ANC: Adaptive Unsegmented Network Coding for Applicability

Chen Chen, Chao Dong, Hai Wang, Weibo Yu
Institute of Communications Engineering, P.L.A. University of Science and Technology
Email: {chchen2001, dch999, haiwang}@gmail.com, bigtouyu@163.com

***Abstract*—Unsegmented network coding (UNC) is a promising technology to overcome poor source information scheduling of segmented network coding (SNC) in large scale networks, where unresponsive feedback slacks the scheduling. However, three unsolved problems limit its applicability. First, UNC employs ACK on witness as the feedback. The frequently triggered witness-ACK will introduce considerable overhead and depress throughput. Second, a new constraint from practical decoding requirement on the slide window has recently been proved. The additional constraint will make UNC much different, which has not been studied. Third, although UNC may outperform SNC in large scale networks, it does not work well in small and moderate-sized networks, exhibiting poor universality. In this paper, we address these problems and propose the Adaptive unsegmented Network Coding (ANC). ANC applies technologies for improvements, which is derived through reinvestigating UNC (solve the second problem), to improve achievable throughput, and save a majority of control overhead (solve the first problem). In addition, ANC incorporates a novel hybrid source packets admission scheme and can well adapt to various network conditions (solve the third problem). Simulation results show that ANC outperforms both SNC and UNC in universal network conditions, and the throughput gain over both can be up to 22%.**

I. INTRODUCTION

Network coding (NC) was introduced in 2000 [1], and has attracted substantial attention since then. In contrast to conventional networks, intermediate node in NC may process received information before forwarding. And remarkable performance improvement can be achieved in terms of throughput [2], delay [3] as well as reliability [4]. One important issue in NC is how to schedule source information for transmission efficiently. On the one hand, transmitting overmuch redundancy leads to low utilization and even congestion; on the other hand, insufficient redundancy may result in decoding failure, which impairs both reliability and throughput. Thus the significance of the source information scheduling in NC lies in the remarkable influence on throughput and reliability.

The simplest method of the source information scheduling in NC is to divide source packets into segments and transit them one-by-one with ACK as the signal for the sender to move to the next [2]. Such method guarantees full reliability, but degenerates in large scale networks since delayed and lossy ACK may slack the scheduling. To improve the scheduling, one can transmit multiple segments simultaneously [5], or let intermediate node initiate ACK once it can decode a segment [6]. Nevertheless, they use segmented network coding (SNC) as well and suffer from the same fundamental difficulty. As another way of source information scheduling in NC, unsegmented network coding (UNC) manipulates source information at the granularity of packet, and exhibits more flexibility [7]. To support such scheduling, UNC incorporates the concept of "witness" in [8] and employs a witness-ACK (ACK on witness) based slide window mechanism [7] [9].

However, stat-of-the-art UNC schemes are faced with three crucial problems, which limits their applicability in practice.

- **High control overhead**. Existent UNC schemes use witness-ACK as the feedback for the sender to control the slide window. Witness-ACK will be triggered every time a new packet is witnessed by the receiver. As a consequence, considerably high control overhead will be introduced, which results in low resource utilization and severe interference between data and feedback.
- **An additional constraint**. Our recent study has that the amount of decoding-unacknowledged packets admitted into the slide window should be restricted (decoding constraint) due to practical decoding requirement [10]. Taking into account the decoding constraint will change the behavior of the slide window, thus making UNC much different, which has not been studied however.
- **Poor universality**. Although UNC may outperform SNC in large scale networks, it is inferior to SNC in small networks. In addition, it is expectable that neither SNC nor UNC works well in moderate-sized networks. This demonstrates poor universality of both UNC and SNC.

