Coverage Enhancement to IEEE 802.11p Using Work-Based Opportunistic Relay-Assisted Network-Coding ARQ

Jung-Chun Kao, Fu-Wen Chen, Ming-Hung Yang, and Te-Li Wang
Department of Computer Science
National Tsing Hua University
Hsinchu, Taiwan, R.O.C.

Abstract—**This paper presents an efficient ARQ protocol, called WO-RANC, to enhance coverage and performance of IEEE 802.11p. WO-RANC exploits relay-assisted network coding and work-based wide-sense opportunistic retransmission. Relay nodes with strong connectivity to destinations opportunistically deliver information to the destinations on behalf of sources, thus enhancing coverage and performance. To minimize redundant retransmissions due to loss of per-packet ACKs and avoid relays from transmitting non-innovative packets, both sources and relays combine packets stored in their buffers for transmission, rather than store and forward. In addition, WO-RANC uses the concept of work to accurately estimate the information deficiency that destination nodes do not received due to failed transmissions. And accordingly, relay nodes transmit packets to supplement the information deficiency. Our simulation results show that WO-RANC outperforms 802.11p and several other schemes in terms of throughput and delay, for a large range of source-destination distances.**

Keywords—ARQ, opportunistic retransmission, network coding, wireless network, vehicular network.

I. Introduction

Dedicated Short-Range Communication (DSRC) is a block of spectrum exclusively allocated to automotive use and a short-range communication service based on a set of standards and protocols. Among these standards, IEEE 802.11p standard [1] is approved in July 2010 to add wireless access in vehicular environments consisting of vehicles and roadside units (RSUs). However, considering the short physical transmission range (300m typically, 1000m max) [2], the mobility of vehicles, the density of deployed RSUs, and the growing demand in data rate, an efficient mechanism is needed to extend RSU coverage and enhance performance of IEEE 802.11p, particularly when the vehicle-to-RSU distance is close to or larger than the physical transmission range. This motivates us to propose a novel relay-assisted solution for coverage and performance enhancement to IEEE 802.11p.

This paper presents the *w*ork-based, *o*pportunistic, *r*elay-*a*ssisted, *n*etwork-*c*oding (*WO-RANC*) ARQ protocol at the *link layer*. The proposed scheme takes advantage of both *wide-sense* opportunistic retransmission and *relay-assisted* network coding. In addition, to enhance coverage and performance without an increase in overhead, WO-RANC has a simple yet novel approach, based on the concept of *work*, for relay nodes to determine when and how many packets should be sent out.

Opportunistic retransmission proposed in [3] is a link-layer technique that leverages the broadcasting nature of wireless communication and the benefit of multi-path transmission: Data packets not reaching the destination node will be retransmitted by close-by relay nodes that overhear the data packets. Such an opportunistic use of multi-path transmission inherently extends coverage and brings performance gain because appropriately chosen relay nodes have stronger connectivity to destination nodes than source nodes have. To enable relays aware of missed data packets, opportunistic retransmission rely on the per-packet acknowledgement (ACK) function. However, ACK loss due to poor channel condition may cause the ARQ timeout, which trigger redundant retransmissions of data packets. A significant communication overhead incurs, particularly in realistic channels with poor and varying channel quality.

Network coding offers an elegant solution to this challenge and can remove the requirement of using per-packet ACKs. Network coding transmits a data segment consisting of several blocks over the network in a more efficient manner: Instead of simply forwarding received blocks, a node takes several blocks and combines them together for transmission. This way, regardless which blocks are lost, the destination node can retrieve the data segment, as long as a sufficient number of blocks reach the destination node. Network coding has been an active research topic in wireless networks. Many studies have shown that network coding brings performance gains [4]-[5] from both theoretic and practical aspects, particularly in specific scenarios with multicast traffic [6]-[8], two-way flows [9]-[10], or multiple unicast flows [11]. Besides, it is shown in [12] that MAC-layer random network coding outperforms Hybrid Automatic Repeat reQuest (HARQ) in WiMAX systems.

