Message from the General Co-chairs

Welcome to Shanghai and the 26th International Parallel and Distributed Processing Symposium. We are extremely honored to have been invited to host IPDPS 2012 and to organize a conference for this community of top researchers. We are especially grateful to the several teams of extremely committed volunteers who have made this conference possible and performed beyond expectations to make this an outstanding and record setting event.

We want to start with our publicity team led by Michela Taufer and including Zhu Yanming, Yinglong Xia, and Alexandros Stamatakis. They have creatively and consistently let the world know about this conference, getting the word out in both English and Chinese. Their strong effort produced record submissions to all the calls for papers, including the main conference as well as workshops and the PhD forum and has helped broaden the base of researchers interested in IPDPS.

Leonid Oliker and Katherine Yelick, the program co-chairs for IPDPS 2012, also honored us by accepting this assignment and bringing together a first-rate group of vice chairs who in turn assembled a program committee of top researchers in our community representing the broad spectrum of IPDPS areas of inquiry. We are grateful to efforts made to involve and attract Chinese researchers, and we believe that the final technical program of papers, keynote speakers, and the panel that Dr Yelick will moderate will make 2012 in Shanghai a distinctive year for IPDPS.

We want to give special credit to our PhD forum co-chairs Luc Bougé and Bo Hong for working closely with China based organizers to publicize this opportunity for student researchers to participate in IPDPS. We also want to recognize their collaboration with the program co-chairs to involve the conference program committee in identifying reviewers for forum submissions, an approach that helps expand the future base of the IPDPS community. Student participation in IPDPS is further encouraged through student travel grants sponsored by TCPP, and we thank TCPP chair Ajay Gupta and his student travel chair Manish Parashar for their focused effort to expand resources for this year in China, which presents special challenges for student participation.

From our knowledge of IPDPS, we have always been impressed by the slate of workshops offered by the conference and the extent to which they broaden the content of the week’s presentations. What we did not realize was the level of energy required to make this happen and to ensure a high standard of programming. This year, there are 24 workshops that we wish to thank the organizers and recognize them for the extraordinary level of volunteer effort they represent. All of us on the IPDPS team owe a tremendous round of applause to the workshops chair Ümit Çatalyürek who does all of the vetting and management to support workshop organizers in meeting the standards the conference sets for them.

The IPDPS proceedings chair Xin Yuan worked closely with all the technical chairs listed above and had good support from his student assistant Santosh Mahapatra. With production chair Sally Jelinek, he was the primary contact with the Computer Society CPS production editor Bob Werner. This team has many responsibilities and also accountability for almost 450 papers that are part of the conference and workshop proceedings. We want to recognize the time and level of communication required of all parties to produce the final proceedings and to thank this team for their valuable contributions to the success of the conference.
Almost five years ago, we began exploring the possibilities of bringing IPDPS to Shanghai and are very grateful for the support from Viktor Prasanna and Bill Pitts and the steering committee to keep the wheels turning to make it happen. Bill overcame tricky financial challenges to make it possible to hold IPDPS in Shanghai and has kept us on track throughout. There are many names we will miss, but Carmen Saliba from the IEEE Computer Society was instrumental in negotiating the final hotel contract. Along with Alkenia Winston and Brookes Little from the Conference Organizing Group, she deserves tremendous credit for enabling Shanghai Jiao Tong University to host IPDPS 2012. After everyone listed here did their part, the local arrangements chairs (Susamma Barua and Hongzi Zhu) filled in the gaps and made this event a reality. They were assisted by four key SJTU staff members, Zhihua Su, Meiju Chen, Qiangbo Zhao, and Jia Hua. Those of you who received invitation letters will recognize the last two names. Without the contributions of all of these individuals, the process of running this symposium would not have gone nearly as smoothly. We especially thank Sally Jelinek for anticipating the jobs to be done and appreciate her competence and skill in developing the needed teamwork with China based volunteers, particularly her assistance to help generate interest in commercial participation.

We are looking forward to an exciting technical program and hope that everyone will have an opportunity to enjoy Shanghai and other parts of China if you are able to extend your visit. Thank you for making the special effort to travel to China and participate in IPDPS 2012.

**IPDPS 2012 General Co-chairs**

Minglu Li  
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**Addendum from Minglu Li:**
This message would not be complete without my thanking my co-chair Cho-Li Wang for being available to work with the team at SJTU and other IPDPS organizers to bridge any knowledge or communication gaps. He has been a valuable partner to ensure that we retained the cultural spirit of IPDPS in this undertaking, and he has also been a strong advocate to ensure the involvement of Chinese researchers and students in IPDPS 2012 and deserves special recognition for this.