This paper addresses above problems. We start by reinvestigating UNC in light of the additional decoding constraint, where we derive new features. Based on the features, we provide technologies for improvements, including achievable throughput maximization and control overhead reduction. The later technology can eliminate a majority of feedback without side-effect, which gracefully addresses the problem of high control overhead in UNC. Furthermore, we design a novel hybrid source packet admission scheme (HSPA) for achieving tunable compromise between UNC and SNC, such that one solution can well adapt to various network conditions.

Incorporating the above technologies to the original UNC, we derive an improved version of UNC, called Adaptive unsegmented Network Coding (ANC). We implement and test ANC on QualNet-5.0. Simulation shows that ANC outperforms SNC and UNC (with the overhead reduction technology) in universal network conditions, which is even beyond our expectation. Moreover, the throughput gain over both UNC and SNC can be up to 22%. Our contributions are four folds:

- We reinvestigate UNC in light of the decoding constraint. We derive new features and provide technologies to maximize the achievable throughput and reduce overhead.
- We propose a hybrid source packet admission scheme to make UNC well adapt to various network conditions.
- We incorporate technologies derived in this paper, and propose an improved version of UNC, Adaptive unsegmented Network Coding (ANC).
- We show by simulation universal throughput gain of ANC over both SNC and UNC, thus validating the applicability.

The remainder of this paper is organized as follows. Sect. II introduces related works. Sect. III deals with the additional decoding constraint and high overhead in UNC. Sect. IV deals with the poor university in UNC, and propose ANC. sect. V evaluate ANC. Sect. VI concludes this paper.

II. Related Work

MORE realized the first practical NC based transmission scheme, which partitions source packets into segments of equal size and transmits the segments one-by-one with end-to-end ACK as the signal for the source node to move to the next one [2]. However, MORE degenerates in large scale networks since unresponsive feedback slacks the scheduling [5]. This motivates several follow-up works. For example, CodeOR transmits multiple segments simultaneously in flight, to reduce gaps between segments [5]. In [6], forwarder is supposed to initiate an ACK once it can decode one segment, such that a ACK can reach the sender earlier. In addition, ACK on degree of freedom can be utilized to assist scheduling decision [11].

UNC was proposed originally to improve the throughput of TCP in lossy environments [9]. Since coded transmission naturally eliminates out-of-order and replicated reception in multipath case, the NC based TCP can be easily extended to the multipath case [12]. Later, SlideOR utilizes UNC to overcome poor source information scheduling of SNC in large networks [7]. SlideOR employs an aggressive window strategy for faster information dissemination, which seriously impairs reliability. Furthermore, SlideOR assumes perfect feedback, and omits performance degeneration caused by feedback traffic, which is actually non-trivial. The decoding constraint for practical UNC is presented in our original work in [10], but its impacts on UNC has not been studied. Note that all these UNC schemes rely on witness-ACK for the slide window operation.

III. Unsegmented Network Coding with the Decoding Constraint

This section take into account the decoding constraint and reinvestigates UNC. We thereby derive new features of UNC, and provide technologies for improvement. Specially, one technology can be used to save a majority of overhead, which addresses high control overhead in UNC.

A. Review of the Original UNC

We start with a brief review of the original UNC. Throughout the paper, we assume that source packets from session are tagged with consecutive sequence numbers and P_i is the i^{th} packet. UNC can be decoupled into four parts.

1) The Slide Window: The sender maintains a slide window with maximum size W for encoding and transmitting source packets. The window operation is decoupled into downside operation and upside operation: the upside operation admits new packets into the window for transmission, while the downside operation removes acknowledged (sect. III-A3) packets from the window. With cumulative ACK, the window size w is equal to the number of unacknowledged packets in the window. It is clear that w is restricted by W, which is referred to as the window constraint.

2) Encoding and Decoding: When the source gets a transmission chance, it randomly generates an encoding vector in a finite field, and linearly combines all packets in the window, i.e. $\sum_{i=l}^{h} \alpha_i P_i$, where $(\alpha_l, \alpha_{l+1}, ..., \alpha_h)$ is the encoding vector, and (l, h) indicate the range of packet sequence number in the window. The coding vector will be attached to and transmitted along with coded packet.