We emphasize that our proposed scheme is very different from most of existing studies for twofold reasons. First, from the perspective of applicability, the scheme of relay-assisted network coding designs for *one-way* relaying systems and thus can easily apply to IEEE 802.11p, while many network-coding-related research efforts in the literature are not readily applicable to IEEE 802.11p because they are designed for

This work is supported in part by National Science Council, Taiwan, under grants NSC 98-2218-E-007-007, NSC 98-2219-E-007-012, NSC 99-2219-E-007-005, and NSC 100-2219-E-007-003.

specific scenarios such as two-way relaying systems and multicast networks. Second, from the technical point of view, we develop a technique called *wide-sense* opportunistic retransmission. Unlike the plain opportunistic retransmission proposed in [3], the way in which the wide-sense opportunistic retransmission determines whether or not to forward overheard blocks is independent of the unfavorable per-packet acknowledgement function. In the WO-RANC protocol we propose, relay nodes use the concept of *work*, an estimation of the amount of information not reaching the destination node, to decide when and how many blocks should be sent out to destination by relay.

The work-based wide-sense opportunistic retransmission scheme we propose is outlined as follows. Relay nodes silently overhear wireless channels and estimate the amount of information not been successfully received by the destination node. This dynamically changing information deficiency is called *work*. Relay nodes transmit a number of packets in order to decrease work. We note that the work-based wide-sense opportunistic retransmission scheme retains the advantages of the plain opportunistic retransmission, while cooperating well with relay-assisted network coding without the need of the per-packet acknowledgement function.

The remainder of this paper is organized as follows. Section II describes the basic concept of our proposed WO-RANC protocol. Section III elaborates on important protocol details including relay selection and source/relay prioritization. Section IV presents our evaluation results. Finally, Section V summarizes this paper.

II. Basic Concept of WO-RANC

In this section, we elaborate on the three key components of WO-RANC—relay-assisted network coding, work-based wide-sense opportunistic retransmission and increment/decrement of work. For simplicity of exposition, we consider the three-node network shown in Figure 1, in which a relay node is appropriately chosen to help data transmission between source and destination when the direct link ($\overline{SD}$) has poor quality.

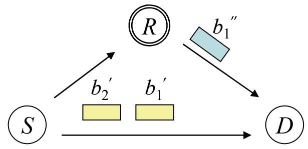

Figure 1. A three-node network containing source (*S*), destination (*D*) and relay (*R*). The source node and relay node send out coded blocks (denoted by b_i') and double-coded blocks (denoted by b_i''), respectively.

A. Relay-Assisted Network Coding (RANC)

To extend coverage, it is important to explicitly cope with challenges occurring when the distance between source and destination is beyond the physical transmission range and the distance from source to relay and the distance from relay to destination are close to the physical transmission range. In such a situation, IEEE 802.11p packets are easily lost in transit and redundant retransmissions of data packets occur frequently due to loss of per-packet ACKs. To reduce these unneeded retransmissions, our proposed scheme uses a technique called the relay-assisted network coding (RANC), which does not rely on the per-packet acknowledgement function.

As in [12]-[13], a data *segment* is divided into *n original blocks*, denoted by $b_1, b_2, \ldots, b_n$. The original blocks are not transmitted by a source node. Instead, as shown in Figure 1, the source node sends out the *coded blocks*, denoted by $b_1', b_2', \ldots$, which are produced by taking linear combinations of all or a subset of the original blocks over a finite field (with a set of coding coefficients $[c_1, c_2, \ldots, c_n]$ over the finite fied):

$$b_i' = \sum_{j=1}^{n} c_{i,j} b_j$$

Without the help of per-packet ACKs, a relay node should not simply forward the coded blocks it overhears; otherwise, the forwarded blocks are likely to be non-innovative because they are replicates of what the destination node has received. Instead, when needed, the relay node produces *double-coded blocks*, denoted by $b_1'', b_2'', \ldots$, by taking linear combinations of all or a subset of the overheard coded blocks. After that, the double-coded blocks are sent to the destination node.

For the simplest version of RANC, named as *plain-RANC*, every time when overhearing a coded block sent by the associated source, a relay node produces a double-coded block. For WO-RANC which exploits and takes advantage of work-based wide-sense opportunistic retransmission, the criterions of when and how many double-coded blocks should be sent out by a relay node are described in sections II.B and II.C.

The destination node receives coded blocks sent by source and double-coded blocks sent by relay. It decodes the received coded and double-coded blocks back to original blocks, by using a progressive Gauss-Jordan elimination process. The progressive decoding process which executes along with the packet reception process is able to discard non-innovative blocks immediately. After the decoding process has recovered the entire data segment, the destination node sends a *per-segment* ACK back to the source node. Upon receiving the per-segment ACK, the segment transmission finishes. Source and relay stop this segment transmission and may start a new segment transmission.

