Heterogeneity-aware Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network

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ABSTRACT

The energy of the node in the Wireless Sensor Networks (WSNs) is scarce and causes the variation in the lifetime of the network. Also, the throughput and delay of the network depend on how long the network sustains i.e. energy consumption. One way to increase the sustainability of network for improving bandwidth utilization and energy consumption is the introduction of heterogeneous nodes regarding energy, and the other is to use the slotted transmission schemethat allow nodes to regularly schedulethe activities.Also, clock skews may cause the errors and be one of the source of delay and energy consumption.To improve the QoS parameters, the paper proposes NodeHeterogeneity-aware Bandwidth Efficient Hybrid Synchronization Algorithm (NHBES). It works on the formation of cluster-based spanning tree (SPT).The nodes in the cluster and cluster heads in the network are synchronized with the notion of the global time scale of the network. To minimize the energy consumptions and delay, NHBES synchronizes the time slots using TDMA based MAC protocol. The hybrid approach used helps to improve the throughput (bandwidth utilization), energy consumption with less delay as compared to the state-of-the-art solutions.

General Terms

Bandwidth utilization, Spanning Tree, Scheduling, and Synchronization.

Keywords

Delay; Energy; Throughput; WSN.

1. INTRODUCTION

Time and clock synchronization are important services for the collaborative and coordinated operation in WSNs. Time synchronization in the WSNs is mainly affected by low-cost clocks, frequent topological changes, error sources during communication, node failures and the resource constraint nature of the nodes. For instance, network protocols such as time division multiple access (TDMA) strictly demands synchronization among sensor nodes. The unsynchronized clocks in the network take more time to send the packet to sink and hence consumes more energy. The nodes used in the formation of the network are scare of energy, and cannot sustain for a long time. Also, some part of node energy is utilized in the synchronization of activities of the nodes according to availability of free scheduling slots. To improve the network lifetime nodes with varying energy are added into the network. Also, the energy consumption of the synchronization algorithm is minimized by matching the global clock of the sink and the local clock of the node [1, 2].The clustering approach usedprovides the scalability to the network and improves the lifetime [3].

The main source of energy consumption is retransmission of packets that collied with each other due to unavailability of free slot of mis-match between the clocks. To manage the schedule and activities of the node an efficient medium-access protocol is required. Itmanages sleep and wake up time of the cluster head (CH) and nodes for the effective utilization of time slots based on current and future state [4]. The activities of the node are scheduled according to the time frame, and all the slots are synchronized with the global clock of the network. Other way to save the energy is to discard the packets that need retransmission. The unusable network conditions and scare resources of WSN make it essential to develop a time and clock synchronized protocol that can sustain the network for long time with reduced energy consumption. The spanning the variation in the clock skews and improper slot allocation to transfer the aggregated packets. The efficient way to reduce the retransmission delay is scheduling MAC protocol to manage the time slots of nodes and cluster head (CH) with global time scale. The data propagation from node to sink may be in one–hop or multi-hop, it depends on the depth of the spanning tree formed in intra and inter-cluster communication. The packet scheduling activities of the nodes are dependent on the availability of the channel, at least, equal to the synchronization time [2]. The neighboring node will synchronize their schedules periodically to prevent long term clock drift. Timing-Sync Protocol for Sensor Networks (TPSN) [5], considers the traditional approach of two-way message exchange between sender-receiver synchronization with an increase in sync errors and energy consumption. The traditional protocols are not energy efficient and difficult to implement for WSNs. Due to the constraints of energy and processing ability, the current time synchronization mechanisms like RBS, NTP and GPS could no longer serve for WSNs well, and need to be modified or redesigned.

The contribution of the paper is twofold; it uses the hybrid approach where TDMA based MAC is used to schedule the time slots, and slots are synchronized with thebalancing of thelocal clock of thenode and theglobal clock of thenetwork. Also, the addition of controlled node heterogeneity regarding energy helps to minimize the energy consumption with reduced delay. The cluster-based SPT with non-ideal clocks works on the level by level synchronization for improvement in throughput - a measure of bandwidth utilization. The frequency of each clock is assumed tobe fixed.

The paper has different sections as; Section 2 focuses on the present work related to synchronization algorithms. Section 3 presents the required assumptions and network model. Section 4 briefs about the NHBES, Section 5 discuss simulation setup and results, and section 6 conclusion along with the future scope.

