16th European Signal Processing Conference (EUSIPCO 2008), Lausanne, Switzerland, August 25-29, 2008, copyright by EURASIP

MULTI-SESSION NETWORK SPREAD CODING

Chadi Khirallah, Lina Stanković, and Vladimir Stanković

Department of Electronic & Electrical Engineering, University of Strathclyde,
Royal College Building, 204 George Street, G1 1XW, Glasgow, U.K.
phone: + 44 (0) 141 548 2679, fax: + 44 (0) 141 552 4968,
email: {chadi.khirallah, lina.stankovic, vladimir.stankovic}@.eee.strath.ac.uk

ABSTRACT

Contrary to single-session network coding which is well understood in both theory and practice, the general problem of multi-session wireless network coding is still a challenge. In this paper, we extend our single-session Network spread coding scheme (NSC) to the more general multi-session NSC (MS-NSC) scheme. In contrast to straightforward NC, MS-NSC uses the linearly independent complete complementary (CC) sequences as encoding vectors that facilitate communication over wireless channel suffering from fading, interference and noise. As opposed to classical NC, MS-NSC requires no intermediate encoding nodes (due to the physical characteristic of the channel). Results obtained under AWGN and flat fading channels demonstrate only minimal performance loss in the multi-session scenario compared to that in the single-session for the two proposed MS-NSC operating modes.

1. INTRODUCTION

Network coding (NC) was first proposed by Ahlswede et al. [1] to increase throughput by combining packets from different incoming data streams on intermediate nodes instead of simply forwarding them. Beside throughput enhancement, NC minimizes both the energy required to multicast a packet in a wireless network (by reducing the number of transmissions per packet), and the delay measured by hop-count for a packet to reach its destination [2].

Strong potentials of NC in wireless packet networks were recently pointed out in [3, 4, 5] and references therein. It was shown in [4] that the full-duplex packet communication can be viewed as a single virtual multicast session, and thus NC is the optimal solution. The provided scheme, dubbed physical piggybacking, achieves a throughput improvement compared to conventional routing based on two unicast sessions (each for sending one information packet).

In [6], a NC-based packet forwarding scheme is proposed for delay-tolerant networks, in which nodes do not simply forward packets they overhear but may send out information that is coded over the contents of several packets they received in order to reduce the data dissemination overhead.

In the case of communicating correlated information from two source nodes over a network to multiple destination nodes [7], authors developed a practical NC design that involves a joint consideration of distributed source coding (compression) and network coding (information relaying). Although the proposed design is in general suboptimal it still offers low complexity and robustness to network dynamics.

In [8], NC was developed for packet exchange in wireless LAN at the network layer using conventional transceivers, e.g., IEEE 802.11, which take care of wireless channel impairments.

However, in order to make the most of NC over wireless broadcast channels, physical-layer NC was proposed [9], where information from different nodes are combined at signal level. Thus, wireless physical-layer NC must directly address channel impairments such as high levels of interference, fading and noise that eventually result in severe reduction in the network throughput. Recently, [10] presented a physical-layer NC scheme termed Analog Network coding (ANC), which exploits signal interference at intermediate nodes to increase throughput. Indeed, for simple network topologies, this scheme outperforms packet-level NC. However, high signal-to-noise ratio (SNR) is assumed with no fading in the communication channel, and the mixed signals have similar power levels. Otherwise, severe degradation in performance is experienced.

In [11], we showed striking similarities between NC and the principle of spreading using the mutually orthogonal complete complementary (CC) sequences and proposed a scheme termed Network spread coding (NSC). NSC operates at signal-level and has the advantages of ANC, since signal-mixing occurs within a channel at the physical layer. As opposed to ANC, NSC addresses noise, fading and interference using spread spectrum with CC sequences [12]. CC sequences were originally proposed as a substitute to the currently used spreading sequences that suffer from loss of mutually orthogonality under asynchronous communications and results in high level of interference between received signals over multiple access channels.

Despite the fact that CC sequences and traditional spreading sequences, (e.g., Walsh sequences) used in CDMA communication schemes, are generated using similar Hadamard matrices, CC posse ideal correlation properties (i.e., zero cross-correlation and zero out of phase auto-correlation), due to their unique spreading and despreading techniques that differ from those used in standard CDMA systems. CC ideal properties eliminate multiple access interference and inter-symbol interference [13].

In multi-session (MS) network communications several mutually independent information sources are generated at possibly different network nodes, and each of the information sources is multicast to a specific set of sinks. The MS-NC problem cannot be decomposed into single-source NC problems even when all the information sources are generated at the same node. Although, special MS-NC problems have been shown to be decomposable, a practical MS-NC scheme is still an ongoing design challenge [14].

In this paper, we extend the single-source NSC system [11] to the more challenging MS-NSC system and investigate its error performance under fading, inter-node interference, and noise effects. Our results show only a small performance loss in the MS scenario compared to the single-session case.

