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A Multi Route Rank Based Routing Protocol for Industrial Wireless Mesh Sensor Networks

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Abstract: *Wireless Mesh Sensor nodes are deployed in harsh environments, like Industrial Wireless Mesh Sensor Networks* (*IWMSN*)*. There the equipment is exposed to temperature and electrical noise, so providing a reliable, interference free and efficient communication in this environment is a challenge. We propose a Multi Route Rank based Routing* (*MR3*) *protocol, which enhances the link dynamics for IWMSN and also provides interference free reliable packet delivery in harsh environments. The rank of a node is estimated based on density, hop count, energy and Signal to Interference plus Noise Ratio* (*SINR*)*. The route discovery phase finds the rank value to forward the data packet in a reliable path. Once the forwarding path is established, subsequently the data packets can be propagated towards the destination without using any location information. Our simulation results show that this method improves the packet delivery ratio and the throughput tremendously, and at the same time minimizes the packet delay, in heavy traffic condition.*

Keywords: *Industrial wireless mesh sensor networks, Signal-to-interference plus noise ratio, Multi-radio, Multi-channel, Partially overlapped channels, Quality of Services* (*QoS*)*.*

1. Introduction

Wireless Sensor Network (WSN) is a collection of wireless sensor nodes deployed in diversified environments and networked together to establish coordination among the nodes to carry the sensed data to the sink. The WSNs are widely used in various applications like military operations, frequency sensing, home automation, health monitoring, underwater sensing in marine engineering, industrial applications, etc., [1-4]. The spatially distributed sensor nodes form a sensor network that can be used to monitor the environmental and physical conditions. The sensor nodes operate on minimal battery power and the lifetime of the nodes can last from months to years. The Wireless Mesh Sensor Networks (WMSN) integrates the strength of WMN and WSN, and it primarily brings in reliability, scalability and energy balancing.

The traditional wired communication mechanism is used in industrial infrastructure, but due to its cost and resource consumption, the trend has been shifted towards the wireless communication for data transfer. The legacy wired communication system in industries is being replaced by wireless sensor networks as the later offers great advantages like low cost of installation and maintenance [7, 10], when deployed in large scale. The Industrial Wireless Sensor Networks (IWSN) provides a variety of applications such as environmental monitoring, process monitoring, plant monitoring, and factory automation. The IWSN ensures the reliability and packet delivery among the nodes within a specified time frame [8]. The existing routing protocols like AODV [9], AOMDV [12], and DSR [14] are not suitable for industrial environment considering its inability to withstand in hard environmental conditions, and electromagnetic interference [15].

Due to the harsh environmental condition, the interference between the sensor nodes is high and it results in transmission failure. The delay in process control and failure in reaching the destination within specified time frame makes it unbearable and causes huge damage and financial loss in the industry. So, developing an approach with reliable and timely delivery of packets in the industrial environment becomes challenging. The existing reactive routing protocol fails to transmit the packets within the time limit due to dynamic conditions in industrial environment. The role of a routing protocol is not only to find a path to the destination, it should also consider other factors like delay, reliability and end to end throughput as they influence the productivity in the industry.

In the hazardous industrial environment, sensor nodes suffer from high temperature, deep cold condition, ultraviolet radiations emitted by various industrial equipment, magnetic radiations by electromagnetic devices, etc. These may cause improper working of sensor devices (or) may cause problems in communication among the nodes in the network, which could eventually result in loss of packets in the network. So, reliable communication is a worrisome and challenging problem due to varying channel conditions and node failures, that results in topology change and connectivity problems. The unreliability of the WSN reduces the throughput drastically.

The challenges in Industrial Wireless Mesh Sensor Networks (IWMSN) are:

- Malfunction or failure of sensor nodes arises from the harsh environment conditions.
- Limited resources such as memory and battery power.
- Achieving Quality of Services (QoS) constraints such as reliability and delay.
- Data redundancy.
- High packet error rate due to interference.

