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Cross-Layer Design Approach with Power Consciousness for Mobile Ad-Hoc Networks

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ABSTRACT

The protocols used in mobile ad-hoc networks are based on the layered architecture. The layered approach is highly rigid and strict since each layer of the architecture is only concerned about the layers immediately above it or below it. Recent wireless protocols rely on significant interactions among various layers of the network stack. A cross-layer design (CLD) introduces stack wide layer interdependencies to optimize network performance. The CLD use the state information flowing throughout the network stack to adapt their behavior accordingly. In this paper, CLD based architecture is proposed, where the objective is to provide a solution for power conservation, congestion control, and link failure management. The link quality is determined by the received signal strength at the physical layer. The channel interference, contention and RTS/CTS packets of the MAC layer are used to determine the transmitting power and ensure the Quality of Service at the application layer.

KEYWORDS

Cross-layered design architecture, Optimization parameters, Power conservation, Signal strength.

1. INTRODUCTION

A mobile network is a group of mobile nodes that are equipped with wireless receiver and transmitter using antennas. As the nodes are vastly mobile, the network topology is unpredictable over time and varies actively. An ad-hoc network is very much deployable in this situation and without the need of any central administration. A mobile network is a group of wireless nodes that spontaneously build up independent networks without any fixed infrastructure or centralized administration [1]. For the purpose of communication among the nodes, the nodes need to perform packet routing. All the nodes in the mobile ad-hoc network (MANET) cooperatively maintain the network connectivity. The applications of MANET have wide range of network requirements along with different energy constraints for different network nodes. These requirements must be fulfilled despite of varying link characteristics on every hop, traffic, varying topology, and high mobility. One of the most critical issues of ad-hoc wireless network is that the activities of the nodes are power constrained since the nodes are powered by batteries. The present mobile ad-hoc wireless network protocol is based on layered approach, i.e., TCP/IP model. Each layer in this model is operated and designed independently, with interfaces among the layers. The interfaces are independent of the individual network constraints and applications. This paradigm of the interfaces has greatly simplified the network design and has contributed to robust, scalable protocols of the internet.

The objectives of routing algorithms in ad-hoc networks are based on optimization of multiple parameters instead of concentrating only on minimization of number of hops. Energy efficiency is one of the parameters to be optimized as the nodes have limited energy. In order to achieve that goal, vertical communication amongst the different layers of the protocol stack is required and this can be incorporated by cross-layer architecture. In this approach, different layers share useful information related to routing strategy to reduce the communication overhead and thus minimizing energy consumption of the participating nodes [2]. Some functions of the ad-hoc wireless network like mobility management, energy management, Quality of service (QoS), security, and cooperation cannot be implemented in a single layer of the network protocol. It is possible to implement these functions by exploiting and combining mechanisms of all the layers of the network protocol. A possible way to implement these functions is to avoid the rigid layering in which the protocols in each layer are developed in isolation but rather within an integrated and hierarchical framework that takes advantage of the interdependencies among them. The current ongoing debate among ad-hoc network researchers is cross-layered versus legacy-layered architectures.

In order to achieve desired optimization goal, there is need for information flow among different layers of the protocol stack which is termed as cross-layer design (CLD) approach. It relies on the interactions among layers of the network stack; see Figure 1. Cross layering can provide significant performance benefits though it is proved that the layered design has been one of the key elements of the success of Internet. The layers can share locally available information and this will improve the performance.

<table>
<tr><td>Application Layer</td><td rowspan="5">Energy management
Quality of service
Security and cooperation
Mobility management</td><td>Group Communication, Service Locations</td></tr>
<tr><td>Transport Layer</td><td>Transport Layer Protocols</td></tr>
<tr><td>Network Layer</td><td>TCP/IP routing, Addressing, Forwarding</td></tr>
<tr><td>MAC Layer</td><td>Framing, Error Detection and Control, Congestion</td></tr>
<tr><td>Link Layer</td><td>Antennas, MAC, Bluetooth, Power Control, 802.11, Hyper LAN.</td></tr>
</table>

Figure 1. MANET functions sharing between different layers through Cross Layer Design.

