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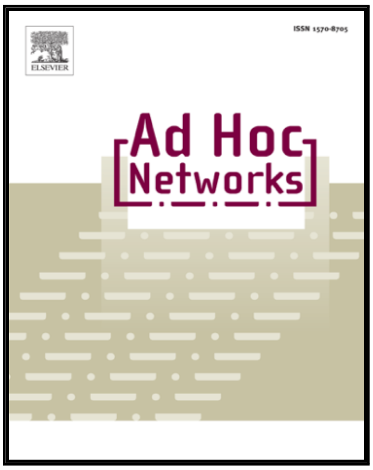

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Extended Shortcut Tree Routing For ZigBee Based Wireless Sensor Network

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Abstract: *Energy efficiency and network lifetime are main concerns in WSN. In order to improve these factors ZigBee plays an important role. Low cost, low data rate features of ZigBee results in low power consumption and makes it useful in wireless sensor networks, increasing life of small batteries of nodes in the network. Since tree routing in ZigBee does not require any routing tables to send the packet to the destination, it can be used in ZigBee end devices that have limited resources. Routing protocols such as AODV (Ad-hoc on demand distance vector routing), ZTR (ZigBee tree routing), and STR (Shortcut tree routing) are compared on the basis of different performance metrics (End to end delay, routing overload, throughput, packet delivery ratio). An extensive simulation in NS2 is carried out. The performance evaluation shows that STR achieves better performance as compared to other two routing protocols. But there are some limitations of STR method. Performance of packet delivery ratio of STR is less as compared to AODV. Performance of end to end delay of STR is poor as compared to AODV. Hence ESTR is proposed. The main aim of proposed ESTR [Extended STR] is to present new ZigBee network routing protocol with goal of improving the performance of ESTR in terms of PDR and delay against STR and AODV.*

Index Terms-ZigBee, IEEE 802.15.4, WSN, Tree routing, STR, ESTR

1 INTRODUCTION

ZigBee is a specification that defines a set of high level protocols for low cost and low power [5] wireless personal area networks. ZigBee is based upon IEEE 802.15.4 standard [1], [9], [10]. ZigBee provides the low power wireless mesh networking and supports up to 64,000 devices in a network with the multihop tree and mesh topologies as well as star topology[3], [4]. It is different from the other personal area network standards such as Bluetooth [7], UWB, and Wireless USB. Based on these characteristics, ZigBee Alliance has various applications like smart home, building automation, health care, smart energy, telecommunication, and retail services. The ZigBee network layer, which is the core of the standard, provides dynamic network formation, addressing, routing, and network management functions. Every node is assigned a unique 16-bit short address dynamically using either distributed addressing or stochastic addressing scheme. The routing protocols of ZigBee are diverse so that a system or users can choose the optimal routing strategy according to applications. ZigBee reactive routing protocol provides the optimal routing path for the arbitrary source and destination pair through the on-demand route discovery. It requires the route discovery process for each communication pair, so the route discovery overhead and the memory consumption proportionally increases with the number of traffic sessions.

In ZTR, since each node is assigned a hierarchical address [2], 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. ZigBee tree routing (ZTR) uses distributed block addressing scheme and prevents the route discovery overhead in both memory and bandwidth. The main advantage of ZTR is that any source node can transmit a packet to an arbitrary destination in a network without any route discovery overheads.

ZTR cannot provide the optimal routing path, as packets are forwarded only by using tree topology to the destination even if the destination is located nearby, though it does not require any route discovery overhead.

Shortcut tree routing (STR) significantly enhances the path efficiency of ZTR by only adding the 1-hop neighbour information. Whereas ZTR only uses tree links connecting the parent and child nodes, STR uses the neighbour nodes by shortcutting the tree routing path in the mesh topology. In STR [2], 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 neighbouring node. The routing path selection in STR is decided by individual node in a distributed manner. STR has the limitation that the routing path is not always optimal in an aspect of the end-to-end hop distance, because the next hop node is selected based on the local information like 1-hop neighbour table.

Our objective is to provide the near optimal routing path like the reactive routing protocol as well as to maintain the advantages of ZTR such as no route discovery overhead and little memory consumption for the routing table.