The reliable and timely transmission is not feasible using a single channel on industrial networks due to congestion and limited channel frequency. The current sensor nodes operate in multiple frequencies, and the proposed multi-channel is a solution to improve the reliability in Industrial networks. In a nutshell, the multi-radio, multi-channel capability increases the capacity of the networks. The contributions of this paper are:

- The forwarding node set is constructed by the route request phase and the rank of the node is calculated in multi-radio multi-channel scenario.
- The actual forwarding candidate set is selected by prioritizing the link.
- The SINR is a key factor which is used to compute the rank to quantify the interference on the link

In this paper, we propose a Multi Route Rank based Routing (MR3) protocol, which defines the process to provide an alternate path in case of node failures, and also identifies the path without interference for reliable delivery of packets. The organization of this paper as follows: The Section 2 presents existing reliable routing, opportunistic routing and energy efficient reliable routing in WSNs. The Section 3 presents system model, constructing forwarding nodes set, actual forwarding candidate set and the rank of the node. The simulation setup, parameters, comparison and performance of MR3 protocol is analysed in Section 4. The conclusion is made in Section 5.

2. Related works

Zeng, Yang and Lou [13] had proposed an opportunistic routing approach, which was modelled as a linear programming to bind the channel to radio and to schedule the packet transmission. The Opportunistic Routing (OR) performs well in multi-channel multi-radio environment, when compared with traditional routing. The OR utilizes less resource and produces better throughput. Hawbani et al. [11] proposed a data routing approach, which divides the sensor nodes into distinct groups. In this approach, the intelligent adaptive scheme avoids flooding and ensures that each node receives only one copy of the message. The group leader selects the forwarding node to send the data along the base station.

Marina and Das [12] proposed an Adhoc On demand Multipath Distance Vector Routing protocol (AOMDV), which extends the functions of Adhoc On demand Distance Vector routing protocol. This protocol efficiently finds an alternate route during route failures and makes fast recovery possible in dynamic networks. It computes multiple paths during the route discovery process and it is primarily focused on high dynamic adhoc networks, where the link failures and path interruptions are most common. As the route discovery is initiated for every link failure, it consumes more time and resources. But AOMDV uses single Route REQuest (RREQ) to find multiple paths through accepting many RREQ packets.

The Qos Intelligent routing using Hybrid PSO-GA [6] considers routing as a multi objective optimization problem in multi-radio multi-channel environment. The QoS parameters are modeled into penalty functions. The CoRCiaR [19] protocol improves TCP performance in Wireless Mesh Networks for better reliability. Johnson and Maltz [14] proposed a Dynamic Source Routing and it is a reactive routing protocol that retains the route cache in every node to maintain the path from source to destination. If there is any route failure during the data transmission, the nodes should get updated with the path to the source node through path establishment phase. Agha et al. [15] proposed an OCARI technology that was mainly developed for specific applications such as warships and power plants. This technology exploits the sensor nodes by using the power aware routing and mesh topology. And the energy is saved by keeping the network elements in sleep mode during the global cycle.

Wang et al. [16] proposed a reliable routing protocol for IWSN to enhance the routing scheme by feedback and redundancy. In this approach, the deterministic schedule is applied for energy saving and data collection. But, the delay, routing metrics and the buffer size are not considered. Heo, Hong and Cho [17] proposed an EARQ protocol for real time transmission that primarily focuses on reliability and energy constraints. The demerit of this routing is the overhead in exchanging control messages, predominantly the major chunk of messages used for finding the global position of the nodes. Kim and Ngo [18] proposed a reliable and energy efficient routing protocol which significantly reduces the control packets and provides a reliable delivery of packets. This method uses a single path to route the packet.

