

Complex Field Network Coding-Based Multipath Routing in Mobile Ad Hoc Networks

Min Luo¹, Juanjuan Feng¹, Li Guan¹, Baolin Sun¹ and Hua Chen²

¹*School of Information Engineering, Wuhan International Trade University, Wuhan 430205, P. R. China*

²*College of Mathematics & Computer Science, Wuhan Textile University, Wuhan 430200, P. R. China*

E-mail: whicu@189.cn, 3704265@qq.com, ygl0090289@sina.com, blsun@163.com, qiuchen_1022@163.com

Abstract

Network coding in Mobile Ad hoc Network (MANET) is well-known in reducing delay, increasing throughput, and improving transmission reliability. While the data throughput capacity of MANETs is unknown, the scaling of capacity with the number of nodes has recently received increasing attention. This paper proposes a Complex Field Network Coding-based Multipath Routing in MANETs (CFNC-MRM). The performance of this routing method is studied using NS2 and evaluated in terms of the packet overhead, packet delivery ratio, and packet loss ratio when a packet is transmitted. Simulation shows that the CFNC-MRM is efficient, providing reliable multipath, promising and applicable in MANETs.

Keywords: MANET; complex field network coding; multipath routing.

1. Introduction

In current mobile ad hoc networks (MANETs), data packets are usually transported by routing, that is, by having intermediate nodes store and forward the data packets. However, routing is not the only operation that can be performed at a network node. Recently, the notion of network coding emerges as a promising generalization of routing.

Network Coding (NC) refers to a scheme where a node is allowed to generate output data packets by encoding (i.e., computing certain functions of) its received data packets, where data flows coming from multiple sources are combined to increase data throughput, reduce transmission delay, and enhance network robustness. Thus, network coding allows information to be mixed, in contrast to the traditional routing approach where each node simply forwards the received data packets. In contrast to the traditional store and forward approach [1-8], it implements a store, code, and forward technique, where each node stores incoming packets in its own buffer and transmits their combinations, where combining is performed over some finite Galois field [9-11].

Network coding was first proposed to achieve the multicast capacity in a multicast network in [1], Ahlswede et al. showed that if network coding is permitted over the nodes of a network, the communication rate can be improved over that obtainable by routing alone. Li *et al.* [5] showed that linear coding is sufficient for solving multicast network coding problems. Jaggi *et al.* [6] gave deterministic polynomial time algorithms and even faster randomized algorithms for designing linear codes for directed acyclic graphs with edges of unit capacity. Yang *et al.* [7] propose an approach to transforming the linear coding problem into a graph theory problem, the linear code is equivalent to a cover in the pseudo dual graph satisfying some constraints. Kagi *et al.* [8] 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.

Common to all these works is that network coding is applied over the Galois Field (GF) thus effecting bit-level operations. To further improve network throughput, the present paper develops a Complex Field Network Coding (CFNC) [9] approach which entails symbol-level operations at the physical layer. CFNC multiplies the source symbols by coefficients which are drawn from a given complex field and enables one-to-one mappings between the source symbol vectors and the received signals. Y. I. Min *et al.* [10] propose a modified maximum likelihood (ML) decision for a relay-based cooperative communication system using complex field network coding (CFNC). In Ref. [11], an algorithm is presented to provide precoding vectors that guarantee every superposed combination of user symbols at the relay is distinguishable and QAM constellations are received at the relay.

For robust delivery of packets, multipath routing [8, 12-16] is very important because the routes in ad hoc networks are easily fragile. The dense deployment of nodes in a ad hoc network 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 [12-16]. The main objectives of multipath routing protocols are to provide reliable communication and to ensure load balancing 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.

This paper proposes a Complex Field Network Coding-based Multipath Routing in MANETs (CFNC-MRM). Specifically, for a MANET with one source node S , R_L router paths and one common destination node D , a setup represented by the triplet $(1, R_L, 1)$. This clearly improves the throughput of Galois Field Network Coding (GFNC) $(1/(1+R_L))$ and that of traditional relying $(1/(1+R_L))$, especially as R_L grow large. 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 2, we introduce multipath routing and network coding in MANETs. Section 3 presents complex field network coding scheme. Some simulating results are provided in section 4. Finally, the paper concludes in section 5.

2. Multipath and Network Coding

A. Traditional Multipath Routing

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. Ad hoc On-demand Multipath Distance Vector (AOMDV) [14] is an extension to the AODV [13] protocol for computing multiple loop-free and link-disjoint paths. The protocol computes multiple loop-free and link-disjoint paths. The Scalable Multipath On-demand Routing (SMORT) is proposed in [15], which establishes fail-safe paths between intermediate nodes and the destination, reducing the delay and routing overhead, while achieving higher packet delivery ratios.

