Network Coded Information Raining over High-Speed Rail through IEEE 802.16j

Christopher Sue, Sameh Sorour
Dept. of Electrical & Computer Eng.
University of Toronto
Toronto, ON, M5S 3G4, Canada
{csue,samehsorour}@comm.utoronto.ca

Youngsoo Yuk
Mobile Comm. Technology Research Lab.
LG Electronics, Inc.
Anyang-shi, Kyungki-Do, Korea 431-749
yukyoungsoo@gmail.com

Shahrokh Valaee
Dept. of Electrical & Computer Eng.
University of Toronto
Toronto, ON, M5S 3G4, Canada
valaee@comm.utoronto.ca

***Abstract*—In [1] and [2], two-hop network architectures, with wireline and 802.16a backhauls, respectively, and 802.11 repeaters/relays, were proposed for high-speed rail. The resulting infrastructure cost in the former, and complexity of dual mode wireless relays in the latter, urge the need for more technically and economically efficient solutions.**

In this paper, we first propose a two-hop wireless network architecture for high-speed rail employing 802.16j. Due to its backward compatibility with 802.16e, the use of 802.16j not only mitigates the restrictions of the previous two-hop heterogeneous solutions but also allows a third direct communication link from the base-station to the trains, thus providing opportunities for throughput improvements. We then propose a network coded downlink transmission scheme over the proposed network architecture to both eliminate the undesirable ARQ overhead in high-speed rail communications and better exploit relay diversity. We refer to our proposed scheme as network coded information raining. Simulation results show the merits of our proposed solutions.

***Index Terms*—High-Speed Rail, IEEE 802.16j, Network Coding.**

I. Introduction and Motivation

Delivering internet access to high-speed trains using conventional cellular systems is complicated due to the need to perform hand-off for many subscribers, all with high mobility. In addition, capacity is reduced due to poorer radio channel conditions as existing multipath channel impairments are exacerbated by the Doppler shift caused by high velocities. Doppler shift is particularly disruptive to wireless access technologies that rely on orthogonal frequency division multiplexing (OFDM) modulation, such as IEEE 802.16e [3], since the shifting of subcarrier frequencies results in the loss of their orthogonality.

To address the problem of providing internet access to high-speed rail systems, [1] proposed a solution called *information raining*, where track-side repeaters would establish a high-speed bridging link between the train and the internet. The repeaters used a wireline backhaul and a IEEE 802.11b mobile link. Repeaters close to the train do benefit from line of sight (LOS) channels to establish better wireless connectivity to the train. However, the use of a wireline backhaul for all repeaters requires laying cables and related infrastructure along the length of the track, which increases the implementation cost of this solution.

[2] investigated the use of a wireless backhaul based on IEEE 802.16a and proposed a spatio-temporal scheduling scheme to selectively forward data to advanced repeaters with known good channels. The use of a wireless backhaul would allow wireless network operators to leverage existing base-station sites and equipment. Since IEEE 802.11g is not restricted to the lower capacity, direct sequence spread spectrum modulation used by IEEE 802.11b, it was employed for the mobile link. By eliminating the wireline component, the repeaters may now be viewed as wireless relays, and the overall system as a two-hop wireless network. However, these relays, as proposed by [2], must support two wireless technologies. This heterogeneous design increases the complexity of a relay, and hence the overall cost of implementation.

Recent developments concerning IEEE 802.16j [4] present an opportunity to reduce relay complexity. IEEE 802.16j is an extension to IEEE 802.16e that introduces support for mobile multi-hop relay communication. Much of the physical layer remains unchanged, with the intention of allowing existing IEEE 802.16e terminals to operate without any knowledge that they are communicating through relays. The overlap in technology allows equipment manufacturers to leverage existing research and manufacturing knowledge used to develop commercial implementations of 802.16e, known as WiMAX, reducing the cost of relay deployment.

On the other hand, it has been shown in [5] that network coding has many advantages over conventional automatic repeat request (ARQ) schemes for packet retransmissions in WiMAX. These advantages arise from its ability to perform efficient packet retransmissions without the knowledge of lost packets. This property not only eliminates the undesired overhead of packet positive/negative acknowledgements (ACK/NAK), necessary in conventional ARQ operation, but also does not suffer from the undesirable effects of potential errors/losses in these packet ACK/NAK.