B. Work-Based Wide-Sense Opportunistic Retransmission

The performance of RANC can be improved by leveraging opportunistic retransmission. However, the plain opportunistic retransmission proposed in [3] does not apply to RANC because it requires the per-packet acknowledgement function. To cooperating RANC without the need of per-packet ACKs, the work-based wide-sense opportunistic retransmission is proposed to replace the plain opportunistic retransmission.

Figure 2 gives a high-level overview of the work-based wide-sense opportunistic retransmission. For a source-destination pair, the associated relay node silently overhears wireless channels and estimates the amount of information not been successfully received by the destination node. This dynamically changing information deficiency is called *work*. The relay node does not begin to send out double-coded blocks from the very beginning. Instead, the relay node may delay the first retransmission. As the source node keeps overhearing coded blocks, the value of work monotonically increases until work exceeds a threshold w. After that, the relay node may send out a number of double-coded blocks to decrease work.

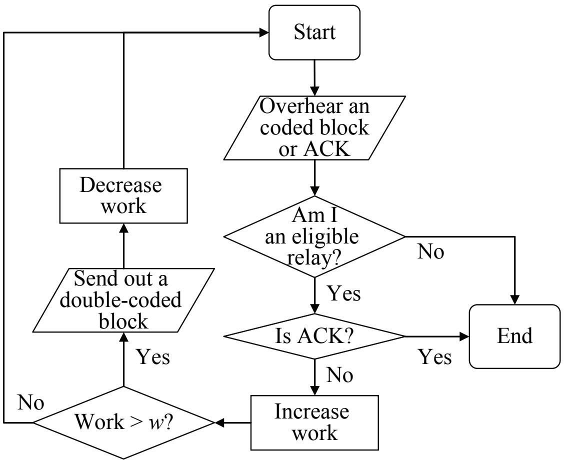

Figure 2. Flowchart of wide-sense opportunistic retransmission at a relay node, in which "ACK" means a *per-segment* acknowledgement.

C. Increment and Decrement of Work

Wide-sense opportunistic retransmission does not need the per-packet acknowledgement function; however, it needs a mechanism that uses information other than received per-packet ACKs to increase and decrease the value of work at a relay node. To this end, we propose an information-theoretic method which is simple yet effective.

Consider the probabilistic model shown in Figure 3. (In reality, the link reception probability values can be computed with the help of measured RSSI values and a lookup table.) Suppose each innovative block carries one unit of information. Every time when the source node transmits a block, because the block reaches the destination node with a probability of P_{SD}, the destination node gains P_{SD} unit of information on average. And the average information lost in transit is $1 - P_{SD}$.

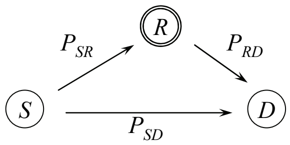

Figure 3. Link reception probabilities of blocks (denoted by P_{SD}, P_{SR}, and P_{RD}), for a given source-destination pair.

Since the purpose of a relay node is to help information delivery, a relay node has the responsibility to supplement the information deficiency. Therefore, a relay node increases its work by $1 - P_{SD}$ when overhearing a block sent by source.

Knowing the increment of work, let us consider the decrement of work. It makes no sense for a relay node to send out blocks when the relay node has zero or little work. Instead, a relay node may send out one or multiple blocks only if it has accumulated enough work. For every innovative block sent by relay, the destination node gains P_{RD} unit of information on average. Therefore, the relay node decreases its work by P_{RD} after sending out a single block.

According to the above explanation, our mechanism for the decrement of work is summarized as follows. Denote the current work value by W. If W is greater or equal to the threshold $w = P_{RD}$, the relay node start to transmit (double-coded) blocks until the value of work becomes smaller than P_{RD}. Since transmission of a single block decreases work by P_{RD}, the relay node sends $\lfloor W / P_{RD} \rfloor$ blocks in succession and the remaining work becomes $W - \lfloor W / P_{RD} \rfloor P_{RD}$.

III. Relay Selection

In this section, we describe the mechanisms of relay selection and source/relay prioritization.

A. Relay Selection

Using poor relays can hurt performance since failed and redundant transmissions result into waste of channel capacity. As shown in Figure 4, our proposed scheme consists of two stages—the relay selection and the data transmission stages.

When a source node needs to find an appropriate relay, it enters the relay selection stage and sends a relay request (REQ) packet. Once overhearing REQ, the destination node and relay candidates reply relay response (RES) packets. The destination node replies RES immediately after waiting a DIFS interval, while relay candidates back off random times before replying RES packets. The distribution of backoff time depends on the link quality—the better link quality, the shorter backoff time on average. This way helps the source node to select a relay node which is appropriate and at the same time reduces the occurrence of collisions.

