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Random Linear Network Coding Over Connected Dominating Set In on-Demand Multicast Routing Protocol For Wireless Sensor Network

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Abstract

Multicast routing becomes the most challenging problem in Wireless Sensor Networks (WSN). Multicasting is an effective way to facilitate group communication in which the multicast data need to be sent from a source node to multiple receivers. Multicast routing based on Random Linear Network Coding (RLNC) over Connected Dominating Set (CDS) is a promising approach to deliver a multicast data in high throughput for WSN. The objective of this paper is to improve the performance in terms of throughput, reliability, end-to-end delay and packet delivery ratio in On Demand Multicasting Routing Protocol (ODMRP) using RLNC over CDS for WSN, so that bandwidth utilization can be increased in the network. In this paper, a simple and efficient algorithm (i.e. CDS) is used to form a virtual backbone as forwarding group of the network. The CDS aims at minimizing the number of nodes, where only a specified subset of the nodes should be dominated, which are responsible for forwarding the multicast packets by applying over RLNC. RLNC has great potential to improve the performance of multicast routing protocol for WSN. The proposed approach, named Random Linear Network Coding over Connected Dominating Set in On-Demand Multicasting Routing Protocol abbreviated as RLNCDS-ODMRP can be potentially used in designing efficient on-demand multicast routing protocol based on CDS and RLNC for WSN. Performance analysis and experimental results show that RLNCDS-ODMRP outperforms the classical multicast routing protocols that use CDS and RLNC alone for WSN.

Keywords: Wireless Sensor Network, Multicast Routing, ODMRP, CDS, RLNC, High Throughput

Introduction

A Wireless Sensor Network (WSN) is a wireless network consisting of relatively large number of sensor nodes to monitor physical or environmental conditions [1]. WSN is currently receiving significant attention due to their wide range of applications such as environment monitoring, building structures monitoring, habitat monitoring, traffic surveillance, military sensing and information gathering, wildfire detection, pollution monitoring, etc [1]. Multicast is the transfer of same message to multiple receivers at the same time within the transmission range of the sender. Multicast is an essential component in many Wireless Network applications. Multicasting is a more efficient method of supporting group communication than unicasting or broadcasting. Applications of multicasting are conference meetings, military control operations to multicast tactical information [2].

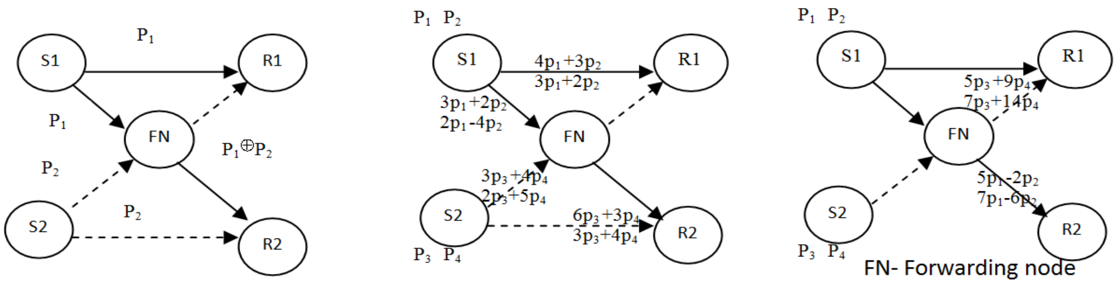
The multicast routing protocol is mainly classified into three categories i.e., reactive, proactive and hybrid [3]. The reactive routing protocol is called as on-demand routing protocol. It creates routes only when desired by the source node. Example for reactive multicast routing protocol is: ODMRP [4]. The proactive routing protocol is called as table-driven routing protocol. In which, the route for all the nodes is maintained in routing table. The hybrid routing protocol is combination of both reactive and proactive.

In WSN, network backbone formation and channel capacity are some networking issues [5]. To solve these issues two most popular techniques were used, they are, (1) Connected Dominating Set (CDS), (2) Random Linear Network Coding (RLNC).

A dominating set (DS) *S* of graph *G = (V, E)* is a subset of *V*, such that each node is either in the DS or adjacent to some node in the DS [6]. A Connected Dominating Set (CDS) is a subset of the nodes such that it forms a DS and all the nodes in the DS are connected. The most redundant transmission can be reduced by forming a CDS as a virtual backbone in the network [7]. In CDS, DS nodes are relaying the messages, maintain routing tables, reduce the communication cost, reduce the redundant traffic, localize the routing information, save storage space and it provides reliable connectivity between the nodes.

Network coding is a technique where forwarding nodes mix the packets using mathematical operations, which reduces the number of transmissions and save the bandwidth in wireless network [8]. Network coding can be classified as either inter or intra-session. In the inter session network coding, the coded packets are received from different sources to be mixed to solve the bottleneck problem. In the intra-session network coding, the coded packets are received and mixed from same source to address the packet loss problem [9]. Network coding also can be classified into XOR (binary) coding, Reed-Solomon and Random Linear Network coding (RLNC).In binary coding, XOR operations are performed between the packets as shown in Fig.1. XOR-based NC is very well explained by Ahlswede et al [8] using the famous butterfly network.

In RLNC, the forwarding nodes create coded packets of the form $\sum_{i=1}^{k} \alpha_i p_i$, where α_i is a random coefficient chosen over a finite field called Galois Filed (GF), and p_i can be coded or uncoded packets. RLNC allows the forwarding nodes to randomly mix packets before forwarding them and has two important benefits relevant to multicast routing in wireless network. First, by mixing the packets, it is able to reduce the number of transmission necessary to convey packets to multiple receivers for both multi-hop and single-hop routing, which can lead to a large increase in throughput for multicast traffic. Second, it reduces the need for coordination among routers in multi-hop routing. NC utilizes less computational power to increase network efficacy number of transmitted packets [8].



(a) (b)

Figure 1: (a). XOR coding (b) Random Linear Network Coding

Motivation and Justification

In this work, CDS and RLNC techniques are used in ODMRP to send code updates or other data from a sink node to a group of sensor nodes for WSN. Finding connected dominating set of the network is a promising approach in WSN. Recently, some researchers have proposed CDS alone to construct a virtual backbone for multicast operation and to improve performances of multicast routing protocols in WSN [10], [11], [12]. The idea of connected dominating set based multicasting is CDS forms a virtual backbone by which minimum number of nodes are responsible for multicasting the data in the backbone instead of all the multicast group members of the network [7]. In general, CDS can be constructed and calculated by using either global or local network information and centralized or distributed way respectively. However, due to the characteristics of wireless sensor networks, it is hard to obtain and maintain global network information also CDS calculation in a single node is not efficient [13]. Therefore, the proposed multicasting routing protocol focuses on local information and distributed way to construct and calculation of CDS in WSN.

Javad A.T et.al [5] proposed weighted Steiner connected dominating set (WSCDS) of the network graph for multicast routing in wireless ad-hoc networks. Shuai Wang et.al [14] explored energy minimal broadcast protocols in wireless ad hoc networks proposed by combining network coding and connected dominating set (CDS). Zhao zhang et.al [15] introduced polynomial time approximation scheme (PTAS) for minimum CDS in WSN. Hongjie Du et.al [16] presented distributed algorithm to construct weakly connected dominating set for secure clustering in distributed sensor network. Xiaoyan kui et.al [17] investigated the problem of constructing a energy balanced CDS based network backbone to extend the network life time in data collection.

Using routing, the multicast data cannot be communicated to destination nodes at a time. However, if the member nodes of the network have been allowed to perform linear network coding operations in addition to routing, the multicast data can be communicated to destination nodes at a time and achieves the maximum capacity of multicast network [18]. Ahlswede [8] illustrated this through famous "butterfly network". Therefore, RLNC is essential to communicate a source to multiple receivers at a time. Most of the researchers has been applied RLNC alone for various multicast applications and increases the capacity of the network in MANET and Wireless Mesh Network (WMN) [19-24]. In which, RLNC has great potential to improve the performance in terms of throughput, reliability and minimize the transmission delay in MANET. WSN differ from the MANET in terms of performance metrics, traffic patterns, and their amount of available memory and processing resources. These differences are considered in RLNC and it makes some of the network coding approaches proposed for WSN [25-29]. RLNC provides loss recovery in low quality wireless links and economical path diversity, which is particularly important for multicast traffic in the unstable and lossy environment characteristic of WSN [30].