2. RELATED WORKS

This section provides the idea how one can improve the QoS of the network by use of synchronizing the clocks of the node and sink.[6] Proposes TDMA based slot allocation for transferring the aggregated packets from CH to sink with reduced energy consumption even though the mobility of node restructures the cluster and increases the energy consumption. The TDMA scheduling demands the proper synchronization for reduced packet collisions. [7] Defines a time synchronization protocol based on spanning tree. A spanning tree formed by the nodes is divided into multiple sub-trees. The sub-tree synchronization process helps to minimize the synchronization errors by adjusting the clock time within the level. [8] Presents Clustered Time Synchronization algorithm and energy model that conserves the energy beside accuracy while synchronizing the WSNs. [9] uses Reference Broadcast Synchronization Protocol (RBS) for synchronization between two receivers by the intermediate node within the listening range of the sender and receiver.The intermediate node sends the message for recording the time, hence saves the energy in clock updates. The energy waste in synchronization of reference node reduces the lifetime of the network. [10] Proposes the distributed clustering data aggregation algorithm with consideration of mobile and heterogeneous nodes into the clusters. The mobility of node frequently changes the structures and accordingly consumes more energy. [11] Considers the network with heterogeneous nodes regarding energy with a mobile sink. It shows improvement in throughput and network lifetime. Due to the mobility of sink control overheads are increased and consumes some part of node energy. [12] Consider hybrid synchronization scheme for WSNs used to analyze the vibrations with minimum sync errors. Authors used the partial offset time synchronization of TPSN and clock adjustment for reduced energy consumption of ‘K’ nodes. [13] Proposes the hybrid scheme to ensure the sync accuracy with minimum energy. It considers partial scheme to calculate the time offset of few child nodes. [14] Considers time synchronization of node and network at the time of cluster tree formation. It reduces the energy consumption and relative time drifts used in data collection from the tree. [15] Proposes the cycle-based sync scheduling in the delay-sensitive applications to achieve low packet delay and high throughput in the communication of packets from intra to inter-cluster communication. It re-arranges the transmission order by optimizing the cycle length. It has a limitation of overhead with increased network size and synchronization error.[16] Proposes the Bandwidth Efficient Hybrid Synchronization Algorithm [BESDA] which uses the combination of scheduling and synchronization algorithm to improve the throughput. [17] Mobility–aware Hybrid synchronization (MHS)consider the random mobility of node to improve the throughput and delay, but the mobility of nodes causes the energy consumption in collecting the packets from nodes to CH and CH to sink. [18] Minimizes the cock skew by synchronizing the local clock of the node concerning the global clock of the network.

Time and clock synchronization is the important issue of WSNs for improving the network parameters. The clock drifts and unbalancing of the global clock of the network with the logical clock of the node results in sync errors during synchronization. Also, slot allocation for collision-free data transmission plays an important role. This paper proposes the technique of adding the heterogeneous nodes with energy in the network so that it can sustain for a long time and minimizes the energy loss and error. The spanning tree mechanism is used to transfer the packets to sink level by level with collision-free slot allocation. The active period of the parent node is scheduled in TDMA so that only one parent and its associated children nodes are active. It saves the energy and prolongs the network lifetime.

3. PROPOSED NETWORK MODEL

The paper proposes the cluster-based hybrid approach which considers the allocation of free time slots to nodes for transfer of packets and time synchronization for balancing the clocks of nodes with theglobal clock of thenetwork. It uses the SPT mechanism for synchronizing the slots as well as clocks of the heterogeneous nodes with the global clock of the network (sink). The clusters in the network are used to form the spanning tree with ‘V’ set of CHs connected with ‘E’ wireless linksas shown in Fig. 1. The network graph $T(V, E)$ is divided into many sub-trees of clusters T1, T2, T3,…,Tn. The sink is located at the root of the tree. The network has sub-tree of clusters (inter-cluster) with one CH and a number of nodes within the cluster. Also, a spanning tree of all nodes in the cluster is created and then divides into sub-levels (inta-cluster). The frequency of each clock is approximately fixed and maintains the time stamp which is synchronized with the global clock of the network during synchronization.

