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A Survey on Efficient Routing Techniques in ZigBee Wireless Networks

Ummu Habeeba K.[1], Sajitha M.[2], Shiju Kumar P. S.[3]

[1,2,3] *Department of Computer Science and Engineering*
MES College of Engineering, Kuttippuram
Kerala, 679573, India

Abstract—ZigBee is a wireless personal area network, which is a world wide standard targeted to low-power, cost-effective, reliable, and scalable products and applications. In data communication networks, one of the most important functions is routing among the nodes. ZigBee standard supports a combination of tree routing and on-demand vector routing. An on-demand routing protocol needs more processing and memory resources, which is the main constraint in the low power wireless sensor networks. Also, the on-demand routing protocols are based on the route discovery, a process which increases the initial latency. On the other side, in hierarchical tree routing, each node sends data to the child nodes or parent node by using parent-child links without using routing table and without using path searching and updating. Therefore, tree routing is simple and uses the resources more efficiently. These features make tree routing suitable for networks consisting of small-memory, low-complexity lightweight nodes and low-power. The study involves various routing techniques in ZigBee wireless networks.

Keywords—ZigBee, Tree routing, On-demand routing, Wireless sensor network.

I. INTRODUCTION

ZigBee is a wireless personal area network and which is a world wide standard that defines a set of protocols for communication for low-data-rate, short-range wireless networking [1]. The frequency bands in which ZigBee-based wireless devices operate in 868 MHz, 915 MHz, and 2.4 GHz and 250 K bits per second is the maximum data rate. It is targeted mainly for battery-powered applications where the main requirements are low data rate, low cost, and long battery life. The wireless device is engaged in any kind of activity is very limited in many ZigBee applications; most of its time the device spends in a power-saving mode, also known as sleep mode. As a result, ZigBee enabled devices are capable for several years of being operational before their batteries need to be replaced.
ZigBee is ideally suited for the wireless control market which has a number of unique needs, because ZigBee is:

- Highly reliable
- Cost-effective
- Able to achieve very low power
- Highly secure
- An open global standard

This wireless networking standard fits into a market that is simply not filled by other wireless technologies (Fig. 1). ZigBee aims for low data rates, while most wireless standards are striving to go faster and ZigBee aims for a tiny stack that fits on 8-bit microcontrollers, while other wireless protocols add more and more features. ZigBee looks to control a light or send temperature data to a thermostat, while other wireless technologies aims to deliver streaming high-definition media or to provide the last mile to the Internet. ZigBee is designed to run for years, while other wireless technologies are designed to run for hours or perhaps days on batteries and ZigBee products can typically provide decades or more of use, while other wireless technologies provide 12 to 24 months of shelf life for a product. In fact, the slogan for ZigBee is, Wireless Control That Simply Works.