The destination and relay candidates may reply RES multiple times (up to the RES retry limit), if previous RES packets fail to reach the source node. After receiving RES packets replied by relay candidates and the destination node, the source node decides the relay node(s) for this segment transmission, according to the measured RSSI values and the information conveyed in the RES packets. Once the source node determines relay(s), both source and relay(s) enter the data transmission stage, transmitting coded and double-coded blocks in the way as what Section II describes.

We note that depending on the performance metric, the relay selection algorithm which finds the best relays still remains an open question and is out of the scope of this paper. Decentralized relay selection mechanisms can be found in the literature such as [3] and [14]. In our simulation, a simple heuristic is used to select relay nodes.

In our simulation, for each segment transmission, a source node selects exact one relay node among relay candidates, unless there is no relay candidate around or the S-D link itself has great quality. (Relaying does not really provide significant performance gain when the S-D link is of great quality.) Relay candidates are the destination's neighbors which have good link quality to source. Link quality is measured by received signal strength indicator (RSSI). To reduce fluctuation, RSSI values are averaged using exponential weighted moving average. Nodes with RSSI values below a threshold are not qualified to be relay candidates. The better link quality, the more likely a relay candidate will reply the RES message early. Among the relay candidates, the one which replies RES earliest is chosen to be the relay for this segment transmission.

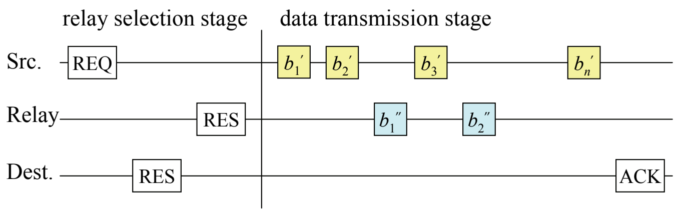

Figure 4. The two stages—relay section and data transmission.

B. *Source/Relay Prioritization*

Because an appropriately chosen relay node typically has a better connectivity to the destination than the source node has, it is advantageous for a relay node with a sufficient amount of work to transmit double-coded blocks as soon as possible, rather than to wait the source node to transmit more coded blocks. To achieve that, a possible solution is coordination between source and relay, for example, by distributing feedback for each failed transmission.

However, to be maximally compatible to the IEEE 802.11 standard as well as to avoid overhead of distributing feedback among source and relay, we do not suggest sending feedback. Instead, we suggest taking advantage of the built-in mechanisms of the 802.11 standard, for example, by managing the backoff time at source and relay. The minimal and maximal contention window sizes (CW_{min} and CW_{max}) can be adjusted to set different priorities to source and relay.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed WO-RANC and compare it with several schemes including 802.11p, plain-RANC, and TwoHop. 802.11p is the IEEE 802.11p standard ratified in 2010. Plain-RANC is the simplest version of relay-assisted network coding introduced in Section II.A. TwoHop is the same as 802.11p, except there are fixed relay nodes located in the middle of source-destination pairs and source nodes always send packets to destination nodes via the fixed relay nodes. Performances of these schemes are compared in terms of throughput and end-to-end delay.

A. *Simulation Settings*

We use the network simulator NS-2 to simulate our proposed protocol in vehicular environments. The simulation setup is described as follows. The network covers an area of 3000×1000 m^2. The source-destination distance varies from 100 meters to 3000 meters. 50 nodes (including source and destination nodes) are placed randomly in this area. All the nodes move according to the random waypoint model. The simulation time is 1100 seconds for each run.

The initial distances between source and destination nodes are controlled, ranging from 100 meters to 3000 meters. This setting enables us to study the impact of the source-destination distance on the performance in terms of throughput and packet delivery ratio, from which we can learn how much coverage enhancement and performance enhancement to IEEE 802.11p are achieved by using our proposed scheme.

The traffic pattern is described as follows. Each source has 50 segments to transmit to its corresponding destination. Each segment is divided into 100 original blocks. The block size is set to 1000 bytes. After all the 50 segment transmissions finish, the source-destination pair is replaced by another randomly chosen S-D pair.

In each segment transmission, a mobile node is selected to be the relay. The RES retry limit is set to 8 to avoid causing too much overhead in the relay selection phase. The Nakagami propagation loss model with parameters set according to [15] is used to model the non-deterministic nature of packet reception. Other parameters are set according to [16]. Some important parameters are summarized in Table I.