On receiving a coded packet, the receiver checks whether the packet is innovative, i.e. linearly independent from previously received ones. Innovative packets will be buffered, otherwise discarded. Let w' be the degree of knowledge space of unknown packets at the receiver and x' be the number of unknown packets that the receiver is aware of. When $w' = x' > 0$, the receiver can decodes all x' unknown packets by Gauss elimination and matrix inversion.

Relay node processes received packets similarly to the receiver, and recodes packets similarly to the sender. Note that such operation is not employed in end-to-end NC schemes.

3) Feedback: The slide window at the sender is advanced strictly according to witness-ACK such that full reliability is guaranteed. A node is said to have seen packet P_k, if it has received enough information to compute a linear combination of the form $P_k + q$, where q is a linear combination involving only P_j $(j > k)$ [8]. The witness-ACK contains the minimum sequence number of unwitnessed packets, and will be triggered on witnessing each new packet at the destination.

4) Redundancy: UNC introduces source redundancy to combat losses, which is derived by creating difference between transmission and admission. Let R be the redundancy factor. It means that R coded packets will be transmitted on admitting each source packet. Redundancy only could not guarantee decoding. When the window gets full without chance of decoding, UNC enters its 2^{nd} phase to perform SNC-like operation: the sender keeps transmitting coded packets until an ACK flushes some or all source packets in the window.

B. New Features and Technologies for Improvement

We assume that the minimum sequence number of undecoded packets is also attached to each ACK. Then source packet can also be decoding-acknowledged. Let x be the number of decoding-unacknowledged packets that have been admitted into the network, namely admitted into the slide window. Then x should be restricted in practice.

Theorem 1: (**Decoding constraint**) For practical UNC window operation, there must be a constraint X on the number of decoding-unacknowledged packets that have been admitted into the slide window at the sender, namely x.

Refer to our previous work in [10] for the proof.

Hence, the (upside) window operation in practical UNC is subjected simultaneously to the decoding constraint and the window constraint, as shown in fig. 1. With the additional decoding constraint, UNC exhibits new features.

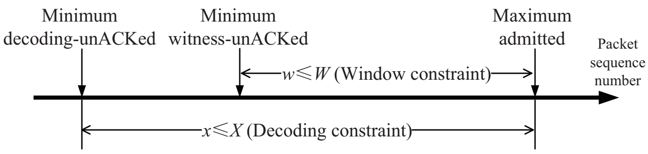


Fig. 1: The constraints on the slide window operation in UNC

Theorem 2: When $W \geq X$, the window constraint on UNC window operation is invalidated.

Proof: Since being witness-unacknowledged implies being decoding-unacknowledged, the number of witness-unacknowledged packets must be less than or equal to the number of decoding-unacknowledged packets, i.e. $w \leq x$. Combined with theorem 1 that x is restricted by X, it yields that w is actually restricted by $\min(X, W)$. When X is less than W, w will be restricted by X before it reaches W. In another word, the window could never get full, which demonstrates invalidated window constraint. ■

In light of theorem 2, we derive the following conclusions which are helpful for improving the performance of UNC.

1) Achievable throughput maximization: With fixed X, the achievable throughput is maximized when $W \geq X$. This arises from the intuition that if the window size W is small, UNC is unable to efficiently utilize bandwidth resources, and thus its throughput suffers. To achieve higher throughput, larger W is always preferred. On the other hand, with determined X, W equal to X suffices, because larger W will make no difference, as stated in theorem 2.

2) Control overhead reduction: When $W \geq X$, witness-ACK is useless and can be eliminated, whereas decoding-ACK suffices for UNC window operation. This is simply because that $W \geq X$ invalidates the window constraint, as stated in theorem 2. Since witness-ACK is triggered by witness of every packet, eliminating it can save a majority of control overhead of UNC, which addresses the problem of high control overhead in UNC. Note that, without witness-ACK, a packet will be removed from the window when it is decoding-acknowledged, which indicates that the window size turns to be x.