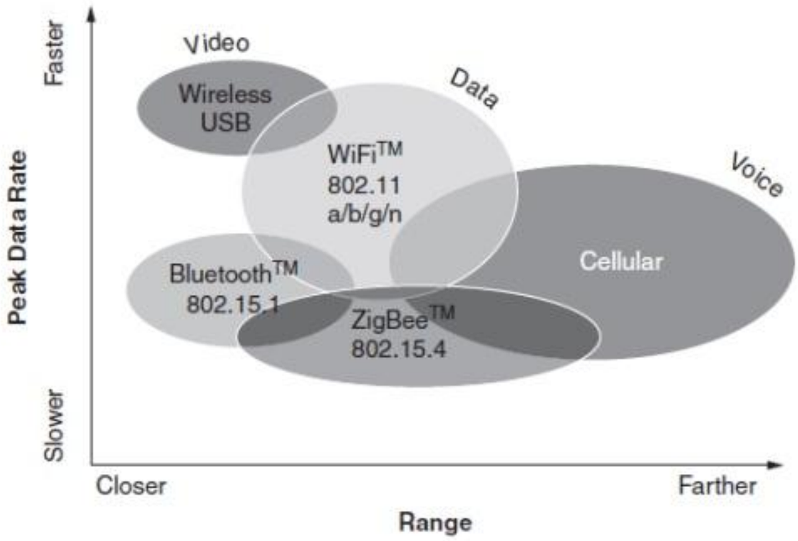

Fig. 1. Wireless Technologies Compared

Low power wireless mesh networking is provided by Zig-Bee and it can supports up to thousands of devices in a network, different from Bluetooth, UWB, and Wireless USB which are some other personal area network standards. Smart home, building automation [2], health care [3], smart energy [4], telecommunication, and retail services are the diverse application areas to which ZigBee Alliance has extended the applications based on these characteristics. Home patient monitoring is one of the application of ZigBee and by wearable devices a patient's blood pressure and heart rate, for example, can be measured. The patient wears a ZigBee device that interfaces with a sensor that gathers health-related information on a periodic basis. The data is then wirelessly transmitted to a local server, initial analysis is performed there. The vital information is finally sent to the patient's nurse or physician via the Internet for further analysis.

The ZigBee Alliance developed the ZigBee standard [5], which has hundreds of member companies, to original equipment manufacturers (OEMs) and installers from the semiconductor industry and software developers. In 2002, the ZigBee Alliance was formed as a non-profit organization open to everyone who wants to join. IEEE 802.15.4 as its Physical Layer (PHY) and Medium Access Control (MAC) protocols has adopted by the ZigBee standard. Therefore, a ZigBee- compliant device is similar with the IEEE 802.15.4 standard as well. The ZigBee wireless networking protocol layers are shown in Fig. 2 and the ZigBee protocol layers are based on the Open System Interconnect (OSI) basic reference model. There are a number of advantages on dividing a network protocol into layers. For example, it is easier to replace or modify the layer that is affected by the change if the protocol changes over time, rather than replacing the entire protocol and also, the lower layers of the protocol are independent of the application and can be obtained from a third party, in developing an application, so all that needs to be done is to make changes in the application layer of the protocol. Protocol stack software is the software implementation of a protocol. As shown in Fig. 2, IEEE 802.15.4 standard defines the bottom two networking layers [5]. This standard is developed by the IEEE 802 standards committee and was initially released in 2003. The specifications for PHY and MAC layers of wireless networking is defined by IEEE 802.15.4, but it does not specify any requirements for higher networking layers. The ZigBee standard adopts IEEE 802.15.4 PHY and MAC layers as part of the ZigBee networking protocol and it defines the networking, application, and security layers of the protocol. Therefore, any ZigBee-compliant device conforms to IEEE 802.15.4 as well.