TABLE I. SOME IMPORTANT SIMULATION PARAMETERS

Parameter	Value
Network area	3000×1000 m^2
# of nodes	50
Tx power	0.1 W
Propagation loss	Nakagami
Segment size	100 blocks
Block size	1000 bytes
Mobility model	Random waypoint model
802.11p retry limit	4

B. *Simulation Results*

Figure 5 shows the simulation results of throughput as a function of the S-D distance. When the S-D distance is short (equal or smaller than 400 meters), WO-RANC, plain-RANC and 802.11p perform almost equally well. This is because when the direct link $\overline{SD}$ is of great quality, no relay node is selected in the relay selection phase and consequently both WO-RANC and plain-RANC degrade to 802.11p. When the S-D link is short, TwoHop performs worse than all other schemes. This is because TwoHop stubbornly takes two transmissions for each packet, despite a single direct transmission from source can reach destination successfully.

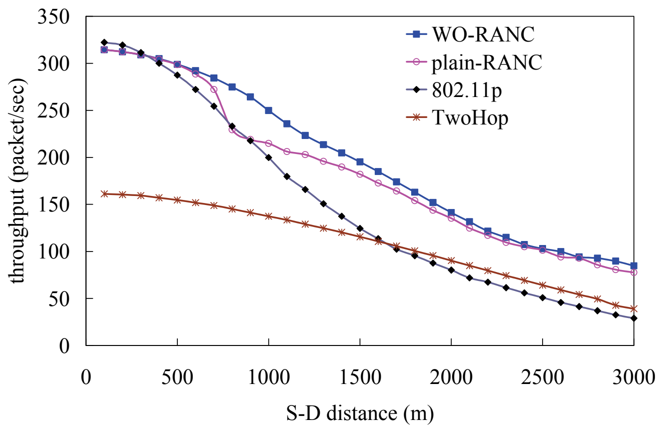

Figure 5. Performance comparison in terms of end-to-end throughput.

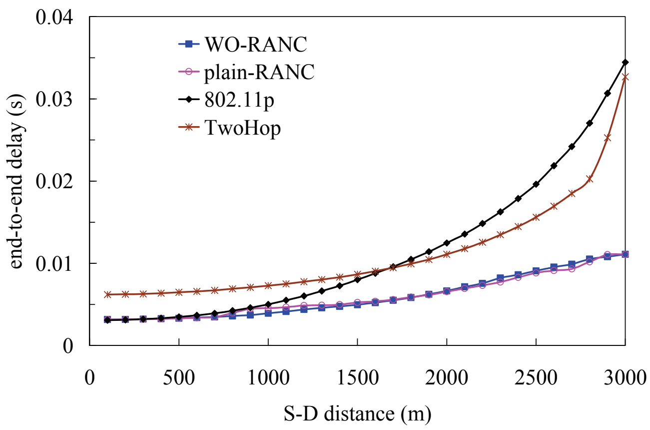

Figure 6. Performance comparison in terms of delay.

When the S-D distance is medium (between 500 meters and 1600 meters), we observe in Figure 5 that WO-RANC performs best, plain-RANC is the runner-up, 802.11p is the third place and TwoHop performs worst. The underlying reason is that both network coding and work-based wide-sense opportunistic retransmission contribute to performance improvement.

Wide-sense opportunistic retransmission can also enhance performance. This can be observed by the throughput gap between WO-RANC and plain-RANC, particularly when the S-D distance is 700 meters to 1600 meters. The only difference of WO-RANC from plain-RANC is that WO-RANC exploits a work-based wide-sense opportunistic retransmission but plain-RANC does not. With the concept of work in WO-RANC, relay nodes estimates the information deficiency that destination nodes have not received yet and avoid transmitting non-innovative blocks to destination. This is why WO-RANC outperforms plain-RANC.

When the S-D distance is long (equal or larger than 1700 meters), it is observed in Figure 5, TwoHop outperforms 802.11p. Unlike the cases when the S-D distance is short to medium, most of direct communications from source to destination fail due to overlong distance. Therefore, the TwoHop relaying mechanism brings performance improvement over 802.11p in this situation. WO-RANC and plain-RANC still are the first place and the second place in this situation. However, we observe in Figure 5 that the throughput gap between WO-RANC and plain-RANC is not as large as that at a medium S-D distance. At a medium S-D distance, the gap is mainly due to a considerable number of non-innovative blocks sent by relays. At a large S-D distance, the gap becomes small because most of coded blocks fail to reach destination and hence relay nodes under plain-RANC seldom transmit non-innovative blocks.