The different characteristics of the existing CLD architecture are enlisted as given below:

a) CLD involves the combinations of layers physical-MAC-network, MAC-network, network-transport only.

b) It provides individual solution for power conservation, energy minimization, flow control, congestion control, and fault tolerance.

c) Only the local link information from its MAC layer is used by the congestion avoidance algorithm.

d) There is high and expensive overhead.

The above mentioned features have certain drawbacks. There is still no work done on complete integration of MAC-network-transport layers. The local information from the MAC layer is not sufficient to replicate the network situation when the whole network becomes unstable. There is still no complete solution for power conservation, energy minimization, flow control, congestion control, and fault tolerance. Only individual solutions are there for these problems.

Due to high mobility of the nodes, there is always a high chance for frequent change of topology. To accommodate the dynamic topology and to facilitate communication in multi-hop fashion, reactive protocols are available. The Ad-hoc On-demand Distance Vector (AODV) is a reactive protocol that creates route to the destination only when the sender node has data to transmit by initiating a route discovery mechanism and maintains it until it is required by the source [3]. The source node initiates route establishment by broadcasting Route Request (RREQ) packet to its neighbours and waits for the Route Reply (RREP) packet from the destination or intermediate nodes that have fresh route information to the destination. A new CLD is proposed in this paper to provide a solution for unidirectional link failure management, reliable route discovery, and power conservation.

In view of all these, the paper is organized as follows. Section 2 presents the related works done in cross-layering design. Section 3 discusses the proposed cross-layer design architecture. Section 4 describes the simulation results, and the paper concluded in Section 5.

2. RELATED WORKS

A. J. Goldsmith *et al.* have identified that cross-layer approach to network design can increase the design complexity [4]. The layered protocol is useful in allowing designers to optimize single layer design without complexity and concerning other layers. The cross-layer design must consider the advantages of the layering keeping some form of separation among the layers. Each layer is identified by certain parameters that are to be shared by the layers just above or below it. The parameter sharing of the layers assists in determining the operation modes that are suitable for application conditions, network, and current channel situation.

S. Shakkottai *et al.* have discussed that Layer Triggers (predefined signals) are the basic cross-layer design implementation that provide quantifiable performance improvements by attaining compatibility through the extension of layered approach [5]. The example of Layer Trigger is Transmission Control Protocol (TCP) with Explicit Congestion Notification (ECN). The ECN mechanisms have an advantage to TCP by showing the differences between congestion loss and wireless channel related loss. TCP with ECN also avoids delays and packet loss, thereby improving the performance of the network.

L. Chen *et al.* have discussed the design of cross-layer congestion control and scheduling for wireless ad-hoc networks [6]. The scheduling constraint is formulated earlier by considering multi-commodity flow variables and resource allocation in networks with fixed wireless channels. The resource allocation problem resulted to three sub-problems: routing, scheduling, and congestion control.

B. Ramachandran *et al.* have discussed about a simple CLD between physical layer and MAC layer for power conservation based on transmission power control [7]. The carrier sense multiple access with collision avoidance of IEEE 802.11 is integrated with the power control algorithm. The exchange of Request-To-Send (RTS) / Clear-To-Send (CTS) control signal is used to piggyback the information to enable the sender node to discover the minimum power requirement to transmit the data.

An Adaptive Link-Weight (ALW) routing protocol is proposed by A. N. Al-Khwildi *et al.* [8]. This protocol selects an optimum route based on low delay, long route time, and available bandwidth. Cross-layering technique is used in which the ALW routing protocol is integrated with the application and physical layer. The proposed design allows applications to convey preferences to the ALW protocol to override the default path selection mechanism.

Premalatha *et al.* have discussed about the design challenges for energy constraint ad-hoc wireless network [9]. The full CLD architecture tries to exploit protocol design and layer interdependencies to optimize the overall network performance. In this case, control information is continuously flowing top-down and bottom-up in the protocol stack. An adaptive routing may be developed based on traffic, network, and current link condition. The application layer can utilize a notion of soft QoS by adapting the underlying network condition.

S. Mahlnecht *et al.* have proposed the use of explicit signaling to minimize the impact of mobility and link disconnection [10]. The explicit signaling includes route failure notification and route reestablishment notification from the intermediate nodes to notify the sender TCP about the disruption and to establish a new route.

X. Xia *et al.* have discussed that layer triggers are not sufficient to fix ad-hoc networks performance problem due to TCP-IP-MAC interactions [11]. Two-link-level mechanisms, link-RED, and adaptive spacing is introduced to improve TCP efficiency; hence a joint design of the TCP protocols and MAC protocols are essential.

