Incorporating Network Coding into TCP Grounded on Network Utility Maximization in Multi-Radio Multi-Channel Wireless Mesh Networks

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Abstract

A new approach, named TCP-I^{2}NC, is proposed to improve the interaction between network coding and TCP and maximize the network utility in interference-free multi-radio multi-channel wireless mesh networks. It is grounded on a NUM formulation, and this NUM problem is decomposed into a rate control problem and a packet scheduling problem. The solutions to these two problems perform resource allocation among different flows. Simulations demonstrate that TCP-I^{2}NC derives a significant throughput gain and a small delay jitter Network resource is fairly allocated via the solution to the NUM problem and the whole system also runs stably. Moreover, TCP-I^{2}NC is compatible with traditional TCP variants.

Keywords: network utility maximization; network coding; wireless mesh network; TCP

1 Introduction

Mesh routers and mesh gateways in Wireless Mesh Networks (WMNs) are deployed as a static multi-hop backbone wireless network, and this backbone network is used to supply community or city-wide Internet access for mobile mesh clients [1], as illustrated in Fig. 1. In typical deployments of WMNs, mesh routers are equipped with only one IEEE 802.11 radio which is typically a single-channel [2]. However, single radio makes the available throughput for each mesh node decreases as $O(1/n)$ due to the half-duplex nature of the wireless medium [3]. Recently, one popular deployment method is to equip mesh routers with multiple radios based on IEEE 802.16 standard [4]. These radios operate on orthogonal channels. As a result, the interference between each other is significantly reduced and the available throughput for each mesh node is increased.

Besides the effort in the framework of WMNs, there are also other methods to improve the network performance. For example, Network Coding (NC) has become an interesting approach to increase throughput over WMNs [5-10]. Before forwarding a packet, a mesh node combines as many packets as possible together as long as all the concerned destinations have enough information to exact the data intended to them and sends it via broadcast. By doing this, multiple packets are forwarded to their destinations in one single transmission, which may translate to a higher throughput. But the throughput gain achieved by NC may be lower than expected under some conditions. First of all, the behavior of NC is not compatible with TCP's congestion control mechanisms, thus, the throughput gain is much lower in term

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of TCP flows [5, 7]. Secondly, the obtained gain is heavily relied on network topologies, packet losses and traffic patterns [5], and it may disappear as network environment changes. Thirdly, most of the proposed NC approaches don't consider network resource management and optimization problem in WMNs. Therefore, they can't make sure that network resource is fairly allocated to each user. In addition, researchers in NC area usually concentrate on the improvement of throughput. As a result, the performance of delay in WMNs is not well studied.

To address these problems above, a new approach, named TCP-I^{2}NC, is proposed to improve the TCP throughput and cope with random packet losses in lossy multi-radio multi-channel WMNs by incorporating network coding into TCP. A short version of this paper has been published in MSN 2011 [11]. But the resource allocation in [11] is not optimized. We extended TCP-I^{2}NC [11] to a Network Utility Maximization (NUM) framework [12] in this paper. The solution to the problem of maximizing the total utility of the network decomposes into several parts with an intuitive interpretation, such as packet scheduling and rate control.

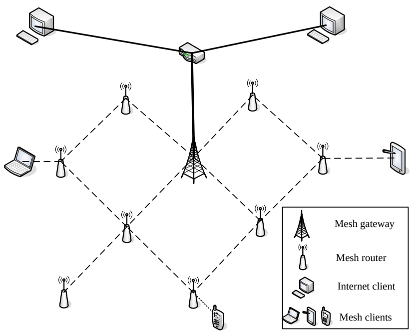


Fig.1 Demonstrate of WMNs

TCP-I^{2}NC works on mesh nodes and performs inter-flow and intra-flow network coding without overhearing opportunities. It can significantly improve the throughput of TCP and derive a reasonable end-to-end delay. The contributions of this paper can be summarized as follows:

- It presents a novel approach to incorporate network coding into TCP which is transparent to TCP applications on mesh clients or Internet side nodes and compatible with TCP's congestion control mechanisms.
- It is grounded on a NUM framework. The rate of each TCP flow is adaptively changed based on the network utility formulation. As a result, TCP-I^{2}NC achieves good fairness in resource allocation.

