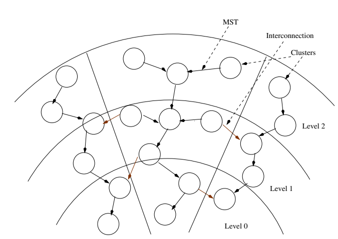

Fig. 7. Connection of sector MST to other neighboring sectors

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In summary, Cognitive-WSN is represented as a network of Minimum Spanning Trees. The architecture comprises of following connections:

- Nodes of a cluster are connected using star like connection.
- Cluster Heads (CH) within each sector are connected using single MST.
- Cluster heads which are near sector boundaries also connect with MST of neighboring sector.

III. Process Flow

This section describes the algorithmic details for defining the proposed architecture. In order to use the process defined in this section, the base station should have following capabilities:

1) Base station should have transmitters powerful enough so that it can send packets directly to all nodes (single hop).
2) Base station should be able to adjust power of transmission so that nodes at distance greater than specified distance can't receive the transmission.
3) Base station should also have directional antennas which have both capabilities mentioned in points 1 and 2 above.

A. Sectors, Levels and Clusters Formation

First sensor network field is divided into equi-angular regions called sectors as discussed in [10]. Each sector is uniquely identified with the help of sector ID. In order to inform nodes their sector IDs, the base station sends Sector Broadcast Packets (SBP) with directional antennas such that only nodes within a sector receive this broadcast. SBPs contain sector ID and information about the base station. Sample sectors created with 30 degree regions are shown in figure 5.

Then entire field is divided into various levels as discussed in [10]. Levels help in construction of MSTs and they also help in interconnection among neighboring sectors MSTs. To divide sensor field into various levels, the base station sends packets containing level ID for level 1 with minimum power level. All the nodes that receive this signal set their levels as 1. Next the base station increases its signal power to reach the next level and sends packet containing next level ID. All the nodes that receive this signal, if have not already set their level ID, set their level to 2. This process continues until the base station has sent signals corresponding to all levels. The number of levels into which the network gets divided is equal to the number of different power levels at which the base station has transmitted the signal.

Leveling can also be done using hop-count ratio-based technique [10]. In this technique, hop-count of all the nodes is initialized to infinity. First sink broadcasts packets with hop-count field set as zero. Nodes that directly receive these packets set their level as 1. These updated packets are again broadcast after incrementing hop-count field by 1. Nodes that receive these packets update their level to '$HopCount+1$', if their current level is higher than '$HopCount+1$'. The nodes that are having their level equal to or less than the '$HopCount+1$' value of the received packet then they don't update their current level value. In wireless communication most of the time Line of sight path is not available, and hence fading problems can occur. In such case hop-count ratio-based technique is preferred.

If D is the distance between two levels and d is transmission range of a sensor node then

$$d > 2 * D \tag{1}$$

The total number of levels into the network is calculated based on this equation.

Finally sensor nodes are grouped together in clusters and this process is done in two phases [11], [12]. First the cluster heads (CH) are selected and then the sensor nodes are aligned to selected cluster heads. Clustering is done with modified Algorithm for Cluster-head Election by Location (ACE-L) [13]. The reference points for distance measurement are set to be the center points of the zones, and the criteria to elect a cluster head is energy along with the distance from the reference points, as is case in ACE-L. In this technique, first a sensor node generates a random number between 0 and 1. If this random number is less than the threshold $T(n)$, the sensor node is a CH. $T(n)$ is calculated as

$$T(n) = \begin{cases} \frac{P}{1-P*[r \ mod(1/P)]} & if n \in G \\ 0 & otherwise \end{cases} \tag{2}$$

where P is the desired percentage to become a CH, r is the current round, and G is the set of nodes that have not being selected as a CH in the last $1/P$ rounds. After the CHs are selected, the CHs advertise to all sensor nodes in the network that they are the new CHs. Once the sensor nodes receive the advertisement, they determine the cluster to which they want to belong based on the signal strength of the advertisement from the CHs to the sensor nodes. The sensor nodes inform the appropriate CHs that they will be a member of the cluster.

B. Tree Construction

After completing sector, level and cluster formation, MSTs are constructed by assigning weights to edges.

1) Weight Assignment to the edges: Weights are assigned to edges with the help of levels formed during previous steps. Edge connecting sensor nodes in levels a, b is assigned weight $a-b+1$, if $a > b$. Thus edges between nodes which belong to same level is set as one and edges between nodes which belong to different levels is set as difference between levels plus one.