3. System model

3.1. Multi-radio Multi-channel scenario in IWMSN

In the proposed approach, a multi hop WMSN with closely positioned nodes are considered; each node in the network has more numbers of neighbours. In order to attain parallel transmission and reception, each node is equipped with multiple interfaces (multi-radio) and multiple-channels are set for each radio. The WMSN operates on IEEE 802.11b/g standard which provides 11 frequency channels, but only 3 channels are non-overlapping channels which are used for data transmission; it is difficult to achieve parallel transmission in WMSN with limited channels. In this work, all 11 channels are used for transmission, but interference becomes a major threat in using Partially Overlapping Channels (POC). The efficient channel assignment algorithm can greatly reduce the interference by mapping non-interfering channels to interfaces.

The channels are assigned based on edge coloring algorithm described in [5], to avoid adjacent channel interference with the help of POC used in multi-radio multi-channel IWMSN. The channel to interface binding is indicated in Fig. 1, where neighbouring nodes get notified if they happened to be assigned with same frequencies. For example, node 3 has four Network Interface Cards (NICs) which are assigned with non-interfering channels 1, 6, 11 and 8. In contrast to the existing work, this paper focuses more on POC based routing, where radios are assigned with channels in such a way that no interference with neighbour links exists.

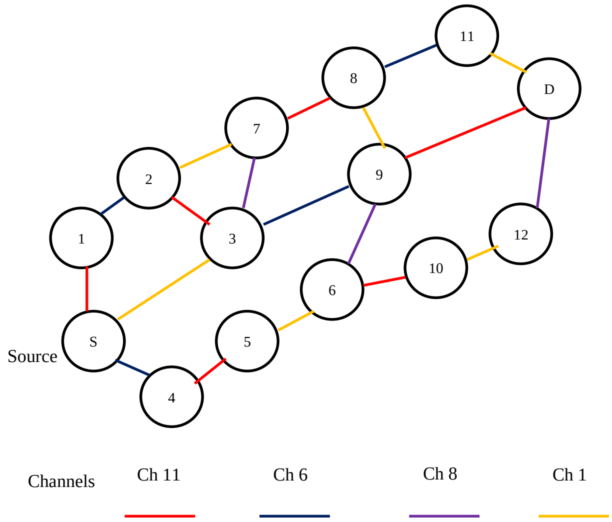

Fig. 1. Multi-radio Multi-channel in IWMSN

3.2. Architecture

Fig. 2 describes the overall architecture of multi route rank based routing protocols. This approach is a cross layer design between MAC and network layers for increasing the resilience on the dynamics of the link. The MAC layer estimates SINR, energy, density and the hop count, and these values are communicated to the routing layer to compute the rank. The route discovery process at network layer estimates the rank of each node, and the next hop node selector picks a node with less interference and maximum density. The nodes are prioritized on the basis of the rank, and multiple routes are made instead of a single route for reliable packet transmission.

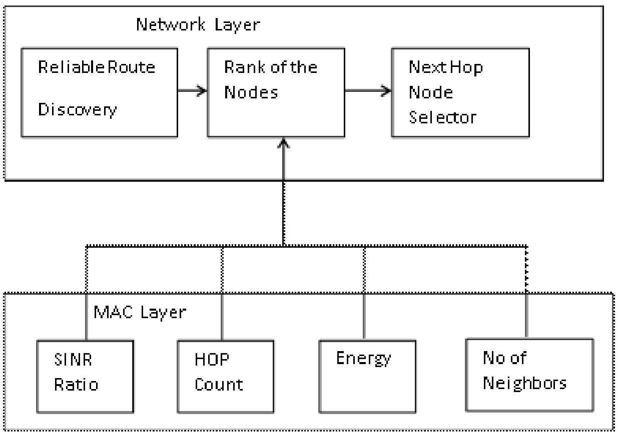

Fig. 2. Architecture of multi route rank based routing protocol

The capacity of the link is not only based on physical distance, but interference on the link is also considered. Let's assume that nodes *u* and *v* are assigned with common channels for communication; the SINR is computed at node v using the next equation.

