A Cooperative Cache Management Scheme for IEEE802.15.4 based Wireless Sensor Networks

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ABSTRACT

Wireless Sensor Networks (WSNs) based on the IEEE 802.15.4 MAC and PHY layer standards is a recent trend in the market. It has gained tremendous attention due to its low energy consumption characteristics and low data rates. However, for larger networks minimizing energy consumption is still an issue because of the dissemination of large overheads throughout the network. This consumption of energy can be reduced by incorporating a novel cooperative caching scheme to minimize overheads and to serve data with minimal latency and thereby reduce the energy consumption. This paper explores the possibilities to enhance the energy efficiency by incorporating a cooperative caching strategy.

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1. INTRODUCTION

With the tremendous response received by the Wireless Personal Area Networks (WPANs), the wireless networking community has been looking for new avenues to enable wireless connectivity to be extended to newer dimensions and explore wide range of applications.

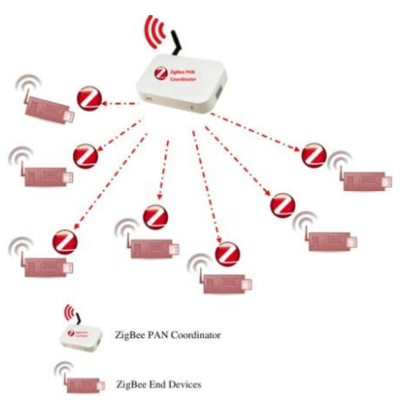


Figure 1. Wireless Sensor Network based on IEEE 802.15.4/ZigBee Devices

The optimization of the Total Link Cost can lead to an efficient sensor network design [1] where in Power Consumption and the Quality of Service (QoS) are the two major attributes that should be controlled for which the researcher must focus on both the energy consumption and high routing efficiency.

ZigBee is a low rate- wireless personal area network (LR-WPAN) device based on the IEEE 802.15.4 standards. According to study the most important sources of energy consumption in such devices are transmission and reception of data packets aggregated to the Sink Node, overhearing, idle listening of motes, collisions and packet overheads (multiple packets generated due to unicast or multicast).

According to Narottam Chand [2], providing continuous information to the sink with uninterrupted communication is a big challenge in designing large-scale ubiquitous sensor networks. Caching is one of the most effective ways for increase in performance and the cache sizes in the recent years have witnessed a significant increase in various computing systems.

2. COOPERATIVE DATA CACHING

In Wireless Sensor Networks, Cooperative Caching helps nodes to share and coordinate cached data to lower the communication/ link cost and to exploit the aggregate cache space of cooperating sensors. A sensor node based on the IEEE 802.15.4 is accompanied with a flash memory that caches the frequently accessed data items. The data cached in the flash memory satisfies the nodes own request but also caters the data requests passing through it from other nodes. When a data miss is encountered the node first searches the data in its zone /cluster before forwarding the request to the next node that lies on a path towards the data source. The process of cache admission control (CAC) depends on the distance criteria of the node from the sink node and gives high priority to the nodes near to the sink. Caching plays an important role in reducing the number of communications from a sensor node (SN) to sink by caching the useful or frequently accessed data.

Caching is a technique which provides faster data access in any computing system. With the discovery of cache the accessibility of data has been increased as it stores data to be needed in future and can be retrieved simultaneously with the request to access. Caching [8] has made its impact in the Wireless sensor networks also.

Providing constant data to the sink with continuous correspondence is a major task in executing extensive scale sensor systems. A great deal of research in information routing [3], [4], data compression [7] and in-network data aggregation [5], [6] has been done in WSNs amid late years. The problem of efficient data dissemination has been tried to solve to certain extent by incorporating Cooperative Caching in Wireless Sensor Networks. The optimal implementation of caching can lead to reduced network traffic and enhanced data availability.

3. RELATED WORK

A number of schemes related to caching have been proposed. Jinbao Li et al [9] proposes a caching scheme for the multi-sink sensor network. The sensor network forms a set of network trees for a particular sink. A common subtree is formed out of these sets of trees and the root of the common subtree is selected as the data caching node to reduce the cost of communication.