Multicasting with network coding was investigated quite intensively in recent years. Ahlswede et.al [8] proposed network coding in information theory to improve throughput in wireless networks and showed that network coding can achieve maximum multicast rate in the network. S.Katti et.al [31] presented the core idea of mixing packets by the XOR operation to increase the network throughput. Tracey Ho et.al [32] presented a distributed random linear network coding approach for transmission and compression of information in general multisource multicast networks. Rout, RR et.al [27] attempted to enhance the lifetime of WSN using duty cycle and NC. Zhu et.al [33] applied network coding to overlay network to improve capacity by constructing a 2-reduandant multicast graph. Dumitrescu et.al [34] proposed a layer multicast with network coding. Jaggi et.al [35] presented a polynomial time construction showing that network coding at intermediate nodes could obtain larger rates than without coding. Zhi-jie Han et.al [26] proposed a set of distributed algorithms for improving the multicast throughput in wireless sensor networks. Angelos antonopoulos et.al [36] introduced a network coding-aided energy efficient Medium Access Control (MAC) protocol which act as helpers in cooperative Automatic Repeat reQuest-based (ARQ-based) wireless networks.

To the best of the author's knowledge, there is no work on ODMRP with RLNC over CDS for WSN. The reason for choosing a random linear operation is that the algorithms for coding and decoding are simple, efficient and easily understood [37]. The proposed protocol RLNCDS-ODMRP aims to develop efficient and high throughput multicast routing protocol for WSN. But, WSN protocols must be simple in both computation and communication load and should be easily implemented also it should be scalable, efficient and adaptive in terms of minimizing redundant retransmissions in various situations, therefore all the aforementioned conditions are considered in the proposed protocol (RLNCDS-ODMRP) for WSN. Therefore, the proposed approach can be potentially used in designing efficient on-demand multicast routing protocol based on CDS and RLNC for WSN. Efficient multicast routing protocols are important for achieving throughput, reliability, packet delivery ratio, minimum end-to-end delay, security and energy efficiency in WSN. Thus, the proposed protocol is essential to develop efficient multicast routing protocol for WSN.

Outline of The Paper
The outline of the paper is depicted in the Fig.2

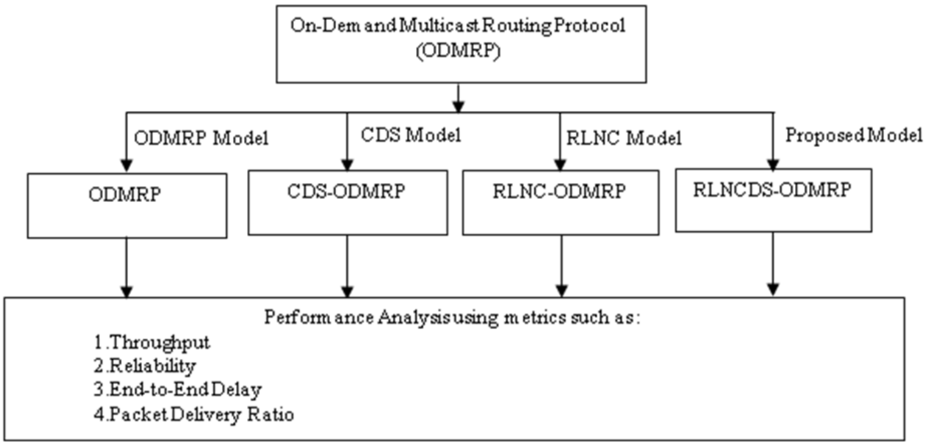


Figure 2: Outline of The Paper

This paper first presents a comprehensive investigation of connected dominating set (CDS) and Random Linear Network coding (RLNC) and a thorough survey on these techniques is conducted with details of their operations. Performance of these techniques is also evaluated alone with ODMRP and these techniques are combined by proposed algorithm with ODMRP for WSN. It is shown that the proposed protocol outperform the other combinations of ODMRP for WSN.

Organization of The Paper
The rest of the paper is organized as follows: Module descriptions are given in section 2. In section 3, detail of proposed approach is given. Section 4 discusses about the experimental results of proposed approach. Finally, conclusion about the proposed approach is given.

Module Descriptions

In this paper, two most popular techniques were used in ODMRP for WSN, they are, (1) Connected Dominating Set (CDS), (2) Random Linear Network Coding (RLNC)

Connected Dominating Set
The concept of the CDS comes from the graph theory [38]. It defines a set of nodes for a given network. The definition of a CDS can be described as follows:

Definition 2.1. For a given connected network G = (V, E), where V is the set of vertices (nodes) and E is the set of edges (links) that connects the nodes. A dominating set (DS) is a subset V′ of V, where for each vertex u of V, u is either in V′ or at least adjacent vertex of u is in V′. A DS is called a CDS if the sub-graph induced by the vertexes in the DS is connected [6].

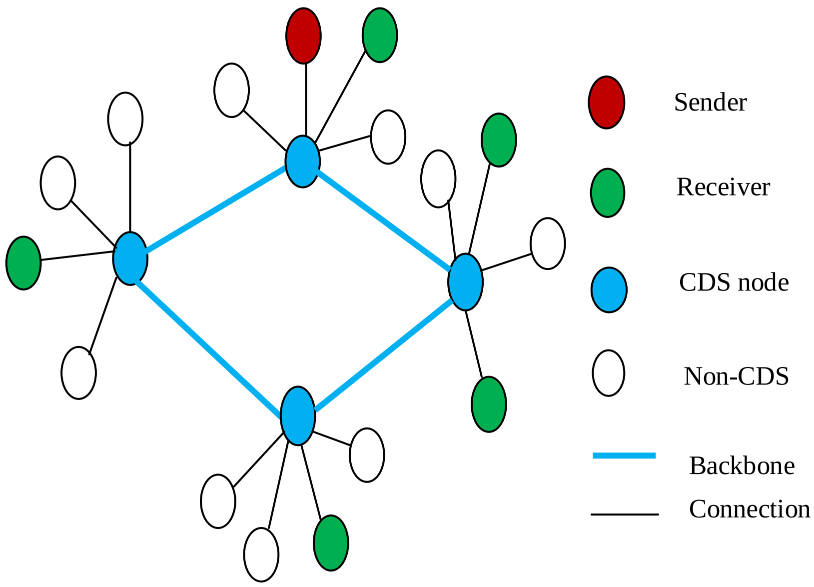


Figure 3: The CDS Network

The CDS network is shown in Fig3. From the definition, a dominating node in CDS network has connection with every other node in the network and they are connected themselves also no separate node in the network. In this network, nodes in blue form a CDS and they are connected through the blue bold lines, which represent the backbone of the network. All other nodes that are marked in white and green node (receiver) can be reached by the blue nodes in the CDS. In this network, CDS reduces the redundant transmissions by sending multicast messages forwarded by nodes in order to reach all the receivers.

CDS Algorithms

The multicast routing process in a connected dominating set based routing is usually in the following steps [39] as shown in the Fig.4:

Step 1: The source node check whether it is a gateway host, if so, source gateway act as new source to forward the route request packet, otherwise the source node forwards the packets to a adjacent gateway host of source gateway.

Step 2 : Check the current node belongs to network of connected dominating set or adjacent to source node in CDS, if so, mark the node as dominating node in the CDS, otherwise select another routing path and repeat the earlier process to find dominating node. After finding dominating node, collect the neighbour information of its neighbour node and update the routing table.

Step 3: Check whether the selected node is a destination gateway host, if so, the destination gateway host forwards the packets to destination node directly and send reply packets to the source node. Otherwise, forward to its neighbour node in the CDS and repeat the earlier process.

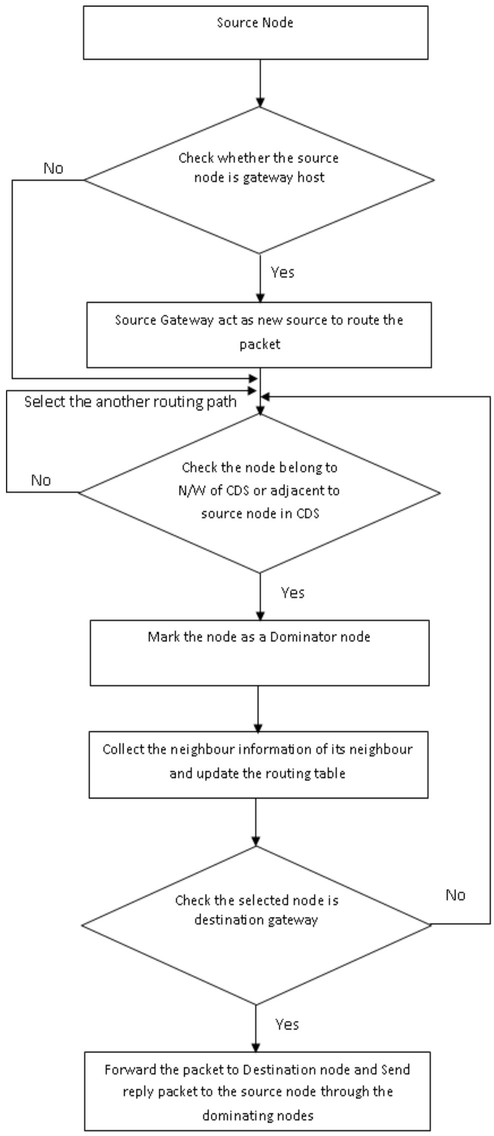


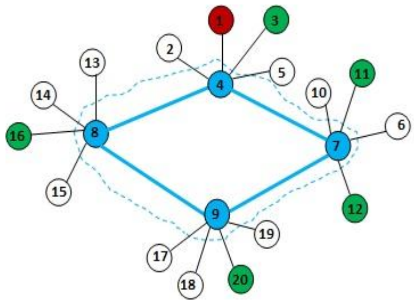
Figure 4: Flow Chart For CDS Formation

Principle of Connected Dominating Set- based Multicast

Connected Dominating Set is popularly used for constructing virtual backbones for multicast operation in many wireless networks. Constructing a virtual backbone (CDS) in WSNs is an important issue in the WSN. CDS helps in improving the throughput, reliability, packet delivery ratio and reducing the end-to-end delay in the network, because a limited number of sensors are engaged in message transmission.