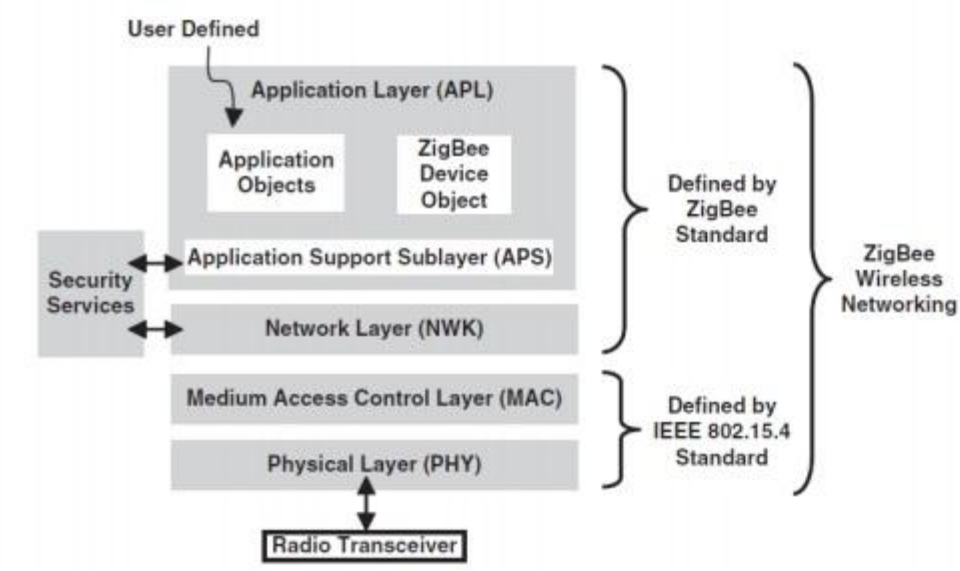

Fig. 2. ZigBee Wireless Networking Protocol Layers

II. ZIGBEE NETWORKING TOPOLOGIES

A. ZigBee Devices

In an IEEE 802.15.4 network, an FFD (Fully Function Device) can take three different roles: coordinator, PAN co ordinator, and device [1]. A coordinator is an FFD device that is capable of relaying messages. PAN coordinator, if the coordinator is also the principal controller of a personal area network (PAN) and If a device is not acting as a coordinator, it is simply called a device. Slightly different terminology is used by the ZigBee standard (Fig. 3), a ZigBee coordinator is an IEEE 802.15.4 PAN coordinator, and a ZigBee router is a device that can act as an IEEE 802.15.4 coordinator. Finally, a ZigBee end device is a device that is neither a coordinator nor a router. A ZigBee end device has the least memory size, fewest processing capabilities and features and is known as Reduced Function Device (RFD) and also an end device is normally the least expensive device in the network.

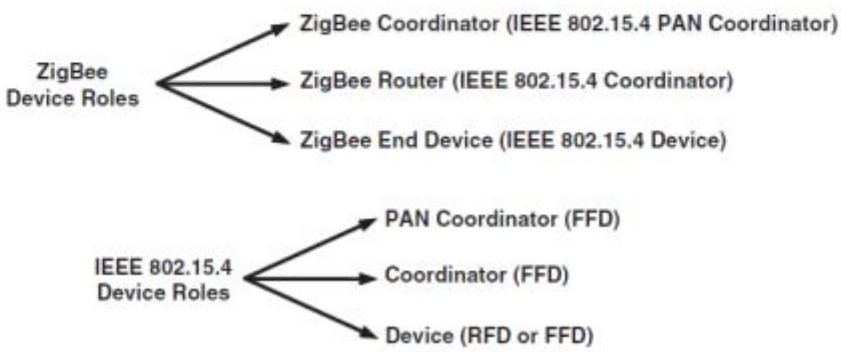

Fig. 3. Device Roles in the IEEE 802.15.4 and ZigBee Standards

B. ZigBee Networking Topologies

The network formation is managed by the ZigBee networking layer. The network must be in one of two networking topologies specified in IEEE 802.15.4: star and peer-to-peer [1]. In the star topology, shown in Fig. 4, every device in the network can communicate only with the PAN coordinator. A typical scenario in a star network formation is that an FFD, programmed to be a PAN coordinator, is activated and starts establishing its network. The first thing this PAN coordinator does is select a unique PAN identifier that is not used by any other network in its radio sphere of influence and the region around the device in which its radio can successfully communicate with other radios. In other words, it ensures that the PAN identifier is not used by any other nearby network. In a peer-to-peer topology (Fig. 5), each device can communicate directly with any other device if the devices are placed close enough together to establish a successful communication link. Any FFD in a peer-to-peer network can play the role of the PAN coordinator.

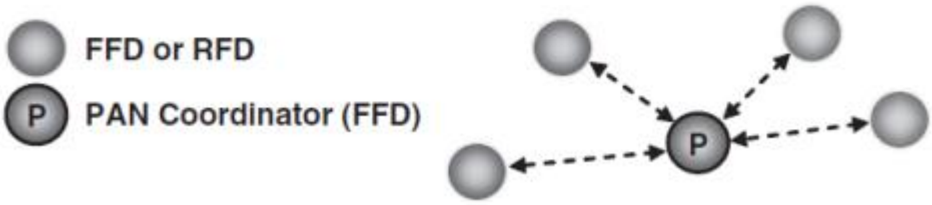

Fig. 4. A Star Network Topology

One way to decide which device will be the PAN coordinator is to pick the first FFD device that starts communicating as the PAN coordinator. In a peer to peer network, all the devices that participate in relaying the messages are FFDs because RFDs are not capable of relaying the messages. However, an RFD can be part of the network and communicate only with one particular device (a coordinator or a router) in the network. A peer-to-peer network can take different shapes by defining restrictions on the devices that can communicate with each other. If there is no restriction, the peer-to-peer network is known as a mesh topology. Another form of peer-to-peer network