J. Xu et al [10] proposed a waiting cache scheme which anticipates for the data of the same cluster to become available within a threshold and then aggregating it with the packet from the lower cluster and sending it to the sink later, thus reducing the number of packets travelling in the network. Md. A. Rahman et al [11] proposed an effective caching mechanism by negotiating data between base station and the sensors, developing an expectancy of data change and data vanishing.

A cooperative caching scheme was proposed by T.P. Sharma et al [12] which exploits cooperation among various SNs in a defined region. Apart from its own local storage, a node uses storages of nodes from other clusters around it to form larger cache storage known as Cumulative Cache. In this scenario a token based cache admission control (CAC) scheme is devised where a node holding the token can cache or replace data item. One of the drawbacks of the proposed model is that more number of packet overheads is generated to maintain & rotate the token. Then later N. Dimokas et al [13], [14], have identified various targets which are required to be optimized such as energy consumption, access latency, number of copies of data items to be placed at different locations. Disadvantage of schemes is that node importance (NI) index considers neighborhood of a particular node. So, overhead to find NI for all the nodes consumes energy which in turn reduces the lifetime of sensor network.

P. Kumar and N. Chauhan et al [15] proposed a novel proactive approach for caching data in MANETs in which the data of the leaving node is cached. In this approach all nodes leaving a particular zone will broadcast a “LEAVE” message to all neighboring nodes. The data that is to be cached is decided by the

Zone Managers based on the Caching Information Table (CIT) of the leaving node. They also explained that a good cooperative cache management technique for MANETs should address the following issues:

a. A Cache Discovery algorithm that may be efficient enough to fetch and deliver requested data items from the neighbor nodes.
b. A Cache Admission Control Algorithm is required that is able to decide which data items can be cached for future use. In cooperative caching this decision is taken not only considering the needs of the caching node but also depends on the needs of other nodes.
c. There should be a cache replacement algorithm to replace the cached data items when the caching space is not enough to cache the new ones.
d. A cache consistency algorithm to ensure that the cached data items are updated based on their Time-to-Live (TTL) value.

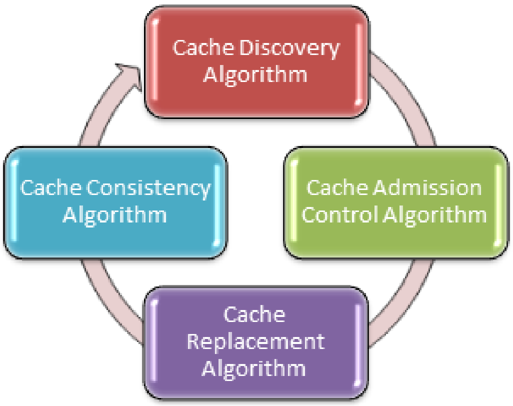


Figure 2. Requisites for Cooperative Cache Management

4. SYSTEM ENVIRONMENT

We consider a Wireless Sensor Network consisting of Sensor Nodes (SNs) that are based on the IEEE 802.15.4/ZigBee devices and are capable of sensing physical data while interacting with the environment. Based on the type of transmission these networks are classified as operating in either a) Push Mode, or b) Pull Mode. In push mode, the sensor nodes are sensing data all the time and once the data is aggregated it is pushed towards the Sink node or the PAN Coordinator which later is responsible for taking Control decisions for the system. In such a system, each sensor node itself is a Source of information. Whereas, in pull mode the data is sensed only when the Requester/Sink node expresses an interest for a particular data at an instant. Thus we see that Caching may not be much helpful in Push Mode because all the sensors are sensing data and all the neighboring nodes are sources of information. The adhoc on demand distance vector (AODV) is one such on demand routing protocol that makes all the nodes to work in Pull Mode in which all routes are discovered only when needed and are maintained as long as they are being used [16]. A data request initiated by a sink is forwarded hop-by-hop along the routing path along with a beacon signal until it reaches the source and then the source sends back the requested data. The beacon signal makes all the radios in its routing path to wake-up and acknowledge the request made by the Sink/Coordinator. Caching in such a system improves the overall system performance by reducing the number of packet overheads in requesting information from neighboring nodes and the data availability is increased.