Above improvement requires $W = X$. Since X could not be quite large [10], and is commonly less than 64, a slide window sized $W = X$ is completely feasible and acceptable.

IV. Adaptive Unsegmented Network Coding

Although UNC may outperform SNC in large scale network, it is inferior to SNC in small network. In addition, both UNC and SNC are expected to be suboptimal in moderate-sized network. The poor universality of UNC can be attributed to that its advantage on efficient scheduling vanishes as the network scalability shrinks, while the cost remains, including high control overhead from frequent feedback and low coding efficiency caused by encoding over minor packets. This section proposes a novel Hybrid Source Packet Admission scheme (HSPA) to address the poor universality of UNC.

By incorporating HSPA and applying the technologies in sect. III-B to UNC, we derive an improved version of the original UNC, called Adaptive unsegmented Network Coding scheme (ANC), which will be evaluated in the next section. In the rest of this section, we focus on HSPA.

A. The Design of HSPA

Our inspiration comes from the intuitive idea that if a NC scheme can achieve tunable compromise between UNC and SNC, then it can well adapt to various network conditions. On the other hand, we notice that the fundamental distinction between UNC and SNC lies in the source information scheduling. SNC schedules source information for transmission at the granularity of segment, namely block of packets, whereas UNC admits/removes source information into/from the slide window at the granularity of packet. Specially, the original UNC admits one packet into the slide window each time.

To achieve the compromise between UNC and SNC, we resort to a Hybrid Source Packet Admission scheme, in which both block admission and packet admission can be employed. Which operation will be executed is determined by the slide window status. In our design, we introduce a threshold X_0 $(1 \leq X_0 \leq X)$ for x. In the case that $x < X_0$, block admission would be employed, where $X_0 - x$ packets will be admitted into the slide window. Namely, x is directly increased to X_0. In the case that $x \geq X_0$, one packet will be admitted into the slide window, which is identical to the original UNC. We will describe the merits of such design in sect. IV-B.

Algorithm 1 HSPA(R, X_0, w, x, W, X)

if $w < W$ (Window constraint) **then**
  if $x < X$ (Decoding constraint) **then**
    if $x \geq X_0$ **then**
      $N \leftarrow 1$
    else
      $N \leftarrow \min(X_0 - x, W - w, X - x)$
    end if
    Admit next N source pkts into the window
    Generate NR coded pkts, add them to the TX buffer
  end if
end if

Fig. 2: Hybrid source packet admission scheme

When N (may be one) packets are admitted into the slide window, the sender is supposed to transmit NR coded packets.

Nevertheless, it does not always have to transmit all those packets, since it is possible that a feedback, which acknowledges all packets in the window, might reach the sender and clear the unfinished packets in the buffer. We describe HSPA in fig. 2. Without loss of generality, we reserve the window constraint (line 1,6) for compatibility. HSPA will be called when coded packets are sent out or cleared by ACK, such that desired redundancy is derived.

B. The Advantages from HSPA

Two advantages that ANC can obtain through HSPA are quite obvious:

1) Universality: Through tuning X_0, ANC achieves different balance of compromise between SNC and UNC: with larger X_0, ANC approaches SNC, and at the same time trends to be away from UNC. Two extreme cases in ANC are: 1) when $X_0 = 1$, ANC degenerates to the original UNC; 2) when $X_0 = X$, ANC degenerates to SNC with segment size of X as long as $W \geq X$. Hence, in the worst cases, ANC can optionally degenerate to the better one of UNC and SNC.

