Enhancing Collection Tree Protocol for Mobile Wireless Sensor Networks

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Abstract

The Collection Tree Protocol (CTP) is widely used for data collection in Wireless Sensor Network applications. However, its usage has been mostly limited to static networks and previous studies indicate that the performance of standard CTP drops sharply in mobile sensor networks. In this paper, we first show that CTP outperforms standard MANET routing protocols in these scenarios. Then, we propose an enhancement to CTP, named Fixed-Node Aided CTP (FNA-CTP) to further improve the performance of CTP in mobile sensor networks. We use simulation results to show the superior performance of FNA-CTP in mobile environments and discuss various design issues associated with this scheme.

Keywords: CTP; Sensor Networks; Performance Evaluation; Wireless Networks; Mobile Networks; Data Collection.

1. Introduction

1.1. Background

Collection Tree Protocol (CTP) has been shown to be a very efficient data collection routing protocol for applications in static Wireless Sensor Networks (WSN) [1]. However, wireless sensors are increasingly being employed in mobile environments such as Vehicular Ad hoc NETworks (VANETs), wild life monitoring, body area networks, pollution monitoring and other mobile environments. Another application where mobile sensor networks could be more effective than static sensors is in the monitoring of large areas, where mobile sensors would provide more efficient coverage [2].

The main challenge in Mobile WSN is the fact that the network topology and connectivity change over time as the nodes move around, hence requiring dynamic and robust methods to ensure packet delivery.
There are several routing techniques designed to address mobility in MANETs, but most of them target general communication patterns as opposed to those patterns encountered in mobile sensor nodes. For example, the numbers of nodes in a WSN can be much larger than a typical MANET; the sensor nodes in a WSN use broadcast communication where as in a MANET point to point communication is dominant; and the data in a WSN flows from the source nodes towards the sink but in MANETs the data flows are bidirectional and could potentially flow between any pair of nodes.

In this paper we examine an enhanced CTP protocol to address these drawbacks and demonstrate its efficiency in handling mobile WSNs scenarios using simulations. The rest of this paper is organized in the following manner. In Section 2 we present a detailed description of modeling CTP in WSN. Section 3 presents a new architecture for CTP-based mobile WSN which we refer to as Fixed-Node-Assisted CTP (FNA-CTP). We present performance results in Section 4 to show that the new approach significantly enhances the data delivery ratio in mobile WSN. Conclusion and future work are presented in Section 5.

1.2. Prior Work

Prior work on CTP mostly focused on evaluating the performance of this protocol in static wireless sensor networks. Santini et al [3] implemented CTP in the Castalia wireless sensor network simulator [4], which is based on OMNET [5] and uses advanced channel and radio models based on empirically measured data. The underlying MAC module in Castalia is T-MAC (Tunable-MAC) which does not support all features of CTP. The performance of CTP was evaluated in [3] through a set of WSN application metrics such as data delivery ratio, control overhead, hop count and the number of duplicate packets. The study showed that as the number of sensor nodes increased in a given network configuration, the delivery ratio decreased because of an increase in the number of collisions as more packets were travelling through the network. As the distance between the sink node from the source or from other relay nodes approached the node’s transmission range, significant degradations in performance was observed. The root cause of this problem is the retransmissions that are needed in such cases for successful delivery of a packet. The retransmission packets would queue up and fill the buffers quickly and the new incoming packets would be dropped.

The performance of CTP in mobile environments was studied in [7] where it was shown that the delivery ratio may drop even below 50% when network environment changes from static to mobile. That study also showed that the control overhead, defined as the ratio of the control traffic (beacons sent throughout the network to maintain the tree) to the actual data traffic, decreases as the probability of simultaneous data transmission by multiple nodes increases. The additional data packets travelling in the network reduce the number of control packets for maintaining the routing tree, because the data packets themselves can be used to keep track of any link quality changes. In case of a cluster of nodes becoming disconnected from the rest of the network (but within the transmission range), a high control packet count overhead was observed as the remote nodes frequently exchange control packets with the sink or relay nodes. The hop count and the duplicate packets number are higher when more nodes are active in the network, because more data packets are sent which results in congestion, packet drops and lost acknowledgements. This issue significantly affects the performance of CTP.