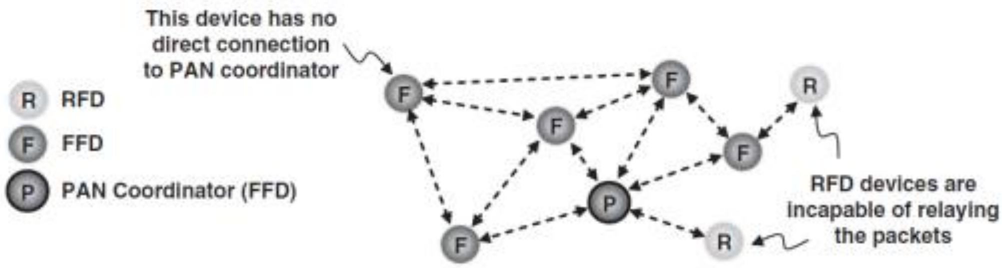

Fig. 5. A Mesh Networking Topology

ZigBee supports is a tree topology. In this case, a ZigBee coordinator (PAN coordinator) establishes the initial network. ZigBee routers form the branches and relay the messages. ZigBee end devices act as leaves of the tree and do not participate in message routing. ZigBee routers can grow the network beyond the initial network established by the ZigBee coordinator. Th e PAN coordinator controls the network and performs the following minimum duties:

- Allocate a unique address (16-bit or 64-bit) to each device in the network.
- Initiate, terminate, and route the messages throughout the network.

- Select a unique PAN identifier for the network. This PAN identifier allows the devices within a network to use the 16-bit short-addressing method and still be able to communicate with other devices across independent networks.

There is only one PAN coordinator in the entire network. A PAN coordinator may need to have long active periods; therefore, it is usually connected to a main supply rather than a battery. All other devices are normally battery powered. The smallest possible network includes two devices: a PAN coordinator and a device.

III. LITERATURE SURVEY

Routing techniques in ZigBee wireless networks mainly falls into two categories: the reactive routing protocol AODVjr (AODV junior) and ZigBee hierarchical or tree routing protocol. All remaining routing techniques have their roots in these basic categories.

A. ZigBee Reactive Routing Protocol

The reactive routing protocol in ZigBee is derived from AODVjr (AODV junior) [6], which is one of the representative routing protocols in mobile ad hoc networks (MANET). ZigBee reactive routing protocol gives the optimal routing path for the arbitrary source and destination pair through the ondemand route discovery, similar with other MANET routing protocols. AODVjr algorithm has many great advantages in energy saving and network performance and the algorithm only keeps thev valid route and does not maintain the routes which couldn't reach at the routing destination during communications. Nodes only remember next hop rather than remember the entire route as the source routing node. The AODVjr algorithm can build a dynamically, auto-start by-hop routing in the network between the mobile nodes. When the link is broken, AODVjr will notify the affected nodes, so that they are recognized as invalid routing ones. AODVjr allows mobile nodes to response sub-channelization conditions and update the network topology in time. AODVjr operates on non-circulation, and avoids fast convergent infinite computational problems when adhoc network topology changes, especially when one node enters the network. The ZigBee route discovery process can be illustrated in the following:

• Route discovery process
When a node want to transmit data to another, it first checks whether there is an entry in the routing table for the destination. If there is, it directly gets the next hop address from the routing table. Otherwise, it has to perform routing discovery process before sending the data in order to build a routing path by broadcasting RREQ.

• Receive a route request command frame
The destination receives the RREQ command frame and it will generate a RREP frame. Then, the RREP frame will be sent to the source node.

• Receive the route reply command frame
After the source node of route discovery process receives the route reply command frame (RREP), it get the destination node routing. When the source node of route discovery process receives the RREPs from multiple paths, the node will choose the path of the smallest consumption path as a route to the destination node. When there are more than one path, the source node of the route discovery process will select the path that received RREP first.

The route discovery process is required by AODVjr algorithm for each communication pair, so with the number of traffic sessions the route discovery overhead and the memory consumption proportionally increase. Moreover, route discovery packets are flooded to the overall network, this makes interference with transmission of other packets even in the spatially uncorrelated area with the route discovery.

B. ZigBee Tree Routing

ZigBee tree routing (ZTR) [7] prevents the route discovery overhead in both memory and bandwidth using the distributed block addressing scheme. In ZTR, since each node is assigned a hierarchical address, a source or an intermediate node only decides whether to forward a packet to the parent or one of the children by comparing its address with the destination address.