**Addendum from Cho-Li Wang:**
It has been my honor to be invited to serve as co-chair with Prof Li and to be able to work with his team at SJTU to share my knowledge of IPDPS and my many years of experience with the conference, starting with my graduate school days at USC, where Prof Prasanna served as my advisor and annually drafted me to serve as a student volunteer. The IPDPS associations continued after I came to the University of Hong Kong, and I have enjoyed introducing my colleagues and students in China to the IPDPS community. Over the years, I have come to know key organizers of the conference including Sally Jelinek, Susamma Barua, Bill Pitts, and George Westrom. We have relied heavily on the wealth of experience and unparalleled dedication they provide. It was a pleasure to be on familiar ground in my role as general co-chair, knowing they would be there to help us over the various hurdles of organizing IPDPS in China.
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Network Coding-Based On-Demand Multipath Routing in MANET

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Abstract—A Mobile Ad Hoc Network (MANET) is a dynamic wireless network that can be formed without the need for any pre-existing infrastructure in which each node can act as a router. Due to bandwidth constraint and dynamic topology of mobile ad hoc networks, multipath supported routing is a very important research issue. This paper proposes a Network Coding-Based on-demand Multipath Routing algorithm in MANET (NCMR). It is typically proposed in order to increase the reliability of data transmission or to provide load balancing. In our simulation, we compare NCMR routing protocol with AODVM routing protocol, in terms of the packet delivery ratio, packet overhead, and average end-to-end delay when a packet is transmitted. The simulation results show that the NCMR routing protocol provide an accurate and efficient method of estimating and evaluating the route stability in dynamic MANETs.

Keywords—MANETs; Network coding; AOMDV; Multipath routing algorithm

I. INTRODUCTION

Mobile ad-hoc networks (MANETs) are a key part of the ongoing evolution of wireless communications. MANETs are defined as the category of wireless networks that utilise multi-hop radio relaying and are generally capable of operating without the support of any fixed-line infrastructure [1-10]. Each node has the capability to communicate directly with other nodes, acting not only as a mobile wireless host but also as a router, forwarding data packets to other nodes. In other words, such networks are self-creating, self-organising and self-administrating. Key application areas for these types of networks include: conference networking, disaster relief, military networks and sensor networks.

A typical approach to increase reliability in MANETs is to exploit path diversity. The dense deployment of nodes in a MANET makes multipath routing a suitable and cheap technique to cope with the frequent topological changes and consequently unreliable communication services. Several multipath routing protocols were proposed for ad hoc networks [4-10]. The main objectives of multipath routing protocols are to provide reliable communication, to ensure load balancing, and to improve quality of service (QoS) of ad hoc and mobile networks. Other goals of multipath routing protocols are to improve delay, to reduce overhead and to maximize network life time.

In their pioneering work [11], Ahlswede et al. showed that if network coding is permitted over the nodes of a network, the communication rate can be improved compared to that obtainable by routing alone. Li et al. [12] showed that linear coding is sufficient for solving multicast network coding problems. Two alternative formulations of this condition are presented in [13]. These two formulations are closely tied to network flow and provide further insights and connections with combinatorial optimisation.

The max-flow min-cut theorem establishes that the maximum flow to the destination is equivalent to the number of disjoint paths. Hence, for the unicast case, an alternative to multipath construction is to use alternative methods that guarantee a certain maxflow to the receiver without relying heavily on specific path constructions. Jaggi et al. [14] gave deterministic polynomial time algorithms and even faster randomized algorithms for designing linear codes for directed acyclic graphs with edges of equal capacity. Noguchi et al. [15] showed that network coding can balance the load of a network. Chou et al. [16] presented a scheme for practical network coding in real networks and simulated the scheme on graphs of several Internet service providers (ISPs). Kagi et al. [17] proposed an efficient and reliable packet transmission method by using multipath routing constructs from multiple node disjoint routes, and by applying network coding, which allows packet encoding at a relay node.

For example, a wireless network coding scheme depicted in Figure 1. In this example, two wireless nodes need to exchange packets $a$ and $b$ through a relay node. However, the network coding approach uses a store and forward approach in which the two packets from the clients are combined by means of an XOR operation at the relay and broadcast to both clients simultaneously. The clients can then decode this coded packet to obtain the packets they need.