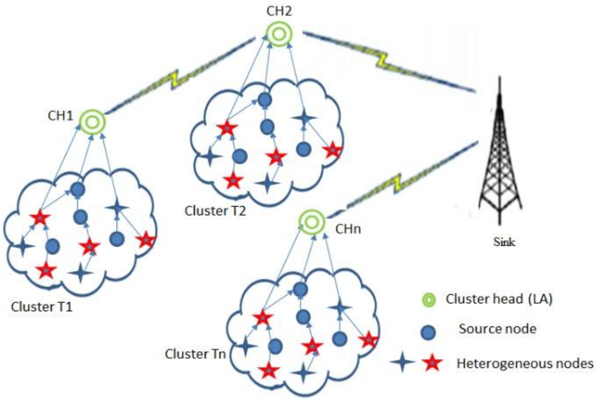

Fig 1. Proposed Network model.

4. PROPOSED MECHANISM

The main objective of proposed node heterogeneity-aware approach is to minimize the energy consumption and delay with improved bandwidth utilization. The main contributions of the proposed work are:

1. Form the cluster-based spanning tree and perform level by level aggregation.
2. Schedule the activities of the nodes and CHs according to free slots to reduce the collision of packets.
3. Synchronize the slots and activities of the node with global clock of network to reduce energy consumption,
4. Reduce the errors occurred due to clock skew, hence the energy consumption and delay.
5. Improve the throughput(bandwidth utilization) using hybrid approach (Scheduling +Synchronization)

4.1 Spanning tree formation

The main goal of thehybrid approach is to schedule the activities of nodes by adjusting the sleep and wake-up time while transferring the aggregated packets from lower level toward thesink. Also, synchronizing the local clock of all nodes within the cluster with CH and then with sink helps to reduce the sync errors and energy consumption. In the initial stage, all the randomly distributed nodes are grouped into a number of clusters based on the clustering algorithm [10, 11] at time interval‘t’. The re-election of CH is not considered to minimize the energy consumption in broadcasting the messages. The CH is assumed to have level 0 and broadcast the message, nodes receiving broadcast messages at one-hop are connected and arerepresentedas a set of theforest. The Kruskal algorithm is used to form the minimum spanning tree of nodes with the edge forming the loop are discarded as shown in Fig.2

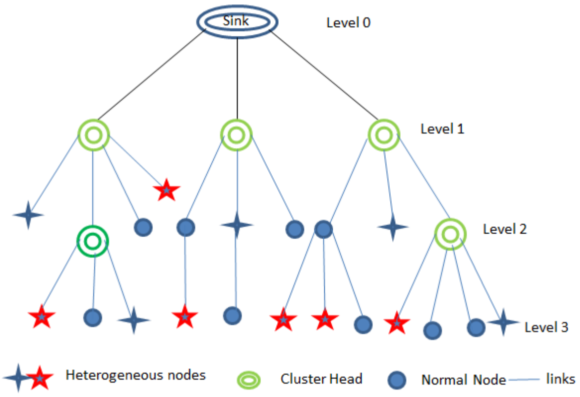

Fig 2. Proposed Spanning Tree Mechanism.

In the second level (inter-cluster), the spanning tree of CH is formed with different level and sink at root with 0 level. It broadcast a level discovery packet that contains level and ID. Neighbors of the root node receive this packet and increment level themselves based on previous level. The CHs directly connected to sink are at level 1 and the remaining CHs and nodes will maintain the higher order according to the depth of spanning tree. All the CHs at level 1 are synchronized with level 0, level2 with level1 and so on. The process of synchronization continues in the same manner inside the cluster till all nodes in the network have been synchronized with sink. The sink node maintains the global notion of time to synchronize the clocks of all nodes in the formation of spanning tree and communication of packets. The errors due to clock skew between local and global clock will occur during the synchronization process. The level by level synchronization of child and parent node reduces the clock drifts and overheads required to maintain equal time scale among all nodes at one time.

