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SCRRM: a stability-aware cooperative routing scheme for reliable high-speed data transmission in multi-rate mobile ad hoc wireless networks

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SUMMARY

In this paper, we propose a Stability-aware Cooperative Routing scheme for Reliable high-speed data transmission in Multi-rate mobile ad hoc wireless networks, called SCRRM, to provide high data transmission with stable and reliable routes. The main features and contributions of our proposed routing scheme are as follows: First, we use the cross-layer concept with network layer, media access control (MAC) layer, and physical (PHY) layer. Second, a stable routing path based on link lifetime calculated from node mobility information is selected as the main routing path. Third, we use the received signal strength indicator (RSSI), PHY delay, and MAC delay for adaptively choosing relay and appropriate data rate. Fourth, we derive mathematical models to investigate the tradeoff between point-to-point transmission rates and the corresponding effective transmission ranges. The performance evaluation through analysis and simulation demonstrates that our proposed routing scheme can adaptively select optimal data rate and outperforms single-rate routing protocol in terms of packet delivery ratio, network throughput, and average end-to-end delay in all settings of node density and node mobility. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: mobile ad hoc wireless networks; route stability; cooperative routing; multi-rate; rate adaption; effective transmission range

1. INTRODUCTION

Mobile ad hoc wireless networks consist of many mobile nodes communicating in a decentralized manner. As mobile wireless devices are developed rapidly, consumer demand for communication in mobile ad hoc wireless networks includes both high speed and reliability. Currently, wireless devices using 802.11a, 802.11b, 802.11g, and HiperLAN2 can operate at many different transmission rates. The physical layer phenomena and medium access control that affect the performance of multi-rate ad hoc wireless networks are discussed in the work of Awerbuch, Holmer, and Rubens [1].

The benefit of multi-rate wireless networks compared with single-rate wireless networks is illustrated in Figure 1. As we can see in Figure 1, the routing path from source node (S) to destination node (D) consists of two intermediate nodes. In single-rate wireless networks, all nodes send data packet at the same rate regardless of the relationship between wireless channel condition and the distance between wireless nodes. However, in multi-rate wireless networks, the relationship...
between wireless channel condition and distance of wireless nodes is taken into account to select appropriate data transmission rates for wireless links. If two nodes are near to each other, they can communicate at high speed and vice versa. Dynamic-selecting data packet transmission rate for each wireless link in multi-rate wireless networks helps to increase network throughput. Specially, with packet length $L$ kbits and the assumption that there is no delay due to buffer overflow, the total transmission time to transmit the packet is $L \times (1/1 + 1/1 + 1/1) = 3L$ ms for single-rate wireless networks as in Figure 1(a) and is $L \times (1/3 + 1/2 + 1/6) = L$ ms for multi-rate wireless networks as in Figure 1(b). The benefit is significantly higher when the hop count of multi-hop path from source node to destination node increases. Moreover, transmitting data packets at higher rate helps to prevent overflow of packet in wireless node’s buffer. Also, bandwidth occupation time is reduced, resulting in lower packet collision in the networks.

We observe an important fact that in mobile ad hoc wireless networks, it is meaningless if mobile nodes are ready to send data at high speed, but wireless links do not exist due to node mobility or short effective radio range. Therefore, multi-rate devices must have routing protocols that can adaptively select the appropriate next hop and data rate for each wireless link. This issue is extremely challenging in dynamic networks such as mobile ad hoc wireless networks. The main contributions of this paper are both to derive mathematical models to evaluate network connectivity and to provide stability-aware cooperative routing scheme using our proposed metrics with cross-layer concept for adaptive-selecting robust and high-speed routes in mobile ad hoc wireless networks.

The rest of this paper is organized as follows. In Section 2, we review researches on multi-rate wireless environment. In Section 3, we define our multi-rate model used for analysis and simulation. We also derive mathematical formulas showing the tradeoff between effective transmission range and network connectivity. In Section 4, we present our proposed stability-aware cooperative routing scheme. The performance of our proposed scheme is intensively evaluated in Section 5. Finally, Section 6 concludes the paper.

2. RELATED WORKS

Most existing routing protocols in single-rate mobile wireless ad hoc networks construct routing paths based on route selection criteria such as minimum hop count as in Ad-hoc On-demand Distance Vector (AODV) [2] or minimum transmission time as in Dynamic Source Routing (DSR) [3]. Those routing protocols try to delivery data packets from source node to destination node in the shortest time. They generally assume that the channel conditions of different wireless links are identical and independent of the distance between wireless nodes. Practically, due to the physical properties of communication channels, that is, the signal quality decreases as the distance between two devices increases, there is an inherent tradeoff between transmission rate and effective transmission range to support reliable communication. Both high-speed and long-range transmissions cannot be achieved simultaneously.
Therefore, routing protocols in single-rate mobile ad hoc wireless networks may not perform well in multi-rate wireless ad hoc networks because some good-quality wireless channels are not fully utilized to send data packet at higher rates.