Hence we propose ESTR, which 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 neighbour information. The Source Initiated Bulged Multi-Path Routing scheme provides multiple disjoint paths from source to destination. Hop count of all nodes is considered from sink. In this, only one path from each node is considered which is one hop away and is having hop count less than that of the source node. The current reporting rate is divided by number of upstream neighboring nodes of source and this new reporting rate is assigned over each path. The node will receive the packet and forward it only if it is from that dedicated path, else it will discard that packet. This process will be carried till packet reaches to destination.

The main contributions of this paper are as follows: First, ESTR is proposed to resolve the main reasons of overall network performance degradation of ZTR and STR, which are the detour path problem and the traffic concentration problem. Second, it is proved that the multipath routing used by ESTR improves the routing path efficiency and alleviate the traffic load concentrated on tree links in ZTR. Third, analyse the performance of ESTR, STR, and AODV.

This paper is organized as follows: Section 2 describes ZTR and STR and their problems. Section 3 presents the extended shortcut tree routing algorithm and analyses the properties of ESTR in a mathematical way. The diverse performances are evaluated in Section 4, and conclude this paper in Section 5.

2 ZIGBEE TREE ROUTING

ZTR is designed for resource constrained ZigBee devices to choose multihop routing path without any route discovery procedure, and it works based on hierarchical block addressing scheme.

With the hierarchical addressing scheme, we can easily identify whether the destination is descendant of each source or intermediate node. In ZTR, each source or intermediate node sends the data to one of its children if the destination is descendant; otherwise, it sends to its parent. The example of the routing path of ZTR is described in Figs. 1a and 1b, where a packet is routed through several hops toward the destination even though it is within the range of sender’s 2-hop transmission range. To solve this detour path problem of ZTR, ZigBee specification has defined the direct transmission rule that allows a coordinator or a router to transmit a packet directly to the destination without decision of the routing protocol as shown in Fig. 1a, if the corresponding destination is in the neighbour table.

However, this method cannot fundamentally solve the detour path problem of tree routing, as shown in Fig. 1b. In case that the destination is located more than 2-hop distance away from a source node, we cannot apply the direct transmission rule. In addition to the detour path problem, ZTR has the

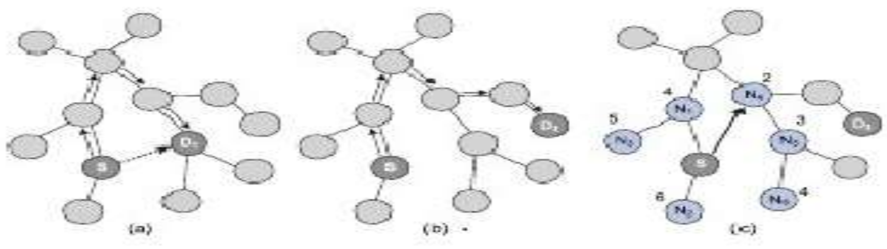


Fig 1.ZigBee Tree routing and Shortcut tree routing

traffic concentration problem due to limited tree links. Since all the packets pass through only tree links, especially around the root node, severe congestion and collision of packets are concentrated on the limited tree links. This symptom becomes worse and worse as the number of packets increases, and it finally causes the degradation of the packet delivery ratio, end-to-end latency, and other network performances.

3 SHORTCUT TREE ROUTING

STR algorithm solves these two problems of the ZTR by using 1-hop neighbour information. It solves detour path problem completely but traffic concentration partially. The STR algorithm basically follows ZTR, but chooses one of neighbour nodes as the next hop node when the remaining tree hops to the destination can be reduced. For example, in Fig. 1c, STR computes the remaining tree hops from the next hop node to the destination for all the neighbour nodes, and selects the N4 as the next hop node to transmit a packet to the destination D2. The main idea of STR is that we can compute the remaining tree hops from an arbitrary source to a destination using ZigBee address hierarchy and tree structure as discussed in previous section. In other words, the remaining tree hops can be calculated using tree levels of source node, destination, and their common ancestor node, because the packet from the source node goes up to the common ancestor, which contains an address of the destination, and goes down to the destination in ZTR.
STR has the limitation that the routing path is not always optimal in an aspect of the end-to-end hop distance, because the next hop node is selected based on the local information like 1-hop neighbour table. For example, in Fig. 1c, the optimal path from S to D2 is S-N5-D2, but, it requires 2-hop neighbor information in order for the source S to know that N5 is within 1-hop communication range of theD2. It is obvious that maintaining 2-hop neighbor information incurs high protocol overhead in the network with high node density; thus, we selected to provide a resource efficient routing protocol in a view point of memory consumption and routing overhead.