SMORT has the best performance for multipath routing [16]. The SMORT 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.

B. Network Coding Scheme

For example, a MANET 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 code 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.

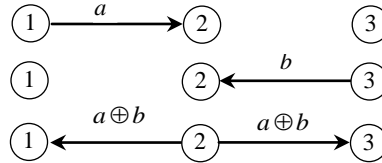


Figure 1. MANET Network Coding

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 $a \oplus b$ not only is a form of coding but also belongs to the more restricted form of linear coding.

3. Complex Field Network Coding Scheme

In our proposed scheme, 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 [8].

A. Basic Model

A communication network can be represented as a capacity graph $G = (V, E)$, where V and E are the set of vertices and edges respectively. In essence, a capacity graph models the connectivity of a communication network as well as the supported bit rates for the underlying communication links. In our proposed method, network coding (NC), multiple link-disjoint routes are constructed. Figure 2 shows an example of L link-disjoint routes. Consider a one-way MANET with one source node S , L router paths and relays nodes R_1, R_2, \dots, R_L , and one destination D , a setup represented by the triplet $(1, R_L, 1)$. There is no direct path between the source and the destination. Symbol level synchronization is assumed. First, S modulates codewords w_1, w_2, \dots, w_k into data packet s_1, s_2, \dots, s_k , let $M_s(\cdot)$ denote the coding vector scheme adopted by S , and we have $s_k = M_s(w_k), 1 \leq k \leq L$.

Source node S sending data packet s_1, s_2, \dots, s_k to all the relays node R_1, R_2, \dots, R_L . After detecting these data packet, the relays node R_1, R_2, \dots, R_L forward them to the destination node using a specific network coding scheme. Since this paper focuses on the transmission from the relays to the destination node D , it is assumed that the data packet from the source to the relays are error free. This clearly improves the throughput of GFNC($1/(1+R_L)$) and that of traditional relaying ($1/(1+R_L)$), especially as R_L grow large.

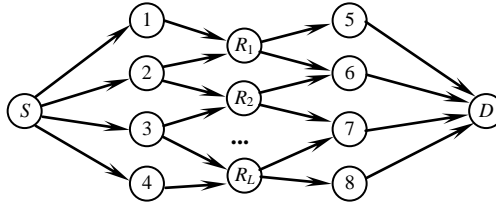


Figure 2. Multipath Routing and System Model between S and D

Figure 3 describes a traditional uncoded relay network. First, source node S transmits $D_S[i]$ to relay node R during time slot 1. After detecting $D_S[i]$, R forwards $\check{D}_S[i]$ to D during time slot 2. Likewise, destination node D transmits $D_D[i]$ to relay node R and R forwards $\check{D}_D[i]$ to source node S during time slot 3 and time slot 4, respectively.

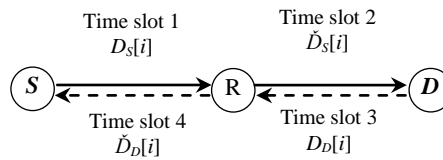


Figure 3. MANET using the Traditional Relay

Therefore, the traditional uncoded relay node has a problem where data packet to be transmitted has to spend a lot of time communication. To overcome this inherent limitation, the relay node based on CFNC is considered for improving throughput. Figure 4 illustrates a basic concept of the CFNC scheme.

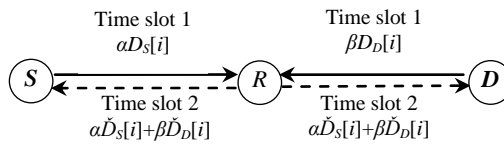


Figure 4. MANET using CFNC

In the first time slot, the source node S and the destination node D send data packet $\alpha D_S[i]$ and $\beta D_D[i]$ immediately node R , where α and β are CFNC factors ($\alpha + \beta = 1$). After detecting $D_S[i]$ and $D_D[i]$ as $\check{D}_S[i]$ and $\check{D}_D[i]$, respectively, from the superposition of received data packet, R transmits CFNC data packet $D_R[i]$, which is defined as (1), to S and D during time slot 2.

$$D_R[i] = \alpha \check{D}_S[i] + \beta \check{D}_D[i] \quad (1)$$

All data packets are assumed available to all nodes. The data packet received by destination node D at time t is

$$y_t = M_R \left(\sum_{k=1}^K c_k^t w_k \right) + n_D^t \quad (2)$$

where $n_D^t \sim N(0, N_0)$ is the Complex Gaussian distribution, $c_t = [c_{t,1}, c_{t,2}, \dots, c_{t,k}]$ is the coding coefficient vector. w_k and c_k^t are drawn from a finite field \mathbf{F}_q .