The SINR at receiver v is given by

$$\text{SINR}_{uv} = \frac{P_u G_{uv}}{N_v + \sum_{w \neq (u,v)} P_w G_{wv}}, \tag{1}$$

where P_u is the transmission power of node u; G_{uv} indicates channel gain for nodes u and v influenced by path loss index and the physical distance between nodes u and v; N_v is the thermal noise at receiver v.

When the nodes are deployed into wireless mesh sensor networks, they send hello handshake packets to the neighbouring nodes to find its density or the number of supporting nodes in its transmission range. On completion of this process, each node in the network would have identified the possible number of supporting nodes and the decision of the next hop selection is made based on rank of the nodes.

The following annotations are defined using Fig. 1 to add more clarity to the system model:

Forwarding Nodes Set (FNS). It includes the nodes which are eligible to forward the packets; the eligibility is determined by transmission range of the node; also the node and its neighbours are tuned to the same channel. The route discovery process creates a set of possible paths from source to the destination and it is denoted as FNS = $\{F_1, F_2, \ldots, F_i\}$, where i represents the maximum available path,

$$F_1=\{S, 1, 2, 3, 7, 8, 9, D\},$$
$$F_2= \{S, 1, 2, 7, 3, 9, D\},$$
$$F_3= \{S, 1, 2, 3, 9, D\},$$
$$F_4= \{S, 1, 2, 7,8,11, D\},$$
$$F_5= \{S, 3, 9, D\},$$
$$F_6= \{S, 4, 5, 6, 10, 12, D\},$$
$$F_7=\{S, 1, 2, 3, 7, 8, 11, D\},$$
$$F_8=\{S, 4, 5, 6, 9, D\}.$$

Actual Forwarding Candidate Set (AFCS). It is a subset of FNS; these nodes send and receive packets. It is built on the base of the rank assigned to the nodes,

$$\text{AFCS} = \{S, 3, 9, 10\}.$$

3.3. Constructing forwarding node set

When a node has data to the destination, the on-demand route discovery process gets initiated if there is no history of recent path to the destination. Each sensor node in a wireless mesh sensor network must find a path to the destination before data transmission is initiated. This path must be reliable and cost effective to deliver the packets to the destination. In this process, the source creates RREQ packets and broadcasts it, if there is no existing path to the sink. As soon as the destination receives RREQ, it would in turn send a reply to RREQ along the same path or possibly on a different path.

Route request process. When a node senses data on the environment, it forwards data to the next hop if the path already exists. Otherwise it starts flooding RREQ packets. Each RREQ packet consists of: requester node identifier, destination to be reached, sequence number and nodes visited so far. The intermediate nodes which receive RREQ packet find their own rank. Once the RREQ reaches the destination, Route REPly (RREP) message is returned back. The hop count and the rank of each intermediate node are attached into the RREP packets. The source receives many RREP packets and using them the forward node set is constructed.

The rank is calculated for each and every node in the path to find the actual forwarding candidate nodes. It is computed by using the following metrics: hop count, signal to noise ratio, node energy and density. The node which is having less interference will also be included in the actual forwarding candidate set. The rank is calculated based on signal to interference plus noise ratio, energy for better reliability. The rank is the key factor for path selection as it decides the energy and interference levels and reliability.

The node v_j receives RREQ from the node v_i, the rank of a node v_j is denoted by r_{ij}. The r_{ij} is defined as

(2) $$r_{ij}(t)=\frac{\text{Hopcount}}{\sum \text{SINR}_{ik}\text{SINR}_{kj}+1}+\frac{E(v_j)}{\text{Density}},$$

(3) $$E(v_j)=\frac{E_i(v_j)}{E_r(v_j)},$$

where the hop count indicates the distance between source and node v_j; SINR is the signal to noise ratio; density denotes the number of common neighbours between node v_i and v_j; $E_r(v_j)$ is the current residual energy in node v_j; $E_i(v_j)$ represents the initial energy in node v_j and t is time slot. $E_i(v_j)$ denotes the maximum energy in joules in the deployed node. $E_r(v_j)$ indicates the energy left in node v_j. Let us assume that v_k is a common node between v_i and v_j. SINR_{ik} is the signal power received at node k from node i and SINR_{ij} is the signal power received at node j from node i. Then the signal to noise ratio SINR_{ik} will be greater than SINR_{ij} and SINR_{kj} will be greater than SINR_{ij}.