CDS based multicast routing is not only applied for proactive routing, it can also be applied to reactive routing, where routes are computed in on-demand. In this paper, reactive multicast routing protocol, ODMRP is considered. The ODMRP with CDS works as follows as shown in Fig.5. First of all, construct the CDS network by applying CDS algorithm. In the CDS network, each dominating node keeps following information: Dominating node's membership list, routing table and forwarding node table. Dominating node's membership list is a list of non-CDS node which are adjacent to its dominating node. Routing table includes one entry with membership list of dominating node. Each entry also contains the next-hop information of a shortest path and the distance to the specified CDS destination. Second, this work extends the ODMRP algorithm by adding further routing information as shown in Fig.5 (b) to be sent between CDS nodes to a quite selective multicast process for WSN.

Example:



(a)

Sender= 1

Receiver= 3, 11,12,16,20

Forwarding Group= 4,7,8,9

Gateway Domain member list of node 4: 2, 5

Gateway routing table of node 4:

Destination	Member list	Next Hop	Distance
7	6,10,11,12	7	1
8	13,14,15,16	8	1
9	17,18,19,20	7	2

(b)

Figure 5: (a).Multicast data transmission through CDS (b) Multicast routing information

Multicast Routing Protocol For WSN

In this work, the selected reactive or on-demand routing protocol is On-Demand Multicast Routing Protocol (ODMRP). Because, most of the researchers show that reactive method has better effect than the proactive method in different aspects such as network life time, nodes movement, self-organizing network model also states that the major strength of ODMRP are its simplicity and scalability[4].

On-Demand Multicast Routing Protocol for WSN

ODMRP is a state-of-art on-demand multicast routing protocol [4]. It is a mesh based and a source initiated protocol. It uses the forwarding group concept to establish a mesh. It follows "soft state" approach to maintain a mesh.

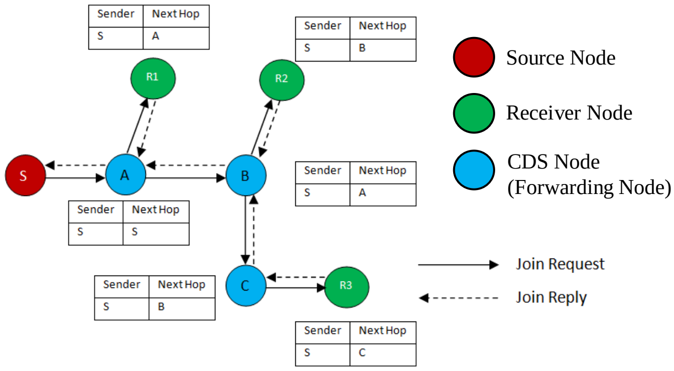


Figure 6: An ODMRP Protocol Overview

When a source node wants to send data packets to the multicast group, it broadcasts the network with a JOIN_REQUEST periodically. Each intermediate node that receives the JOIN_REQUEST, it checks if it is a duplicate packet based on sequence number present in the packet header. If not, it stores its upstream node identifier in its routing table and rebroadcast the packet. If the JOIN_REQUEST reaches its member node of the multicast group, the node creates a join table and it broadcast a JOIN_REPLY message with join table to its neighbour nodes. The join table has two fields as shown in Fig.6, they are source node and the last hop from which node received the JOIN_REQUEST message. When a node receives a JOIN_REPLY message, it checks whether it is the last hop in any of the entries in the join table. If so, the source node realizes that the current node is on the path to the source node and update in its joining table thus becomes a part of the forwarding group (FG) of the source node by setting its forwarding group flag (FG_Flag). Now, the source node broadcasts its own JOIN_REPLY, which contains matched entries. The next hop address can be obtained from the message cache, which is used to update the route from sources to receivers and builds the forwarding group as shown in Fig.7. Route information and membership is updated by periodically by sending JOIN_REQUEST message.

After establishment of the forwarding group and route construction process, sources can multicast packets to receivers via forwarding groups and selected routes. When a source node wants to send a data packets, it periodically sends JOIN_DATA packets to refresh the forwarding group nodes and selected routes. When receiving a multicast data packet, the forwarding node forwards it only when it is not a duplicate packet and the setting of the FG_Flag for the multicast group has not expired. When source node wants to leave the group, it simply stops sending JOIN_DATA packets, since it does not have any multicast data to send to the multicast group.

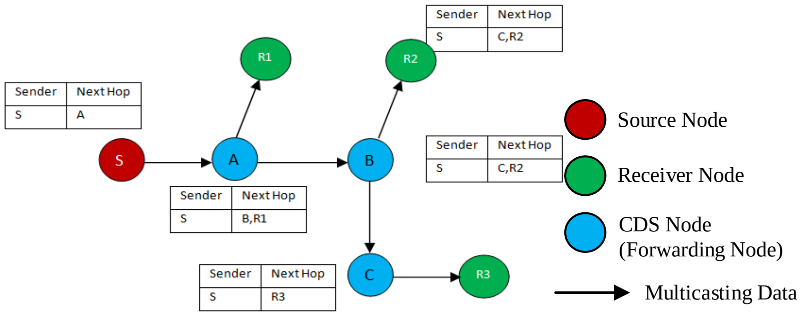


Figure 7: Multicast Data Forwarding Through CDS Node

In ODMRP, no explicit control packets need to be sent to join or leave the group. Three type of tables in ODMRP architecture namely member table, routing table and forwarding group table. The member table is used for storing the source information. It has two fields, they are “source ID” and “time of last JOIN_QUERY received”. Routing table is created on demand and is maintained by each node. It is updated when a non-duplicate JOIN_ QUERY is received. Forwarding node maintains the group information in the forwarding group table.

Random Linear Network Coding

Recently, RLNC is emerged promising technique for various applications in wireless networks, which has been applied in multicast routing to increase the capacity of a network for maximum multicast flows and reduce the multicast traffic in WSN.

In RLNC, the output data of a given node is obtained as a linear combination of its input data. The coefficients selected for this linear combination are completely random in nature, hence named Random Linear Network Coding (RLNC). The forwarding node combines a number of packets it has received or created into one or several outgoing coded packets. Typically, RLNC performs three different operations [40], they are 1. Encoding, 2.Re-encoding, 3.Decoding

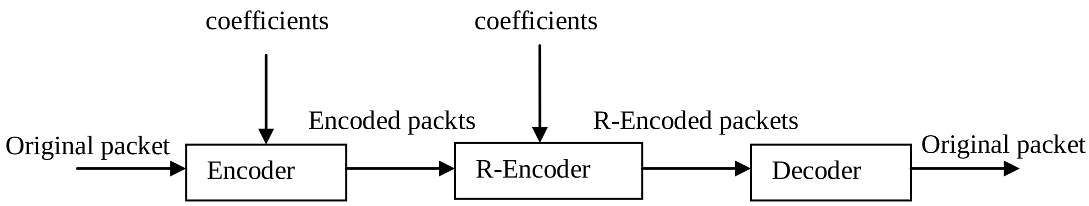


Figure 8: RLNC Process

From the Fig.8, the encoding process can be done at source node of the network. Re-encoding process can be done at forwarding node, which is almost similar to encoding process but the coefficients are completely newly generated. Finally, decoding process can be done at destination nodes. The encoding, re-encoding and decoding operations are implemented via matrix operations. First consider the unicast network, when there is a single-source single-destination capacity (max-flow) is achievable by Min-cut Max-Flow, in other words, the maximum amount of flow is equal to the capacity of a minimum cut [18].