In the literature, the researches on multi-rate wireless environment are mostly on the Media Access Control (MAC) layer [4–9]. The Automatic Rate Fallback (ARF) is proposed in [4] to use in WaveLAN-II for IEEE 802.11 operation. ARF is based on observing timer and missed Ack frame. In ARF, the wireless node works at the highest data rate by default. When an ACK is missed for the first time following the previous successful transmission, the wireless node still works at the same rate. When the ACK is missed again, it switches to the next lower available data rate and sets the timer. If the node receives 10 consecutive ACK frames successfully, it will upgrade to the next higher data rate. In [5], Receiver Based Auto Rata (RBAR) is presented. In this algorithm, receiver measures the received Signal-to-Noise Ratio (SNR) of the Request-To-Send (RTS) frame and compares with predefined threshold to select appropriate data rate. In [6–9], cooperative MAC protocols are proposed to improve data transmission between two wireless nodes with the help from a relay. Recently, the rate adaption algorithm is extended to network layer in ad hoc networks [10–12]. In [10], Medium Time Metric (MMT) is presented. The MMT aims to minimize the total medium time consumed on sending packets from a source to a destination, which results in an increase in total network throughput. In [11], the authors propose a routing protocol based on the received signal strength and the ability of wireless link to deliver data packets. However, the metric is complex and does not show the data rate–transmission range relationship. As far as we know, only the authors in [12] propose a multi-rate aware routing protocol for mobile ad hoc networks. However, the metric for selecting relay node does not include the transmission time of MAC header and PHY header. Also, there is no mathematical model to show the data rate–transmission range tradeoff and the performance of that proposed routing protocol with different node density and node mobility is not investigated.

3. THE MULTI-RATE MODEL TO SUPPORT STABILITY-AWARE COOPERATIVE ROUTING SCHEME

In this section, we first describe the multi-rate model used in our analysis model and stability-aware cooperative routing scheme. Then, from that model, we derive mathematical expressions to show the impact of data rate and corresponding effective transmission range on network connectivity and transmission time. Finally, by using those mathematical expressions as routing metrics, we propose a stability-aware cooperative routing scheme to provide high-speed data transmission through stable and reliable routes from a source node to a destination node.

3.1. Multi-rate model

In our multi-rate model, there is a mapping relationship between the distance of two mobile nodes and the corresponding transmission rate in which the channel between them can be supported as in Figure 2.

That relationship depends on the hardware characteristic of mobile nodes and the environment of considered wireless networks and is standardized by organizations. In this paper, we use the IEEE 802.11b/g standard showing the data rates and corresponding transmission ranges in a wireless environment [13]. The mapping relationship between the effective transmission ranges and the corresponding data rates of IEEE 802.11b/g is plotted in Figure 3. As we can see in Figure 3, effective transmission range does not linearly decrease with the increase of data rate.

3.2. Transmission range versus network connectivity

In this section, we will use the aforementioned multi-rate model to show the tradeoff between transmission rate and effective transmission range, which correlates with network connectivity. We consider a mobile ad hoc network with $N$ nodes uniformly distributed inside the network area $a^2$. The probability that a mobile node has $m$ neighbor nodes in semicircular forwarding area $\pi R^2/2$ can be approximated by Poisson distribution as
\[ P_m(m) = \frac{(\rho \gamma)^m}{m!} e^{-\rho \gamma}, \]  

where \( \rho = N/a^2 \) is node density and \( \gamma = \pi R^2/2 \) is semicircular forwarding area.

A point-to-point wireless link exists if there is at least one node in semicircular forwarding area with effective transmission range \( R \). Thus, the connectivity of point-to-point link is

\[ p_{p2p} = P(M \geq 1) = 1 - P(0) = 1 - e^{-\left(\frac{N}{a^2}\right) \times \left(\pi R^2/2\right)}, \]  

Equation (2) is plotted in Figure 4(a) with \( N = 50 \) and different effective transmission ranges and network sizes. The cross-sections at network size \( a = 1000, 2000, \) and \( 3000 \) m are shown in Figure 4(b).