Fig. 3 illustrates the rank calculation of the node, and Algorithm 1 describes the route request process. When a node receives RREQ packets, it calculates its rank and considers itself as one of the forwarding candidate node. For example, source S sends RREQ packets to neighbouring nodes 1, 2, 3, 4, 5, and then those nodes find their own rank. Each node maintains a neighbour table, and from that table the node 3 identifies the nodes 1, 2, 4 and 5 are mutual nodes. The rank of node 3 is calculated as 1.11 according to the formula (1). The priority is given to the route with more neighbours or supporters, and with less interference and high energy level. The sink node sends back the Route reply packet to the source node along the reverse path through which it is traversed. At the end, the source constructs the forwarding node set from the identified path.

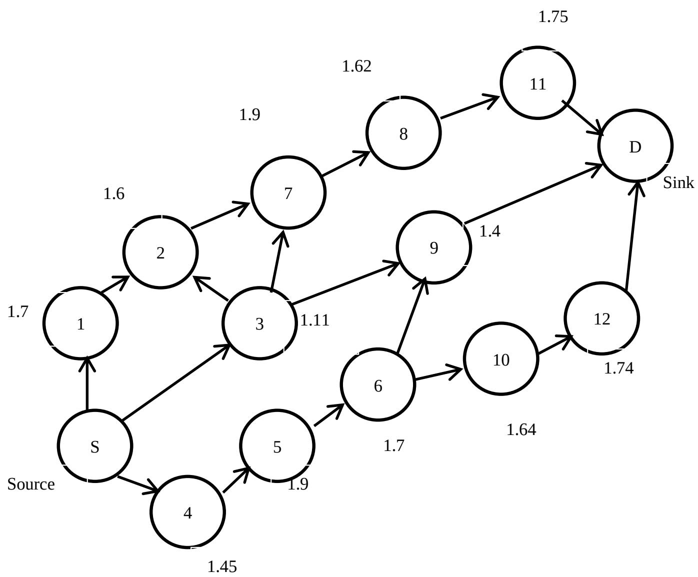

Fig. 3. Forwarding RREQ packets

Algorithm 1. RREQ at node v_j
Step 1. void RREQ (packet p)
Step 2. If node v_j receives a RREQ packet p from node v_i **then**
Step 3. **if** the RREQ is non-duplicate **then**
Step 4. **if** the received node v_j is destination **then**
Step 5. Send RREP packet
Step 6. **else**
Step 7. Calculate r_{ij}
Step 8. Forward RREQ packet to neighbours
Step 9. **endif**
Step 10. **else**
Step 11. Discard RREQ packet p
Step 12. **endif**
Step 13. endif

3.4. Actual forwarding candidate set

The Fig. 4 is an example of route RREP propagation phase. For instance, if 9 is the current forwarding node, then (D, 9) will be attached in the RREP and the rank of the node is marked as 9. In this fashion, all the nodes in the network identify its neighbouring nodes and attach them in the RREP packets. The table 1 indicates the packet format of RREP, where id and rank of node v_i and also the id and rank of downstream node v_{i+1} are attached and forwarded to upstream node v_{i-1}. Finally, the source gets multiple forwarding paths to ensure the reliability. The adjacent channel interference, interference from other sources, hop count and energy level of the node are evaluated at each node. The higher value of the rank indicates the stronger interference. The forwarding node set with minimum value as rank is selected as the actual forwarding candidate set, and finally the average rank is calculated for multiple received paths.