M. Conti *et al.* have discussed that the protocols belonging to different layers can cooperate by sharing the network status information but at the same time maintaining the separation of layers for protocol design [12]. The proposed solution has the advantage of balanced cross-layer design. The cross-layering is limited to parameters and implemented through data sharing called network status, which is a shared memory that every layer can access. Interlayer cooperation is obtained by variable sharing and the protocols are still implemented in each layer.

3. PROPOSED CROSS-LAYER DESIGN

An approach is made to design a cross-layer architecture that is aimed at providing a combined solution for link failure management and power conservation.

a. To address the link failure problem, the received signal strength from the physical layer can help to determine the link quality. The links with low signal strength are discarded from the route selection [13].
b. To address congestion control, the channel interference and contention of the nodes can be estimated and notified to the application layer. This estimation of the MAC layer can be utilized by the application layer and the transmission rate can be adjusted accordingly, to avoid congestion.
c. To address the power conservation, the MAC layer RTS/CTS packet exchange can be used. The minimum required power can be estimated and accordingly the application layer can adjust the transmitting power.

3.1 Link Failure Management

The signal strength of the received signal can be estimated at the physical layer. This information is transferred to the MAC layer along with the signal strength information. The MAC layer uses this information for making calculations, later it is passed to the routing layer along with routing control packet. In the routing layer, the information is stored in the neighbour table (or routing table) and it is used in some decision making process. The IEEE 802.11 is reliable MAC protocol and it assumes fixed maximum transmission, since RTS must reach every exposed node and every CTS must reach every hidden node to avoid collision.

3.1.1 Power Consciousness for Energy Conservation

The nodes are having limited power and storage capacity, so power conscious cross-layer design is essential to save battery. A sender node while sending the RTS packet also attaches its transmission power. The receiver node measures the signal strength while receiving the RTS packet using the following relationship as shown in Eqn. (1).

$$T_R = T_S(\alpha/4\pi d)^2 S_T S_R \tag{1}$$

Here α is the wavelength of the carrier signal, d is the distance between the sender node and the receiver node. S_T is the unity gain of sending nodes omni-directional antennas and S_R is the unity gain of receiving nodes omni-directional antennas. T_S is the sender nodes transmission power and T_R is the received signal power at the receiving node.

The receiving node calculates the path loss experienced as shown in Eqn. (2).

$$Path\_loss = T_R - T_S \tag{2}$$

The minimum required transmission power P_{min} of the node is calculated by Eqn. (3).

$$P_{min} = L \times (Path\_loss + X_{th}) \tag{3}$$

Here L is the multiplying factor that provides marginal hike in minimum required transmission power to withstand against the effect of interferences on packet reception. X_{th} is the receiver threshold, the minimum received power essential for proper signal detection.

There are a set of protocols available for power control in mobile ad-hoc networks based on the common power approach [14]. These protocols are complex and have been analyzed that the variable range transmission power is a better approach than the common power.

In this paper, power control is also introduced to the RTS/CTS packets based on the received signal strength. When a source node wants to transmit data, it initiates the AODV routing protocol by broadcasting the RREQ packet to the neighbour nodes and the RREP packet is received from the intermediate nodes via the shortest route and then enters it in their routing table about the next hop to which the later data packets are needed to be forwarded.

For power conservation, the RREP packet is identified by an identifier (id) at the MAC layer and its signal strength information is obtained from the physical layer. The nodes that receive the AODV's RREP packet, compute two parameters— (i) path loss experienced using Eqn. (2) and (ii) minimum required transmission power using Eqn. (2) and Eqn. (3). The P_{min} and the next destination node information are stored in the routing table.

The proposed CLD works as follows:

a) The nodes that send the RTS would refer to the routing table for the details of the minimum required transmission power.

b) The sender node would then tune its transmission power and also inserts this value as an extra field in the RTS packet.

c) The receiver node, on receipt of RTS, would tune its transmission power and replies back with CTS packet.

d) Then the sender node would send the data with the requisite transmission power.

e) The receiver node would also send the ACK with requisite transmission power.