2) Further gain: ANC can simultaneously enjoy partial advantage of both SNC and UNC: 1) the block admission stage avoids encoding over minor ($< X_0$) packets, which leads to high coding efficiency; and also increases average decoding matrix size, which declines frequency of feedback; 2) the packet admission stage at large x ($> X_0$) suppresses the possibility of halted slide window, which leads to full use of slide window and thus efficient scheduling. The above analysis implies that ANC is promising to achieve further gain over even the better one of UNC and SNC.

V. Performance Evaluation

We test ANC on QualNet-5.0. For ease of illustration, we consider a wireless tandem network in fig. 3, but we emphasize that our solution is applicable to any topology. Both the transmission range and the interference range are up to adjacent neighbors. The MAC protocol is TDMA. Nodes are scheduled in group, where group i ($i = 1, 2, 3$), consisting of nodes $\{i, i+3, i+6, ...\}$, can access the channel on slots $\{i, i+3, i+6, ...\}$. Hence the network is collision-free. We assume the sender has infinite packets to be transmitted. We assume sufficiently large field size to eliminate the problem of linearly dependence. We assume equal loss probability ϵ on wireless links. Thus the end-to-end loss probability is $e = 1-(1-\epsilon)^{K-1}$. ACK packets are assumed to be loss-free, for the reason that the network is collision-free and they are small to be well protected by error correction code. Finally, we let both X and W be 20 as an instance of ANC, and witness-ACK is eliminated. We vary e from 0.09 to 0.6, and K from 10 to 60 to simulate various network conditions.

Two examples of throughput performance of ANC are shown in fig. 4, where R is simply set to $\frac{1}{e}$. Recall that ANC with $X_0 = 1$ and $X_0 = X$ are identical to UNC (with the overhead reduction technology) and SNC respectively. As expected, UNC outperforms SNC in small network in fig. 4(a). In contrast, SNC outperforms UNC in large network in

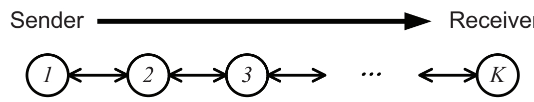
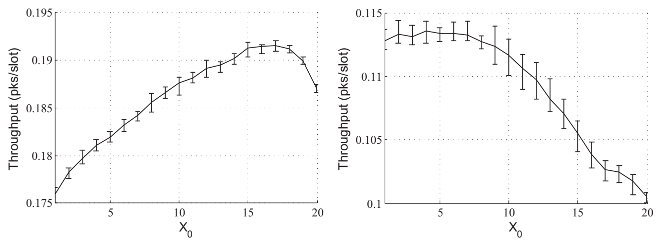


Fig. 3: Wireless tandem network with K nodes

fig. 4(b). Non-monotonic curves in both sub-figures show that ANC with proper X_0 can outperform both SNC and UNC. It suffices to justify the throughput gain of ANC over SNC. But the gain over UNC is not sure yet, because the performance of UNC and ANC depends on R, and they may be suboptimal with current R. We are not going to study the topic of optimal R. Instead, we derive it through simulation.