Table 1. RREP packet format

Type	Flags	Reserved	Hop count	Sequence No	MR3 flag	v_i	Rank of v_i	v_{i-1}	Rank of v_{i-1}	Life time

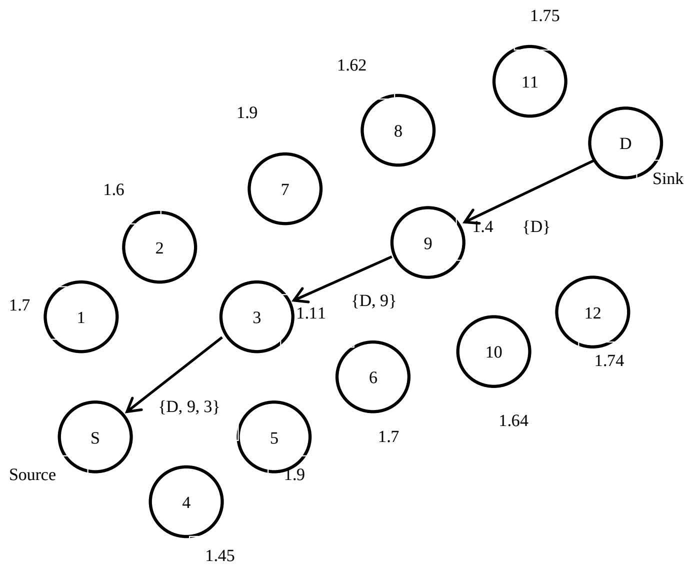

Fig. 4. RREP packets forwarding

The source node computes the average rank as follows:

(4) $$\text{Average Rank} = \frac{\sum_{F \in \text{FNS}} r_F}{|F|},$$

where F is the forwarding nodes in set FNS and $|F|$ is the number of nodes.

The rank for the nodes r_3= 1.11, r_9= 1.4. So AFCS includes {3, 9, D}, where $S \rightarrow 3 \rightarrow 9 \rightarrow D$ is the actual optimal path to reach the sink. The rank of multiple paths and the average rank are indicated in Table 2.

Table 2. Forwarding Path and the average rank of the node

Path	Rank of the forwarding node	Average rank
S, 1, 2, 3, 7, 8, 9, *D*	1.7, 1.6, 1.11, 1.9, 1.62, 1.4	1.16
S, 1, 2, 7, 3, 9, *D*	1.7, 1.6, 1.9, 1.11, 1.4	1.10
S, 1, 2, 3, 9, *D*	1.7, 1.6, 1.11, 1.4	0.96
S, 1, 2, 7, 8, 11, *D*	1.7, 1.6, 1.9, 1.62, 1.75	1.22
S, 3, 9, *D*	1.11, 1.4	0.62
S, 4, 5, 6, 10, 12, *D*	1.45, 1.9, 1.7, 1.64, 1.74	1.20
S, 1, 2, 3, 7, 8, 11, *D*	1.7, 1.6, 1.11, 1.9, 1.62, 1.75	1.21
S, 4, 5, 6, 9, *D*	1.45, 1.9, 1.7, 1.4	1.075

Algorithm 2. RREP at node v_j
Step 1. void RREP (packet *p*)
Step 2. If node v_j receives a RREP packet p from node v_i **then**
Step 3. **if** the RREP packet is non-duplicate **then**
Step 4. attach r_{ij} to RREP and forward to neighbour node
Step 5. else
Step 6. discard RREP packet *p*
Step 7. endif

3.5. Cooperative data forwarding

Data generated at source is forwarded to a node with AFCS; the cooperative forwarding method is used to avoid collision or interference on the link. The node with higher rank (less average rank) will start forwarding the packets and the rest will await their timer to be expired. The rank is interpreted as waiting time to get its turn to forward the data packets. If the node is assigned with higher rank or less waiting time, then it would get opportunity first to forward the data packets. Once the waiting time is expired, the node will start forwarding data to the downstream node and sends the ACK back to the upstream node. The other lower priority nodes in the transmission range also would hear ACK packets. If the node has not heard the ACK within a time window, the waiting timer expires and the next higher rank node will get opportunity to forward the data packets.