The rest of the paper is organized as follows. Section II presents related work. The system model, basic notions and NUM formulation are introduced in section III. Section IV gives a description to the proposed approach. The implementation details are presented in section V. Simulation results are given in section VI. Finally, section VII is the conclusion.

2 Related work

2.1 Network coding in WMNs

COPE [5] combines several packets into one packets by performing XORs network coding and achieves a significant throughput gain. Huang et al. [6] improved COPE by inducing small delays at relays. TCP/NC [8–9] first incorporates network coding into TCP based on the

Rank metric. Inspired by it, Senger et al. [10] proposed a mechanism grounded on the Hamming metric.

2.2 NUM in coded systems

Recently, there is a large body of work that formulates and solves a network utility maximization framework in context of network coding. For inter-flow network doing, NCAQM [13] was proposed following a NUM formulation to fully exploit network coding opportunities; Sudipta et al. [14] proposed a multi-path and coding-aware routing for COPE based on a theoretical formulation to maximize the throughput; Prasanna et al. [15] developed optimal and adaptive joint network coding and MAC scheduling schemes for COPE to achieve the throughput gains expected; Keivan et al. [16] took into account the reliability information and proposed an approach to increase the aggregate network utility in a wireless inter-flow network coding system; Danail et al. [17] proposed a systematic, suboptimal, yet practical approach for multiple unicasts based on a linear optimization framework; Forward Error Correction (FEC) was combined into NC to alleviate the different link status between the relay node and intended receivers [18]; CLONE [19] was proposed to introduce adequate redundancy in local NC operations which makes optimal formulations easy to realize in practice. For pairwise inter-flow network coding, an optimal joint coding, scheduling, and rate-control scheme was proposed in [20].

3 System model, notation and network utility maximization formulation

In this section, system model used in our problem is first introduced. Next, some notations that used throughout this study are presented. Finally, the network utility maximization formulation is introduced in detail.

3.1 System model

A packet-switched wireless mesh network is modeled as a Graph (N, L), where N is the set of nodes and L is the set of wireless links. Let R be the set of radios equipped on mesh nodes and H the set of available orthogonal channels for each radio. Link $(i, j)\in L$ has a capacity c_{ij}, propagation delay d_{ij} and packet loss rate p_{ij}. A packet forwarded on a link is either received by the receiver without error or lost. A mesh node is equipped with multiple radio interfaces and radios in the direct interference range are operated on different orthogonal channel.

3.2 Notation

Random linear network coding: The idea of random linear network coding [21] is adopted throughout this study. A node in our system is allowed to perform random linear network coding instead of simply forwarding packets. For example, assuming node A wants to send packets to node B and there are packets **m1** and **m2** in node A. Then node A uniformly chooses coefficients from a sufficiently large Galois Field $F_q = GF(q)$ and forwards combinations of these two packets, where q is the field size, and q is set to 256 in our system. It may send $\mathbf{n1} = \alpha\mathbf{m1} + \beta\mathbf{m2}$ and $\mathbf{n2} = \lambda\mathbf{m1} + \mu\mathbf{m2}$, where $\alpha, \beta, \lambda, \mu \in GF(q)$. The encoding process can be expressed as0

$$\begin{bmatrix} \mathrm{n1} \\ \mathrm{n2} \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ \lambda & \mu \end{bmatrix} \begin{bmatrix} \mathrm{m1} \\ \mathrm{m2} \end{bmatrix} = C \begin{bmatrix} \mathrm{m1} \\ \mathrm{m2} \end{bmatrix}, \tag{1}$$

where C is the coefficient matrix, and coefficient vectors $[\alpha, \beta]$ and $[\lambda, \mu]$ are its row vector.