4 ESTR (Extended STR)

Fig. 2 shows Source Initiated Bulged Multi-Path Routing scheme provides multiple disjoint paths from source to destination. Hop count of all nodes is considered from sink. In this, only one path from each node is considered which is one hop away and is having hop count less than that of the source node. The current reporting rate is divided by number of upstream neighboring nodes of source and this new reporting rate is assigned over each path. The node will receive the packet and forward it only if it is from that dedicated path, else it will discard that packet. This process will be carried till packet reaches to destination. It solves detour path problem and traffic concentration problem completely by using multipath routing mechanism.

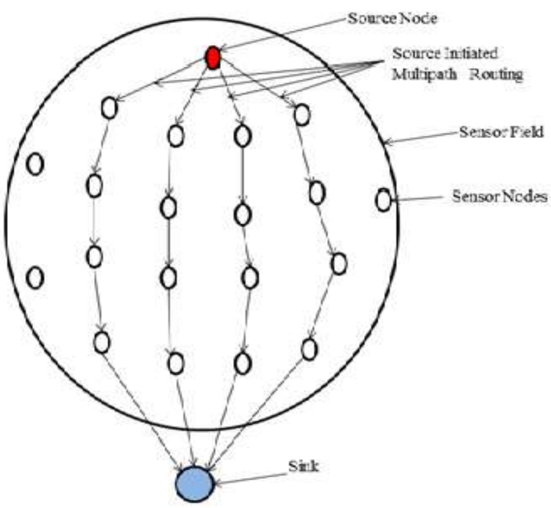


Fig2. Multipath Routing mechanism in ESTR

4.1 Algorithm to find ancestor

```
nsaddr_t ESTR_Agent::ancestor(ESTR_Packet &p)
  /* extract the packet information and initialize the parameters */
{
  int HopToTree = 1;  //HopToTree value is started with value 1 at the sink
  // call to broadcast HCM function
  BroadcastHCM(p, HopToTree);
  hdr_estr *estrh =  (hdr_estr*)
  p.pkt->access(off_estr_);
  hdr_cmn *cmh =  (hdr_cmn*)p.pkt->access(off_cmn_);

  // first make sure we are the ``current'' host along the source route. If we're not, the
previous node set up the source route incorrectly.
  assert(p.route[p.route.index()] == net_id || p.route[p.route.index()] == MAC_id);

    for (int c = (estrh->cur_addr()-1); c < estrh->num_addrs()-1 ; c++)
      {
         // means
  if (p.route.index() > p.route.length() && FirstSendingu(p, true);)
    {
      //directly unicast to the destination
    cmnh->next_hop() = hdr_estr ->HCM_id;
    p.route.index (c) = p.route.length+1;
    // node c updates value of the hoptotree field in message HCM
    hdr_estr ->HCM_id = hdr_estr ->u_id;
    // node u updates the value of the hope to tree field in the message HCM
    p.route.length =  p.route.index (c);
// node u sends a broadcast message of the HCM with new values
    FirstSendingu(p, false);
}
else
{
// node u discard the packet of HCM
      drop(p.pkt, DROP_HCM_ROUTE_LOOP);
      p.pkt = 0;
      // maybe we should send this packet back as an error...
      return nsaddr_t ancestor;
    }

  }
}
```