In this paper, we propose a wireless network architecture for high-speed trains where IEEE 802.16j would be deployed on all base-stations and relays, while the train would use IEEE 802.16e technology. Due to the backward compatible transmission from the base-stations and relays, the use of

This work was sponsored in part by the LG Electronics Corporation.

IEEE 802.16j not only mitigates the restrictions of previous two-hop heterogeneous solutions, but also allows a third set of direct communication links from the base-station to the train. Although the train is traveling at high speed and will experience non-line of sight (NLOS) channel conditions to the base-station, this ability to overhear provides direct reception opportunities that did not exist in previous two-technology network designs and that may achieve throughput improvements. We also propose a downlink transmission scheme over the IEEE 802.16j frames that employs random network coded packet retransmissions in order to eliminate the undesirable effects of ARQ ACK/NAK packets. Moreover, the use of pre-designed independent coding coefficients at the different relays is expected to better exploit relay diversity than the retransmission of the same packets from these relays.

The rest of the paper is organized as follows. In Section II we introduce the details of our proposed system architecture and network coded transmission scheme for high-speed rail. The channel models and simulation parameters, employed to evaluate our proposed scheme, are described in Section III. In Section IV the merits of our proposed solutions are demonstrated through simulations results. Section V concludes the paper.

II. Proposed System Architecture

A. Network Topology and Frame Structure

The network topology and technologies of our proposed architecture are illustrated in Figure 1. As in [1], the train carries multiple antennas with each antenna associated with the nearest active track-side relay. All train antennas are connected to IEEE 802.16e transceivers and all relays and base-stations support IEEE 802.16j. Because the train's presence on the track can be detected by treadles, the train's position and velocity can be known or accurately predicted. Consequently, base-stations know when the train has entered or left their coverage area, and the transfer of radio resources from one base-station to another is conducted in a transparent fashion such that the train's WiMAX terminals perceive a single, uninterrupted radio channel. Similarly, relays turn on or off based on whether or not the train is in their coverage area. The number of actively transmitting relays is always equal to the number of antennas on the train.

In IEEE 802.16j, the downlink sub-frame begins with the downlink access zone [4], where the base-station has exclusive access to the radio channel. The base-station's preamble is used as training data for both the relays and train to estimate their channels from the base-station. The downlink access zone could be followed by several possible zones depending on the relays' mode of operation. We decided to use non-transparent relays because they are in close proximity to the train. In the non-transparent mode, relays transmit their own preambles, perceived by the train as mid-ambles, providing training data for the train to estimate the relay to train channels. All active relays transmit simultaneously on different frequency ranges, so that they do not interfere with one another.

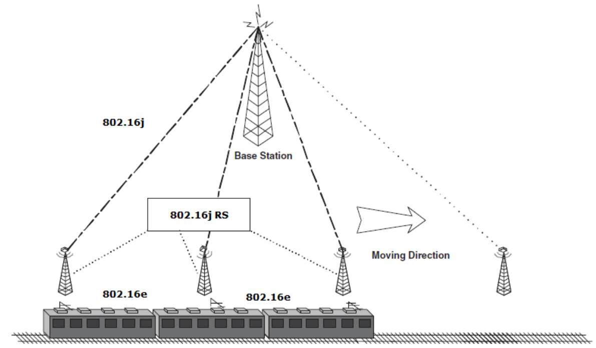

Fig. 1. Proposed network topology.

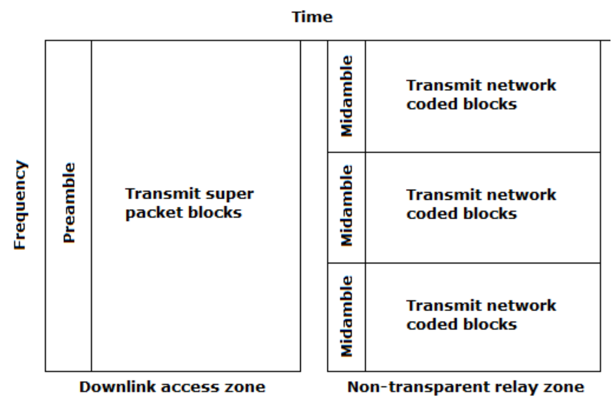

Fig. 2. Proposed downlink sub-frame structure.