After receiving the packets n1 and n2, the receiver can obtain the original packets by inverting the matrix C using Gauss-Jordan elimination and the decoding process can be expressed as

$$\begin{bmatrix} \mathrm{m1} \\ \mathrm{m2} \end{bmatrix} = C^{-1} \begin{bmatrix} \mathrm{n1} \\ \mathrm{n2} \end{bmatrix}. \quad (2)$$

The receiver needs as many coded packets that have independent coefficient vectors as the number of original packets involved.

TCP flows: Let F be the set of TCP flows from sources to destinations. Each flow $f \in F$ is associated with a rate x_f and a utility function $U(x_f)$ which is a strictly concave function of x_f. Different types of fairness can be achieved via different utility functions. A class of utility functions is defined as follows [22-23]:

$$U^a(x) = \begin{cases} \log x, & if \ a = 1, \\ \dfrac{x^{1-a}}{1-a}, & a \geq 0, a \neq 1. \end{cases} \quad (3)$$

The utility function used in our system is given by

$$U(x) = U^{a=1}(x) = -\frac{1}{x}. \quad (4)$$

Routing: Each flow f is forwarded along a single path from the source to the destination which is pre-determined by a routing protocol, e.g., MR-LQSR [24], and given as an input to our problem.

3.3 Network utility maximization formulation

A network is stable if the total output traffic at node i is larger than the total input traffic, which is given as

$$\sum r_{ij}^f - \sum r_{ji}^f - x_{f\{s(f)=i\}} \geq 0, \quad (5)$$

where $x_{f\{s(f)=i\}} = x_f$ if $s(f) = i$, or 0 otherwise. We also have

$$\sum r_{ij}^f \geq 0, \quad (6)$$

$$\sum_{f \in F} r_{ij}^f \leq c_{ij}. \quad (7)$$

The total network utility is $\sum_{f \in F} U(x_f)$. Network utility maximization formulation is to find the flow rate to solve

$$\max \sum_{f \in F} U(x_f) \ \text{ subject to (5),(6),(7).} \quad (8)$$

4 Proposed approach

In this section, a new approach that incorporates network coding into TCP, which can effectively cope with random losses and significantly improve the throughput of TCP, is proposed. It introduces a hop-by-hop Inter- and Intra-flow Network Coding (I^2NC) scheme which was detailed illustrated in [11]. In this study, rate control and packet scheduling algorithms decomposed from the solution to the problem of NUM are proposed to perform congestion control.

The solution to the NUM problem (8) can be obtained via the dual formulation [12, 25] by incorporating the constraints into the maximization as follows:

$$D(\vec{q}) = \max \sum_f U(x_f) - \sum_{l \in L} q_l \left(\sum_{f:l \in f} x_f - c_l \right) \\ = \sum_f E(q_l) + Z(\vec{q}), \tag{9}$$

where q_l is the Lagrange multiplier for each constraint, and

$$E(q) = \max U(x_f) - x_f q, \tag{10}$$

$$Z(\vec{q}) = \max \sum_{(i,j) \in L} c_{ij} \max_f (q_i^f - q_j^f). \tag{11}$$

Given $\vec{q}$, the dual problem can be decomposed into the rate control problem (10) and the packet scheduling problem (11) [25]. q_i^f can be interpreted as the cost from node i to the destination of flow f. Finally, the optimal rate control and packet scheduling algorithms are given by