![Figure 1. Wireless Network Coding.](image)

The binary symbol $a \oplus b$ is a mathematical function of $a$ and $b$. Calculation of a function from received data is called coding. This shows the merit of mixed coding...
among multiple messages at an intermediate node. This is called network coding (NC). In algebra, \( a \oplus b \) is called the binary sum of \( a \) and \( b \). Interpreting in more general terms of linear algebra, this is the linear sum \( 1 \cdot a + 1 \cdot b \) over the binary field. Thus, the calculation of \( a \oplus b \) is not only a form of coding but also belongs to the more restricted form of linear coding.

This paper proposes a Network Coding-based on-demand Multipath Routing algorithm in MANET (NCMR). It is typically proposed in order to increase the reliability of data transmission, by applying network coding which allows packet encoding at a relay node. Because the encoding packet is generated by a relay node, the source node does not need to encode the packets but to send only data packets to each route. Thus, the packets transmitted by the source node are not increased.

The rest of the paper is organized as follows: In section II, we introduce multipath routing in MANETs. Section III presents network coding method in MANET. Some simulating results are provided in section IV. Finally, the paper concludes in section V.

II. MULTIPATH ROUTING IN MANETS

Many routing protocols preserve a caching mechanism by which multiple routing paths to the same destination are stored. Multipath routing is essential for load balancing and offering quality of service. On-demand routing protocols are inherently attractive for multipath routing, because of faster and more efficient recovery from route failures. Multipath algorithms based on the AODV [5] protocol have also been proposed. AOMDV [6] is based on a prominent and well-studied on-demand single path protocol known as ad hoc on-demand distance vector (AODV) [5]. AOMDV extends the AODV protocol to discover multiple paths between the source and the destination in every route discovery. Multiple paths so computed are guaranteed to be loop-free and link-disjoint paths. AOMDV has three novel aspects compared to other on-demand multipath protocols. First, it does not have high inter-nodal coordination overheads like some other protocols. Second, it ensures disjointness of alternate routes via distributed computation without the use of source routing. Finally, AOMDV computes alternate paths with minimal additional overhead over AODV; it does this by exploiting already available alternate path routing information as much as possible.

To improve the performance of AODV protocol, a multipath version of AODV called AODVM has been proposed in Marina et al. [7]. In the AODVM protocol, a destination node selects paths that pass through more reliable nodes. AODVM uses a method to find a pair of link-disjoint paths by selecting a route, which has a less number of common intermediate nodes on its path. We know that in route discovery process which sets up a reverse route using the RREQ(Route REQuest) arriving first. In route utilization process, the AODVM lets each neighboring node of a primary route to maintain its own backup route. This multipath method provides load balancing and avoids the inefficiency of AODV that needs a new route discovery during a path breaks. In route maintenance process, this method introduces a keep-alive packet that is periodically inserted to prevent timeout expiration of backup routes.

Aiming at maximally disjoints path maintenance for traffic distribution, the Split Multipath Routing (SMR) is proposed in [8]. SMR uses two link-disjoint paths where the traffic is split. The traffic is distributed between the two paths through a per-packet allocation technique. Duplicate RREQs are not necessarily discarded. Instead, intermediate nodes forward RREQs that are received through a different incoming link, and whose hop count is not larger than the previously received RREQs. The Scalable Multipath On-demand Routing (SMORT) is proposed in [9], which establishes fail-safe paths between intermediate nodes and the destination, reducing the delay and routing overhead, while achieving higher packet delivery ratios. Figure 2 shows multipath routing mobile ad hoc network.

III. NETWORK CODING METHOD

In our proposed method, multiple link-disjoint paths are constructed, and then the source node sends packets to a neighbor node on each path. The neighbor node generates an encoded packet when it receives the necessary data packets for encoding, then the neighbor node sends the encoded packet [17].

A. Basic Model

In our proposed method, network coding (NC), multiple link-disjoint routes are constructed. Figure 3 shows an example of two link-disjoint routes.

Primary path: \((S, 1, 3, 4, D)\).
Secondary path: \((S, 2, 3, 5, D)\).

Even if the data packets are lost, the destination node decodes the coded packets and successfully retrieves the data packets.