As we can see in Figure 4, the connectivity of wireless link depends on both node density and effective transmission range.

Next, we will study how different effective transmission ranges of wireless links affect the stability of multi-hop path. During the routing path discovery, the processes of selecting next hop as forwarding...
node are independent. Therefore, the probability that a $k$-hop routing is successfully established between a source node and a destination node can be expressed as

$$p_k = \prod_{i=1}^{k} p_{p2p}^i = p_{p2p}^1 \times p_{p2p}^2 \times \ldots \times p_{p2p}^k = \left[1 - e^{-\frac{(N/N')\times(\pi R^2)}{2}}\right]^k,$$

(3)

where $p_{p2p}^i$ is the connectivity of wireless link $i$.

Equation (3) is plotted in Figure 5 with $N = 50$, different network sizes and different lengths of multi-hop paths, that is, $k$ is variable.

As we can see in Figure 5, the stability of multi-hop path decreases when the node density and node’s effective transmission range decrease. Especially, the stability of multi-hop path is remarkably low when the node density and node’s effective transmission range are low. Therefore, in single-rate mobile ad hoc wireless networks, selecting an inappropriate node’s transmission range seriously affects the connectivity of the networks. Meanwhile, in multi-rate mobile wireless ad hoc networks, a routing scheme which can adaptively select routing path to provide both reliable and high-speed data transmission is essentially needed.

Figure 5. The stability of multi-hop path with different effective transmission ranges and multi-hop path lengths.
4. THE PROPOSED STABILITY-AWARE COOPERATIVE ROUTING SCHEME

We apply the cross-layer concept for our proposed stability-aware cooperative routing scheme. The proposed scheme consists of two algorithms. Initially, the first algorithm selects a stable routing path. That stable routing path is used as the main routing path from a source node to a destination node. The second algorithm works in adaptive manner to select relay nodes for supporting nodes on main routing path to send data faster. We will present in detail two algorithms in the following parts.

4.1. Selection of stable routing path

Figure 6 illustrates the algorithm for selecting stable routing path in our scheme.

We extend the idea in our previous work [14] by using optimal mobile node’s transmission range calculated from (2) in Section 3.2. For details of how to calculate link duration and use it to select stable routing path, please refer to our previous work [14].

The flow chart of stable path selection algorithm is shown in Figure 7.

In the following, we present step-by-step the algorithm:

- **Step 1**: At the initial time, all nodes select base transmission rate at which the probability of establishing wireless point-to-point links \(p_{p2p}\) calculated by (2) is greater than or equal to 0.99. If there is no transmission rate at which \(p_{p2p}\) is greater than or equal to 0.99, the transmission rate which has highest \(p_{p2p}\) is selected as base transmission rate. The pseudo code for selecting base transmission rate is presented as follows:

```plaintext
Input number of node N and network size a
Sort all transmission rates that wireless node can work in descending order
for i = 1 to all above data rates \(R_{tx(i)}\)
    find the transmission range corresponding to \(R_{tx(i)}\)
    calculate \(p_{p2p}\) according to (2)
    if \((p_{p2p} >= 0.99)\)
        base transmission rate = \(R_{tx(i)}\)
        break
    else
        base transmission rate = \(R_{tx(i)}\)
    end if
end for
```

Then source node (S) broadcasts its location and waypoint in Route Request (RREQ) packet at base transmission rate. The idea of using base transmission rate for control overheads is that we can always establish a ‘backbone’ routing path to delivery data packets from source node to destination node.

- **Step 2**: When a mobile node receives unduplicated route reply (RREP) packet, it uses the location and waypoint information of itself and pre-hop to calculate link duration of the link between it and pre-hop. If this link duration is greater than the one stored in routing cache, node updates the information in RREQ then forwards it. Otherwise, it does nothing.
Step 3: Upon receiving RREQ packet, a destination node (D) chooses the most stable path from available routing paths. It copies the route record and route life time (i.e., the link duration of the weakest link) of this path to RREP packet and sends RREP packet back to source node.

Step 4: After receiving RREP packet, the source node sends data packet through this stable path.

4.2. Selection of relay and cooperative data transmission

Figure 8(a) presents the cooperative process operating on mobile nodes in the cooperative region, whereas Figure 8(b) presents the basic concepts of cross-layer stability-aware cooperative routing in multi-hop path, respectively.