4.2 Synchronization phase

In the formation of spanning tree, different levels are maintained with sink node at level 0.The CH directly connected to sink are at level 1. The remaining CH and nodes will maintain the higher order according to the depth of spanning tree. All other nodes under CHs will be assigned the next levels and two-way message exchange between a pair of nodes can synchronize them.Consider node ‘A’ sends the synchronization packet at time interval T1 to another node‘B,' which receives the packet at T2 time then T2 is

$$T2 = T1 + \Delta + d \qquad (1)$$

Δ- the clock drift between the two nodes, d - propagation delay

At time T3, ‘B’ sends back an acknowledgment packet to ‘A’. At time T4 ‘A’ receives an acknowledgment packet from ‘B’. Node ‘A’ then calculate the clock drift and propagation delay with level and T1, T2, T3, T4 as:

$$\Delta = (T\,2 - T\,1) - (T\,4 - T\,3) \qquad (2)$$

$$d = (T\,2 - T\,1) + (T\,4 - T\,3) \qquad (3)$$

Node ‘A’ can correct its clock by knowing the drift, and then it synchronizes to node B. Where the sender synchronizes its clock to that of the receiver. Root nodeinitiatestime syncpacket andreceiver node R_x wait for random time to avoid contention before two-way message exchange between a pair of nodes.If thenodeis not assigned with level, it sends level request message and its close neighbor reply with its level to update called local discovery.If acknowledgment to sender is not received it retransmit synchronization packet. If acknowledge is not received even after three retransmissions,then root node sends level request message once again.In this way all the nodes in the level and network are synchronized.

4.3 Energy and Delay Analysis

The main objective of adding the heterogeneous nodes in the network is to sustain the network for a long time with minimum energy consumption and delay. NHBES considers the energy model used in [11], with introduction of controlled node heterogeneity the total initial energy of cluster is given by eq.4

$$Ei=n\ (\alpha En+\beta Ea+\gamma Es) \qquad (4)$$

α = % of normal nodes with energy En = 20 J, β = % of advanced node with energy Ea = 30J, γ = % of super nodes with energy Es = 40J, with equal number of nodes in the network $\alpha = \beta = \gamma = 1/3$, n= number of nodes in cluster.

In WSNs, the energy consumption depends on the time required for communication of aggregated packets, depth of spanning tree and clock skews causing errors. According to the depth of SPT i.e. from node to CH, CH to sink, and the number of packets transmitted by the nodes in the lower level to CH, and to 0 levels by CH., the energy consumption is given by eq.5

$$e(d_i)= k(e_t\, d_i^{\mu} +e_0)\ t_{slots} \qquad (5)$$

Where μ- path loss and depends on the distance of a node to CH and sink, k- the number of packets, e_t- transmitter energy, e_0- initial energy. The energy consumption according to radio states as transmitter (E_{tx}), receiver (E_{rcv}), listen (E_{lst}) and sleep (E_{slp}) and clock skew ‘es’ is considered according to [16] is

$$\text{Energy consumption}= (E_{tx} +E_{rcv} +n * E_{lst})\ L * t_{slot} *es \qquad (6)$$

Where synchronization period ‘T’ is composed of consecutive time slots L as shown in Fig 3.

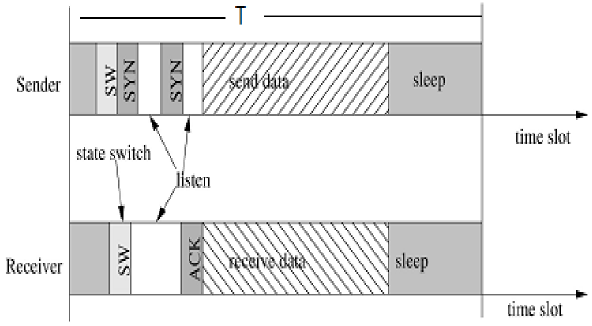

Fig 3. Synchronization frame.

The total time is logically divided into slots as t_{slot}, and these slots are synchronized among nodes to avoid collision of packets and clock skews. Also, the time required to schedule the ‘k’ packets with ‘N’ nodes at CH is calculated according to the number of forwarding’s as shown in eq.7

$$T_{ch}= ((N/k)-1)\ t_{slot} \qquad (7)$$

The total time required to send the aggregated packets to sink:

$T_{sink} = k.\ t_{slot}$ (8)

Hence, total time required for packets to reach to sink is:

$T = [((N/K)-1) + K]\ t_{slot}$ (9)

All the activities of each node are scheduled and synchronized in the time slot $1 \le t_{slot} \le T$.