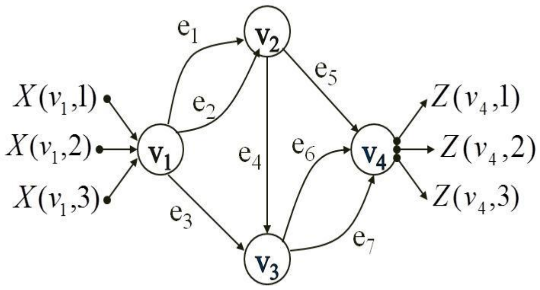
Theorem 1:Min-Cut Max-Flow

The capacity of the noiseless graphical relay network G = (N, E, C) with destination node N is

$$C = \min_{\substack{s \subset N \\ 1 \in S, N \in S^c}} \text{C(S) bits / transmission}$$

Where C(S) = $\sum_{j \in S, k \in S_c} C_{jk}$ is the capacity of cut S

The basic idea of RLNC for unicast communication in WSN can be illustrated in the Fig.9-12.



Source input: $X(v,l) = \{x_0(v,l), x_1(v,l), \ldots\}$

Information along the edges: $Y(e) = \{y_0(e), y_1(e), \ldots\}$

Sink output: $Z(v,l) = \{z_0(v,l), z_1(v,l), \ldots\}$

Where, 0, 1, 2…is time index

Figure 9: A Simple Example of RLNC For Unicast In WSN

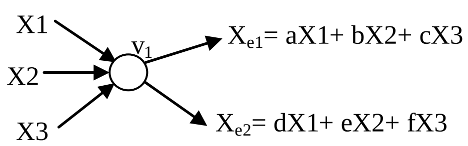


Figure 10: Encoder at Source node

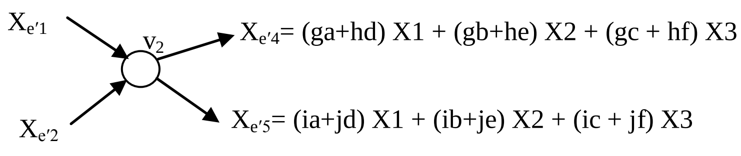


Figure 11: Re-Encoder At Intermediate Node

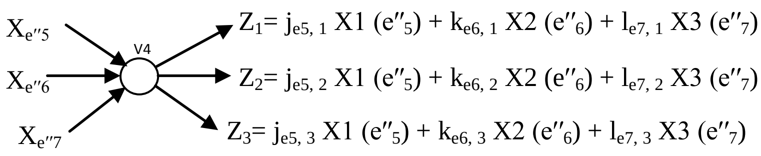


Figure 12: Decoder

The data X1, X2 and X3 are given to node V_1 as input then node V_2 received two coded packets: aX1+ bX2+ cX3 and dX1+ eX2+ fX3 as output of node V_1. In order to perform the re-encoding operation on the two received coded packets, the node V_2 generates two random coefficients g and h for the two coded packets to be re-encoded. The coding vector of the new re-encoded packet can be calculated as following:

g (aX1+ bX2+ cX3) + h (dX1+ eX2+ fX3) = (ga+hd) X1 + (gb+he) X2 + (gc + hf) X3

where, (ga+hd), (gb+he) and (gc+hf) are the new coefficients of the re-encoded packet. The decoding operation is performed at the node V_4 by collecting the coded packets. The coded packets are decoded by forming a matrix from linear coefficients. The matrix is referred to as decoding matrix or transfer matrix [40].

Random Linear Network Coding for Multicast

In this section, multicast network is considered with multiple independent messages in WSN, when a source node wants to send multi message to a set of destination nodes, cutset bound is tight and is achieved error-free using random linear network coding [18]. Distributed RLNC has been applied to multicast routing in WSN, in which destination nodes decode the output data by taking random linear combinations of input data. RLNC process for multicast is depicted in the Fig.13.

Theorem 2: Network Coding [14]

The capacity of the noiseless multicast network G = (N, E, C) with destination set D is

$$C = \min_{j \in D} \min_{\substack{S \subset N \\ 1 \in S,\, j \in S^c}} C(S)$$

Where C(S) is the capacity of the cut S

The basic idea of RLNC for multicast communication in WSN can be illustrated in the fig.14 [41], [42].

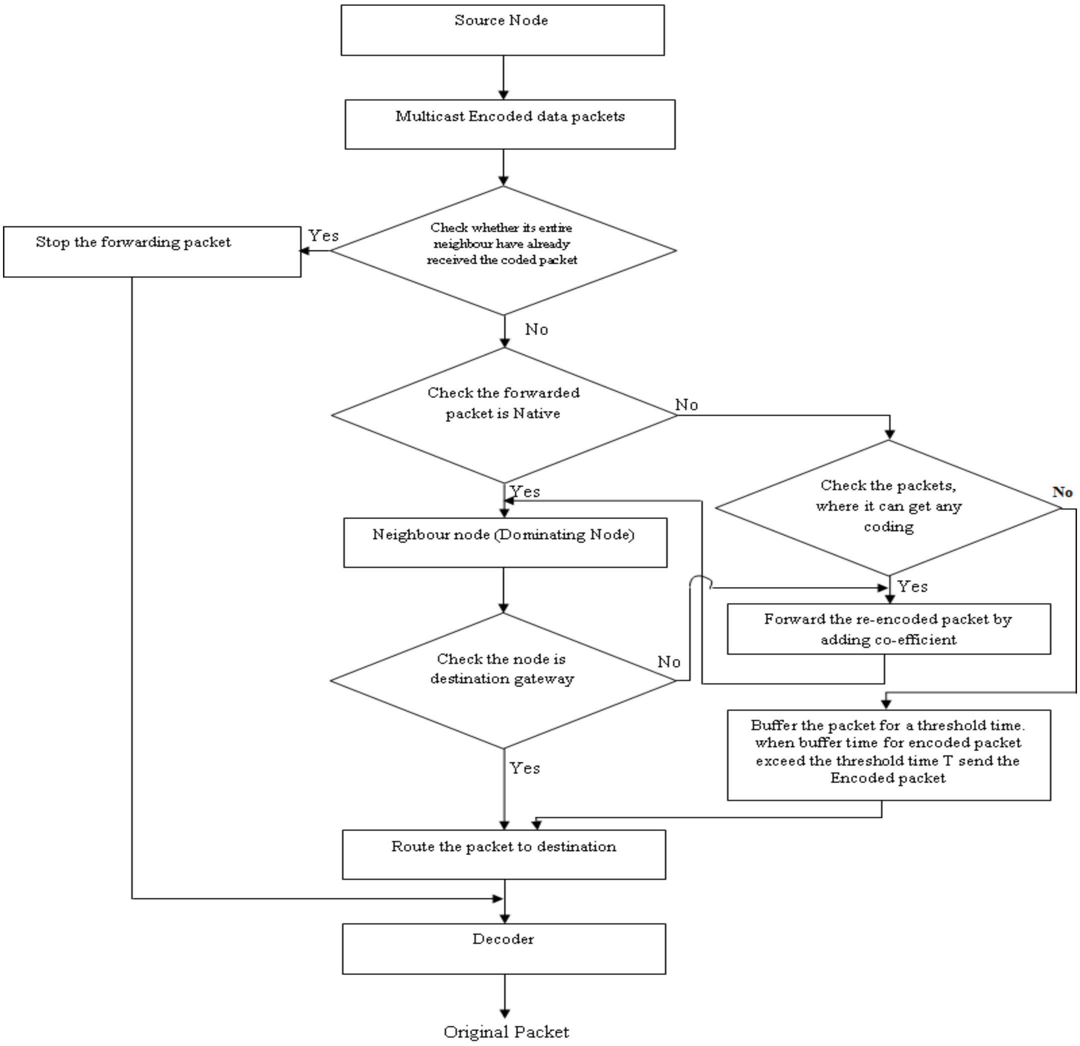
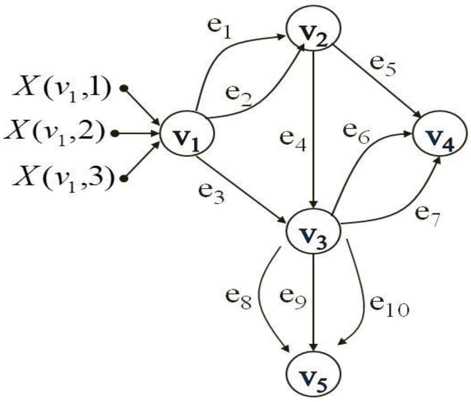


Figure 13: Flowchart For RLNC For Multicast



Source input: $X(v,l) = [x_0(v,l), x_1(v,l), \ldots]$

Information along the edges: $Y(e) = [y_0(e), y_1(e), \ldots]$

Sink output: $Z(v,l) = [z_0(v,l), z_1(v,l), \ldots]$

Where, 0, 1, 2…is time index

Figure 14: RLNC In Single Source Multicasting For WSN

Consider a multicast network G= (V, E) as depicted in the above Fig.14. Where, V is the set of nodes and E is the set of edges. The source node V_1 wants to send packets to receivers V_4 and V_5 with the help of forwarding nodes V_2 and V_3, the source node V_1 observing three source packets X_1, X_2 and X_3 also called native packets and randomly chosen coefficients α, β, and γ from finite field for encoding, there are three paths from V_1 to V_4 and another three paths from V_1 to V_5. Forwarding nodes V_2 and V_3 performs the re-encoding operation on the two received coded packets with the random coefficients, the coding vector of the new re-encoded packet can be given as input to the node V_4 and V_5. Decoding operation is performed at the node V_4 and V_5 by collecting the coded packets. These packets form linear equations and can be solved by forming a matrix which is referred as decoding matrix or transfer matrix.