Any node staying in cooperative region is neighbor node of both sender and receiver. When a data packet with length $L$ is transmitted, the transmission time $\tau$ corresponding to direct transmission and cooperative transmission via relay node will be

$$\tau = \begin{cases} 
\tau_d = T_{\text{MAC}} + \frac{L}{R_{tx-rx}} + T_{\text{PLCP}} & \text{direct transmission} \\
\tau_c = 2T_{\text{MAC}} + \frac{L}{R_{tx-r}} + \frac{L}{R_{rx-r}} + 2T_{\text{PLCP}} & \text{cooperative transmission}
\end{cases}$$

(4)

where $R_{tx-rx}, R_{tx-r},$ and $R_{rx-r}$ are the data transmission rates of wireless sender–receiver channel, sender–relay channel, and receiver–relay channel, and $T_{\text{MAC}}$ and $T_{\text{PLCP}}$ are additional time associated with transmitting header of MAC layer and physical layer, respectively. According to IEEE 802.11b/g standard, the MAC and PHY headers are transmitted with fixed rate; only the data unit is transmitted with variable rates. Therefore, the condition for cooperative transmission would be
In this paper, the sizes of MAC header and Physical Layer Convergence Procedure (PLCP) header are 272 and 192 bits, respectively. They are both transmitted at 1 Mbps. The length of data packet is 4 kbits.

The flow chart of cooperative transmission algorithm is shown in Figure 9.

In the following steps, we describe in detail the relay selection and cooperative data transmission algorithm by using Figure 8(a) and Figure 8(b), respectively. The format of control overheads Coop-Ack and data frame is in Figure 10.

- **Step 1**: By overhearing the data forwarding from node $N_i$ to node $N_j$ on the main routing path, mobile node $R$ staying in cooperative region can obtain the data packets sent from them. From
the received signal strength, node R calculates the distance from it to node Ni and node Nj. Then, it will select the appropriate data transmission rate for channel Ni–R and Nj–R using the mapping relationship in Figure 3. Node R also checks the cooperative condition by using the metric in (5). If the condition is met, it participates in cooperative transmission by sending Coop-Ack packet with cooperation valid set to 1. The data rates for the wireless channels Ni–R and Nj–R are specified in Rtx-r and Rrx-r, respectively. Then those data rates are set to the signal field of data frame to inform physical layer of sending that data frame at those rates. Node R also adds node Ni’s ID and node Nj’s ID to its routing table. From now, if relay node R receives data packet from node Ni, it will forward to node Nj at rate Rrx-r. If relay node R cannot receive three consecutive data packets sending from node Ni, it will remove Ni’s ID and Nj’s ID from its routing table for not participating in cooperative transmission.

• Step 2: When the wireless link Ni–R or Nj–R is broken due to node mobility and node Nj cannot receive three consecutive data packets sent from relay node R, node Nj will send Coop-Ack to node Ni in which cooperation valid is set to 0 to inform switching to direct transmission mode. The Coop-Ack does not have packet fields Rtx-r and Rrx-r if cooperation valid is 0.

• Step 3: The cooperative transmission process repeats if there is another relay node that can participate in cooperative transmission.

5. PERFORMANCE EVALUATION

In this section, we use OPNET Modeler to evaluate the performance our proposed stability-aware cooperative routing scheme with different node density, node mobility, and data rate in terms of packet delivery ratio and network throughput to compare with DSR protocol [3]. The simulation is conducted on a computer workstation equipped with 2 GHz (Intel Core 2 Duo T7250) processor, 4 GB of RAM, and Windows XP. For all simulation scenarios, Constant Bit Rate/User Datagram Protocol (CBR/UDP) traffic is used. In order to eliminate the packet loss due to buffer overflow, light traffic is generated. Specifically, a source node sends CBR traffic at 80 kbps, where data packet length is 4 kbits. There are 50 mobile nodes in the network area. The optimal base transmission ranges of mobile nodes selected by our first algorithm in Section 3.1 are 304, 396, 610, and 610 m with respect to network size a = 1000, 1500, 2000, and 3000 m which can be verified in Figure 4(b). Each simulation is executed 10 times and the average results are plotted in the graphs.

5.1. The effect of node density on network performance

Figures 11 and 12 show the packet delivery ratio (PDR) and network throughput as a function of network size, respectively. We change node density by increasing network size while node mobility is kept at 20 km/h. As we can see in Figure 11, the PDR obtained from our proposed scheme outperforms the PDR of single-rate DSR routing protocol in all cases because mobile node can adaptively select optimal data rates so that with corresponding effective transmission ranges network connectivity is ensured. Our scheme also selects the most stable route during route discovering process.