B. Network Coding Scheme

The network coding idea was introduced by Ahlswede *et al.* [4]. 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 [5]. The linear network coding scheme is an encoding method such that coding vector $g_i = (g_{i1}, g_{i2}, \dots, g_{iN})$ is given, and input packet $M = (M_1, M_2, \dots, M_N)$ is converted into output packet P_i by the following expression [8].

$$P_i = \sum_{j=1}^N g_{ij} M_j \quad (3)$$

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

C. Capacity Scaling

Capacity scaling quantifies how fast the information-theoretic capacity increases with the network coding size N . The pertinent metric is provided by the scaling exponent $e(N)$, which is defined as

$$e(N) = \lim_{n \rightarrow \infty} \frac{\log C(N)}{\log N} \quad (4)$$

where, $C(N) = N(N-1)R(G)$, $R(G)$ is the rank of matrix G .

Theorem 1(Upper Bound): The aggregate throughput in the network of CFNC is bounded above by

$$C(N) \leq KN^2 \log N \quad (5)$$

with high probability for some constant K independent of the network coding size N .

Theorem 2(Lower bound): With $\alpha \geq 2$ and for any $\epsilon > 0$, there exists a constant $K_\epsilon > 0$ independent of N such that with high probability, the aggregate throughput

$$C(N) \geq K_\epsilon N^{2-\epsilon} \quad (6)$$

is achievable by the network model of CFNC with network coding size N .

With the destination node D capable of decoding the source bits from the CFNC data packets, Within a path, each node distributes N coding vector data packets to each of the other nodes, so that at the end of this data packets.

The achievable capacity scaling per path in multipath scheme suffers a penalty of L relative to the multipath. Thus, the aggregate capacity scaling per path in the multipath is

$$C(N) = \frac{R(G)}{L} \frac{N^2}{(2R(G)+1)^{\log_L(N)} - 1} \quad (7)$$

$$C(N) = O(N^{2-\log_N(L)-\log_L(2R(G)+1)}) = O(N^{2-\epsilon}) \quad (8)$$

4. Simulation Experiments

A. Simulation Model

In this section, we present various simulation results for the proposed Complex Field Network Coding-Based Multipath Routing in MANETs (CFNC-MRM) scheme. The proposed scheme was compared with SMORT [15] in MANET environment. The corresponding simulation parameters are summarized in Table 1.

Table 1. Simulation Parameters

Number of nodes	100
Terrain range	1000m × 1000 m
Transmission range	250 m
Simulation time	600 seconds
Speed	0-20 m/s
Mobility model	Random way point
Propagation model	Free space
Channel bandwidth	2 Mbps
Data payload	512 bytes/packet
Node pause time	0-10 seconds
Communication model	Constant bit rate(CBR)
Examined routing protocol	SMORT [15]

To conduct the simulation studies, we have used randomly generated networks on which the algorithms were executed [17]. The results of the simulation are positive with respect to performance. We use the NS-2 simulator [18] to evaluate the Complex Field Network Coding-Based Multipath Routing in MANETs.

B. Performance Metrics

We will compare the performance of CFNC-MRM and SMORT multipath routing methods under the same movement models and communication models. We evaluate the performance according to the following metrics:

1. **Packet overhead** — the total number of scheme overhead packets over transmitted data packets and encoded packets.

2. **Packet delivery ratio** — Packet delivery ratio is the ratio of the number of data packets actually delivered to the destinations to the number of data packets supposed to be received. The packet delivery ratio shows the transmission efficiency of the network with the given scheme.

3. **Packet loss ratio** — the ratio of the data packets originated by the sources fails to deliver to the destination. Packet loss represents another important measure that quantifies performance and also qualifies the good put characteristics presented earlier.

C. Simulation Results

Figure 5 shows the packet overhead as a function of the node's mobility speed for each scheme. The packet overhead increases as the packet loss rate increases because the node's mobility speed increases. The CFNC-MRM, which sends both the data packets and encoding packets, has lower packet overhead than SMORT. For this simulation factors, the CFNC-MRM using CFNC scheme have smaller routing overhead than the SMORT scheme. On the CFNC-MRM scheme reduces the routing overhead by 15-25% as compared to SMORT scheme.