RLNC operations for multicasting is illustrated through the following equations, the information through the edges i.e e_1, e_2, e_3 can be calculated by equation (1).

$$Y(e) = \sum_{l=1}^{\mu(v)} \alpha_{l,e} X(v,l) + \sum_{e':head(e')=tail(e)} \beta_{e',e} Y(e') \quad (1)$$

Where Y(e) is coded packets on the outgoing edges from node V_1,which are linear combination of the sources X(v,1), X(v,2), X(v,3)

The information at the destination nodes can be calculated by equation (2), which is received from forwarding nodes,

$$Z(v,j) = \sum_{e':head(e')=v} \varepsilon_{e',j} Y(e') \quad (2)$$

Where Z(v, j) is re-encoded packet at destination nodes, which are received from forwarding nodes.

Linear combinations of coded packets y (e_1), y (e_2), y (e_3) on the edges e_1, e_2, and e_3 can be expressed as

$$Y(e_1) = \alpha_{1,e_1} X(v,1) + \alpha_{2,e_1} X(v,2) + \alpha_{3,e_1} X(v,3) \quad (3)$$

$$Y(e_2) = \alpha_{1,e_2} X(v,1) + \alpha_{2,e_2} X(v,2) + \alpha_{3,e_2} X(v,3) \quad (4)$$

$$Y(e_3) = \alpha_{1,e_3} X(v,1) + \alpha_{2,e_3} X(v,2) + \alpha_{3,e_3} X(v,3) \quad (5)$$

Let α denote the 3 × 3 matrix. The above equations (3)-(5) can be written as matrix form as

$$\begin{bmatrix} Y(e_1) \\ Y(e_2) \\ Y(e_3) \end{bmatrix} = \alpha \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix}$$

Where, $\alpha = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{2,e_1} & \alpha_{3,e_1} \\ \alpha_{1,e_2} & \alpha_{2,e_2} & \alpha_{3,e_2} \\ \alpha_{1,e_3} & \alpha_{2,e_3} & \alpha_{3,e_3} \end{bmatrix}$

Linear combinations of re-encoded packets y(e_4), y(e_5), y(e_6), y(e_7) on the edges e_4, e_5, e_6 and e_7 can be expressed as

$$Y(e_4) = \beta_{e_1,e_4} Y(e_1) + \beta_{e_2,e_4} Y(e_2) \tag{6}$$

$$Y(e_5) = \beta_{e_1,e_5} Y(e_1) + \beta_{e_2,e_5} Y(e_2) \tag{7}$$

$$Y(e_6) = \beta_{e_3,e_6} Y(e_3) + \beta_{e_4,e_6} Y(e_4) \tag{8}$$

$$Y(e_7) = \beta_{e_3,e_7} Y(e_3) + \beta_{e_4,e_7} Y(e_4) \tag{9}$$

Let β denote the 3 × 3 matrix. The above equations (6)-(9) can be written as matrix form as

$$\begin{bmatrix} Y(e_5) \\ Y(e_6) \\ Y(e_7) \end{bmatrix} = \beta'.\alpha \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix}$$

where β and α are given by

$$\beta = \begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix} \text{ and } \alpha = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{2,e_1} & \alpha_{3,e_1} \\ \alpha_{1,e_2} & \alpha_{2,e_2} & \alpha_{3,e_2} \\ \alpha_{1,e_3} & \alpha_{2,e_3} & \alpha_{3,e_3} \end{bmatrix}$$

Destination node V_4 recover the original packets from the received re-encoded packets [y(e_5), y(e_6), y(e_7)]^T and obtain,

$$Z(v_4,1) = \varepsilon_{e_5,1} Y(e_5) + \varepsilon_{e_6,1} Y(e_6) + \varepsilon_{e_7,1} Y(e_7) \tag{10}$$

$$Z(v_4,2) = \varepsilon_{e_5,2} Y(e_5) + \varepsilon_{e_6,2} Y(e_6) + \varepsilon_{e_7,2} Y(e_7) \tag{11}$$

$$Z(v_4,3) = \varepsilon_{e_5,3} Y(e_5) + \varepsilon_{e_6,3} Y(e_6) + \varepsilon_{e_7,3} Y(e_7) \tag{12}$$

For the destination node V_5,

Re-encoded data on edges e_8, e_9 and e_{10} denoted by Y(e_8), Y(e_9) and Y(e_{10}). They are linear combinations of Y(e_3) and Y(e_4) and can be expressed as,

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \begin{bmatrix} \gamma e_3 e_8 & \gamma e_4 e_8 \\ \gamma e_3 e_9 & \gamma e_4 e_9 \\ \gamma e_3 e_{10} & \gamma e_4 e_{10} \end{bmatrix} \begin{bmatrix} Y(e_3) \\ Y(e_4) \end{bmatrix}$$

By applying equation (6) in above expression and obtain the following, because, both coded packets y(e_1) and y(e_2) pass through edge e_4, therefore, disjoint paths are not enough for V_5 from V_1.

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \begin{bmatrix} \gamma e_4 e_8 \beta e_1 e_4 & \gamma e_4 e_8 \beta e_2 e_4 & \gamma e_3 e_8 \\ \gamma e_4 e_9 \beta e_1 e_4 & \gamma e_4 e_9 \beta e_2 e_4 & \gamma e_3 e_9 \\ \gamma e_4 e_{10} \beta e_1 e_4 & \gamma e_4 e_{10} \beta e_2 e_4 & \gamma e_3 e_{10} \end{bmatrix} \begin{bmatrix} Y(e_1) \\ Y(e_2) \\ Y(e_3) \end{bmatrix}$$

Further, $[Y(e_1)\ Y(e_2)\ Y(e_3)]^T$ can be represented in terms of $[X(v,1)\ X(v,2)\ X(v,3)]^T$ and denote the above matrix by κ , which share the common coefficients of $y(e_1)$ and $y(e_2)$. Then,

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \kappa.\ \alpha. \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix}$$

Destination node V_5 recover the original packets from the received re-encoded packets $[y(e_8), y(e_9), y(e_{10})]^T$ and obtain,

$$Z(v_5,1) = \gamma_{e_8,1} Y(e_8) + \gamma_{e_9,1} Y(e_9) + \gamma_{e_{10},1} Y(e_{10}) \quad (13$$

$$Z(v_5,2) = \gamma_{e_8,2} Y(e_8) + \gamma_{e_9,2} Y(e_9) + \gamma_{e_{10},2} Y(e_{10}) \quad (14)$$

$$Z(v_5,3) = \gamma_{e_8,3} Y(e_8) + \gamma_{e_9,3} Y(e_9) + \gamma_{e_{10},3} Y(e_{10}) \quad (15)$$

Now, the original multicast data at destination node V_4 is decoded from equations (10) – (12), similarly, destination node V5 is decoded from equations (13)-(15), by solving the relation between $\bar{x}$ and $\bar{z}$,

$$\bar{z} = \bar{x} \cdot M \quad (16)$$

where $\bar{x}$ is the vector of input processes, $\bar{z}$ is the vector of output processes and M is the transfer matrix, which is obtained from solving the following matrix,

$$M = A \cdot \begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix} \cdot B$$

where, and

$$A = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{1,e_2} & \alpha_{1,e_3} \\ \alpha_{2,e_1} & \alpha_{2,e_2} & \alpha_{2,e_3} \\ \alpha_{3,e_1} & \alpha_{3,e_2} & \alpha_{3,e_3} \end{bmatrix} \qquad B = \begin{bmatrix} \varepsilon_{e_5,1} & \varepsilon_{e_5,2} & \varepsilon_{e_5,3} \\ \varepsilon_{e_6,1} & \varepsilon_{e_6,2} & \varepsilon_{e_6,3} \\ \varepsilon_{e_7,1} & \varepsilon_{e_7,2} & \varepsilon_{e_7,3} \end{bmatrix}$$

The square matrices β′.α and κ. α are invertible and unicoding is possible. Each destination node wants to decode the vector data $\bar{z}$. This implies that det(β.α) ≠ 0 and det(κ. α) ≠ 0 $\det(M_i) \neq 0 \ \forall_i$, therefore the product of determinant is non-zero. Determinant is non-zero means that it has some data for the particular destination node.