4.2 Algorithm to find next hop

```
nsaddr_t ESTR_Agent::Nexthop (Event *event, addr u)
{
  //check if adjtable caused the timeout
```

```
  ntable_ent *S; // set of nodes detected event
  ent = t->head; // node of set S selected as leader
  adjtable_ent *p;
  adjtable_ent *p_prev=NULL;
  nexthop_ent *phop = NULL;
  nexthop_ent *phop_prev = NULL;
  assert(p.route[p.route.index()] == net_id || p.route[p.route.index()] == MAC_id);


// repeat
  while (p->next_hop) {
    if (u == p->next_hop)
     {
       p.route.index() = 0;
      // node u is the part of new route build
       ent->u = RELAY;
      // sends REM to its NextHope
       u->sendREM (p->next_hop);
      // node u broadcasts the message HCM with the value of hopetotree = 1

      u->BroadcastHCM(p, 1);
}
}

while (next_hop)
// compute the number of descendents of node u
sons = desc (addr u);
if (sons > 1)
{
// aggregate all data and send it to next hope
if (ntable->existsLink(next_hop->u,u))
{
        cmnh->next_hop() = next_hop->u;
        cmnh->addr_type() = AF_INET;

}
}
if (ent-> u == RELAY)
{
// call to route repair functionality
p.route->route_repaired();
}
else
{
// send data to next hop
send (next_hop->u);
if (ent-> u == RELAY)
{
// call to route repair functionality
p.route->route_repaired();
}
}
}
```

.

5 PERFORMANCE EVALUATIONS

Here ESTR is evaluated in diverse metrics of the routing performance and overhead. The evaluation of the routing performance includes average throughput, end-to-end delay, packet delivery ratio, and the routing overhead is measured with the number of control packets and memory consumption for routing. In this evaluation, as shown in table 1, the network simulator NS-2 and IEEE 802.15.4 PHY/MAC protocols are used for comparing ESTR with STR and AODV.

Every node in each simulation starts association procedure at random time from 0 s and ends with assigned network address within 50 s. Simulation time required is 350s as shown in table 1. In ZigBee, entries of neighbor table are created and maintained by the link status message with a 1-hop broadcast every nwkLinkStatusPeriod seconds, which is set to 15 s in our simulation. This link state maintenance mechanism is mandatory function in ZigBee; thus, ESTR and STR have the same routing overhead and memory consumption in the real deployment. The performance of ZTR is much lower than AODV and STR. Hence here AODV, STR and ESTR are compared.

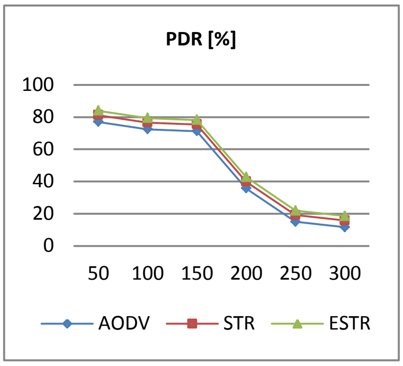
Table 1 Simulation Parameters

Simulation Parameters	**Value**
Deployment Type	Random
Network Size	100m x100m
Number of nodes	50,100,150,200,250,300
Position Of Coordinator	Center
PHY/MAC Protocol	IEEE802.15.4
Network protocol	AODV/STR/ESTR
Propagation Model	Two-ray
Simulation Time	350sec
Traffic type	Any to any/many to one

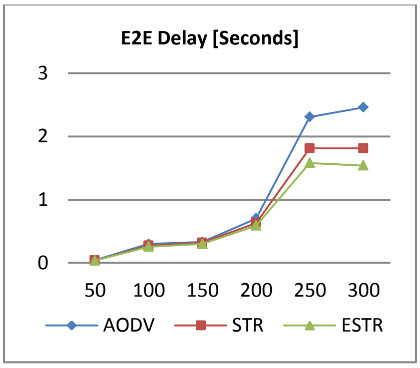
The packet delivery ratio of AODV significantly drops to 12 percent as the number of nodes increases. The main reasons are large hop count to the destination and the overlapped routing path. The packets are concentrated around the root of a tree, so many packet collisions and interferences occur around the root of a tree as the network density increases. On the other hand, STR and ESTR show high packet delivery ratio about 15percent and 18 percent respectively even in the 300 nodes as shown in Fig. 3a; since the routing paths are short enough not to interfere each other and the routing paths are distributed through the neighbour nodes as well.
As ESTR has no queuing delay and route overhead for establishing the routing path, it achieves the high delivery ratio regardless of network density.