This CLD involves the interaction of physical-MAC-routing layers. At the routing layer, the RREQ and RREP packets of the AODV routing protocol are transmitted with maximum transmission power so that bi-directionality of links, connectivity, and number of hops are unchanged. At the MAC layer, all the transmission sequences: RTS-CTS-DATA-ACK uses the minimum required power transmission level. The sender node on receipt of the ACK, calculates the path loss incurred using the currently used minimum transmit power value in its routing table to tackle high mobility. This adaptive transmit power updating mitigates unnecessary link/route failure due to the combined effect of power control and node mobility as transmission power is updated on per packet basis.

3.2 Unidirectional Link Rejection

The nodes in the ad-hoc networks are characterized by asymmetry links that means low-power nodes are able to receive from high power nodes but not vice versa. The AODV routing protocols has been designed for networks, with bidirectional links. The presence of asymmetric links become undetected and the RREP packet transmission along the reverse path fails.

In Figure 2, the route discovery process from node A to node B fails, since the RREP packet could not reach node A. This is due to the fact that, the AODV at the destination entertains the first received RREQ packet and does not reply to the RREQ packet via node C.

The AODV protocol allows only two RREQ retries. It fails to discover a route if there are more than two low-power nodes along the shortest route between the sender and receiver nodes.

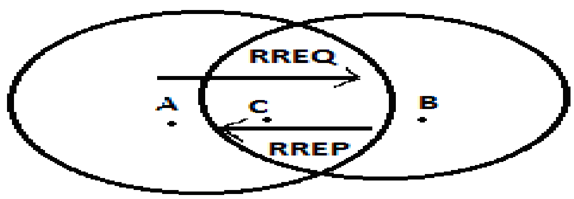

Figure 2. Route Reply failure due to low power nodes B, and C

To tackle the asymmetric links, different mechanisms are used as:

a) Periodic "Hello message" transmission when there is unidirectional link.

b) Black listing of nodes is done by storing the node where unidirectional link occurs and also to store the next hop of the failed RREP.

c) Reverse path search: In this scheme every node maintains multiple reverse paths while broadcasting RREQ. When RREP fails at a node the corresponding reverse path is erased and the RREP is retried along an alternate reverse path [15].

In this proposal, the unidirectional links are identified and rejected in the RREQ broadcast stage itself. If any bidirectional link exists, it is identified at the first RREQ packet broadcast. Whenever a node broadcasts the RREQ packet, it also includes the transmission power and antenna threshold value in the RREQ packet. On receipt of the RREQ packet by the receiver node, the path loss experienced by the RREQ packet is computed. It can detect if the link is bidirectional by comparing the sender node's antenna threshold value and the path loss value by Eqn. (4).

$$T_s > (Path\_loss + X_{th}) \quad (4)$$

If so, then the link is bidirectional and the RREP packet may reach to the sender node. In this manner, the RREQ packet is processed as per route discovery process of AODV and the RREQ packet is broadcasted after replacing the transmission power field by its own transmission power value. If the transmission power is less, the RREQ packet is discarded and the unidirectional link is rejected in the RREQ forwarding phase itself.

3.3 Route Discovery

For reliable route discovery, the proposed CLD considers the received signal strength of RREQ to decide whether to forward or discard. The route discovery done in this manner is aimed to save resources, reduce route failure, and minimize routing overheads. The signal strength is compared to the defined fixed threshold value and decision is taken as to forward or discard [16].

In the proposed technique, the high mobility of nodes is taken into consideration by incorporating a parameter that decides if two nodes are becoming closer and moving apart. The received signal strength of RREQ is stored in the routing table against the address of the neighbouring nodes from which RREQ is received. The current value of received signal strength and the previous value are compared; if the current value is greater, that means the nodes are becoming closer else they are moving away from each other.

4. SIMULATION RESULTS

Network Simulator, NS2 is used for the experiments [17]. The simulation area is a square and the nodes are placed uniformly. Each node chooses a random point and moves towards that point with random speed chosen between minimum and maximum values.

The nodes use distributed coordination function of IEEE 802.11 standard with RTS/CTS extension. Simulations are executed for 1200s for three rounds at varying values. The parameters along with the corresponding values that are considered to carry on the simulation are enlisted in Table 1.

Table 1. Simulation parameters.