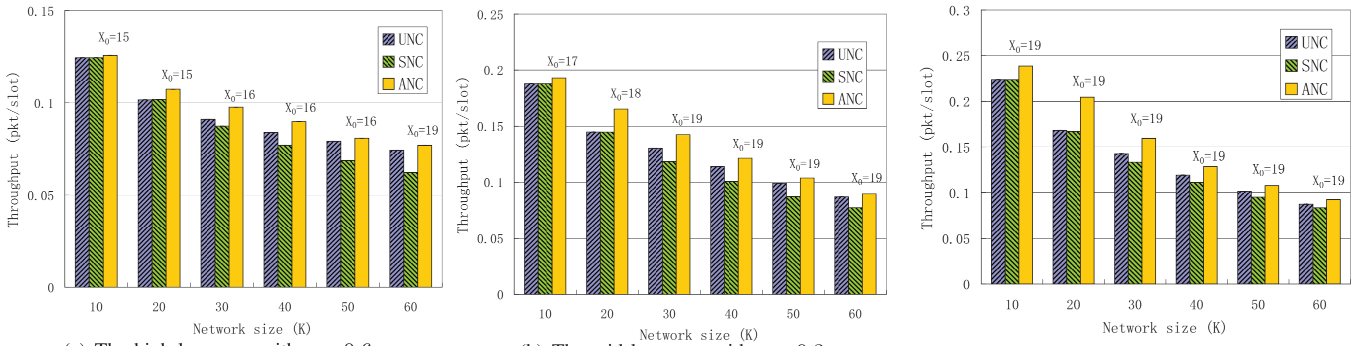
(a) $K = 10$ (b) $K = 40$

Fig. 4: Throughput of ANC v.s. X_0 with $e = 0.3, R = \frac{10}{7}$

The comparison of throughput among SNC, UNC and ANC with optimal R is shown in fig. 5. The optimal X_0 that maximizes throughput of ANC is also labeled. Unexpectedly, UNC dose not lose to SNC in any condition. We attribute this to that UNC with $R = 1$ is similar with systematic SNC, and systematic SNC delivers the same performance as SNC when the field size is sufficiently large.

Let G_{AU} and G_{AS} be the throughput gain of ANC over UNC and SNC respectively. We can see notable G_{AU} and G_{AS} in most conditions in the figure. Even in the worst cases, both G_{AS} and G_{AU} are nonzero, which justifies universality of ANC. We also observe that high G_{AU} is achieved with moderate network size. For example, G_{AU} is 21.7% when $K = 20$ in fig. 5(c). On the other hand, G_{AS} is high with both small and moderate network size. For example, G_{AS} is 23% when $K = 60$ in fig. 5(a), and is 22% when $K = 20$ in fig. 5(c). Let X_0^* be the optimal X_0 that maximizes the throughput of ANC. It is observed in fig. 5 that X_0^* is always relatively large, where X_0^* is at least $15 = 0.75X$. Furthermore, X_0^* will approach $X - 1$ as K increases or e decreases.

To provide an insight into how ANC adapts, we show normalized overhead and average decoding matrix size, denoted by $\overline{M_D}$, in fig. 6 where $K = 10$. It is shown that $\overline{M_D}$ increases with the increase of X_0, and ends at 20 when $X_0 = 20$. The $X_0 \sim \overline{M_D}$ curve reflects the tunable compromise between UNC and SNC: increasing X_0 helps to enjoy the advantage of SNC, but larger $\overline{M_D}$ implies higher possibility of halted slide window, i.e. less efficient scheduling. An interesting finding



(a) The high loss case with $e = 0.6$ (b) The mid loss case with $e = 0.3$ (c) The low loss case with $e = 0.09$

Fig. 5: Throughput comparison among UNC, SNC and ANC in various network conditions

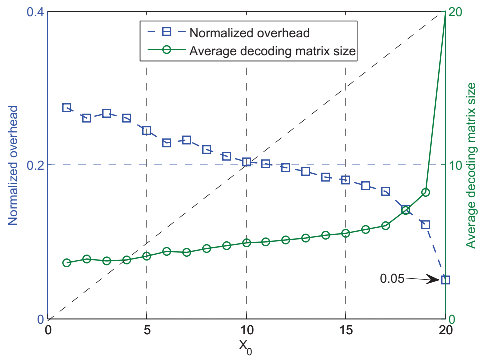


Fig. 6: Normalized overhead and average decoding matrix size with $e = 0.09, K = 10, R = 2.0$

is that with large X_0, $\overline{M_D}$ is always less than X_0. Specially, when $X_0 = 19$, i.e. $X - 1$, $\overline{M_D}$ is less than $10 = \frac{X}{2}$. This implies that, compared with SNC, ANC can benefit much from the advantage of UNC at minor sacrifice of the advantage of SNC. Thus G_{AS} is achievable even in small network. Note that X_0^* is 19 in majority of cases, which coincides with the above analysis. We can prove that G_{AU} can be universally achieved in similar way, which is omitted for limit of space.