WSN consists of sensor nodes which comprises of limited cache storage e.g. for multimedia data, then cooperative caching may also be useful for sharing the cached data among the neighboring nodes. Since WSNs comprises of a group of nodes communicating through omni-directional antennas with the same transmission range. Thus, a WSN topology is typically represented by a graph G= (S, E) where S is the set of sensor nodes SN_1, SN_2, …., and $E \subseteq S \times S$ is the set of links between nodes. The existence of a link (SN_i, SN_j) ∈ E also means (SN_j, SN_i) ∈ E which means that if a link exist between node ‘i’ and ‘j’ then the same exists between nodes ‘j’ and ‘i’. Also nodes SN_i and SN_j are within the transmission range of each other, and are called one-hop neighbors. The set of one-hop neighbors of a node SN_i is denoted by SN_i^1 and forms a zone. The combination of nodes and their one-hop neighbors forms a wireless sensor network.

Following assumptions have also been made in this System Environment:

1) The communication links between Sensor Nodes are bidirectional, and the sensors communicate via multi-hop transmissions.

2) The WSN is homogeneous i.e. the computation and communication capabilities are the same for all sensor nodes.
3) Each sensor node is aware of its geographical coordinates (x, y) using some localization method.
4) Since we assume that there is limited cache storage and once the cache space of a node is full then the node will select some data items to remove from the cache, when it has to cache new data.
5) Each node in the zone will maintain a Table of Cache Information denoted as TCI. This TCI will contain *n* elements where *n* is the number of the data items. There will be four entries related to each node which will be as follows:
   a. The first entry is *d.avail* that shows whether *d* is locally cached at node *X*. This is binary type value and is *TRUE* if data is locally available.
   b. The second entry is *d.neighnode* and shows which neighbor node has cached *d*.
   c. The third entry is *d.acount* which is maintained in order to count how many times *d* is cached by neighbor nodes of node *X* after *d* is cached by node *X*.
   d. The final entry is *d.ttl* shows the *TTL* (time-to-live) value that after how much time *d* is expired. This value is assigned by the data server. The entries of TCI are summarized in Table 1.

Table 1. Entries of the Table of Cache information (TCI)

Sl. No.	Entry Name	Meaning	Initial Value
1	d.avail	shows whether d is locally cached at the requesting node	FALSE
2	d.neighnode	shows which neighbor node has cached d	null
3	d.acount	shows how many times d is cached by neighbors node of node A after d is cached by node A	zero
4	d.ttl	shows after how much time d is expired.	assigned by the data server

6) Before forwarding the request for data to an intermediate one hop neighbor in its route path, each node will check if it contains the required data in its local cache and if it has the data then it will send directly and stop the forwarding else it will forward the request to the one hop neighbor that it knows has cached the data item.

5. CACHING IN COOPERATIVE ZONES (CCZ)

Caching in Cooperative Zones (CCZ) is an adaptive technique for data retrieval in WSNs based on IEEE802.15.4.

In CCZ caching technique, it is beneficial for the SN to share cached data with its one hop neighbors located in the zone. SNs that are part of a zone of a given node forms a cooperative cache system for that particular node since the link cost or the cost of communication with them is low both in terms of energy consumption and data exchange. Figure 3 shows the behavior of CCZ caching strategy for a data request. For each request, one of the following four Scenarios holds:

a. Scenario 1: A Local hit is said to have occurred when a copy of the requested data item is found in the local cache of the sensor node. If the data item is valid, it is used to serve the query and no further cooperation is required.
b. Scenario 2: A Zone hit is said to have encountered when the requested data item is found in the cache of one or more one-hop neighbors of the requester. Message exchange within the territory of the requesting sensor node (local zone) is required during the cache discovery.
c. Scenario 3: A Remote hit is said to have occurred when the data is found with a node belonging to a zone other than the local zone of the requester along the routing path to the data source.
d. Scenario 4: A Global hit is said to have encountered when none of the nodes could have helped then the requested datum is served by the data center or the Source Node.