On the other hand, both of ESTR and STR are insensitive to the network density. It proves that STR and ESTR provide the short routing path regardless of the network topology such as tree levels of the nodes. The hop count of ESTR and STR decreases for the higher network density, since both routing protocols find the more efficient routing path from the increasing number of candidate nodes.
The end-to-end latency in Fig. 3b shows similar trend with the hop count, since the end-to-end latency is mainly affected by the hop distance between a source and a destination. Whereas AODV shows long end-to end latency about 2.46 sec, STR and ESTR show short end-to end latency about 1.81sec and 1.54 sec.
Fig. 3c shows throughput is high for ESTR as compared to STR and AODV.

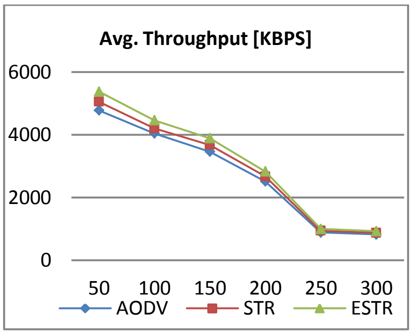
The routing overhead is measured from the number of control packets and the memory consumption as shown in Fig.3d. The routing overhead of AODV is exponentially increased as the network density increases, because the RREQ (Route Request) packets are flooded into the whole network. The routing overhead of STR is counted with the overhead for link state maintenance mechanism, even though it is originally defined in ZigBee standard irrespective of STR. Remind that the link state maintenance mechanism is mandatory function in ZigBee, and ZTR also has same amount of routing overhead with STR in the real deployment of ZigBee.
The routing overhead of ESTR increases linearly with the network density, whereas that of AODV and STR exponentially increases due to increase of the number of nodes participating the route discovery. In other words, AODV brings out route discovery packets proportionally with the number of traffic sessions, and congestion combined with these discovery packets increases the possibility of collision and retransmission of both route discovery packets and data packets. That's why the routing overhead of AODV in 300 nodes is dramatically increased.
STR and AODV store all the 1-hop neighbour information obtained from the link state maintenance mechanism, and AODV additionally requires the memory to maintain the route discovery table and routing table. There is little difference between STR and AODV in terms of memory consumption. AODV is the reactive routing protocol which discovers the routing path only when there is request on packet delivery; thus, both routing overhead and memory consumption of AODV significantly increase as much as the number of traffic sessions.



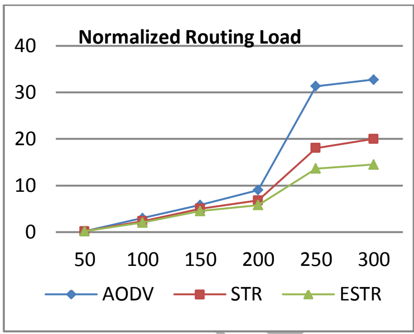
a. Packet Delivery Ratio [%]



b. Avg. End to End Delay [Seconds]



c. Avg. Throughput [KBPS]



d. Routing Load

Fig 3 Routing Performances a. Packet Delivery Ratio [%] b. Avg. End to End Delay [Seconds] c. Avg. Throughput [KBPS] d. Routing Load

6 Conclusions

Detour path problem and traffic concentration problem are the fundamental problems of the general tree routing protocols like ZTR and STR, which cause the overall network performance degradation. To overcome these problems, ESTR is proposed that uses the neighbour table, originally defined in the ZigBee standard. In ESTR, each node can find the optimal next hop node based on the remaining tree hops to the destination. The mathematical analyses prove that the 1-hop neighbour information in ESTR reduces the traffic load concentrated on the tree links as well as provides an efficient routing path. Performance of packet delivery ratio of STR is less as compared to AODV. Performance of end to end delay of STR is poor as compared to AODV. The proposed ESTR [Extended STR] improves the performance in terms of PDR and delay against STR and AODV. The network simulations show that ESTR provides the comparable routing performance to AODV as well as scalability respect to the network density and the network traffic volume by suppressing the additional route discovery process. Therefore, it is expected that ESTR to be utilized in many ZigBee applications requiring both small memory capacity and high routing performances.

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