Figure 2 illustrates the proposed frame structure. We use a downlink sub-frame that is 35 OFDM symbols long. These symbols are divided into downlink access and non-transparent relay zones, each 17 OFDM symbols in length, resulting in a maximum data frame 16 OFDM symbols long. We treat all data frames as super packets resulting from an aggregation of connections, generated using packet aggregation techniques [6]. The train thus appears to the access network as a single user with a large bandwidth demand, and is responsible for demultiplexing the tunnel into multiple connections for its passengers. With only one apparent user, downlink MAP and other control information become unnecessary overhead and are not transmitted. The train then takes care of packet routing to the passengers using the headers of the packets constituting each super packet.

Note that the proposed topology and homogeneous transmission technologies, from both base-station and relays, provides a third set of links between the base-station and the train antennas. Despite the poor channel conditions that these links may suffer, they provide overhearing opportunities that did not exist in the previous two-technology network designs and is thus expected to achieve throughput improvements.

B. Random Network Coding

In the literature, random network coding (RNC) [7] is a known technique that combines all packets of a large block using random non-zero coefficients. To illustrate its operation, let a transmitting terminal have a large block of data that it divides into K packets of fixed size. Let these packets be represented by a vector $\vec{s} = \{s_1, s_2, ..., s_K\}$. A new set of packets $\vec{y} = \{y_1, y_2, ..., y_N\}$ $(N > K)$ is generated by the following equation:

$$y_n = \sum_{k=1}^{K} s_k \alpha_{n,k} \tag{1}$$

The vector $\vec{\alpha}_n = \{\alpha_{n,1}, \alpha_{n,2}, ..., \alpha_{n,K}\}$ is a random coefficient vector, with non-zero entries, employed in generating the n-th coded packet ($n \in \{1, \ldots, N\}$). All inputs and operations take place in $GF(2^q)$. In such context, $\vec{\alpha}_n$ or its generating seed is appended to the header of y_n in order to be used for decoding at the receiving terminal. The resulting coded packets are then protected with forward error correction (FEC) and transmitted. At the receiver, the correctly received coded packets are stored, as well as the corresponding coefficient vectors which are stored in a matrix G_t. When G_t is full rank, the original data may be recovered.

In the proposed system, the IEEE 802.16 protocol stack is augmented with a network coding layer. The coefficient vectors are not transmitted, but relays signal which packets were received during the most recent downlink access zone. The train has knowledge of the seeds used in the pseudo-random number generators of the base-stations and relays. These seeds would be assigned a priori, and the equivalent of a hand-off is for the train to initialize the set of pseudo-random number generators to the seeds of the base-station and relays that it will be communicating with. These pre-determined seeds can be designed such that a large number of coefficient vectors can be guaranteed to be linearly independent, even though they are generated in a deterministic fashion. Thus, this approach not only eliminates most of the coding coefficient overhead but also helps in obtaining full-rank G_t matrices faster, which results in higher throughput and lower decoding delay.

C. Downlink Transmission Schemes

In this section, we illustrate the proposed RNC based information raining scheme in IEEE 802.16j frames. We also illustrate the ARQ based transmission schemes we use for comparison.

For all transmission schemes and for each new super packet, the base-station initially transmits the FEC blocks of this super packet, in a first downlink access zone, without network coding. The train's transceivers and all active relays attempt to decode these FEC blocks. All relays have a memory to store the data from successfully decoded blocks. The train maintains a similar storage space, shared amongst all its transceivers.

1) ***ARQ with Rigid Acknowledgments (ARQ-R):*** In this scheme, each of the relays transmits the blocks it received from the base-station in a round-robin fashion. We assume in this case that no ACK packets can be sent by the train during the whole downlink phase and thus the relays keep transmitting the blocks they correctly received for the whole duration of the non-transparent relay zone. At the end of the downlink frame, the train could then employ the uplink phase to send ACK/NAK packets to the base-station and relays. If not all blocks of the super packet are correctly received, the subsequent downlink frame operates in the same manner described above but only transmits the blocks that are missing at the train. In the downlink access zone of this subsequent frame, the missing packets from the train are repeated in a round-robin fashion to utilize the whole zone. This operation continues until all blocks of the super packet are correctly received at the train.