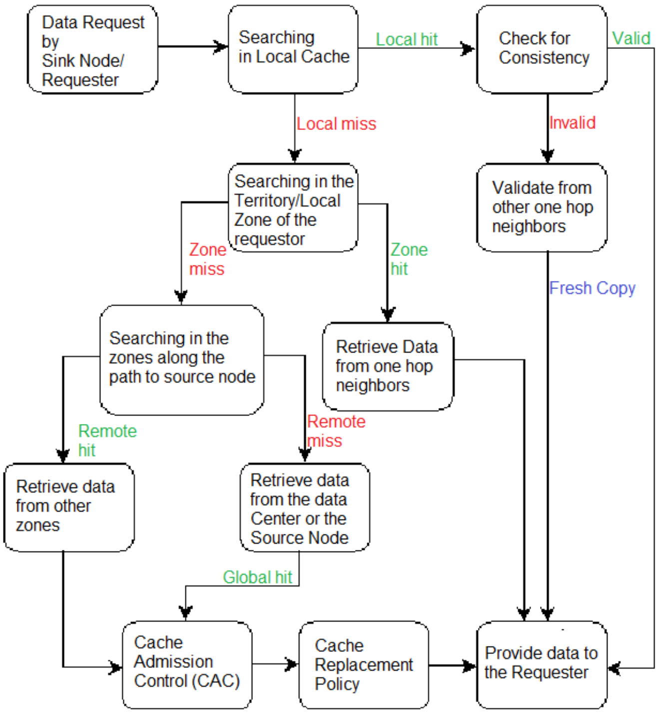


Figure 3. A typical data request being administered by the CCZ Protocol

5.1. Cache discovery process

Caching in Cooperative Zones (CCZ) uses an algorithm for Cache Discovery where in the node which has cached the requested datum is located. Once a data request is initiated by a sink node or PAN coordinator, it first searches the data in its own cache. If the data is found in the local cache then its *d.avail* is found to be'1'or TRUE. Then the data is used by the Requester for further processing. Such type of data retrieval is called a Local hit. If a local cache miss is encountered then the request is forwarded to one hop neighbor of the Requester or the local zone of the requester. In case the zone cache is also missed then the request for the required data is forwarded towards the Source Node and if the data is found while routing in any cluster as indicated by the CCZ algorithm, it will be returned to the requester, such type of retrieval is called a remote hit. Otherwise the data is fetched and returned by the source node, which is called a Global hit.

5.2. Cache admission control

The Cache Admission Control is responsible for making a decision of whether to cache a particular data item at a Sensor Node or not. An efficient cache management ensures caching a data item near to the Sink Node/PAN Coordinator or the Requester so that it is easily accessible. So, Caching also depends on the Distance Function of a node from the Requester, which is calculated as:

$$\delta_f = 1 - \frac{D_i}{S} \quad (1)$$

Where,

$\delta_f \rightarrow$ represents the Distance Function of a node from the Requester/Sink
$D_i \rightarrow$ is the distance between node N_i from the Requester/Sink
$S \rightarrow$ is the Network Size or total no. of Nodes in the Network

A particular data item cached is based on the Distance Function δ_f. If the $\delta_f > Threshold$, then the data should be cached in that particular node. If the $\delta_f < Threshold$, then the data should not be cached. To avoid multiple cached data items a time window concept is incorporated which will not cache the data if the cluster has cached value in the time window t_w. When a data passing through a node is cached in that particular node then it sets cache_tag=1 in the data packet and the field *d.neighnode* will change its value to the Node Number of the cached node.

5.3. Cache consistency

The Cache Consistency ensures that sensor nodes are served with valid and fresh data and no expired data is served for data requests. Two commonly used cache consistency models are the weak consistency and the strong consistency models. Since WSNs are characterized by multihop environment, limited bandwidth and energy constraints so the weak consistency model is more suitable. The CCZ caching approach uses a simple weak consistency model base on the Time-to-Live (TTL), in which a SN a cache copy up-to-date if its TTL has not expired. Once the TTL of a datum expires, the node considers for the replacement of the cached data. When a fresh copy of the same data passes by a Sensor Node, the SN updates its TTL and a cached data item is refreshed.