In ZigBee networks, the network addresses are assigned using a distributed address allocated mechanism. The address is unique within a particular network and is assigned by a parent to its child when a new node successfully joins in the network. Every potential parent is provided with a finite subblock of the address space, which is used to assign network address to its children. The size of sub-block is decided by several appointed parameters: Cm-the maximum number of children a parent may have, Lm-the maximum depth in the spanning-tree network, Rm-the maximum number of routers a parent may have as children. Once those parameters are given, the size of address sub-block at depth d, Cskip(d) can be computed as follows:

$$Cskip(d) = \left\{ \begin{array}{l} 1 + Cm(Lm - d - 1), Rm = 1 \\ \frac{1+Cm-Rm-CmRm^{Lm-d-1}}{1-Rm}, Rm > 1 \end{array} \right\}$$

A node with a Cskip(d) value greater than 0 shall permit other nodes to associate and be capable of allocate addresses. And it can assign its k-th router child and n-th end device child at depth d+1 in a sequential manner, respectively, to the following equations:

$$A_k = A_{parent} + Cskip(d)(k-1) + 1$$

$$A_n = A_{parent} + Cskip(d)Rm + n$$

Where k varies from 1 to Rm and n varies from 1 to Cm-Rm.Therefore, all sensor nodes are organized as a spanning-tree network, and any node can easily check their parent node and descendant nodes. In ZigBee, every device maintains a neighbor table which has all the neighbor information in the 1-hop transmission range. Every entry of the neighbor table include: PAN identifier, Mac Address, Network address, device type, relationship .

In ZigBee, every node has the ability to perform tree-based routing, which does not need extra memory space and path discovery. When any source node with address S at depth d wants to transmit data to the destination node with address D, it firstly checks whether source address S and destination address D meet the following equation.

$$S < D < S + Cskip(d - 1)$$

If the equation is satisfied, it means the destination node is one of the descendant nodes of source node. Then source node directly sends the data to one of its children node. Otherwise, it transmits the data to its parent node.

The most benefit of ZTR is that any source node can transmit a packet to an arbitrary destination in a network without any route discovery overheads. Due to this efficiency, ZTR is considered as a promising protocol for resource constrained devices in diverse applications. However, in ZTR, packets are forwarded along the tree topology to the destination even if the destination is located nearby. Thus, ZTR cannot provide the optimal routing path, while it does not require any route discovery overhead.

C. Hybrid Routing Algorithm

In [8], a hybrid routing algorithm without flooding is proposed. The hierarchical topology information is utilized to optimize the routing request broadcasting to reduce the overhead. And, the residential energy of nodes is considered as one routing metric to balance the energy consumption. Nevertheless, the optimized links are based on hierarchical topology, the coverage of routing request; thus, the routing efficiency remains questionable.

D. Neighbor Table Based Routing Techniques

A shortcut tree routing algorithm is proposed in [9], to reduce the routing cost of ZigBee tree routing by using the neighbor table that is originally defined in the ZigBee standard. While following the ZigBee tree routing algorithm, the algorithm suggest forwarding the packet to the neighbor node if it can reduce the routing cost to the destination. However, the links in their method were still invariable and may lead to rapid decline of energy for some nodes.

In [10], an enhanced routing protocol for ZigBee/IEEE 802.15.4 wireless networks is proposed. In order to make the ZigBee Tree-based routing algorithm more efficient, neighbor nodes are considered and the node with the local shortest path to the destination is selected as next hop node. This thought is based on Greedy algorithm, so we do not need to prove that we will get a whole shortest path at last. The problem associated with this method is that the lifetime of nodes is not considered and load balancing over nodes is not evaluated.

A modified tree routing mechanism with the introduction of neighbour table is given in [11]. The transmission cost via each neighbour device is estimated and compared to improve the routing path. It has a better performance with less power consumption per packet transfer and a long life cycle. But, this algorithm is based on the two-hop neighbour information; it may lead to severe energy and memory overhead in ZigBee networks.

In [12], a routing algorithm named Destination Family Group Tree Routing (DFG-TR) is proposed to find a family relationship between destination and forwarding node’s neighbours. If it finds a neighbour node belongs to the destination family group; then, this method selects the neighbour node as the next hop node to reduce the cost of routing to the destination. However, the life time of nodes and load balancing over nodes are still questionable.

A new tree-based routing algorithm named ESTR (EnergyEfficient Shortcut Tree Routing) to decrease hop-counts and to balance energy in the network by using the information contained in neighbour tables is proposed in [13]. ESTR suggests an optimized low-delay route based on the load balancing over nodes. But this may lead to computational overhead.