Normalized overhead $\overline{M_D}$ is defined as the ratio of the feedback traffic to the throughput. It declines with the increase of X_0, because larger $\overline{M_D}$ lowers the frequency of decoding-ACK. The fact that $\overline{M_D}$ increases sharply as X_0 decreases also explains why X_0^* tends to be large. It is seen that the maximum $\overline{M_D}$ is 0.28, when $X_0 = 1$, namely UNC (with the overhead reduction technology). However, it is obvious that $\overline{M_D}$ in UNC without our overhead reduction technology would be at least 1, since witness-ACK will be triggered when the receiver witnesses every packet.

VI. Conclusion

In this study, we address three crucial problem that limits applicability of UNC in practice, which are high overhead, unknown impact from the practical decoding constraint, and poor universality. We reinvestigate UNC in light of the decoding constraint, derive new features and technologies for improvements, including one that addresses the high overhead. To overcome poor universality in UNC, we design a hybrid source packet admission scheme for adaptability to various network conditions. Incorporating all derived technologies to the original UNC, we obtain the Adaptive unsegmented Network Coding (ANC). Finally, we show by simulation universal throughput gain of ANC over both SNC and UNC, which validates the applicability of ANC.

Acknowledgement

This work is supported in part by the China 973 Project (No.2009CB302402), the China NSF (No.61103224), and the Jiangsu Province NSF (No.BK2011118).

References

[1] R. Ahlswede, N. Cai, S. R Li. and R. W. Yeung, Network information flow, *IEEE Trans. on Information Theory*, 2000.

[2] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, Trading Structure for Randomness in Wireless Opportunistic Routing, *in Proc. of ACM SIGCOMM*, 2007.

[3] L. Huang, S. Pawar, H. Zhang, K. Ramchandran, Codes Can Reduce Queueing Delay in Data Centers, *in Proc. of IEEE ISIT*, 2012.

[4] F. C. Kuo, K. Tan, X. Y. Li, J. Zhang, and X. Fu, XOR rescue: exploiting network coding in lossy wireless networks, *in Proc. of IEEE SECON*, 2009.

[5] Y. Lin, B. Li, and B. Liang, CodeOR: Opportunistic Routing in Wireless Mesh Networks with Segmented Network Coding, *in Proc. of IEEE ICNP*, 2008.

[6] Y. Lin, C. Huang, and J. Huang, PipelineOR: A Pipelined Opportunistic Routing Protocol with Network Coding in Wireless Mesh Networks, *in Proc. of IEEE VTC*, 2010.

[7] Y. Lin, B. Liang, and B. Li, SlideOR: Online Opportunistic Network Coding in Wireless Mesh Networks, *in Proc. of IEEE INFOCOM*, 2010.

[8] J. K. Sundararajan, D. Shah, and M. Médard, ARQ for Network Coding, *in Proc. of IEEE ISIT*, 2008.

[9] J. K. Sundararajan, D. Shah, M. Médard, M. Mitzenmacher, and J. Barros, Network Coding Meets TCP, *in Proc. of IEEE INFOCOM*, 2009.

[10] C. Chen, C. Dong, F. Wu, H. Wang, L. Peng, and J. Nie, Improving Unsegmented Network Coding for Opportunistic Routing in Wireless Mesh Network, *in Proc. of IEEE WCNC*, 2012.

[11] D. E. Lucani, M. Stojanovic, and M. Médard, Random linear network coding for time division duplexing: when to stop talking and start listening, *in Proc. of IEEE INFOCOM*, 2009.

[12] S. Gheorghiu, A. L. Toledo, P. Rodriguez, Multipath TCP with Network Coding for Wireless Mesh Networks, *in Proc. of IEEE ICC*, 2010.