2) ***ARQ with Floating Acknowledgments (ARQ-F):*** The only difference between this scheme and ARQ-R is that we assume the availability of a low bit rate out-of-band signaling channel, in which the train could signal the reception of all the blocks of a super packet anytime during the downlink sub-frame. If this acknowledgement comes during the downlink access zone, then a new downlink access zone begins with a new super packet. If the acknowledgement comes during the non-transparent relay zone, then the relays cease transmission and the base-station begins a new downlink access zone, with one OFDM symbol delay for preamble. This scheme attempts to reduce the number of OFDM symbols that are essentially wasted when the train is able to decode before the end of the sub-frame.

3) ***RNC with Rigid Acknowledgments (RNC-R):*** This schemes differs from the ARQ-R scheme in that each relay transmits new blocks, in its allocated band, generated by performing RNC on all the blocks that it has correctly received from the base-station. In subsequent frames, the same cycle of uncoded base-station and coded relay transmissions is performed until the train is able to decode all the blocks of the super packet.

4) ***RNC with Floating Acknowledgments (RNC-F):*** This scheme is a variant of RNC-R in which the train could signal its reception of all blocks anytime during the downlink sub-frame through a low bit rate out-of-band signaling channel. As in ARQ-F, when this signal is issued by the train, the base-station begins a new downlink access zone with blocks from a new super packet.

III. Channel Models and Simulation Parameters

There are three sets of channels in the system. The first set consists of the channels between the base-station and the relays, which are assumed to be NLOS but stationary. The second set consists of the channels between the base-station and the train transceivers, which are also NLOS but with Doppler impairments due to the train's velocity. The last set consists of the channels between the relays and the train transceivers, which are short-range and LOS, but with Doppler impairments. The first two channel sets are modeled using the IST-WINNER II C2 model, representing an urban macro-cell environment [8]. The last set is modeled using the IST-WINNER II D2a model, representing a high-speed train environment. For the duration of the simulation, the

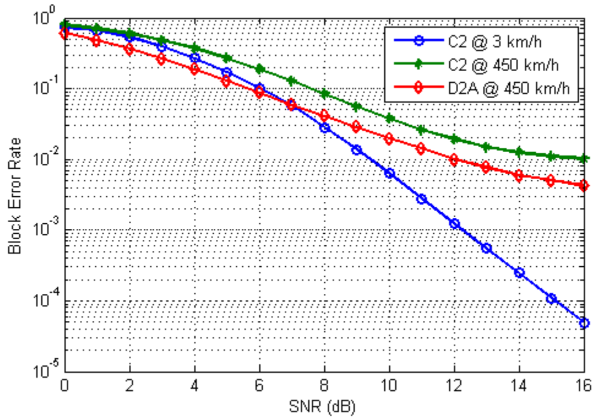

Fig. 3. Block error rates for channels.

Parameter	Value
Frame length	5 ms
FFT	512 points
Cyclic prefix	64 samples
OFDM symbol length	576 samples
Sampling frequency	5.6 Msps
Pilot structure	PUSC
Modulation and Coding Scheme	QPSK CTC 1/3

TABLE I
PHY PARAMETERS FOR 5 MHZ CHANNEL

train's velocity is kept constant at 450 km/h. With a carrier frequency of 3.5 GHz, the coherence time is 0.29 ms, less than the duration of the downlink access and non-transparent relay zones, which is 1.75 ms. Thus it cannot be assumed that the channel responses are constant during either zone. Pilot symbols are used to aid in the estimation of the time-varying channels. A pilot-assisted time-frequency channel estimator is used by a frequency-domain MMSE equalizer to recover the data subcarriers.

Figure 3 shows the FEC block error rates for the three channel sets. We observe that the channel between the relays and the train always has a lower BLER than the channel between the base-station and the train.

The spectrum is divided into contiguous 5 MHz RF channels. There are as many RF channels as there are active relays. The physical layer and FEC parameters for a single RF channel are given in Table I. During the downlink access zone, these channels are bonded and used by the base-station for broadcast. During the non-transparent relay zone, each relay occupies one of these RF channels. Data is divided into blocks of 240 bits which, after the stated modulation and coding is applied, will utilize all of the available data subcarriers in a 512 point FFT profile.

IV. SIMULATION RESULTS

All scenarios were simulated for 2500 seconds, or 500000 frames. Figures 4 and 5 compare the average throughput and delay performances achieved by ARQ-R and RNC-R in both the previous and proposed transmission architectures.