Rate control: the source of flow *f* (i.e., a mesh gateway or a mesh client) sets the rate according to

$$x_j^* = \arg\max_{x_f > 0} U(x_f) - x_f q^f. \tag{12}$$

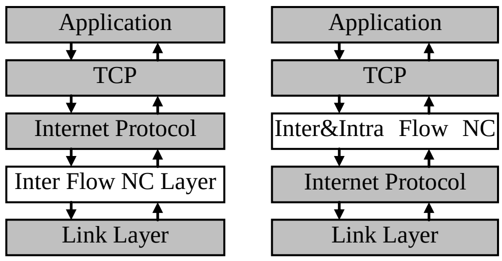
Packet scheduling: the optimal packet scheduling is the solution to

$$f^* = \arg\max \sum_{(i,j) \in L} c_{ij} \max_f (q_i^f - q_j^f). \tag{13}$$

On link (i, j), q_j^f is sent back to node *i* by piggybacked on an ACK of our hop-by-hop I^2NC scheme.

5 Protocol implementation

Our I^2NC scheme, rate control and packet scheduling algorithms are implemented with as little change as possible in the existing protocol stack. As shown in Fig. 2, a new network coding layer is introduced in wireless nodes in WMNs.



(a) Mesh gateway and mesh (b) Mesh client

Fig.2 New network coding layer in the protocol stack

There are a sender module and a receiver module in each NC layer. They are in charge of sending and receiving packets separately, and the details of their operations are presented in Algorithm 1 and Algorithm 2. These two algorithms are based on one-way TCP flows. A mesh node uses queue Q_{el} to buffer those TCP packets that needed to be forwarded to destinations. If a node is an end node, it uses encoding queue Q_{e0} to buffer TCP packets that are not acknowledged by the TCP flows in its TCP layer or Internet side nodes. P_{el} is the loss rate on link *l*.

Algorithm 1 Operation of sender module on link $l(i, j)$

$S_f = 0$
While(1)
1) If node i is the source (or a mesh gateway if flow f is on the Internet side) of flow f & Sender Timer (0.1s) expires,
  a) calculate x_f according to (12),
  b) S_f += $x_f/10$,
  c) generate $\lfloor S_f \rfloor$ ACK to the Transport Layer at source,
  d) S_f – = $\lfloor S_f \rfloor$.
2) Pick N_l packets from Q_{el} according to (13) if there exists, forward $\lfloor N_l / (1–P_{el}) \rfloor$ linear combinations of them, save the sent packet number.
3) If Receiving Timer expires, generate a NC-ACK to the encoder.
4) Check whether there are new and sequential TCP packets in Q_{e0}, if exist, send the packets in sequence.

Algorithm 2 Operation of receiver module on link $l(i, j)$

While (Receive a packet a)
1) If a is a control packet for TCP connection management, forward it directly
2) If a is an ordinary TCP packet, find a's next link m, insert a to Q_{em}.
3) If a is a coded packet, buffer and decode it, and let m denote its next link (m = 0, if this node is an end node),
  a) if successful decoding, generate an ACK to the sender with some information, e.g., q_j^f, P_{el}, etc, update Q_{em}, and cancel the Receiving Timer;
  b) else, run the Receiving Timer.
4) If a is a NC-ACK, and let r denote the rank of the decoding coefficient matrix,
  a) if $r = N_l$, delete those buffered TCP packets, recalculate P_{el}, q_i^f, release the encoder;
  b) else, regenerate $\lfloor N_l/(1–P_{el})–r \rfloor$ random combinations of the corresponding encoding block of TCP packets.

6 Simulation results

In this section, simulation results obtained via ns-2 [26] are introduced.

6.1 Simulation setup

The simulation topology is illustrated in Fig. 3. There are 4 TCP flows between node 0 and node 5. TCP/NC in [8–9] is an end-to-end approach and we denote it as TCP/NC$_{\text{end-to-end}}$. To effectively deal with losses, we extend it to a hop-by-hop approach, named as TCP/NC$_{\text{hop-by-hop}}$, by adding redundancy only before lossy links.