2) MST Creation: Brute force approach for finding MST of a graph is computationally very expensive. Since it is possible for a graph to have more than one MST such that sum of weights of all edges among different MSTs is same. We use Prim's algorithm to construct one of the many possible MSTs of given graph. In Prim's algorithm we choose root vertex v in a given graph G = (V, E) and treat it as origin of the tree. This vertex defines the initial set of vertices A. Then in each iteration, we choose a minimum-weight edge (u, v) connecting vertex v in the set A ($v \in A$) to the vertex u not in set A ($u \ni A$). Then vertex u is brought in to A ($u \in A$). This process is repeated until a spanning tree is formed. During this process we do not add edges if they produce a cycle / loop.

The prim's algorithm is depicted pictorially in figure 8.

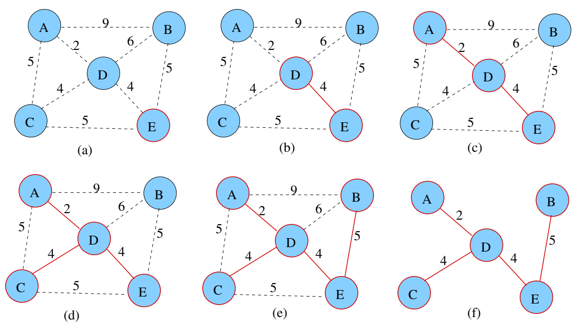

Fig. 8. Prim's Algorithm for MST Creation

3) Interconnection between MSTs: As discussed in section II, the sensor nodes at the boundaries of sectors are also connected with MSTs of neighboring sectors. To identify which nodes belong at boundaries of sector two different approaches are possible:

1) During sectoring border nodes would receive SBP of neighboring sectors with reduced signal strength in comparison to received signal strength of their own SBP. Thus nodes which receive SBP with different sector IDs can identify themselves as boundary nodes.
2) Base-station can also send separate messages with the help of directional antenna to mark the boundary nodes. Only the nodes which receive this special message can identify themselves as boundary nodes.

For building interconnection between MSTs boundary nodes send message as a request for interconnection. Receiving node accept this request only if receiving node differs from sending node in both sector ID and level ID.

C. Routing / Data Transmission

Once MST construction is complete, root node of the MST generates a TDMA schedule for the transmission and circulates it in the MST. Based on the sensed spectrum availability information, base station also assigns the frequency bands available to each of the cluster and sector based MSTs. When nodes are aware of the TDMA schedule and the frequency bands, they transmit data and perform fusion in appropriate time-slots allotted to them. In every slot one or more node transmits gathered data to the lower level nodes. The lower level nodes fuse the received data with sensed data and send the result to the next lower level nodes.

The generation of TDMA schedule for MST is described with the help of example. Consider MST generated in figure 8(f). Table I shows the edge information of the MST. In table I, node-ID is ID of transmitting node and Next Hop Node ID is ID of receiving node. So, node D, E participates in the routing and node A, B, C are the leaf nodes. As node 'A' and 'C' have the same next hop node, they both can't transmit the data simultaneously. Thus in first round only nodes A, B transmit data and in next round node 'C' can transmit its data. In third round node D can transmit fusion result. Thus the sequence of transmissions is A, B, C, and then D. Figure 9 shows the time order of the TDMA schedule generated.

TABLE I
EDGE INFORMATION OF MST

Node ID	Next Hop Node ID
A	D
B	E
C	D
D	E
E	-

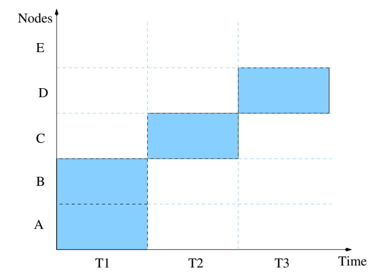

Fig. 9. TDMA Schedule Order of MST

Theorem 1: If MST contain n nodes then communication complexity is of the order $O(n)$.

Proof: Communication complexity is the number of messages forwarded from leaf node to root node in worst case. In MST, every node transmit data to only one another node, hence number of messages required are equal to number of edges in MST, i.e. $n-1$. Thus communication complexity is of the order $O(n)$.

D. Fusion

As described in previous sub-section every non-leaf or routing node performs fusion of received data with sensed data and then sends the result to next lower level nodes. This approach distributes load among large number of sensor nodes. This also leads to reduction in amount of data communicated between the nodes, and hence is more power efficient.

E. Fault Tolerance

The interconnection between neighboring sectors MST makes architecture more fault-tolerant. MST formation process is also dynamic to increase fault tolerance. At periodic intervals node can transit their remaining energy along with sensed/fused data. If this energy is below specified threshold then new MST can be formed keeping the nodes energy level into account so that the node is a leaf node in new MST and does not performs routing and fusion both of which require considerable energy.

IV. Conclusion

In this paper we have proposed a novel architecture for energy efficient data transfer in Cognitive-WSN which consists of a network of Minimum Spanning Trees (MST). Paper also shows that this multi-level network is fault-tolerant and admits simple data collection and transmission technique. This architecture minimizes the data collection and transmission time which reduces the total energy consumption in network.

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