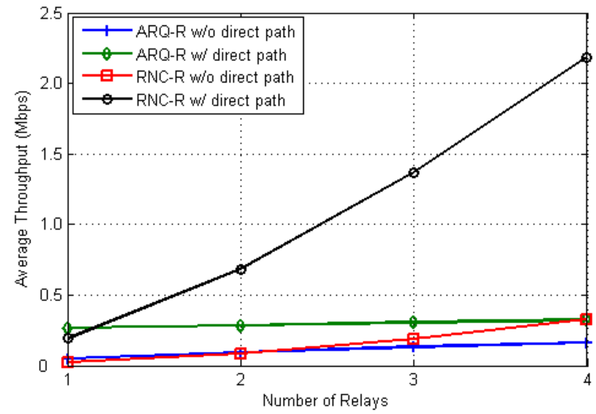

Fig. 4. Average throughput vs number of relays, with and without direct path

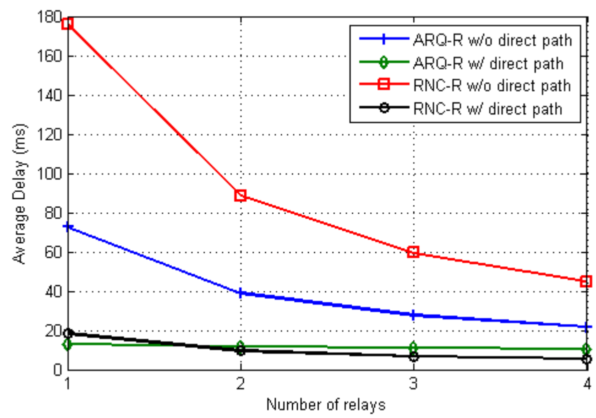

Fig. 5. Average delay vs number of relays, with and without direct path

Recall that the difference between the previous and proposed transmission architectures is the presence of a third set of channels from the base-station to the train antennas due to the use of 802.16j.

From both figures, we first can observe that, for each of the two transmission schemes (ARQ-R and RNC-R), our proposed architecture using 802.16j outperforms the previous architecture in terms of both average throughput and delay. This improvement is clearly due to the presence of the extra set of channels between the base-station to the train in our proposed solution that allow a faster block reception and thus a better performance.

We can also see, in Figure 4, that our proposed RNC-R scheme achieves a higher throughput than the ARQ-R scheme, when the number of relays is greater than 1, for both homogeneous and heterogeneous architectures. The switch in dominance of the ARQ-R and RNC-R performances can be explained by the switch in dominance of two effects. The first effect arises from the fact that RNC-R relays transmit no two similar blocks and every block can contribute to overall successful reception. With ARQ-R relays, a block may not make any contribution because it was previously relayed

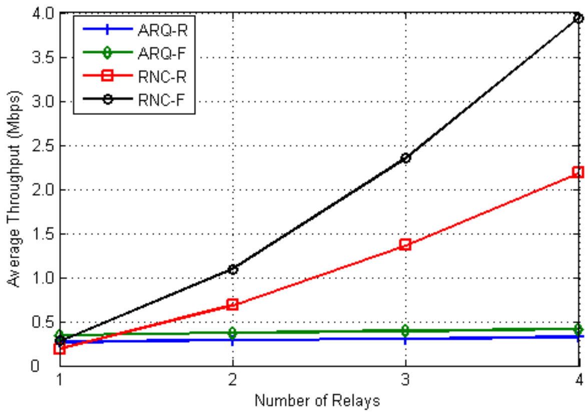

Fig. 6. Average throughput vs number of relays, floating and rigid acknowledgement

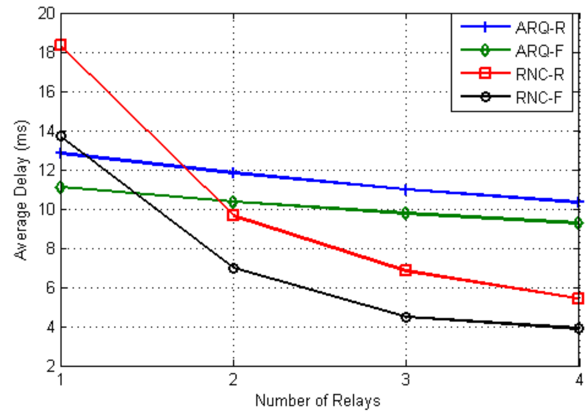

Fig. 7. Average delay performance vs number of relays, floating and rigid acknowledgement