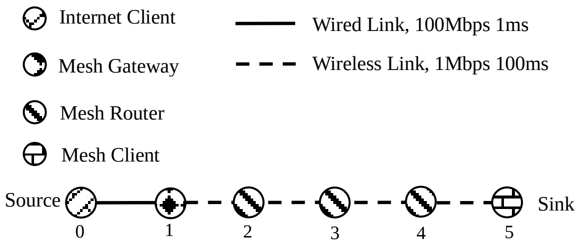


Fig.3 Infrastructure-basd multi-hop wireless network

6.2 Simulation results

6.2.1 Throughput and delay jitter

We use *Max* $Thr_{end\text{-}to\text{-}end}$ to denote the maximum available throughput in theory for an end-to-end approach and *Max* $Thr_{hop\text{-}by\text{-}hop}$ to present the maximum available throughput in theory for a hop-by-hop approach. As shown in Fig. 4, the end-to-end approach $TCP/NC_{end\text{-}to\text{-}end}$ achieves a throughput closing to *Max* $Thr_{end\text{-}to\text{-}end}$; $TCP/NC_{hop\text{-}by\text{-}hop}$ outperforms $TCP/NC_{end\text{-}to\text{-}end}$ by performing hop-by-hop network coding. But network resource is not fully utilized by $TCP/NC_{hop\text{-}by\text{-}hop}$. As a result, the throughput achieved by $TCP/NC_{hop\text{-}by\text{-}hop}$ is lower than TCP-I^{2}NC. TCP-I^{2}NC derives a throughput closing to *Max* $Thr_{hop\text{-}by\text{-}hop}$

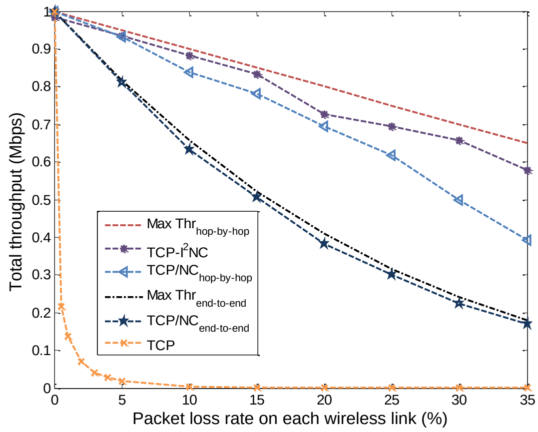


Fig.4 Total throughput vs packet loss rate

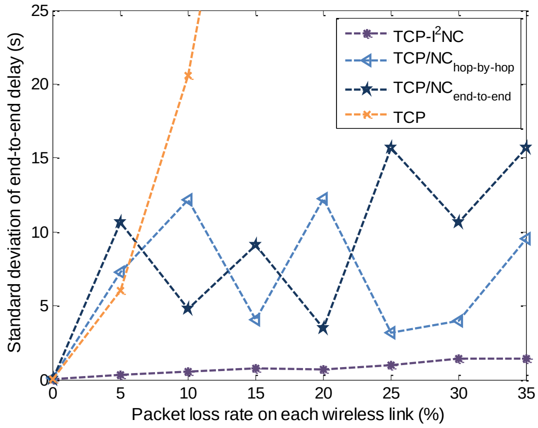


Fig.5 Standard deviation of delay

The delay jitter is also a key factor that greatly affects the experience of users in practice. We evaluate the variation of standard deviation of delay for each approach. As shown in Fig. 5, the standard deviation of delay in TCP-I^{2}NC is relatively stable and remains at a very small value, which means that the delay jitter of TCP-I^{2}NC is small. This property of TCP-I^{2}NC supplys the demand for interactive applications.

6.2.2 Fairness, network utility and system stability

We also study the status of real-time network utility under various packet loss rate. For our simulation, the theoretical maximum network utility is given by

$$\sum_{i=1}^{4} U(x_i) = \sum_{i=1}^{4} -\frac{1}{x_i} = \sum_{i=1}^{4} -\frac{1}{0.25} = -16. \tag{14}$$

When there are packet losses, the theoretical maximum network utility in average is decreased because the available bandwidth for each user is reduced to 1-*P*, where *P* is the packet loss rate on each wireless link. As shown in Fig. 6, the real-time network utility of our approach is relatively stable and is very close to maximum network utilty in theory, which demonstrates our approach works effectively and resource is fairly used.