Taehong Kim et al. [14] proposes the shortcut tree routing (STR) that significantly enhances the path efficiency of ZTR by only adding the 1-hop neighbor information. Whereas ZTR only uses tree links connecting the parent and child nodes, STR exploits the neighbor nodes by focusing that there exist the neighbor nodes shortcutting the tree routing path. In other words, in STR, a source or an intermediate node selects the next hop node having the smallest remaining tree hops to the destination regardless of whether it is a parent, one of children, or neighboring node. The routing path selection in STR is decided by individual node in a distributed manner, and STR is fully compatible with the ZigBee standard that applies the different routing strategies according to each node's status. Also, it requires neither any additional cost nor change of the ZigBee standard including the creation and maintenance mechanism of 1-hop neighbor information.

IV. PERFORMANCE ANALYSIS

The ZigBee routing mainly falls into two categories: the reactive routing protocol AODVjr and ZigBee hierarchical or tree routing protocol. Route discovery overhead and memory consumption are the problems associated with AODVjr. Detour path problem and traffic concentration problem are the fundamental problems of the general tree routing protocols, which cause the overall network performance degradation. STR (Shortcut Tree Routing) reduces the traffic load concentrated on the tree links as well as provides an efficient routing path. It provides comparable routing performance to AODV. STR can be utilized in many ZigBee applications requiring both small memory capacity and high routing performances. Here, we mainly concentrating on the ZigBee routing protocols and more focusing on the tree routing protocols. The experiment is conducted by using network simulator (NS2) and the graph evaluation of the parameters are done by using Xgraph. And also, IEEE 802.15.4 PHY/MAC protocols are used for comparing STR with ZTR. The graphs for packet delivery ratio, end to end delay and throughput were plotted. The general parameter settings and their corresponding values are:

- Network size: 100m by 100m
- Number of nodes: 40
- PHY/MAC protocol: IEEE 802.15.4
- Propagation model: Two-ray
- Interface queue: Priority queue
- Simulation time: 10 s ec, 15 sec, 20 sec, etc.
- Packet type: CBR
- Traffic type: Any-to-any/Many-to-one

Packet delivery ratio is the ratio of packets that are successfully delivered to a destination compared to the number of packets that have been sent out by the sender. Throughput or network throughput is the rate of successful message delivery over a communication channel and end to end delay refers to the time taken for a packet to be transmitted across a network from source to destination.

In ZTR, packets are forwarded along the tree topology to the destination even if the destination is located nearby. So, it will make more end to end delay and thus lower packet delivery ratio and throughput. Whereas ZTR only uses tree links connecting the parent and child nodes, STR exploits the neighbor nodes by focusing that there exist the neighbor nodes shortcutting the tree routing path in the mesh topology, which causes a lower end to end delay and a better packet delivery ratio. Thus, STR reduces the traffic load concentrated on the tree links as well as provides an efficient routing path.

As compared to ZigBee tree routing, simulation results shows that shortcut tree routing have a better throughput (Fig. 6), packet delivery ratio (Fig. 7) and a lower end to end delay (Fig. 8). As a result, STR provides a comparable routing performance to ZTR. But also, STR has the limitation that