Description of Proposed Approach: RLNCDS-ODMRP

This section introduces proposed approach and functionality of algorithm for how to use RLNC over CDS in ODMRP for WSN in detail. The proposed algorithm deals with single source multicasting. In the proposed work, sensor nodes are received the coded packets by taking random linear combinations of its input packets in WSN [32]. For simplicity, the proposed approach considers the case where no restrictions are placed on coding among packets from the same multicast session. This asymptotically achieves optimal capacity of the network.

The basic idea of the proposed work (RLNCDS-ODMRP) is to find multiple disjoint paths from a source to multiple destinations with reduced number of hop to necessary transmission and to improve the performance of multicast routing protocol in WSN. The main contributions of this paper can be summarized as follows: 1) RLNCDS-ODMRP brings RLNC into multicast only with a few minor changes to the protocol packet formats of ODMRP and is compatible with ODMRP. 2) A network prototype system uses CDS for RLNC in ODMRP to multicast data to show the practicality of RLNCDS-ODMRP.

The proposed protocol (RLNCDS-ODMRP) can be implemented in two phases as shown in Fig.15. In the first phase, the source node discovers the route and constructs the Connected Dominating Set using CDS algorithm in ODMRP, in the second phase, the source node transmitting the multicast data by applying RLNC through the constructed Connected Dominating Set (CDS) in ODMRP to its multicast receivers.

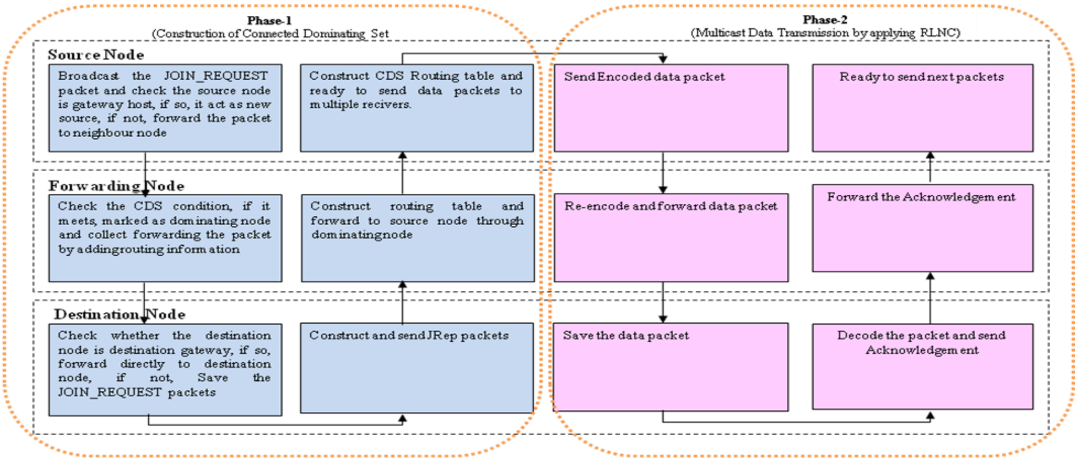


Figure 15: Outline of proposed protocol (RLNCDS-ODMRP)

In the first phase, the source node initiates the route construction process by broadcasting the join request packet JOIN_REQUEST, the source node check whether it is a source gateway host, if so, source gateway act as new source to route the packet and check the node belong to network or adjacent to source node, if yes, mark the selected node as dominating node, otherwise select the another routing path to find dominating node as above steps, then the dominating node collect neighbour information of its neighbour node and member list. Based on the neighbourhood information and member list, the dominating node rebroadcast the JOIN_REQUEST packet to its neighbour, then the neighbour node checks the above condition to find dominating node , finally check whether the selected node is destination gateway, if so , it construct join reply packet JOIN_REPLY and forward to the source node through the dominating node.

In the second phase, RLNC is applied to multicast the packets from a source node to multiple receivers. The source node multicast encoded data packets to its receivers through the dominating node (forwarding node) of CDS, based on the neighbourhood information it checks whether it's entire neighbour already have received the coded packet, if yes, it simply stops the forwarding packet, otherwise it checks whether coded packet is a native one. If so, it sends the coded packet to its neighbouring dominating node directly. Otherwise, dominating node forward the re-encoded packet by adding co-efficient to its adjacent dominating node. When dominating node receiving a native packet, it checks whether it can getting any coding opportunities to encode the packet with the remaining packets in the output queue that it needs to forward, if yes dominating node forward the re-encoded packet. If not, the dominating node buffers the packets for a threshold time T and transmit it later. When buffer time for the encoded packet exceeds the threshold time T send the encoded packet to its destination node. The dominating node check whether it is a destination node, if so, destination node save and decodes the original multicast packet and send acknowledgement to the source node through the connected dominating nodes. Otherwise, forward the re-encoded packet to its neighbour node until the re-encoded packet reached to its destination node, now the source node is ready to multicast next packet to its receivers.

Simulation Environment and Performance Evaluation

Experimental Setup

In the simulation experiment, nodes were placed uniformly at random locations in an area of 500 m × 500 m. The multicast traffic is Constant Bit Rate (CBR) with 250 bytes data packet.The simulation scenarios are created by the setdest tool of ns-2. The simulation time is 200 seconds. Mobility model uses a random waypoint model in a rectangular field. Here, 1-to-many multicast concept has been taken, i.e., Sender is fixed as one and only the receivers are varied from 9 to 99. The minimum and maximum speed were set from 0 to 20 m/s, respectively while pause time duration is 1 simulation seconds, which corresponds to constant motion and transmission rate is 128 Kbps, transmission range is 50 m for all nodes. The simulation parameters are summarized in Table 1.

Table 1: Simulation Parameters

S.No	Parameters	Particulars
1.	Simulator	Network Simulator-2
2.	Routing protocol	ODMRP
3.	No.of nodes	100

4.	Simulation time	200 secs
5.	Simulation area	500 m × 500 m
6.	Node movement	Random way point
7.	Sender & Receiver	Sender-1 Recevier-09-99
8.	Pause time	1 sec
9.	Traffic	CBR
10.	CBR Packet size	250 bytes
11.	Transmission rate	128 Kbps
12.	Mobility speed	0,5,10,15,20 m/s
13.	Transmission range	50 m
14.	Topology	Multi-hop
15.	Methods	CDS and RLNC

Performance metrics

Throughput

Throughput can be defined as the number of data packets generated by source node to the number of data packets received in the destination node [2].

$$\text{Throughput} = \frac{\text{Number of bytes received} \times 8}{\text{Simulation Time} \times 1000} \text{ kbps} \tag{17}$$

Reliability

Reliability is defined as the successful end-to-end data delivery ratio [43].

$$\text{Reliability}(r_0, r_1 \ldots r_{h-1}, r_h) = \exp\left(- \sum_{i=1}^{h} \frac{d^k_{ri-1ri}}{snr_{ri-1ri}} \right) \tag{18}$$

Where $(r_0, r_1 \ldots r_{h-1}, r_h)$ is route

d^k_{ri-1ri} is distance between the nodes

snr_{ri-1ri} is the transmitted signal-to-noise power

End-to-End Delay

The end-to-end delay is defined as the interval that elapses between the time a packet is sent and the time at which the packet is successfully delivered [19].

$$Delay = \frac{1}{R} \sum_{j=1}^{n} (r_j - s_j) \tag{19}$$

where R is the number of successfully received packets, j is unique packet identifier, r_j is time at which a packet with unique id j is received, s_j is time at which a packet with unique id j is sent and delay is measured in sec. It should be less for high performance.

Packet Delivery Ratio (PDR)

PDR is the ratio of the number of data packets delivered to the destination to the number of packets generated by the source node [44] as below:

$$PDR = \frac{\text{Total number of packets received at destination}}{\text{Total packets sent}} \tag{20}$$

Where, total number of packets received at destination= $\sum_{i=1}^{n} \text{Number of source nodes} \times$ Number of packets × Received at destination by each node total packet sent = $\sum_{i=1}^{n} \text{Number of nodes} \times$ Number of packets sent by each node

Experimental Results and Analysis

In this section, simulation results of the proposed approach (RLNCDS-ODMRP) for the performance metrics of throughput, reliability, end-to-end delay and packet delivery ratio for WSN are elaborated. The proposed protocol is simulated and analyzed by the following two criterias: a) Varying the number of nodes and b) Varying the speed of the nodes

Criteria-I - Varying the number of nodes

In the first criteria, the performance of proposed protocol is measured for the four performance metrics considered in this paper for WSN by increasing number of nodes from 09 to 99 nodes for fixed minimum speed of 0 m/s (static) in network coverage area. The following graphs shows that performance comparison between proposed RLNCDS-ODMRP multicast routing protocol, ODMRP with RLNC, ODMRP with CDS and normal ODMRP separately after filtering the data from trace files generated after simulation.

Throughput Analysis

Throughput should be high for better performance of wireless network. Throughput depends on the number of forwarding nodes between source and destination of the network. Participation of less number of forwarding nodes gives more throughput than large number of forwarding nodes. On increasing the number of nodes, throughput is also increasing. In Figure 16 simulation results of throughput (kbps) versus number of nodes are plotted.