5. RESULTS AND DISCUSSIONS

The parameters considered for simulation of randomly placed heterogeneous nodes are summarized in Table I. The cluster-based SPT used operates level by level in the intra and inter-cluster aggregation and communication of packets towards the sink. The performance of Node heterogeneity-aware Bandwidth EfficientSynchronization algorithm (NHBES) is compared with SDA [2], BESDA [16], and MHS [17] and time synchronization (TPSN)[5] a network-wide time sync protocol.Also, an attempt is made to improve the throughput of NHBES by applying the hybrid approach and performance is compared with scheduling algorithm with SPT and hybrid approach.

Table 1. Network Parameters

Node parameters	Value
Number of nodes	25,50,75,and 100
Number of sources	24,49,74, and 99
Number of sinks	1
Placement of source and sink	Random and sink at the root level 0
Initial energy of nodes	20J, 30J, and 40J
Ideal power	14.4mW
Receive power	14.4mW
Transmit power	36.0mW
Simulation runs	20

5.1 Results with Node Heterogeneity

In the initial part, the results are obtained only for the heterogeneous nodes showing that NHBES is energy efficient than the other algorithms presented in the state–of-the-art.

5.1.1 Synchronization error

Fig 4 shows the result of synchronization errors with TPSN and SPT synchronization mechanisms. It is seen that the performance in case of SPT mechanism is better than TPSN. The major reason for better performance is level-by-level synchronization performed by the proposed mechanism. CHs next to sink will receive the clock from the sink while nodes that are at a lower level will receive it from respective CH. In TPSN mechanism, the global timescale is applied across the network at one time, and every node has to synchronize with global time, it introduces the clock drifts at different levels and performance decreases.

5.1.2 Average Energy Consumption

Fig 5 shows that, the average energy consumption of NHBES is less as compared to TPSN, BESDA and MHS (30.66%, 18.01%, and 34.44% respectively) but more than SDA. The average energy consumption by TPSN is more than that of NHBES because TPSN tries to apply global timescale across the network at one time while NHBES uses the SPT-based synchronization mechanism. It works on a level by level. The clustered-tree architecture does not require to transmit the message for long distance hence saves energy. Also, BESDA and MHS uses the fixed and random mobility of the nodes, which requires more energy in message exchange for the formation of thetree, The mobility of nodes frequently changes the network structure and consumes energy[10]. In the NHBES, the nodes are added with controlled heterogeneity and re-election of CH is avoided this saves the energy and sustains the network for a long time.

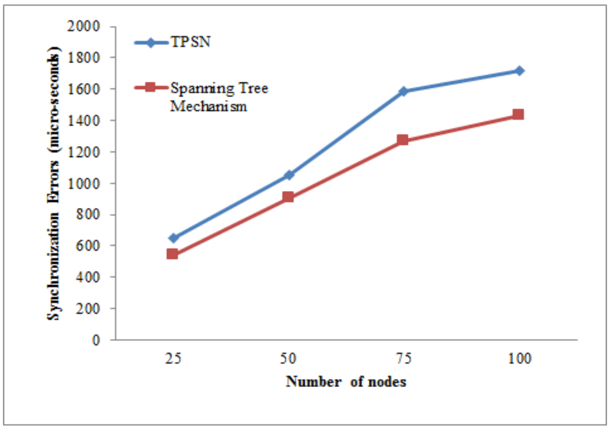

Fig 4. Synchronization Error.

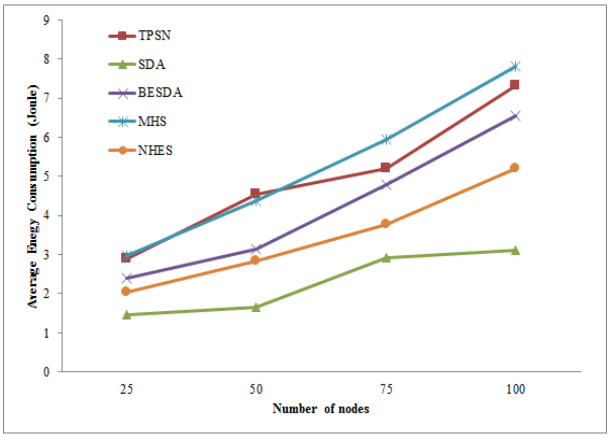

Fig 5. Average Energy Consumption.