Parameters	**Values**
Radio frequency	2.5 GHz
Bandwidth	2 Mbps
Packet size	512 bytes
Inter-packet interval	0.3 s
Number of nodes	30
Network protocol	IP
Transport protocol	TCP
MAC protocol	IEEE 802.11
Routing protocol	AODV
Antenna gain	0 dBm
Receiver threshold	–80 dBm
Receiver sensitivity	–90 dBm
Grid area	500 m × 500 m
Speed	0 and 20 m/s
Traffic	Constant Bit Ratio (CBR)

Performance Metrics:

1. Average end-to-end delay: The end-to-end delay is averaged over all surviving data packets from the source to the destination.
2. Throughput: It is the number of packets received successfully.
3. Drop: It indicates the number of packets dropped.
4. Average Energy: It indicates the average energy consumption of all nodes sending, receiving and forwarding operation.
5. Average packet delivery ratio: It indicates the ratio of packets received successfully and the number of packets sent.

4.1 Energy Conservation

To analyze the properties for improving energy conservation with AODV routing protocol, the CLD was changed to transmit power control for all MAC packets. The CBR traffic was varied to change the offered load with randomly selected sender and receiver node. The amount of energy conservation in cross-layer design protocol (CLDP) ranges in between 10% to 25% as shown in Figure. 3 The modified cross-layer design protocol shows more collision than unmodified protocol (UMP) of IEEE 802.11 and AODV due to uneven power usages by the nodes; the low-powered nodes suffer from high interference caused by high-power nodes. The minimum power requirement can be estimated by the RTS/CTS packets of the MAC layer. The node sending RTS packet needs to refer the routing table and accordingly tunes its transmitting power as per the signal strength value. This value is also added as an extra field in the RTS packet such that the receiver can tune to this power while sending the CTS packet. In this way the collisions can be minimized.

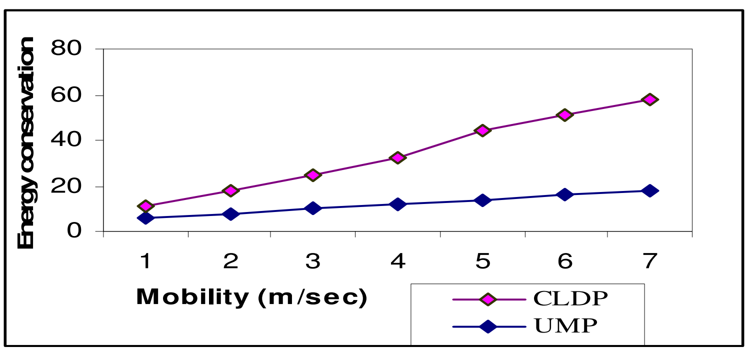

Figure 3. Energy conservation versus number of nodes for the cases of UMP and CLDP

4.2 Asymmetric Link Rejection

In the simulation model, all the nodes with 7 dBm are designated as high-powered with transmission range of about 250 m and nodes with 1 dBm are considered as low-powered with transmission range of 125 m. The simulation setup uses 25 nodes where 50% nodes are low-powered and the mobility of the nodes varies between 0 to 20 m/s. Four nodes are randomly selected as sender and receiver nodes, and the experiment is carried out for three times. In all the cases, it has been observed that there is improvement on packet delivery ratio of about 25-35% around the heterogeneously powered ad-hoc networks. There is reduced delay in route discovery. In heterogeneous environment, both the AODV and CLDAODV cause MAC collision. Link asymmetry causes low powered nodes to be hidden from the high powered nodes and this increases the number of collisions in the low powered communications. The simulation is considered with 50% low powered and 50% high powered nodes. In both situations the AODV and CLDAODV perform in the same manner due to dynamic network properties.

This implies that the CLDAODV's implementation does not degrade the performance in any form. The MAC collision is reduced to about 70-80% and the routing overhead is reduced to 75-85%. Hence, the proposed cross-layer design offers better performance since the unidirectional links are quickly identified and rejected before RREQ is broadcasted by the sender node.

4.3 Route Discovery Simulation Results

The AODV protocol with fixed threshold value is independent of the node's speed; so it is not justified for all speed values. In the proposed cross-layer protocol, AODV protocol is modified to tackle the situation of node mobility by considering the threshold values. The signal variant is fixed to −75 dBm in AODV and the modified AODV (MAODV) uses the set of values {−81, −80.5, −80, −78, −75 dBm} and it actually depends on the speed of the nodes in the range of 0-25 m/s.