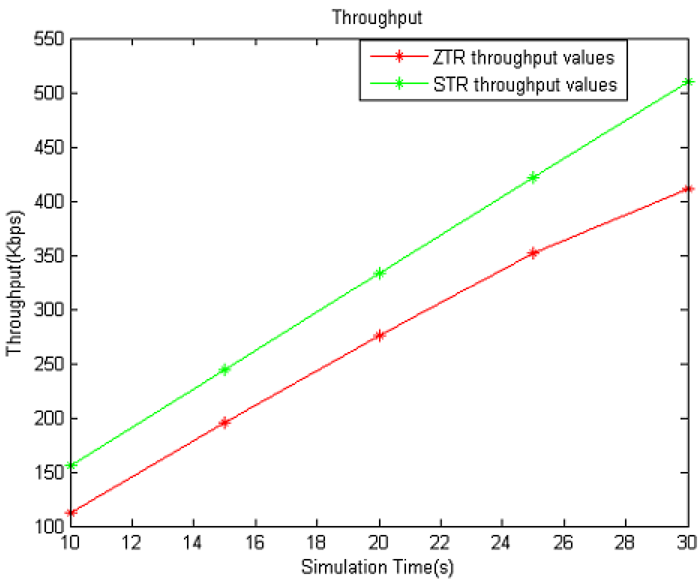

Fig. 6. Throughput

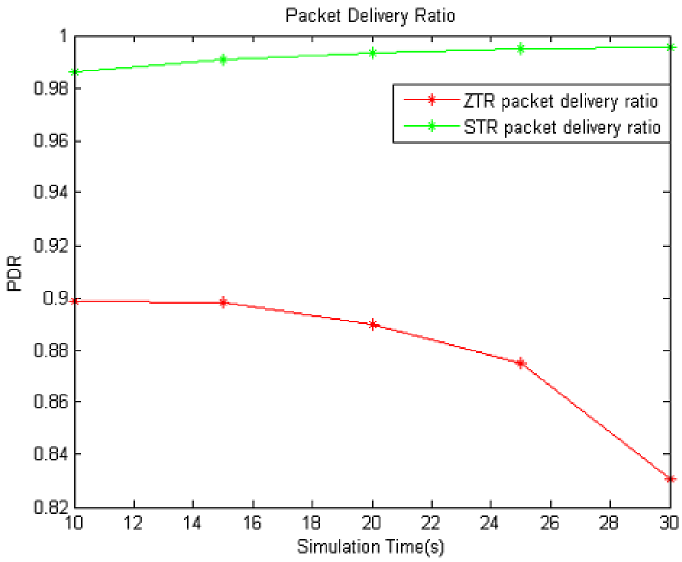

Fig. 7. Packet delivery ratio

the routing path is not always optimal in an aspect of the end-to-end hop distance. It is obvious that maintaining twohop neighbor information incurs high protocol overhead in the network with high node density. So, an enhancement to the STR along with the information about the geographic location of the nodes can be proposed as a future work. That is, neighbor table is used to find the neighbor nodes within one hop range with the source node and from which the distance between the neighbor nodes and destination is used as one of the parameter to find the best route. If a route with minimum geographical distance is found, then the source node will transmit data to that particular neighbor node. Else, the network will follow the shortcut tree routing algorithm.

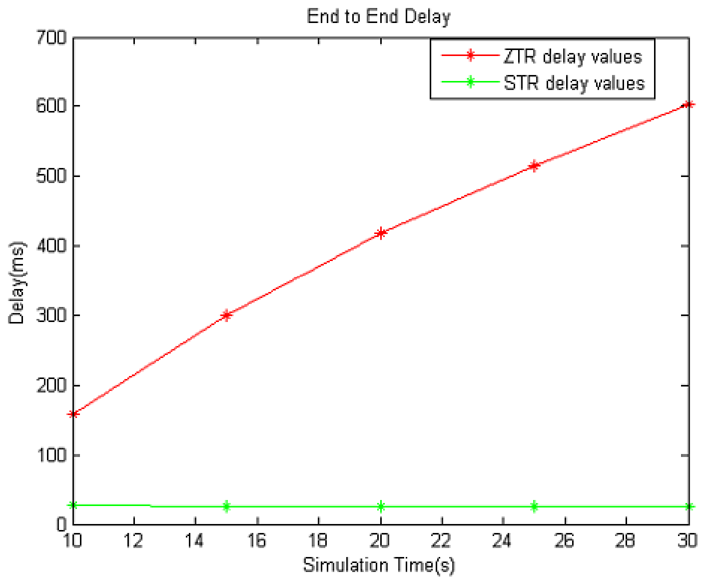

Fig. 8. End to end delay

V. CONCLUSION

The ZigBee routing mainly falls into two categories: the reactive routing protocol AODVjr and ZigBee hierarchical or tree routing protocol. Route discovery overhead and memory consumption are the problems associated with AODVjr. Detour path problem and traffic concentration problem are the fundamental problems of the general tree routing protocols, which cause the overall network performance degradation. STR (Shortcut Tree Routing) reduces the traffic load concentrated on the tree links as well as provides an efficient routing path. It provides comparable routing performance to AODV. But also, STR has the limitation that the routing path is not always optimal in an aspect of the end-to-end hop distance. So, an enhancement to the STR along with the information about the geographic location of the nodes can be proposed as a future work.

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