5.4. Cache replacement policy

The CCZ is a cooperative caching technique that enables data replacement in the cache once the TTL value of the data expires. Hence we reach to a conclusion that the Cache Replacement Factor (CRF_i) for a data item d_i at a sensor node N_i depends on the following three factors:

a. Popularity $\left(P_{d_i}\right)$: The probability of a data item, d_i being accessed by a host represents the Popularity of that data, which is computed as:

$$P_{d_i} = \frac{d.acount_i}{\sum_{k=1}^{N} d.acount_k} \tag{2}$$

b. Where, $d.acount_i$ → is the mean access count of a data item d_i being accessed by a host node.
c. Distance(D_i): is the distance between the caching node N_i and the Requester/Sink Node and is the measure of the number of hops between Requester Node and the caching node.
d. Consistency (TTL_i): Sometimes the cached data is not accessed at all by the requester in such a case to maintain the consistency of the system the Time-to-Live value of a data item is considered. When the TTL_i value of a data is expired the data item will be removed from the Cache.

Based on these attributes the Cache Replacement Factor (CRF_i) for a data item d_i is computed as:

$$(CRF_i) = P_{d_i} \cdot D_i \cdot TTL_i \tag{3}$$

The more the CRF_i value is the more is the utility value of the data item d_i to be kept in the cache. The cache will get up-to-date with fresh data once the CRF_i value of data d_i is found the least. The CCZ algorithm uses a heuristic approach that removes a cached data item, d_i having least CRF_i until free cache space is sufficient enough to accommodate fresh data that is ready to be cached.

6. SIMULATION AND ANALYSIS

6.1. Simulation model

The Simulation of the proposed CCZ algorithm is carried out on NS-2 (version 2.32). The routing protocol used is AODV [1], [16]-[19] to route the data traffic in the Wireless Sensor Network based IEEE802.15.4 MAC and PHY protocol and the free space propagation model as the radio propagation model. The number of nodes is 16, deployed in a sensor field region of 100*100 m^2. The wireless bandwidth is 250kbps that represents the maximum amount or bits of data that can be transferred in a time period, normally in one second.

We have simulated AODV with CCZ caching technique in two analytical models where in we consider the nodes to be connected in STAR connection and in the other network model; the nodes are connected in a Grid.

In Star (Cluster based) network, 16 sensor nodes based on IEEE 802.15.4 PHY standard are considered which are all Full Function devices (FFDs) and are accompanied with a fixed amount of cache memory to store the sensed data as shown in Figure 4.

In Grid based network, sixteen sensor nodes are placed equidistant in an area of 100m *100m, and all devices are IEEE 802.15.4 PHY and MAC compliant, as shown in Figure 5. All devices are associated with some fixed amount of cache to store and update it with fresh data.

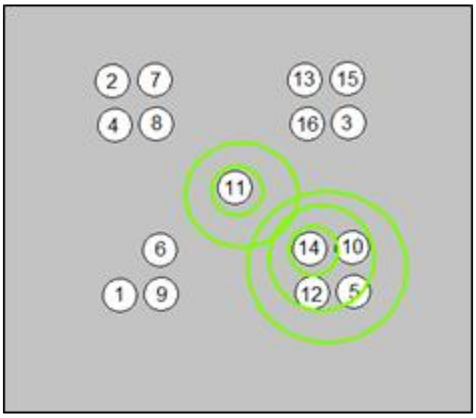


Figure 4. Star based Network Model

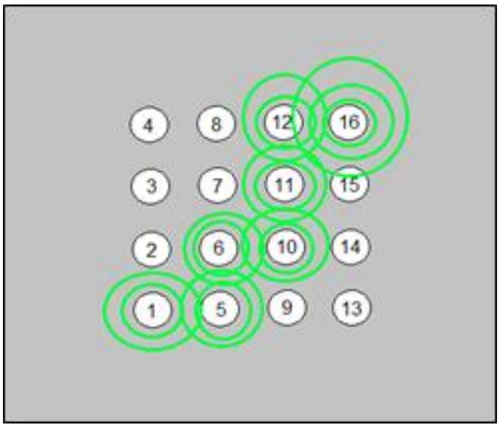


Figure 5. Grid based Network Model

Table 2. Radio Characteristics

Operation	Energy Dissipated
Transmit Power	31mW
Receive Power	35mW
Idle Power	30mW

Table 3. Simulation Parameters

Parameter	Default Value	Range
Number of Nodes	100	1~100
Number of Data Items	500	
Payload Size	64bytes	
PHY and MAC Layer	IEEE802.15.4	
Channel Frequency	2.4GHz	
Bandwidth (kbps)	250	
Waiting interval (t_w)	10s	
TTL	300s	100~300s
Cache Size (KB)	800	200~1400
Traffic Type	CBR	
Routing Protocol	AODV	
Beacon Order	3	
Superframe Order	2	