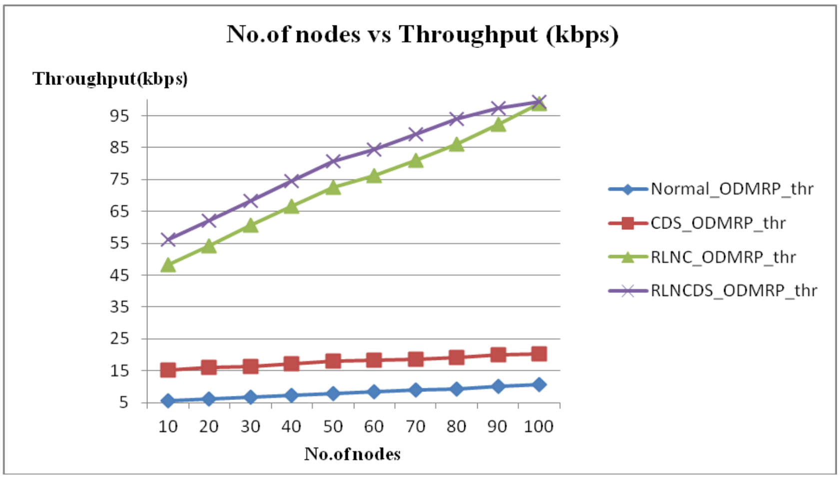


Figure 16: No. of Nodes Vs Throughput (Kbps)

From the Fig.16 it is observed that, on increasing the number of nodes, the proposed protocol RLNCDS-ODMRP provides higher throughput than other combination of ODMRP and delivers data packets at higher rate due to their operations of code updates and less number of hop for transmission. RLNC_ODMRP shows better performance than CDS and RLNC of ODMRP since, any one of the destination has poor link, it may provides throughput degradation for the other destinations. CDS_ODMRP provides average results, because minimum number of nodes are taking responsibility for transmission of data. Most of the nodes are trying to participate in data transfer in Normal_ODMRP, so congestion may occur even for a single destination which provides worst performance in throughput than other multicast routing protocols.

Reliability Analysis

Reliability should be high for better performance of the network. Reliable protocol consumes less bandwidth by reducing the retransmission and acknowledgement of participating nodes in a network. As described in the fig.17, efficient techniques can be used to improve the reliability. To achieve certain reliability, limited number of transmission, neighbourhood nodes estimation and channel quality link between source and destination node is important.

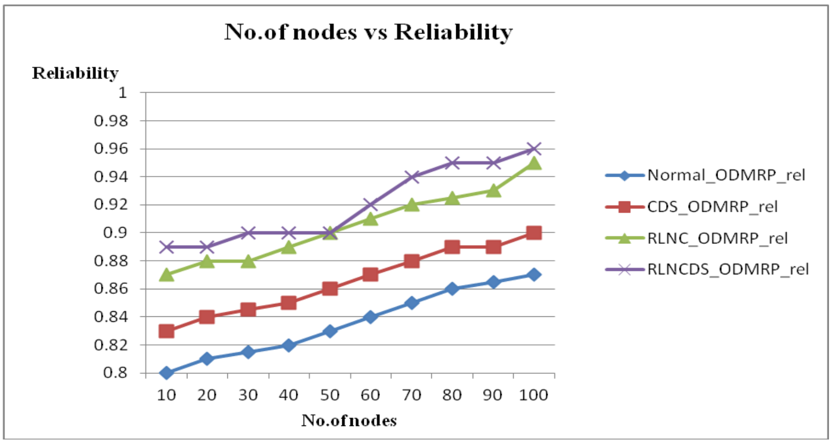


Figure 17: No. of nodes vs Reliabilty

Fig 17 shows the reliability versus number of nodes with low load. In the single source multicasting, collisions between multicast packets are very rare under low load therefore, reliability increases for all protocol. Nevertheless, it is observed that, on increasing the number of nodes, the proposed protocol RLNCDS-ODMRP provides better reliability (received messages) than other multicast routing protocol because, it reduces packet error rate in end-to-end in dynamic environment. ODMRP with RLNC offers average reliability because of communication overhead. As nodes are strongly connected in ODMRP with CDS, the reliability is improved than Normal_ODMRP.

End-to-End delay Analysis

End-to-End delay should be less for better performance of the network. Participation of more number of nodes takes more transmission time between source and destinations to multicast, which (end-to-end delay) affects the entire performance of the network. Figure 18 shows the graphs for end-to-end delay (sec) versus number of nodes.

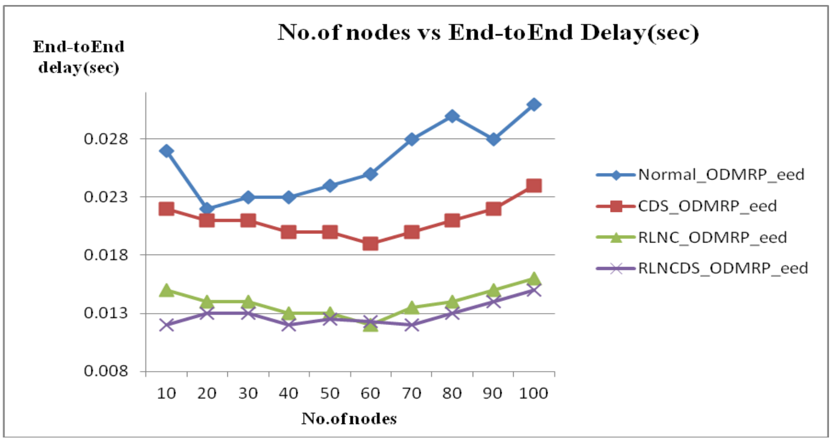


Figure 18: No. of nodes vs End-to-End delay (sec)

The Fig.18 shows the RLNCDS-ODMRP exhibits lesser values of end-to-end delay, because its route discovery mechanism is fast due to CDS, therefore it shows better delay performance than the other multicast protocols at low pause time, when increasing the number of nodes. ODMRP with RLNC provides better delay than others because, it minimizes the number of transmissions need to multicast. In CDS_ODMRP, dominating nodes have neighbor information and member list due to this earlier routing information offers high end-to-end delay. Normal_ODMRP shows worst performance in the case of end-to-end delay because, most of the nodes are participated in communication so it takes more time in route discovery, control overhead and packet overhead are high which leads to greater end-to-end delay.

PDR Analysis

PDR should be high for better performance of wireless network. When increasing the number of nodes, PDR decreases dramatically also delayed route discovery process affects the packet delivery ratio of the network. Fig 19 shows packet delivery ratio (%) versus number of nodes.

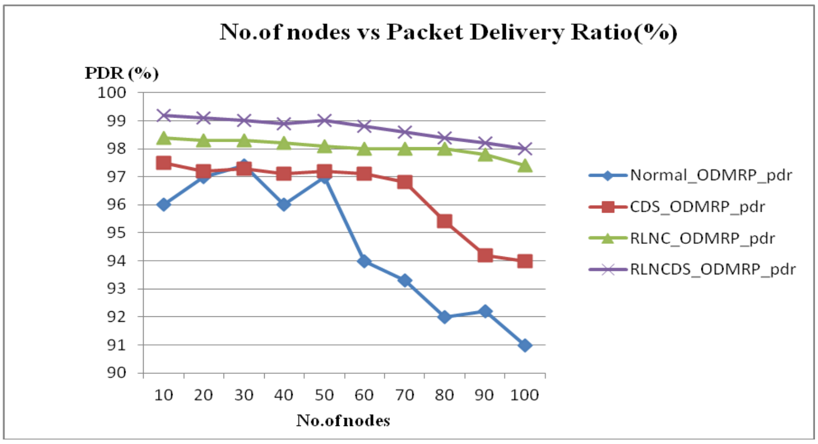


Figure 19: No. of nodes vs Packet Delivery Ratio (%)

Based on the simulation results shown in Fig.19, the packet delivery ratio of RLNCDS-ODMRP is higher (99%) than other multicast routing protocol. The packet delivery ratio is gradually decreases when increasing the number of nodes from 10 to 100 nodes. The proposed protocol limits the forwarder nodes and reduced the number of transmission for multicast therefore it achieves maximum packet delivery ratio. ODMRP with RLNC shows better (98%) packet delivery ratio than other protocols since it reduces packet error rate and send data better than other protocols. ODMRP with CDS offers average performance. Normal_ODMRP shows worst performance because all the nodes are involved in the network to multicast, so it cannot form a routing table proficiently with route error or route discovery failure.