by another relay or was received earlier in the downlink access zone. This effect becomes more dominant with the increase in number of relays, since they send more and more contributive blocks, when using RNC-R, but fall into more non-contributive block transmissions, when using ARQ-R. This leads to much higher gains for the RNC-R scheme over the ARQ-R scheme. On the other hand, if the super packet is not delivered in a frame, the base-station and relays retransmit only missing blocks at the train when using ARQ-R, and all the packets when using RNC-R. This makes the base-station retransmission more efficient for the ARQ-R scheme. This effect dominates when the number of relays is small, thus leading to the observed results for the 1-relay case.

Figure 5 shows that the RNC-R does not achieve the same level of gains in average delay as in throughput. In fact, the ARQ-R scheme outperforms the RNC-R scheme when there is no direct path. This can be explained by the fact that RNC-R retransmits coded blocks that are decoded only when a certain number of blocks is correctly received, whereas ARQ-R retransmits original packets directly. However, we can see that our proposed architecture with RNC-R scheme achieves the lowest average delay, over all considered architecture and transmission scheme combinations, when the number of relays is greater than 1. This is justified by the high gains of the RNC-R's throughput over that of ARQ-R when a direct path exists. Thus, super packets are received much faster with our proposed solution leading to a lower average block delay.

Figures 6 and 7 compare the average throughput and delay performances achieved by ARQ-R, ARQ,F, RNC-R and RNC-F, over 802.16j, against the number of relays. We can clearly see that transmission schemes with floating acknowledgments outperform those with rigid acknowledgments in both average throughput and delay. This obtained result is intuitive. Moreover, the figures show the superior throughput and delay performances of RNC-R and RNC-F over ARQ-R and ARQ-F, respectively, when the number of relays is greater than 1. The explanation of this result is similar to the one described for Figures 4 and 5.

V. Conclusion

In this paper, we have proposed a system architecture for high-speed rail based on information raining. The proposed architecture employs IEEE 802.16j over two-hops . The use of backward compatible transmission technology allows the deployment of cost-effective relays and provides direct channels from the base-stations to the trains. Moreover, we proposed the use of random network coding for packet retransmissions to avoid the undesirable effects of ARQ overhead and further exploit relay diversity. Extensive simulations have demonstrated that the proposed architecture outperforms previous heterogeneous architectures in terms of average throughput and delay. Moreover, the results showed considerable gains when RNC retransmissions are employed instead of ARQ, if two or more active relays are simultaneously connected to the train.

References

[1] D. Ho and S. Valaee, "Information raining and optimal link-layer design for mobile hotspots," *Mobile Computing, IEEE Transactions on*, vol. 4, no. 3, pp. 271–284, 2005.

[2] S. Motahari, E. Haghani, and S. Valaee, "Spatio-ternporal schedulers in IEEE 802.16," in *Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE*, vol. 1, 2005, p. 5 pp.

[3] "IEEE standard for local and metropolitan area networks part 16: Air interface for fixed and mobile broadband wireless access systems amendment 2: Physical and medium access control layers for combined fixed and mobile operation in licensed bands and corrigendum 1," *IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005 (Amendment and Corrigendum to IEEE Std 802.16-2004)*, 2006.

[4] S. Peters and R. Heath, "The future of WiMAX: multihop relaying with IEEE 802.16j," *Communications Magazine, IEEE*, vol. 47, no. 1, pp. 104–111, January 2009.

[5] J. Jin, B. Li, and T. Kong, "Is random network coding helpful in WiMAX?" *IEEE Conference on Computer Communications (INFOCOM'08)*, pp. 2162–2170, April 2008.

[6] Z. Tao, K. Teo, and J. Zhang, "Aggregation and concatenation in IEEE 802. 16j mobile multihop relay (MMR) networks," in *Mobile WiMAX Symposium, 2007. IEEE*, 2007, pp. 85–90.

[7] P. A. Chou, Y. Wu, and K. Jain, "Practical network coding," in *Proceedings of the Forty-First Annual Allerton Conference On Communication, Control, and Computing*, 2003, pp. 40–49.

[8] "WINNER II channel models," Tech. Rep. IST-4-027756 WINNER II D1.1.2 V1.2, Feb. 2008.