In general the IEEE 802.15.4 based sensor node can be in one of these modes: Idle, Transmit Mode, or Receive Mode. In the simulation we set the BO=3 and the SO=2, for which the Duty Cycle comes out to be:

Duty cycle= $2^{-(BO-SO)} = 2^{-(3-2)} = 2^{-1} = 2^{-1} = \frac{1}{2} = 0.5$ or 50%. A sensor node with very low duty cycle goes to sleep mode until a beacon signal arrives again to wake up the radio.

The data items are updated at the source nodes. The source serves the requests on First-Come-First-Serve (FCFS) Basis. Once the node sends the data item to a sink node the TTL value of the data is also piggybacked along with it to the requester/sink. As soon as the TTL expires, the sensor node has to update its cache space with new refreshed data either from the source or from other nodes (which have maintained the data in its cache) before serving the query.

The radio parameters and the simulation parameters are illustrated in Table 2 and Table 3 respectively.

6.2. Performance metrics

The following three performance metrics have been evaluated:

Average Query Latency $\left(T_{q_{avg}}\right)$: The query latency $'T_q'$ can be defined as the time interval between a query sent by a requester and the response received back by the requester/sink. The average query latency is the query latency $'T_q'$ averaged over all the generated queries.

Byte Hit Ratio(B): The byte hit ratio B is defined as the ratio of total bytes of data retrieved from the cache to the total number of requested data bytes by the sink/requester node. The byte hit ratio B includes bytes retrieved from a local hit known as a Local Byte Hit(B_{local}); bytes retrieved from a zone hit known as a Zone Byte Hit(B_{zone}) and the bytes retrieved from a remote hit known as a Remote Byte Hit(B_{remote}).It is to be noted that bytes retrieved from a Global hit is a freshly sensed data and cannot be considered to have been retrieved from the cache.

Total Energy Consumption (E_{total}): The total energy consumption is defined as the amount of energy consumed by each IEEE 802.15.4/ZigBee sensor nodes during transmission, reception and sleep mode. The unit of energy consumption for the simulation is considered in mWh.

$$E_{total} = E_{transmit} + E_{receive} + E_{sleep} \quad (4)$$

6.3. Results

Figure 6 shows the effect of varying cache sizes on the Average Query Latency for both the analytical network models that is Star/ Cluster connected Network and the Grid Based Network. The simulation reveals that the average query latency $\left(\boldsymbol{T}_{\boldsymbol{q}_{avg}}\right)$ decreases with increase in Cache Size as more number of requests is satisfied. This is due to the fact that more required data items can be found in the local cache as the cache size increases. The average query latency in the Grid/Peer-to-Peer Connected Network is less as compared to the Star/Cluster Based Network. Thus, on an all the performance of CCZ caching algorithm in Grid Connected Network outperforms than the Star Connected Network.