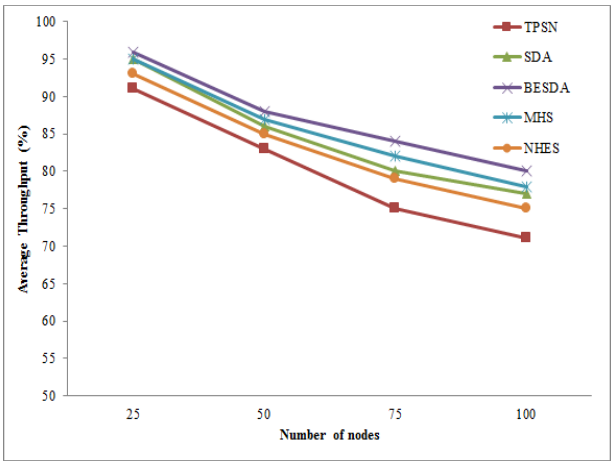

Fig 6. Average Throughput.

5.1.3 Throughput

Fig 6 shows a comparison of average throughput measured at the sink. The average throughput of SDA, BESDA and MHS is greater (1.76%, 4.59%, and 2.92%) than NHBES. The reason is that the mobility of nodes in the network increases the probabilities of one-hop neighbors to transmit the aggregated packet. By adding controlled heterogeneity, the network remains operative even though some nodes die early. It shows improvement in throughput of NHBES as compared to TPSN. This improvement in the result is due to synchronizing the clocks of parent and child nodes -level by level.

5.1.4 Delay

Fig 7 shows the delay that causes in the transmission of packets from nodes to CH, and CH to sink. With the introduction of controlled heterogeneity of nodes, an avg delay in matching the local and global clock is reduced by 16.40%, 5.35 % and 11.94% with SPT as compared to TPSN, SDA, and BESDA since network sustains for a long time. The larger time drifts introduced in TPSN takes a large time to make a decision on schedule as compared to NHBES. Also, the retransmission delay is caused due to mismatch of clocks. The overheads in the network are increased, which leads to increased delay and reduced throughput in case of TPSN.

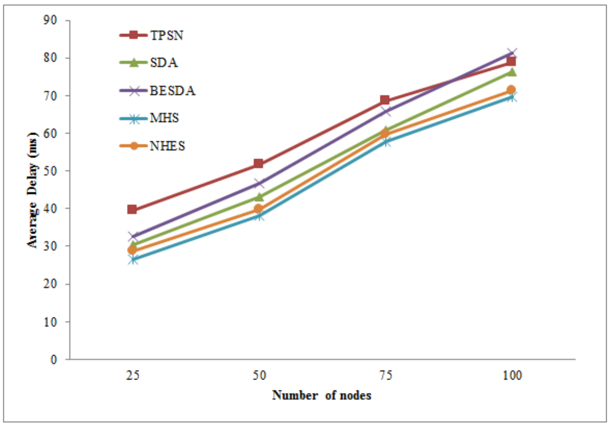

Fig 7. Average Delay.

5.2 Results with Hybrid Approach

In this part of the work, an attemptis made to combine the advantages of both concepts, scheduling and synchronization, adapting to current network conditions to show that NHBES improves its throughput and energy consumption. Throughput is the measure of bandwidth utilization.

5.2.1 Average energy consumption

The average energy consumption of the NHBES after application of the scheduling and synchronization algorithm is reduced by 14.62% and 36.77% as compared with BESDA and MHS. But higher than SDA and NHBES with SPT. The basic reason is BESDA and MHS operates on the mobility of nodes which takes more time to decide the schedule and then synchronize as shown in Fig 8. Hybrid approach also helps to reduce the clock skews and routing overheads from node at lower level towards root hence reduced energy consumption

5.2.2 Average Throughput

The hybrid approach used in the NHBES improves the packet delivery ratio hence throughput. The improvement is due to theproper balancing of slots and maintaining the active period of the nodes. Also, according to the adjusted time slots and synchronizing the clocks of the nodes and network level by level thethroughput of NHBESis increased by 4.5%, 9.58% and 30.08% as compared with SDA, BESDA, and MHS as shown in Fig 9. In thecase of MHS and BESDA, some control overheads are increased which takes more time for thenode to schedule and synchronize the activities according to free slots. The increased throughput is the measure of bandwidth utilization.