As shown in Figure 3, first, source node S sends a data packet named data1 to node 1. Node 1 receives data1 then forwards it to the next node, Node 3. Node 2 receives data2 then forwards it to the next node, Node 3. Node 3 receives data1 then buffers data1. Next, Source node S sends a data packet named data2. Again, node 2 receives...
data2 then forwards it to the next node, Node 3. Node 3 receives data2, and then generates the encoded packet code1 by encoding from data1, which is buffered, and data2. The node 4, 5 forward the packets on their respective routes.

For example, let us assume data1 is dropped between nodes 3 and 4. However, destination node D receives code1 and the data2, and so data1 can be decoded from these packets. Therefore, the number of transmissions does not need to be increased, and reliability can be improved because the encoded packet can be forwarded to destination node D.

B. Construction of Multiple Routes

We use AODVM [7] protocol to construct the multiple link-disjoint routes. AODVM has the best performance for multipath routing [10]. The AODVM computes the multiple paths with minimal additional overhead, contrary to other multipath routing protocols. If multiple link-disjoint routes are not constructed, the network coding will not be used and all nodes will send only the data packets. Similarly, all nodes send data packets when a single route is constructed.

Based on the distance vector concept, AODVM shares several characteristics with AODV [5], using hop-by-hop routing approach. Moreover, AODVM also finds routes on demand using a route discovery procedure. In AODVM, RREQ propagation from the source towards the destination establishes multiple reverse paths both at intermediate nodes and at the destination. Multiple RREPs (Route REPly) traverse these reverse paths back to form multiple forward paths to the destination at the source and intermediate nodes.

The core of the AODVM protocol lies in ensuring that multiple paths discovered are loop-free and link-disjoint, and finds efficiently such paths using a flood-based route discovery. AODVM route update rules which apply locally at each node and play a key role in maintaining loop-freedom and disjointness properties. The simulation study conducted on AODVM shows that there is a reduction, on the whole, of overhead in the network.

C. Network Coding Method

The network coding idea was introduced by Ahlswede et al. [11]. Usually, the routers or relay nodes just forward and duplicate the packets in the networks. However, network coding permits routers or relay nodes to encode the packets.

In this paper, we use a linear network coding scheme [12]. The linear network coding scheme is an encoding method such that coding vector \( g = (g_1, g_2, \ldots, g_N) \) is given, and input packet \( M = (M_1, M_2, \ldots, M_N) \) is converted into output packet \( P_i \) by the following expression [17].

\[
P_i = \sum_{j=1}^{N} g_j M_j
\]

The destination node can decode input packets because the coding vector \( G = (g_1, g_2, \ldots, g_N) \) and output packet data \( P = (P_1, P_2, \ldots, P_N) \) are obtained from the received packets, and an inverse matrix exists in \( G \).

IV. SIMULATION EXPERIMENTS

A. Simulation Model

To conduct the simulation studies, we have used randomly generated networks on which the algorithms were executed [18]. This ensures that the simulation results are independent of the characteristics of any particular network topology.

Mobility is one of the important characteristics of an ad-hoc network and can be defined as the average change in distance between all nodes over the simulation time. This effectively creates a dynamic topology; links will go up and down. Mobility is varied to investigate the impact it has on the different metrics being measured. The speed parameter is used to control the scenario. By increasing the speed, the mobility will also increase. For randomised simulations, the speed is varied between the interval of 0 and 10 m/s. A speed of 0 m/s corresponds to a static network, whereas a speed of 10 m/s corresponds to vehicle speed, which represents high mobility.

To effectively evaluate NCMR’s performance, we compare it with other famous multipath routing protocols AODVM for cost to control information, average link-connect time, the success rate to find the path and the feature of data transmission. Our simulation modeled a network of mobile nodes placed randomly within 1000m × 1000m area. Radio propagation range for each node was 250 meters and channel capacity of 2 Mbps is chosen. Node initial energy for each node was 80 joules. There were no network partitions throughout the simulation. Each simulation is executed for 600 seconds of simulation time. Multiple runs with different seed values conducted for each scenario and collected data was averaged over those runs. A free space propagation model was used in our experiments. A traffic generator was developed to simulate CBR sources. The size of the data payload is 512 bytes. Data sessions with randomly selected sources and destinations were simulated. Each source transmits data packets at a minimum rate of 4 packets/sec, and maximum rate of 10 packets/sec.

B. Performance Metrics

We will compare the performance of AODVM [7] multipath routing methods under the same movement models and communication models. Four key performance metrics are evaluated.

1. Packet overhead — the packet overhead is defined as the number of all node transmission packets, including data packets and encoded packets.