Figure 6 compares the packet delivery ratio of the CFNC-MRM scheme with SMORT. The delivery ratio presents the ratio of the number of packets received by multipath receivers versus the number of network coding data packets supposed to be received. For all kinds of traffic load, all schemes performance is affected by the node's mobility speed increases. The proposed CFNC-MRM scheme has the better packet delivery ratio than that of SMORT, because SMORT is using a traditional multipath structure, which CFNC-MRM is using the complex field network coding-based multipath route for the packets to deliver.

Figure 7 shows that the packet loss ratio has a decreasing trend as the node's mobility speed increases. Under all max nodes' mobility speed, CFNC-MRM scheme gives much lower packet loss ratio than SMORT scheme does. We can also observe that the packet loss ratio with CFNC and multipath routing degrades more gracefully than with other routing scheme does when the node's mobility speed increases.

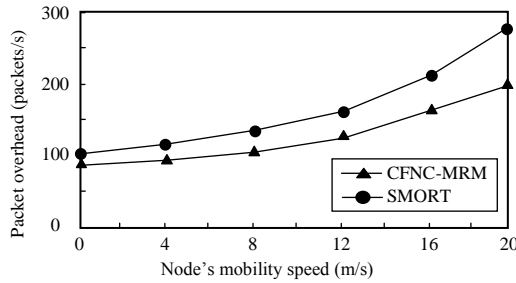


Figure 5. Routing Packet Overhead with Varying Mobility Speed

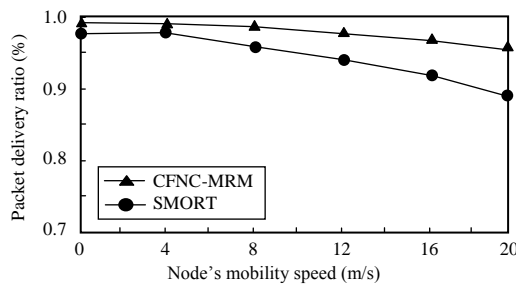


Figure 6. Packet Delivery Rate with Varying Mobility Speed

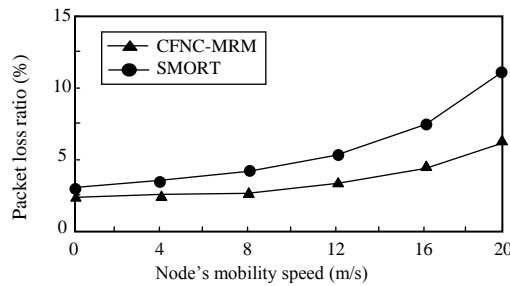


Figure 7. Packet Loss Ratio with Varying Mobility Speed

5. Conclusion

This paper first discusses complex field network coding and multipath routing problem, which may deal with the complex field network coding model for researching the MANETs multipath routing problem. Next, It presents a Complex Field Network Coding-based Multipath Routing in MANETs (CFNC-MRM). It is typically proposed in order to increase the reliability of data transmission, by applying complex field 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. Finally, the performance of this routing method is studied using NS2 and evaluated in terms of the packet overhead, packet delivery ratio, and packet loss ratio when a packet is transmitted.

Acknowledgment

This work is supported by The Social Science Foundation of China (No. 14BJY171), The Young and Middle-aged Elitists' Scientific and Technological Innovation Team Project of the Institutions of Higher Education in Hubei Province (No. T200902), Natural Science Foundation of Hubei Province of China (No. 2014CFA055, 2013CFB035, 2013CFB309), Key Scientific Research Project of Hubei Education Department (No. B20129205), Key Project of Hubei Province Education Science during the 12th Five-Year (2012A042, 2013B128).