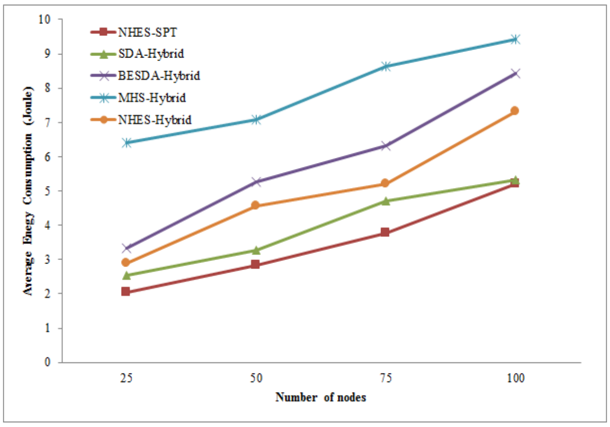

Fig 8. Average Energy Consumption-Hybrid.

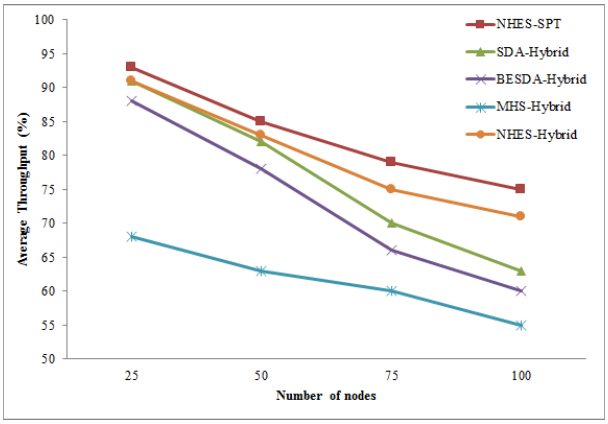

Fig 9. Average Throughput-Hybrid.

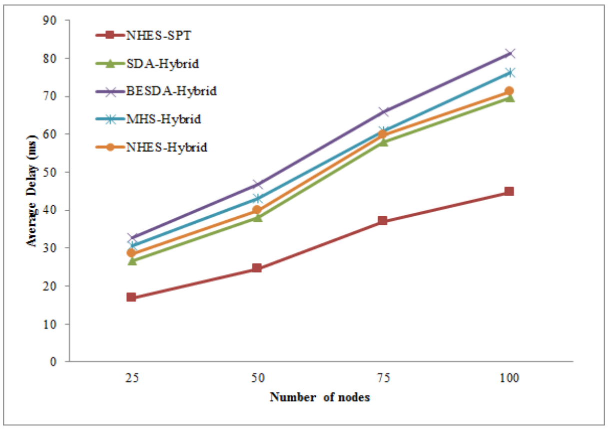

Fig 10. Average Delay-Hybrid.

5.2.3 Average Delay

Fig 10 shows the average delay after application of hybrid technique on the NHBES and other algorithms. Due to reduced clock skews and retransmission of messages for synchronizing the slots and nodes in the present level reduces the delay in the transmission of packets. The delay of NHBES with hybrid approach is less by 11.94%, and 5.35% as compared with BESDA and MHS, but is more as compared with SDA.

6. CONCLUSION AND FUTURE WORK

The proposed hybrid approach with spanning tree mechanism shows improvement in energy consumption and delay as compared with TPSN, BESDA, and MHS. The addition of heterogeneous nodes in the network along with the synchronization of local and global clock helps to sustain the network for a long time. Scheduling of slots and synchronization reduces the clock drifts, hence errors that results in an increase of the throughput and reduced delay. With the introduction of controlled node heterogeneity, and hybrid approach used shows improvement in throughput by 3.5 %. Also, the level by level synchronization reduces the possibility of retransmission of packet and reduces the delay. Form the results and discussion the paper concludes that with hybrid approach NHBES shows increased throughput as compared to BESDA and MHS,hence improved bandwidth utilization. The work can be extended by considering sink mobilityand increased node mobility to match the real-time applications.

7. ACKNOWLEDGMENTS

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