2. Average end-to-end delay of data packets — it represents the average value of the time that the received data packets take to reach the destination from their origin.

3. Packet delivery ratio — the packet delivery ratio is the ratio of the correctly delivered data packets, and is obtained as follows.

\[
\text{Packet delivery ratio} = \frac{\text{No. of packets delivered}}{\text{No. of packets sent}}
\]

The number of delivered data packets is the summation of total numbers of delivered data packets received by each node. The number of sent data packets is the summation of total numbers of sent data packets of each node. The
packet delivery ratio shows the transmission efficiency of the network with the given protocol.

4. Packet loss — the failure of one or more transmitted packets to arrive at their destination.

C. Simulation Results

The results of the simulation are positive with respect to performance. We use the ns-2 simulator [19] to evaluate the NCMR protocol.

Figure 3 shows the packet overhead as a function of the node’s mobility speed for each protocol. The packet overhead increases as the packet loss rate increases because the node’s mobility speed increases. NCMR, which sends both the data packets and encoding packets, has lower packet overhead than AODVM does, because AODVM sends only the data packets. Figure 3 shows a comparison of packet overhead. On the average NCMR reduces the routing overhead by 20-30% as compared to AODVM.

![Packet overhead vs. Node's mobility speed](image1)

Figure 3. Routing packet overhead with varying mobility

The average end-to-end delay includes all possible delays from the instant the packet is generated to the instant it is received by the destination node. Figure 4 depicts the comparison of average end-to-end delay under total of network nodes for both protocols. If the node’s mobility speed is high, the packet loss probability increases, and a longer route setup time is needed (i.e., the exchange time of route request (RREQ) and route reply (RREP) is longer). From the Figure 4 we can see that when the node’s mobility speed increases, NCMR average end-to-end delay is lower than that of AODVM.

![Average end-to-end delay vs. Node's mobility speed](image2)

Figure 4. Average end-to-end delay with varying mobility

From the simulation results we obtained, we can conclude that, compared to AODVM, NCMR has almost the same performance with low mobility and low network load. However, when the speed of the nodes or the network load increases, NCMR has a better delivery ratio and a shorter delay than AODVM has due to the ability to distribute the packets through different paths. In our settings, the speed is from 0 m/s to 10 m/s. From the trends we observe that NCMR offers more advantages than AODVM at even higher speed.

Packet delivery ratio is a key metric as it shows the loss rate, which in turn affects the maximum throughput of the network. With regard to the network coding when a byte of data is transmitted, Figure 5 shows the simulation results of NCMR routing protocol, and AOMDV. Figure 5 shows the packet delivery ratio as a function of the node’s mobility speed for each protocol. As the speed of the nodes increases, the probability of link failure increases and hence the number of packet drops also increases. However, NCMR has a higher ratio of packet delivery in comparison with that of AODVM. The NCMR is more robust with high load, and stays at about 80% even with high mobility. The delivery ratio is always superior to 80%, the AODVM protocol is more unstable with the high load. With a speed superior to 6 m/s, it drops to about 70%.

![Packet delivery ratio vs. Node's mobility speed](image3)

Figure 5. Packet delivery ratio with varying mobility

Packet loss represents another important measure that quantifies performance and also qualifies the links characteristics presented earlier. Packet loss mechanisms are much more complicated in MANETs because wireless links are subject to transmission errors and the network topology changes dynamically. Packet loss for the two schemes is shown in Fig. 6; NCMR has the lower packet loss, a consequence of lower route discovery latency. Packet loss takes into account packet drops at the MAC and the network layer. Packet losses follow increases in mobility because the protocol is sending RREQ packets on a broken route that it still considers being valid and, thus packets in node buffers are dropped because of congestion and timeouts. Packet loss in NCMR is lower simply as a consequence of better link fault tolerance when compared with the other schemes.

![Packet loss vs. Node's mobility speed](image4)

Figure 6. Packet loss with varying mobility
V. CONCLUSION

This paper discusses the multipath routing problem, which may deal with the network coding model for researching the MANET multipath routing problem. It presents a Network Coding-based on-demand Multipath Routing algorithm in MANET (NCMR). As a result, by taking packet delivery ratio, packet overhead, and average end-to-end delay into account, the NCMR allows packet encoding at a relay node. Because the encoding packet is generated by a relay node, the source node does not need to encode the packets, and sends only data packets to each route. The NCMR routing algorithm can be easily extended to other mobile networks QoS routing problems with NP complexity.

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