Algorithm 3. Data forwarding at node v_j
Step 1. Void Data forwarding (packet *p*)
Step 2. If node v_j receives a packet *p* from node v_i **then**
Step 3. Check **if** the received node (v_j) is the destination **then**
Step 4. Send ACK packet
Step 5. else if $v_j \in$ AFCS **then**
Step 6. call waiting timer(*t*)
Step 7. Forward the data packets when waiting timer expires
Step 8. else $v_j \notin$ AFCS **then**
Step 9. Waiting timer is expired but no ACK is received yet
Step 10. Forward data packets
Step 11. Endif

For example, among the nodes 1, 2, 3, 4 and 5, node 3 has higher rank or less waiting time, so node 3's timer expires first compared to other nodes. Hence, the node 3 forwards the data packets first. Similarly, node 9 forwards the packets before other nodes in the next hop; hence the data traverses along the path Source→3→9→sink. The destination node sends ACK to the source to supress other nodes. The higher preference is given to the route with more neighbours or supporters and for the nodes with high energy level.

4. Simulation result

Table 3. Simulation parameters

Parameter	Value
Platform	NS2 version 2.29 with Multi-radio Multi-channel patch
Network Area	1500×800 m
Network Topologies	Chain topology and Random topology with Multi-radio
Transmission Range	50 m
Interference Range	100 m
Frequency	2.4 GHz
MAC Protocol	IEEE 802.11
Traffic Type	TCP
Packet Size	50 kB
Maximum queue length	50
Simulation Time	100 s
Transport Type	TCP
Data rate	1 Mbps

The MR3 protocol is demonstrated in network simulator 2, and the comparison study is carried out with other reactive routing protocols such as AODV-ETX and REPF [16]. The multi-radio, multi-channel patches are included in network simulator 2. The node density is the maximum number of nodes deployed in a given area. The higher node density makes the link more reliable and connectivity better. The simulation setup area is 200×200 m square. The deployment of nodes can be in any sensor environment and done randomly without any pre-specified metrics. The transmission range for each node is set within the radius of 50 m, and the parameter T is set to 0.005 s. Not every route reply packet is acknowledged by the nodes in order to avoid collision. Route reply is acknowledged directly by the receiver, not by every hop nodes. Performances of all three protocols are evaluated against diverse node densities and the results are shown in Figs 5, 6, 7 and 8 with node densities variation from 50 up to 200.

Fig. 5 indicates the packet delivery ratio of different routing protocols in different node densities. Multi route rank based routing protocol achieved very high packet delivery ratio with densely deployed nodes. MR3 protocol achieves 98% packet delivery ratio and the PDR increases with node density as shown in Fig. 5. REPE achieved less PDR as the cooperation among neighbouring nodes is limited. Fig. 6 describes the performance comparison of end to end delay against node density. Since AODV-ETX experienced more delay, comparatively, the delay or time consumed for retransmitting a packet was much larger.

Fig. 7 shows throughput recorded for MR3P, AODV-ETX and REPF. It can be observed that the throughput of MR3P increases quickly along with increase in the node density, where the other protocols AODV-ETX and REPF shown little increase with the node density. When more number of forwarding nodes are used, the multi-channel increases the throughput in MR3P; on the other hand the AODV-ETX and REPF use single channel, hence more competition for channel contention between forwarding nodes. Fig. 8 describes the comparison of control message cost against node densities. The control message cost of MR3P is slightly equal to REPF as retransmission of packets does not require control messages since path is identified at the beginning of the route establishment phase. AODV-ETX has higher control message cost compared to other two routing protocols.