In [8] the authors proposed a new architecture for better handling of mobility in wireless sensor networks. They proposed a hierarchical network architecture including a low level sensing layer with mobile sensor nodes and a high level routing layer with fixed routing nodes. The mobile sensor nodes transmit their sensed data to the static routing nodes which then further process and forward the data to the sink. This solution is particularly suitable for scenarios such as vehicular ad hoc networks in which we can deploy a number of fixed nodes with enough processing, storage and communication range on the side of the road to receive data from the mobile nodes at a one hop distance away, but it does not provide multi-hop communication between the mobile sensor nodes. Even in the case of VANET, multi-hop
communication may be required in cases where the distance between moving sensor nodes and fixed routing nodes is more than the transmission range of the low-power radios of the sensor nodes. It has also been shown that hierarchical or flat multi-hop routing schemes cannot efficiently support mobility in wireless sensor network applications [9,10]. The frequent link breakages due to node movements cannot be handled fast enough by their routing mechanism to provide reliable performance.

The LEACH-Mobile protocol supports mobility in wireless sensor networks [11]. In LEACH-Mobile each sensor uses a two way communication mechanism to become part of a cluster. The cluster head sends a message to the sensor nodes in its cluster and if it does not hear from a sensor node it is assumed to have moved out of the range of the cluster and tries to connect to other clusters. This protocol also suffers from high packet losses and energy consumption due to the overhead of the cluster membership management mechanisms. In general clustering algorithms are not well suited for mobile applications because of additional messaging overhead encountered to maintain the cluster formation.

2. Model Description

2.1. CTP Design Overview

The objective in CTP is to determine the best path from any of the sensors, called the source nodes, to the data collector node, called the sink and placed at the root of the tree. If there are multiple root nodes in the network, the data is routed to the one with minimum cost/distance. CTP can also support multiple independent CTP trees that are identified using a CTP tree identifier routing over the same nodes. CTP is a destination initiated protocol and employs directed diffusion. At network start up, the root nodes advertise themselves in the network and the source nodes use these advertisements to choose their next hop (upstream node) toward the root node based on a routing gradient.

CTP uses Expected Transmission value (ETX) as its routing gradient [12]. ETX is an indicator of link quality. For each link, the value of ETX is calculated as the number of transmissions it takes for a node to send a unicast packet to its neighbor whose acknowledgement is successfully received. The ETX for a node is equal to the sum of the ETX values of all hops (links) on the path from this node to the root node. The ETX of the root node is zero. Nodes advertise their ETX values to their neighbors to assist them in minimum cost path calculation. When a sink node sends a request for information, each node updates the hop count and total cost (ETX) information in the request before passing it to the neighbors. Each node will choose the neighbor with the minimum ETX value as its next hop (parent) on the collection tree. The routing beacon packets are sent periodically to calculate the bidirectional link quality between the neighbors. In a stable network, data packets can be used to keep track of any link quality changes, thus reducing the number of required control packets. The outbound quality estimate value is the ratio of number of data packets transmitted to the number of acknowledgements received. The MAC layer gives the acknowledgement information to the forwarding engine. The forwarding engine removes the data packet from its send cache and informs the link estimator engine about the acknowledgement.

The CTP implementation in [3] uses adaptive beaconing. In a stable network with few link changes and breakages, the volume of control traffic is reduced over time using the Trickle algorithm [13]. A topology change forces the resetting of routing packet intervals to adapt to the change, to refresh the routing tables and to calculate the link estimator neighbor table. This is a very important part of protocol configuration, as a higher volume of routing packets would be costly. On the other hand, long silent intervals in routing control packets may result in stale topology information and hence affecting the protocol performance. Studies have shown that most of the overhead is a result of periodic link quality estimation used in CTP i.e. the ETX metric. Whenever the link dynamics change or the topology changes due to node mobility, the CTP does not respond fast enough and results in packet losses. This limitation
of CTP motivates us to come up with a better route update algorithm to promise better delivery ratios and fact recovery mechanism in case of faulty links.