The graphs in Figures 4(a)-4(d) depict the effect of mobility. There is improvement of Packet delivery ratio, average end-to-end delay and number of transmission in case of cross-layer designed AODV (CLDAODV) to the normal AODV protocol. The number of collisions is more in case of AODV than CLDAODV.

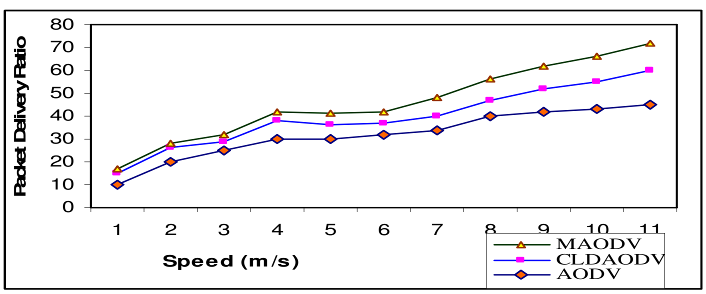

Figure 4(a): Packet delivery Ratio Versus speed(m/s) for MAODV, CLDAODV and AODV.

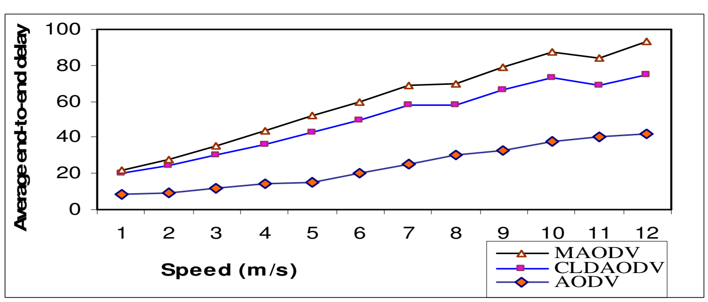

Figure 4(b). Average end-to-end delay versus speed(m/s) for MAODV, CLAODV and AODV.

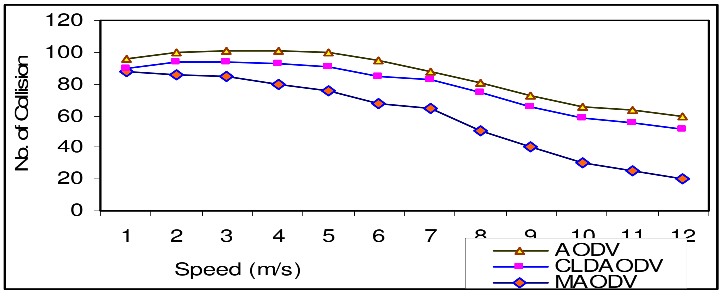

Figure 4(c). No. of collisions versus speed for MAODV, CLAODV and AODV

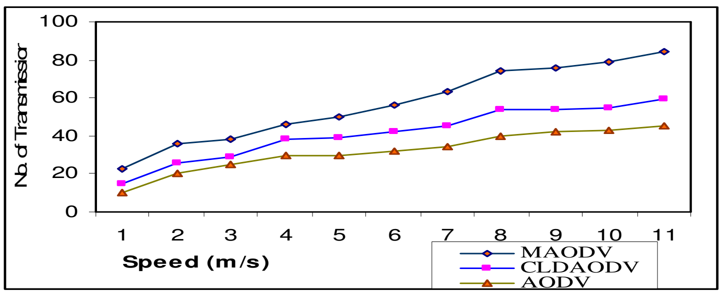

Figure 4(d). No of Transmission versus speed for MAODV, CLAODV and AODV

The MAC layer RTS/CTS packet exchange, help to estimate the minimum required power. The signal strength is obtained form the physical layer and this information is used by the routing layer.

Figures 5(a)-5(d) depict the effects of node density. Improvement is seen in the packet delivery ratio, average end-to-end delay and number of transmission. The collision rate is reduced in the CLDAODV.