Criteria-II - Varying the speed of the nodes

In the criteria-II, the performance of proposed protocol is measured for the four performance metrics considered in this paper for WSN by increasing the speed of the nodes from 0 to 20 m/s for the fixed 20 nodes in network coverage area. The following graphs shows that performance comparison between proposed RLNCDS-ODMRP multicast routing protocol, ODMRP with RLNC, ODMRP with CDS and normal ODMRP separately after filtering the data from trace files generated after simulation.

Throughput Analysis

Throughput will vary according to speed of the node. When node speed increases, multicast routing traffic also increases which affects the overall throughput in the network. As described in the fig.20, throughput constantly maintain in the given network. But, in normal routing protocol throughput decreases since more routing traffic.

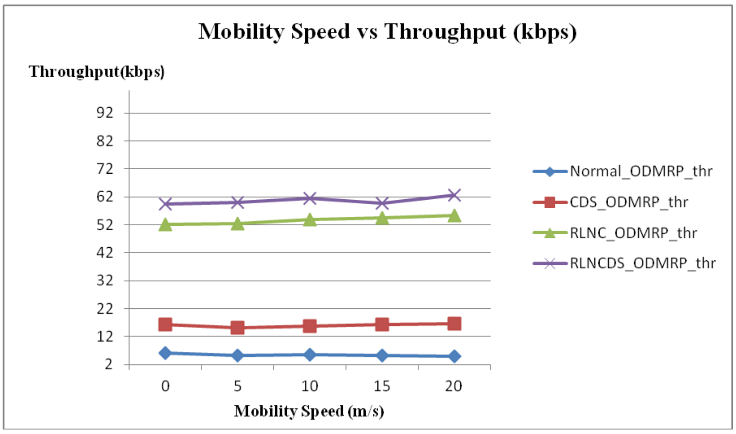


Figure 20: Node speed vs Throughput

In Figure 20 simulation results of throughput (kbps) versus mobility speed (m/s) are plotted. From the fig.20, it is observed that, throughput of RLNCDS-ODMRP is high. As speed increases proposed protocol RLNCDS-ODMRP still provides better results than other combination of ODMRP since, finding the route requires more and more routing traffic as speed increases. Therefore minimum number of channel will be used for data transfer, thus decreasing the overall throughput in other multicast routing protocol.

Reliability Analysis

When nodes are moving in a coverage area at different speed, it constructs multiple independent paths from source to destinations dynamically. This ensures that reliability of a network. Non-acknowledged virtual backbone multicasting is improving the reliability of network. Fig.21 shows that the reliability versus mobility speed (m/s)

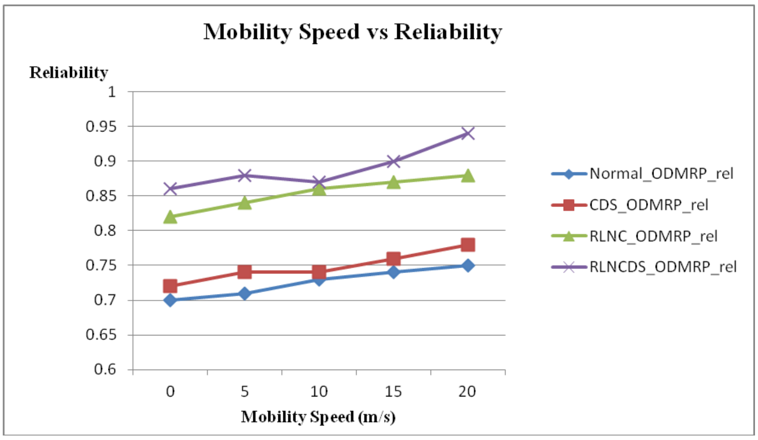


Figure 21: Mobility speed (m/s) vs Reliability

It is observed that, on increasing the speed of nodes, the proposed protocol RLNCDS-ODMRP provides better reliability than other multicast routing protocol because it has less delay for transmission of message and also each node moves within a speed of 0 –20 m/s. The message load is low and the message size is low. On the other hand, ODMRP with RLNC, ODMRP with CDS and normal ODMRP has less reliability, because it has higher delay where every message is delayed for further transmission.

End-to-End Delay Analysis

Virtual backbone formation reduces delay between source and destinations in a network. When varying the speed of the nodes in a mesh structure, it generates multiple paths which reduces the times of routing discovery from source to destinations. Figure.22 shows the graphs for end-to-end delay (sec) versus mobility speed (m/s).

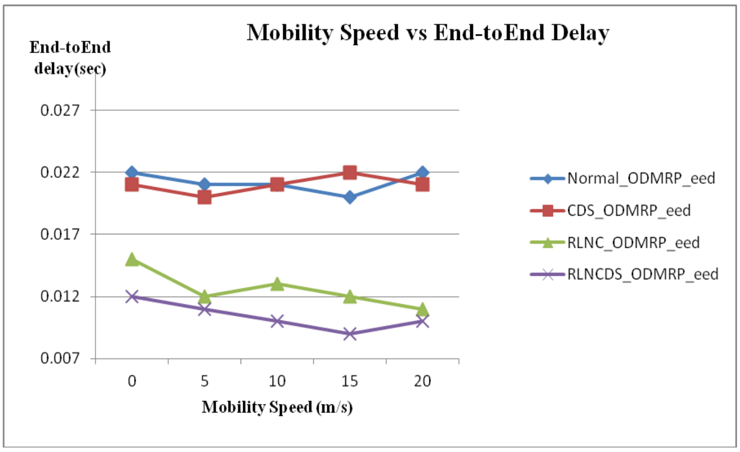


Figure 22: Mobility Speed vs End-to-End Delay

Figure 22 shows an end-to-end delay of four multicast routing protocols considered in this paper by varying the node speed. It is observed that RLNCDS-ODMRP exhibits lesser values of end-to-end delay than other multicast routing protocol. Increase of node speed induces topology change frequently and therefore the probability of broken links has also increased. These links may cause additional route recovery process and route discovery process. For this reason, as the node speed increases, end-to-end delay of packet also increased.

PDR Analysis

Due to redundant paths in a large size and mesh structured network, reliability is increased with higher packet delivery ration under mobility. Fig 23 shows packet delivery ratio (%) versus mobility speed (m/s) for the studied multicast routing protocols in this paper.

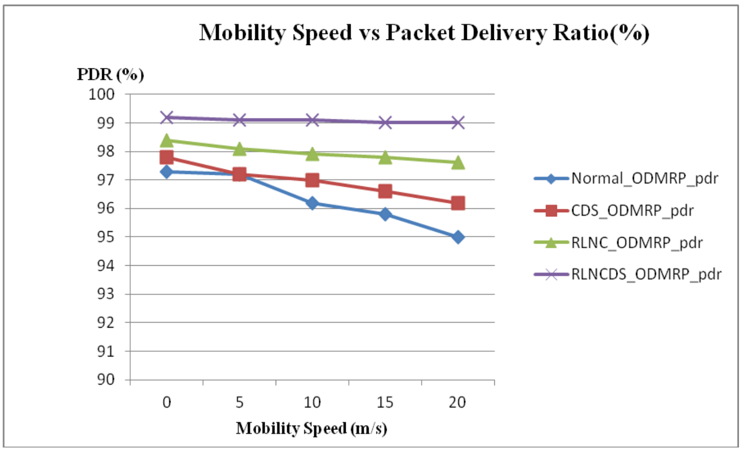


Figure 23: Mobility Speed vs Packet Delivery Ratio

Based on the simulation results, the packet delivery ratio of conventional ODMRP and combination of CDS and RLNC of ODMRP alone is decreases as speed increases but the proposed protocol RLNCDS-ODMRP still provides better results. It is observed that packet delivery ratio is very close to 95% for all multicast routing protocols at speed 0 m/s. However, as node speed increases, the packet delivery ratio is decreases dramatically.

Conclusion

In this paper, Random Linear Network Coding over Connected Dominating Set in ODMRP is proposed to improve the performance of multicast routing protocol for WSN. Based on the experiments, it is concluded that: (1) RLNCDS-ODMRP consumes less time to construct multicast topology than normal ODMRP, (2) throughput of proposed protocol RLNCDS-ODMRP is 10 times of its conventional ODMRP, (3) RLNCDS-ODMRP provides high throughput, high reliability, high packet deliver ratio and less end-to-end delay than individual techniques alone. (4)

RLNCDS-ODMRP usually achieves 90% of the theoretical maximum multicast capacity which is several times of ODMRP's, meanwhile only with about 20% extra bandwidth consumption compared with ODMRP also this paper gives valuable suggestion to design multicast protocols by integrating CDS and RLNC to reduce the number of transmission for multicast and maintains reasonable bandwidth cost. As future work, to face the key challenges of sensor nodes such as limited energy, limited bandwidth, short memory and limited processing ability the performance of RLNCDS-ODMRP will be enhanced and increase the life time of a WSN by adding efficient techniques. On the other hand, security is the major challenge in WSN, this also will be considered for improving the performance of RLNCDS-ODMRP in WSN.

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