2.2. Performance Metrics and Network Model

The key evaluation metrics for wireless sensor networks include data delivery ratio, average packet delay and communication overhead. Other performance factors for routing in wireless sensor networks include network life time, link quality, node density, throughput, and optimal buffer size of nodes.

Network life time has many definitions, it can be considered to be the total time that the network is fully functional (all nodes are alive) or until the first node runs out of power. Determining the energy consumption for each operation of the node is important for monitoring applications. The maximum energy consumption happens during the communication and hence any energy-efficient protocol must try to minimize control packet overhead in the network; i.e. the volume of control packet traffic for estimating the cost/quality of links and for choosing the best path from the source to sink.

The latency of the data communication from the source nodes to the sink nodes also has a critical impact on the performance of alarm based applications. In many cases a tradeoff exists in minimizing both the energy and the source-sink delay simultaneously. Node buffer size is also a very important design parameter as it specifies how many packets a node can handle which in turn has an impact on congestion and packet loss in the network.

In this work the WSN is modeled as a system consisting of N identical sensor nodes. The sensor nodes are randomly distributed in a rectangular region. It is assumed that the sink node collects all the information sensed and collected by the source nodes and is located at the 0,0 coordinate location. All sensor nodes are assumed to have the same radio range $r$ and are equipped with omnidirectional antennas.

The phenomena sensed by the sensor nodes are stored as data units of fixed size in the buffer at the sensor. The buffer is modeled as a FIFO queue and its length is a design parameter and is implementation-dependent. It must be noted that sensors are half-duplex as they cannot receive and transmit a message at the same time. The time is divided into unit durations and reception/transmission can occur for only one data unit at one time slot. Further details on the traffic pattern, wireless channel model used, and mobility models are given below.

A simple data traffic scenario is considered here which is very typical of wireless sensor network applications. The physical phenomenon used here is the same as the one in [3]. We assumed that the nodes in the network are loosely synchronized so that their wake and sleep cycles are easily scheduled. The nodes are required to provide “snapshots” of the values of a physical phenomenon at regular time intervals. The sampling frequency $f_s$ remains fixed from the beginning and is the same for all the nodes in the network. The sensor source nodes wake up at every $T_s = 1 / f_s$ seconds, sample the phenomenon (for example gather the temperature values at that instant), send the data to the sink node and go back to sleep. The sequence sleep-wake up-sleep is called a round and is repeated during the network operation.

The wireless channel model used in this work is the log-normal shadowing model. The path loss in log-normal shadowing model is a function of the distance from the transmitter. We assumed that the multi-hop wireless communication MAC layer is CSMA–based and the physical layer for our network model supports burst-mode (packetized), coded communications. The general framework used for this work applies to both 802.15.4 and 802.11 mesh networks. The modified Tunable MAC that is used by Castalia very closely imitates the MAC functions of the CTP implementation in TinyOS.

In order to model the mobility of the sensor nodes, we used a Random Waypoint Mobility Model in which the mobile node moves a distance $d$ in a direction randomly chosen from (0, $2\pi$). The distance is exponentially distributed. The node moves from its current position for a randomly selected move_time with speed varying between $[\min\_speed, \max\_speed]$. The node bounces back into the test region when it hits a boundary. At the end of the move_time it pauses for a duration of time specified by pause_time.
The pause_time and move_time are chosen randomly at each step. The Random Waypoint model was chosen here as a worst case scenario, because the random mobility pattern of the nodes maximizes the number of changes in the collection tree. Therefore, it can be argued that if a data collection protocol provides good results in this mobility pattern, it will likely provide better results in linear or more predictable mobility patterns. In fact, if the motion is predictable, one could take advantage of this knowledge to even further improve and reduce the control packets sent by CTP when the nodes are in motion.