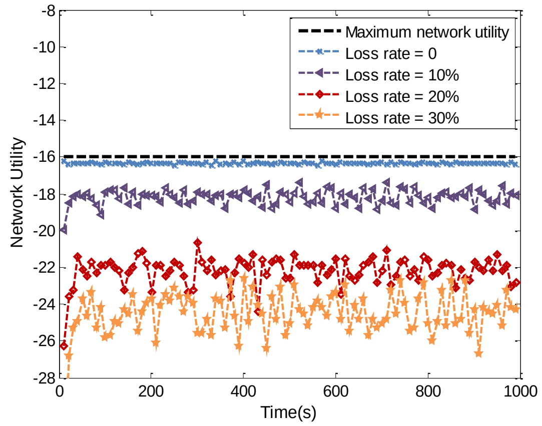


Fig.6 Real-time network utility

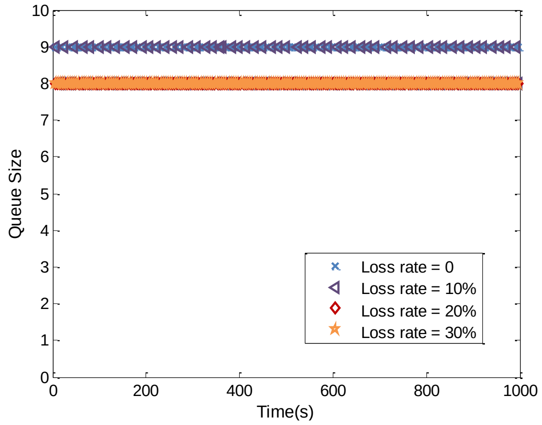


Fig.7 The length of packet queue on node 1

Next the stability of the whole system is studied. There is a bottleneck link (i.e., link(1, 2)) in the network. The variation of packet queue on node 1 and the real-time total throughput reflect the effect of rate control and packet scheduling algorithms. As seen in Fig. 7, the length of packet queue on node 1 is very small and hardly changed which demonstrates our system is very stable. In addition, there is also little or no variation in the real-time total throughput of our approach, no matter what the loss rate is, as shown in Fig. 8. In summary, our congestion control mechanisms works effectively and our system is very stable.

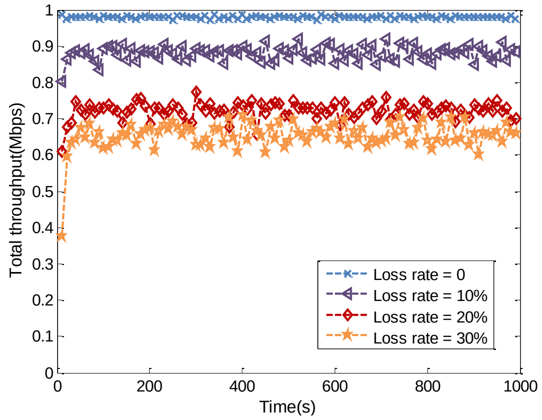


Fig.8 Real-time total throughput

7 Conclusions

TCP-I^{2}NC is grounded on a NUM formulation, and this NUM problem is decomposed into a rate control problem and a packet scheduling problem. The solutions to these two problems perform network resource allocation among different flows. Simulations demonstrate that TCP-I^{2}NC derives a great throughput gain over lossy wireless mesh networks. Meanwhile, the delay jitter is very small, which makes our mechanism is applicable to delay-sensitive applications. Moreover, network resource is fairly allocated via the solution to the NUM problem and the whole system runs stably.

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