References

- [1] B. L. Sun, C. Gui, Y. Song and H. Chen, "A Novel Network Coding and Multi-path Routing Approach for Wireless Sensor Network", *Wireless Personal Communications*, vol.77, no.1, (2014), pp. 87-99.
- [2] B. L. Sun, Y. Song, C. Gui and M. Luo, "Network Coding-Based Priority-Packet Scheduler Multi-path Routing in MANET using Fuzzy Controllers", *International Journal of Future Generation Communication and Networking*, vol.7, no.2, (2014), pp.137-147.
- [3] B. L. Sun, X. C. Lu, C. Gui, Y. Song, and H. Chen, "Network Coding-Based On-Demand Multipath Routing in MANET", *Proceedings of 26th IEEE International Parallel & Distributed Processing Symposium (IPDPS)*, (2012); Shanghai, China.
- [4] R. Ahlswede, N. Cai, S.-Y.R. Li and R. W. Yeung, "Network information flow", *IEEE Transactions on Information Theory*, vol.46, no.4, (2000), pp. 1204–1216.
- [5] S.-Y.R. Li, R.W. Yeung and N. Cai, "Linear network coding", *IEEE Transactions on Information Theory*, vol.49, no 2, (2003), pp. 371–381.
- [6] S. Jaggi, P. Sanders and P. A. Chou, "Polynomial Time Algorithms for Multicast Network Code Construction", *IEEE Transactions on Information Theory*, vol.51, no.6, (2005), pp. 1973–1982.
- [7] M. Yang and Y. Y. Yang, "A Hypergraph Approach to Linear Network Coding in Multicast Networks. *IEEE Transactions on Parallel and Distributed Systems*, vol.21, no.7, (2010), pp. 968-982.
- [8] T. Kagi and O. Takahashi, "Efficient Reliable Data Transmission Using Network Coding in MANET Multipath Routing Environment", in *Proceedings of 12th International Conference on Knowledge-Based Intelligent Information and Engineering*, (2008); Zagreb, Croatia.
- [9] L. Toka, M. Dell'Amico and P. Michiardi, "Online data backup: a peer-assisted approach", *2010 IEEE Tenth International Conference on Peer-to-Peer Computing*, (2010); Delft, Netherlands.
- [10] Y. I. Min, J. H. Jang, and H. J. Choi, "A Modified ML Decision for the Relay-based Cooperative Communication System Using Complex Field Network Coding", *Proceedings of IEEE Region 10 Annual International Conference on TENCON*, (2010); Fukuoka, Japan.
- [11] S. Sharifian, B. Hashemitabar and T. A. Gulliver, "QAM Constellation Design for Complex Field Network Coding in Multi-Way Relay Channels", *IEEE Wireless Communications Letters*, vol.2, no.5, (2013), pp. 483–486.
- [12] M. Tarique, K.E. Tepe, S. Adibi and S. Erfani, "Survey of multipath routing protocols for mobile ad hoc networks", *Journal of Network and Computer Applications*, vol.32, no.6, (2009), pp. 1125–1143.
- [13] C.E. Perkins, E.M. Belding-Royer and I.D. Chakeres, "Ad Hoc On-Demand Distance Vector (AODV) Routing", *IETF Internet Draft*, draft-perkins-manet-aodvbis-01.txt, (2004).
- [14] K. Mahesh, K. Marina and Samir R. Das, "Ad hoc on-demand multipath distance vector routing", *Wireless Communications and Mobile*, vol.6, no.7, (2006), pp. 969–988.
- [15] L. R. Reddy and S. V. Raghavan, "Smort: Scalable multipath on-demand routing for mobile ad hoc networks", *Ad Hoc Networks*, vol.5, no.2, (2007), pp. 162–188.
- [16] H. Zafar, D. Harle, I. Andonovic and Y. Khawaja, "Performance evaluation of shortest multipath source routing scheme", *IET Communications*, vol.3, no.5, (2009), pp.700–713.
- [17] B. Waxman, "Routing of Multipoint Connections", *IEEE Journal on Selected Areas in Communications*, vol.6, no.9, (1988), pp. 1617–1622.
- [18] The Network Simulator - NS-2: <http://www.isi.edu/nsnam/ns/>.

Authors



Min Luo received his M.S. degree from Wuhan University, China in 2003. He is currently a lecturer in computer science and technology of Wuhan International Trade University, China. His research interests include wireless communication and network optimization. E-mail: whicu@189.cn.



Juanjuan Feng received his B.E. degree from Central China Normal University, China in 2003. She is currently a lecturer in computer science and technology of Wuhan International Trade University, China. His research interests include wireless communication, network optimization and database technology. E-mail: 3704265@qq.cn.



Li Guan received his M.S. degree from China University of Geosciences, China in 2008. She is currently an associate professor in computer science and technology of Wuhan International Trade University, China. Her research interests include wireless communication, software engineering and so on. E-mail: ygl0090289@sina.com.



Baolin Sun received his Ph.D. degree from Wuhan University of Technology, China in 2006. He is currently a professor in computer science and technology of Hubei University of Economics, China. His research interests include multipath routing, parallel and distributed computing, network optimization and ad hoc networks. He has published over 130 journal and conference papers and has author of four books in the above areas. E-mail: blsun@163.com.



Hua Chen received his M.S. degree from Wuhan University, China in 2005. She is currently an associate professor of mathematics and computer science of Wuhan Textile University, China. Her research interests include algorithm, wireless communication, performance analysis, and network model. She has published over 30 research papers. E-mail: qiuchen_1022@163.com.