3. Description of Fixed-Node-Assisted CTP

The idea of FNA-CTP is to add a few backup static sensor nodes to the mobile network to act when the main collection tree is disconnected. Mixtures of static and mobile nodes have been used before in a number of applications, in particular in Vehicular Ad-hoc Networks [14]. However, in those applications, static nodes are primarily used as gateway/cluster heads that collect data from mobile nodes within their range. Such arrangements require static super-nodes that can support a continuously high volume of traffic and corresponding bandwidth. We propose the use of static nodes that simply act as backup parents, i.e., similar to other sensor nodes in CTP they may be used as a primary parent if their ETX value is less than other neighbors, in special cases they will be the backup for the main parents and join the tree as part of the failover procedure. Therefore, they typically do not have to handle more traffic than a typical sensor node except when part of the network becomes disconnected. As we will show, this approach significantly improves the robustness and stability of the CTP tree.

In FNA-CTP every deployment of WSN has a few static sensor nodes distributed in the network region. The location of fixed wireless sensor nodes can be optimized based on their transmission range to cover the entire network region or area of interests using a minimum number of fixed nodes [15]. All other mobile source nodes in the network will be in the transmission range of at least one of the fixed nodes. The working of the CTP remains the same except that now every mobile node will have at least one fixed node ETX entry in its link estimation neighbor table and routing table in which the fixed node will be identified by a special flag bit. After each unicast data transmission, if the source node does not receive an acknowledgement, it will forward the packet to the fixed static node. This basically removes from the original CTP algorithm the need to keep calculating the link quality to determine the new parent for its neighbors in response to lost routes. The link quality estimation is still performed periodically using the adaptive beaconing mechanism, except that now the beacon interval does not have to be set to the minimum value for the mobile sensor nodes once lost acknowledgements occur. Upon receiving the unicast data packet, a fixed node may forward it to its parent, which can be a mobile or fixed node. The procedure is repeated until the packet arrives at the sink node.

The advantage of this mechanism is that it improves the packet delivery ratio with minimal control overhead. It still uses the link quality estimation mechanism of CTP benefiting from the multi-hop communication rather than forcing the packets to be delivered to the sink through fixed sensor nodes over long communication distances. The fixed nodes merely provide a back-up infrastructure for the network. This increases the reliability of the network in mobile scenarios as packets are not dropped because a route could not be found due to the changing topology of the mobile network.

This scheme is also different from the standard clustering algorithm as it does not involve the computation of cluster heads. The clustering algorithms are not suitable for sparse networks or in cases where the nodes do not follow a group mobility pattern. In mobile scenarios, the cluster head candidate is also moving, and often nodes have to spend energy in computing new cluster heads, an issue that does not exist in our FNA-CTP scheme.

The tree establishment in FNA-CTP is the same as in CTP. The sink node broadcasts the routing beacons with ETX value 0. The nodes receiving this broadcast attach themselves to the collection tree with the sink node as the tree root, and calculate the inbound link quality ETX value to fill the link estimator neighbor table during the bootstrap mechanism. These nodes further broadcast the routing
beacons with their cost value to the sink node and maintain the link estimator tables with ETX value of their neighbours. In FNA-CTP the fixed nodes behave as any other sensor node in the network except that the routing beacons they broadcast have a special flag called Fixed bit set. The nodes receiving the broadcast messages from the fixed node create an entry in their neighbour table for the fixed node with its corresponding ETX value. If the fixed nodes are deployed to cover the entire region of interest, each mobile node will have a fixed node entry in its neighbour table.