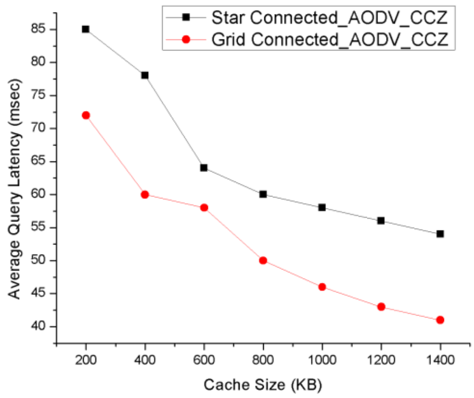


Figure 6. Average query latency with different cache size

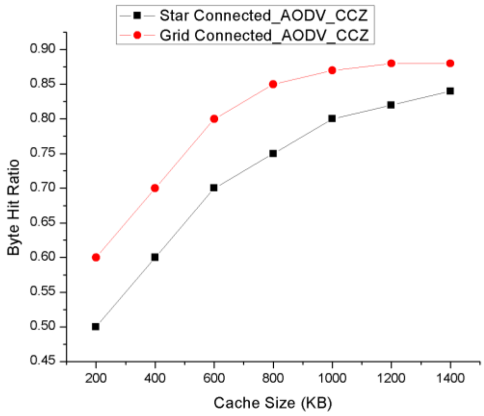


Figure 7. Byte hit ratio with different cache size

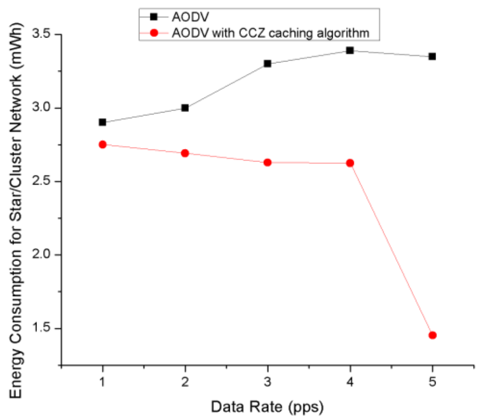
Figure 7 shows the effect of varying Cache Size on the Byte Hit Ratio. Both the schemes that are Star Connected Network and the Grid Connected Network exhibit better byte hit ratio with increasing cache size. When the cache size is small then data is contributed more by zone hit and remote hit but as soon as we increase the cache size the contribution by local hits become significant. This is because more number of data items are found in the local cache as the cache gets larger. The local byte hit ratio increases with the increase in cache size because with larger cache storage more data can be cached locally. According to the simulation results the Byte Hit Ratio of Grid Connected Network is better than that of the Star/Cluster Connected Network.

Figure 8(a) shows the results of total energy consumption by nodes in the network connected in Star (Cluster) connection as shown in Figure 4. The energy consumption by the nodes is evaluated when only AODV is evaluated and also for the evaluation of AODV protocol with CCZ cooperative caching algorithm.

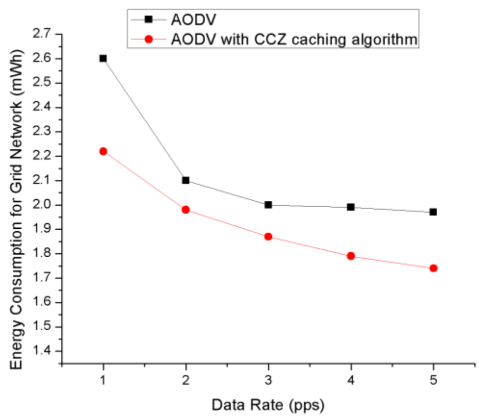
In Figure 8(a), for different data rate that is packets per second the energy consumption in nodes is evaluated when the simulation is conducted with AODV and Figure 8(b) estimates the energy consumption when the AODV routing protocol is combined with the CCZ caching algorithm. So we see that when data rate is 5 packets per second then the energy consumption by nodes is less when AODV is combined with the caching algorithm; it is because the data is retrieved by the requester from a nearby caching node.

For a Star/Cluster network, the average energy consumption by nodes with only AODV routing algorithm was 3.19mWh. And when AODV routing protocol is used with the CCZ caching algorithm then the average energy consumption is 2.43mWh.

For a Grid Network, the average energy consumption by nodes with only AODV routing algorithm was 2.13mWh. And when AODV routing protocol is used with the CCZ caching algorithm then the average energy consumption is 1.92mWh.



(a)



(b)

Figure 8. (a) Energy consumption in star/cluster network, (b) Energy consumption in grid network

7. CONCLUSION

In this paper two analytical models in which the nodes are organized as cluster (star) and grid (peer-to-peer) based networks are analyzed in beacon-enabled mode in which the Beacon Order is 3 and the Superframe Order is 2. The duty cycle for such a system is 50% and the performance of the proposed two network models are evaluated with AODV routing protocol along with a Cooperative Caching algorithm known as the Caching in Cooperative Zones (CCZ). This cooperative caching technique supports efficient data dissemination and query processing. An effective cache management scheme is proposed that comprises of cache discovery, cache admission control, cache replacement policy and the TTL based cache consistency model. The CCZ algorithm ensures that a query is served from the nearest cache or source. Simulation results show that the CCZ caching scheme performs better in grid based or peer-to-peer network model than the cluster based or star network model.

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