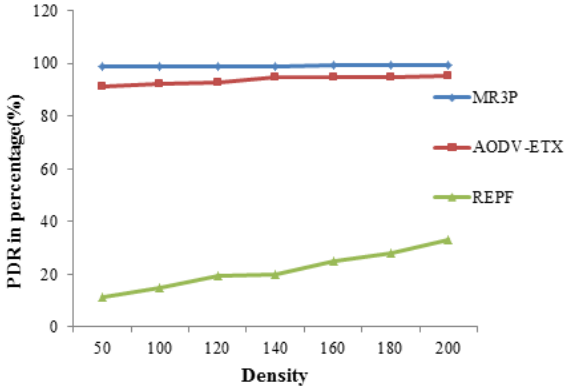

Fig. 5. Density vs packet delivery ratio

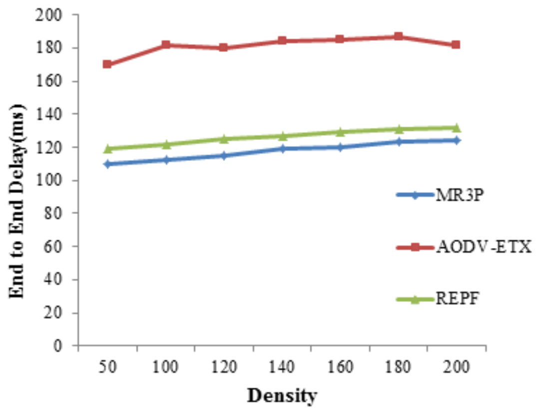

Fig. 6. Density vs end to end delay

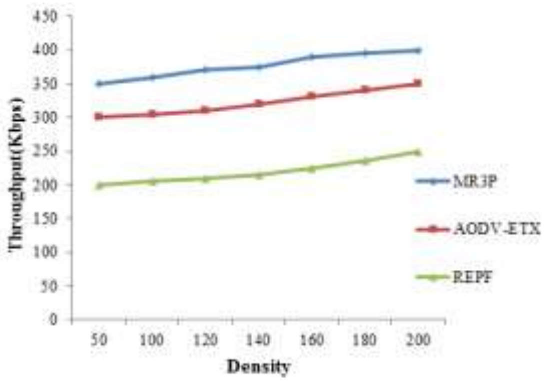

Fig. 7. Throughput vs density

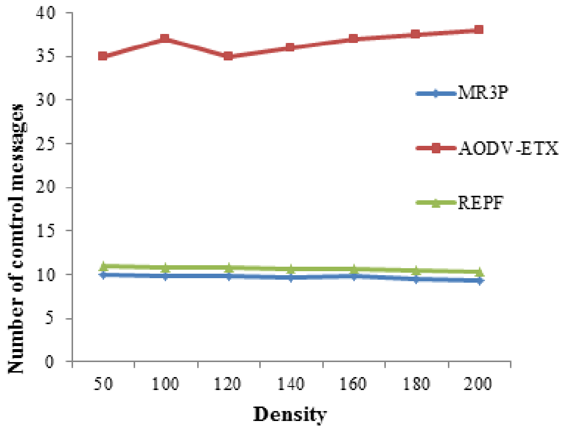

Fig. 8. Number of control messages vs density

5. Conclusion

The proposed multi route rank based routing protocol increases the packet delivery ratio, throughput and is more reliable in packet transmission over unreliable paths. The MR3P finds alternate path or link to transmit the data to the destination in a reliable way without re-establishing the connection. The adjacent channel interference, co-channel interference, self-interference and interference from the external environment are reduced through finding SINR on the link. The rank is introduced to select better channel and path. The proposed MR3 protocol outperforms in multi-channel multi-radio environment compared to other routing protocols like AODV-ETX and REPF.

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