The ‘side effect’ of larger transmission range at lower data rate can be seen in Figure 11. The PDR of DSR 1 Mbps is lower than that of DSR 6 Mbps because the mobile node has much more neighbor
nodes due to larger transmission range and leads to RREP packet storm in the network. This effect is reduced as the node density is lower. With DSR 54 Mbps, the PDR is very low due to lack of network connections. However, our proposed scheme can adaptively selects optimal node’s transmission ranges based on node density. Therefore, there is no ‘side effect’ or lack of connection due to inappropriate node’s transmission ranges, and this results in higher and stable PDR and network throughput. Because network throughput of CBR data in Figure 12 closely relates to PDR, it has quite similar pattern with PDR in Figure 11.

5.2. The effect of node mobility on network performance

Figures 13 and 14 show the PDR and network throughput as a function of node mobility, respectively. We change node mobility while network size is kept at 1500 m × 1500 m. As we can see in Figure 13, the pattern of PDR is different with that in Figure 11 because node mobility does not have ‘side effect’
as node’s transmission range. When node mobility increases, link disconnection also increases that results in lower PDR. Because our proposed SCRRM scheme selects stable routing path as main path, it is more robust against node mobility. Moreover, our scheme performs cooperative transmission with best effort to support the main routing path in sending data at higher rate. Therefore, the PDR and network throughput obtained from our SCRRM scheme are higher than single-rate DSR in all settings of node mobility. Again, network throughput of CBR data in Figure 14 has quite similar pattern with PDR in Figure 13.

5.3. The scalability of QoS support

In this simulation scenario, the route capacity and end-to-end delay of multi-hop path from source node to destination node are evaluated by gradually increasing the data packet sending rate of source node.
Figure 15 shows the network throughput as a function of packet sending rate at source node. We evaluate the network throughput with different network size (or different node density). The number of mobile nodes in the network is fixed at 50 nodes. Node mobility is 20 km/h. As we can see in Figure 15, when node density is low, that is, network size is 1500 m × 1500 m, network throughput of DSR 6 Mbps is lower than our proposed SCRRM scheme because SCRRM can select optimal base data rate to provide high possibility of establishing a routing path from source node to destination node. Moreover, SCRRM selects stable routing path as the main routing path to make it more robust against node mobility. Due to low node density, relay nodes do not always exist to support main routing path in sending data packet at higher rate. That explains why the network throughput of SCRRM is not proportional to the increase of data packet sending rate at source node.

Figure 15. Network throughput versus packet sending rate at source node; node mobility = 20 km/h; number of mobile node = 50.

Figure 16. Average end-to-end delay versus source node’s sending rate; node mobility = 20 km/h; network size = 1000 m × 1000 m.
When node density is high, that is, network size is 1000 m × 1000 m, network throughput of DSR 6 Mbps is better but limited at 6 Mbps because the packet sending rate at source node reaches the wireless link capacity. However, in our proposed SCRRM, network throughput is nearly proportional to packet sending rate at source node because relay nodes can be selected to support main routing path in sending data packet at higher rate if the cooperative condition is met.

Figure 16 shows the average end-to-end delay as a function of packet sending rate at source node. The average end-to-end delay is the total time that a data packet travels from source node to destination node. The average delay plotted in Figure 16 counts only successfully received data packets. Network size is fixed at 1000 m × 1000 m and node mobility is kept at 20 km/h. As we can see in Figure 16, the average end-to-end delay decreases as packet sending rate at source node increases. However, in DSR 6 Mbps, the average end-to-end delay slightly changes when packet sending rate at source node is over 6 Mbps. This is because of queueing delay at node buffer when sending rate approach the wireless link capacity, that is, 6 Mbps. Meanwhile, the average end-to-end delay in our proposed SCRRM is inversely proportional to the packet sending rate at source node because wireless link capacity is dynamically changed based on the communication distance between wireless nodes.

6. CONCLUSION

In this paper, with the given network density, we derive mathematical models to show the impact of transmission rate on network connectivity. We also introduce a cooperative routing metric to adaptively select relay nodes and the optimal data rates with corresponding transmission ranges. Based on that metric, we propose Stability-aware Cooperative Routing scheme for Reliable high speed data transmission in Multi-rate mobile ad hoc wireless networks (SCRRM) that can adaptively select stable routing path and optimal data rate for each wireless link to achieve high rate data transmission with reliability. Our proposed scheme applies the cross-layer concept by using physical layer information and MAC layer information to support selecting relays and data rates efficiently at network layer. The simulation results show that the PDR, network throughput, and average end-to-end delay obtained from our scheme outperform those in single-rate DSR routing protocol in all scenarios.

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