Route Discovery, forwarding and reaction to failed data deliveries is where the FNA-CTP differs from CTP. Route discovery happens after the hop link estimator table has been used to determine the routing table entries. As mentioned earlier, in FNA-CTP link estimator tables and routing tables each have at least one entry for the fixed node. The unicast data is forwarded to the next hop with minimum ETX value, as determined by a table lookup. If the fixed node has the minimum ETX, value the packet is forwarded to it. In case there is a mobile sensor node with a minimum ETX value, the packet is forwarded to that mobile node. Only two attempts are made to get the data delivered to a mobile node. If both attempts fail, the FNA-CTP then chooses the fixed node as the next hop distance. No adaptive beaconing is applied to the mobile sensor nodes to react to failures. The mobile sensor nodes find routes based only on periodical updates. In case of lost acknowledgements, the fixed node uses the adaptive beaconing method to react to lost links. The packet is dropped if no success is achieved within a predetermined interval time.

The routing table lookup remains the same as in the original CTP. The adaptive beaconing mechanism resets the beacon interval to its minimum value when a packet transmission failure occurs.

4. Performance Results

In our simulations, 40 identical mobile sensor nodes were randomly deployed on a rectangular region of 100 m X 100 m with the sink node located at (50, 100). The nodes move in the region according to a random waypoint mobility model. Each node selects a random direction ([0,2π]) and a speed in the range of [0, 10] m/s then goes in the direction for a randomly selected duration, and then the same process is repeated with new direction, speed and move duration. The simulations were run for three different number of fixed nodes k in the network. The transmission range of the mobile nodes and the sink node is set to R = 10 m, and for fixed nodes to Rf = 30 m. Fifty simulation rounds were run for each configuration and the results are averaged.

Figure 1 shows a sample deployment of mobile and fixed nodes. Here we used a grid positioning for the fixed nodes. The performance parameters for comparison include data delivery ratio and control overhead. Figure 2 shows the data delivery ratio for CTP and FNA-CTP with three different values of fixed nodes k. The number of mobile nodes remains the same in all configurations. We observe a significant improvement in data delivery ratio with the FNA-CTP protocol.

Another important metric for any routing protocol is the communication overhead or the cost to get the data samples to the sink. The control overhead for the original CTP was compared with FNA-CTP in three scenarios with different number of fixed nodes. For CTP all the nodes in the network except the sink node are mobile and their average number of transmitted control packets was 87 per node. For the FNA-CTP the average number of control packets transmitted per mobile node was around 47 for all three scenarios of different values of k. But the average number of control packets per fixed node decreased with the increase in the number of fixed nodes in the network. The total control overhead is clearly significantly less in the case of FNA-CTP, given by its data delivery ratio.

The delivery ratio is increased by having more fixed nodes. Some packets were dropped because of the fixed nodes’ queue filled up with unacknowledged packets, in particular when a mobile sensor node gets too far from both its parent and its backup fixed node. This can be avoided by using fixed nodes with a higher transmission range.
Figure 1: FNA-CTP Topology Diagram

Figure 2: FNA-CTP Data Delivery Ratio

Figure 3: FNA-CTP Control Overhead
The duplicate packets were higher in case of FNA-CTP with 12 fixed nodes. The reason is that there are some situations when a packet is delivered to the fixed nodes and no acknowledgement is received, and so the packet is forwarded again. This redundancy in the network increased with the number of fixed nodes.

5. Conclusion

In this work a Fixed-Node Aided Collection Tree Protocol was proposed. These fixed nodes act as a backup when the mobile nodes are not able to deliver the packets to their parents due to the dynamics of a mobile scenario. The results showed that our algorithm gives improved data delivery ratio while reducing control overhead. Forcibly enforcing a tree topology is avoided using the fixed nodes as we do not want a packet to travel a longer distance to fixed node when a moving node is in its proximity and not out of range yet. The work is especially suitable for applications like VANET’s where vehicles speed vary depending on the traffic so at the intersection or a congested road one can use the multi-hop communication with stable links as nodes are not moving.

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References