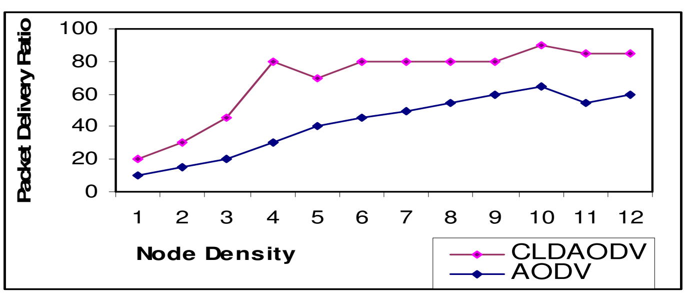

Figure 5(a). Packet delivery Ratio versus Node density for CLDAODV and AODV.

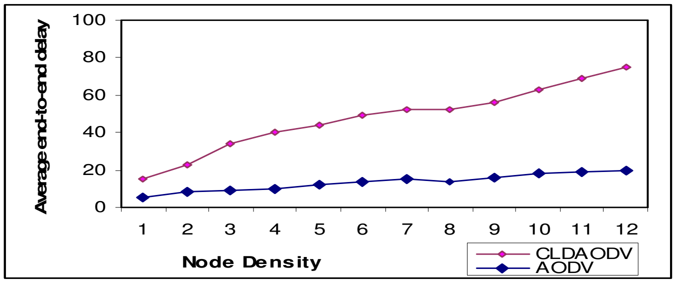

Figure 5(b). Average end-to-end delay versus Node Density for CLDAODV and AODV.

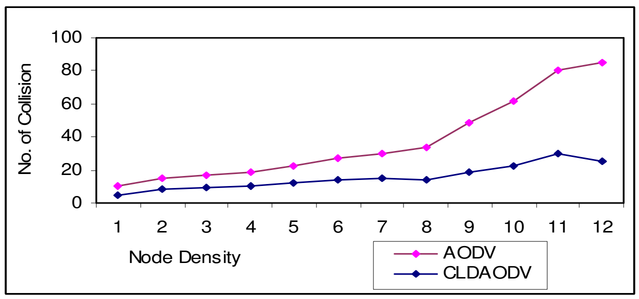

Figure 5(c). No. of collision versus Node Density for CLDAODV and AODV.

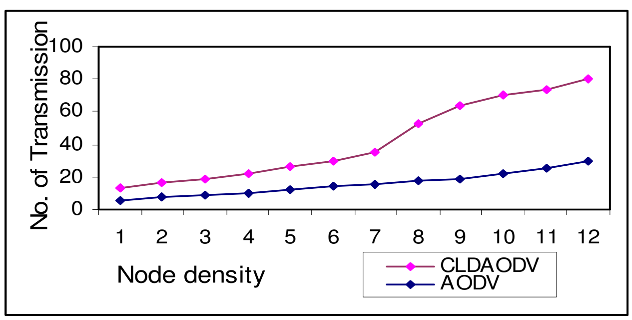

Figure 5(d).No. of transmission versus Node Density for CLDAODV And AODV.

The results as depicted in Figures 6(a)-6(d) show that the modified AODV protocol adaptively considers the threshold value and result into reduced delay, increased packet delivery ratio, and reduced route failure. The imposed threshold value on the signal strength affects the network connectivity. There is also improvement in routing overhead reduction due to reduced route failures. The cross-layer design need to be invoked in high density networks for better performance. The Modified AODV (MAODV) minimizes the number of hops when compared to the AODV with fixed variant. Hence the perfornance is improved in terms of increased packet delivery and reduced delay.

6. CONCLUSION

The high mobility and heterogeneous nature of the ad-hoc network results in collisions. The proposed cross-layer design is aimed to provide a solution for unidirectional link failure management, reliable route discovery, and power conservation. The link quality can be predicted by the received signal strength from the physical layer. The links having low signal strength can be discarded from the route selection. From the MAC layer, the minimum power required can be estimated by performing RTS/CTS packet exchange. Based on this, the application layer can readjust the transmission rate, to avoid collision.

One of the effective methods to reduce collision is to accompany the cross-layer design to achieve greater network capacity and spatial reuse. The proposed cross-layer design makes the AODV routing protocol to survive with heterogeneously powered ad-hoc networks by identifying and rejecting the asymmetric links at the RREQ broadcast stage itself. The most important fact is the network designers who must list down the conditions under which cross-layer design would improve the performance. To make accurate assessment of the state of the network efficient mechanisms need to be built into the protocol stack.

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