The arguments mentioned above in this section can be also consistently observed in Figure 6 from the aspect of end-to-end packet delay. In other words, WO-RANC is able to extend coverage and enhance performance of IEEE 802.11p in terms of both throughput and delay.

V. CONCLUSION

In this paper, we have presented the WO-RANC ARQ protocol, an effective means for source nodes and relay nodes to cooperatively deliver information to destination nodes in wireless networks. By utilizing relay-assisted network coding and work-based wide-sense opportunistic retransmission, WO-RANC can minimize unnecessary retransmissions due to ACK loss and transmissions of non-innovative blocks, while not needing per-packet ACKs. Simulation results show that WO-RANC consistently boosts throughout and decreases delay for a large range of source-destination distances. Therefore, WO-RANC is able to extend RSU coverage and enhance performance of IEEE 802.11p.

REFERENCES

[1] Wireless Access in Vehicular Environments, IEEE Std. 802.11p, 2010.

[2] Fan Bai and Hariharan Krishnan, “Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications,” in Intl. IEEE Conf. on Intelligent Transportation Systems (ITSC), Sept. 2006.

[3] Mei-Hsuan Lu, Peter Steenkiste, and Tsuhan Chen, “Design, Implementation and Evaluation of an Efficient Opportunistic Retransmission Protocol,” in ACM MobiCom, Sept. 2009.

[4] Rudolf Ahlswede, Ning Cai, Shuo-Yen Robert Li, and Raymond W. Yeung, “Network Information Flow,” *IEEE Trans. Information Theory*, vol. 46, no. 4, pp. 1204-1216, July 2000.

[5] Ralf Koetter and Muriel Medard, “An Algebraic Approach to Network Coding,” *IEEE/ACM Trans. Networking*, vol. 11, no. 5, pp. 782-795, Oct. 2003.

[6] S. Bhadra, S. Shakkottai, and P. Gupta, “Min-Cost Selfish Multicast with Network Coding,” *IEEE Trans. Information Theory*, vol. 52, no. 11, pp. 5077–5087, Nov. 2006.

[7] Majid Ghaderi, Don Towsley, and Jim Kurose, “Reliability Gain of Network Coding in Lossy Wireless Networks,” in IEEE INFOCOM, April 2008.

[8] X. Liang, “Matrix Games in The Multicast Networks: Maximum Information Flows with Network Switching,” *IEEE Trans. Information Theory*, vol. 52, no. 6, pp. 2433–2466, June 2006.

[9] Quoc-Tuan Vien, Le-Nam Tran, and Huan X. Nguyen, “Network Coding-based ARQ Retransmission Strategies for Two-Way Wireless Relay Networks,” in Intl. Conf. on Software Telecommunications and Computer Networks (SoftCOM), Sept. 2010.

[10] Shengli Fu, Kejie Lu, Yi Qian, and Murali Varanasi, “Cooperative Network Coding for Wireless Ad-Hoc Networks,” in IEEE Global Telecommunications Conf. (GLOBECOM), Washington DC, USA, Nov. 2007.

[11] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “XORs in the Air: Practical Wireless Network Coding,” in ACM SIGCOMM, Sept. 2006.

[12] Jin Jin, Baochun Li, and Taegon Kong, “Is Random Network Coding Helpful in WiMAX?” in IEEE INFOCOM, Apr. 2008.

[13] Philip A. Chou, Yunnan Wu, and Kamal Jain, “Practical Network Coding,” in Allerton Conf. on Communication, Control and Computing, Oct. 2003.

[14] C. Lo, W. Heath, and S. Vishwanath, "Opportunistic Relay Selection with Limited Feedback," In IEEE Vehicular Tech. Conf., Apr. 2007.

[15] Arijit Khan, Shatrugna Sadhu, and Muralikrishna Yeleswarapu, “A Comparative Analysis of DSRC and 802.11 over Vehicular Ad Hoc Networks,” UCSB Dept. of Computer Science, Tech. Rep., 2008.

[16] Qi Chen, Felix Schmidt-Eisenlohr, et al. (2011, Apr.) Overhaul of IEEE 802.11 Modeling and Simulation in NS-2. [Online]. Available: http://dsn.tm.uni-karlsruhe.de/english/Overhaul_NS-2.php.