The paper is organized as follows. In Section 2 we introduce the MS-NSC scheme, give an example and highlight key properties. Section 3 provides the simulation results for the proposed MS-NSC system in an additive white Gaussian noise (AWGN) and flat fading channels for both MS-NSC operating modes. Finally, Section 4 concludes the paper.

2. MS-NETWORK SPREAD CODING

In this section, the concept of MS-NSC is first introduced. We then explain this concept by means of a simple example. The key properties of MS-NSC are then highlighted.

2.1 Concept

We consider a wireless network with a set of source nodes $\mathbf{\Lambda}$ and a set of receive nodes $\mathbf{T}$. Each node is equipped with an omni-directional antenna. The links are half-duplex. The network has N independent information sources, and each source node S_n transmits N spread signal components over N carrier frequencies at transmission rate R_n, defined as the total number of spread-chips per source symbol.

Then, $R_n = N \times \tau \times (2K-1)/K$, where K is the number of chips in each CC sequence and $1 \le \tau \le K$ is the number of chip-shifts during the offset stack (OS) spreading [12] (e.g., for K = 4 chips and $\tau = 1$, N = 2 and R_n = 14/4 chip per symbol). Note that the larger the τ the lower the source rate

At each source node, each source symbol is spread (encoded) using N CC sequences. Hence, CC sequences correspond to independent linear encoding vectors in NC [11]. The total number of CC sequences (and number of source nodes) N, and the total number P of destination nodes are:

$$N = |\mathbf{\Lambda}| = \sqrt{K} = 2^l, \, l \ge 1 \tag{1}$$

$$P = |\mathbf{T}| \ge N \tag{2}$$

Let $\mathbf{x}^{(i)} = \left[x_1^{(i)}, x_2^{(i)}, \dots, x_K^{(i)}\right]^{\mathrm{T}}$ be a stream of K symbols to be encoded at source node $S_i \in \mathbf{\Lambda}$ into N streams $\left\{\mathbf{C}_1^{(i)}, \ \mathbf{C}_2^{(i)}, \ \dots \ \mathbf{C}_N^{(i)}\right\}$; each stream $\mathbf{C}_n^{(i)}$ is of length $2K-1$ chips and is transmitted to the intermediate node on an orthogonal carrier frequency f_n. The global encoding matrix of dimension (2K-1) ×NK at source node S_i is given by:

$$\mathbf{G}^{(i)} = \left\{\mathbf{g}_1^{(i)} \quad \mathbf{g}_2^{(i)} \quad \dots \quad \mathbf{g}_N^{(i)}\right\}, \text{ where} \tag{3}$$

$$\mathbf{g}_n^{(i)} = \begin{bmatrix} g_{n1}^{(i)} & 0 & \dots & 0 \\ g_{n2}^{(i)} & g_{n1}^{(i)} & \dots & 0 \\ \vdots & \dots & & 0 \\ g_{nK}^{(i)} & g_{n(K-1)}^{(i)} & \dots & g_{n1}^{(i)} \\ 0 & g_{nK}^{(i)} & \dots & g_{n2}^{(i)} \\ \vdots & 0 & \dots & \vdots \\ 0 & \dots & 0 & g_{nK}^{(i)} \end{bmatrix} \tag{4}$$

is the local encoding matrix of dimension (2K-1)× K (that encodes $\mathbf{x}^{(i)}$ into $\mathbf{C}_n^{(i)} = \mathbf{g}_n^{(i)}\mathbf{x}^{(i)}$ to be transmitted over f_n) and $\mathbf{g}_{nj}^{(i)}$ is the jth chip of the nth CC sequence assigned to node S_i. Each CC chip has a value of "+1" or "-1". For any source node i, all assigned CC encoding vectors are mutually orthogonal, i.e., vectors $\{g_{11}^{(i)}, \ g_{12}^{(i)}, \ \dots, g_{1K}^{(i)}\}$,..., $\{g_{N1}^{(i)}, \ g_{N2}^{(i)}, \ \dots, g_{NK}^{(i)}\}$ are mutually orthogonal. This is due to the ideal auto-correlation property of CC sequences [12]. Similarly, the ideal cross-correlation property of the CC vectors assigned to different source nodes is demonstrated by the mutual orthogonality among vectors $\{g_{n1}^{(1)}, \ g_{n2}^{(1)}, \ \dots, g_{nK}^{(1)}\}, \dots, \{g_{n1}^{(N)}, \ g_{n2}^{(N)}, \ \dots, g_{nK}^{(N)}\}$

All signal components sharing the same carrier frequency are simply summed together at an intermediate node r_l. Thus, the signal received at node r_l over the nth carrier frequency f_n is given by:

$$\mathbf{y}_n = \sum_{i=1}^{N} \alpha_i \mathbf{C}_n^{(i)} = \sum_{i=1}^{N} \alpha_i \mathbf{g}_n^{(i)} \mathbf{x}^{(i)} \tag{5}$$

where α_i is the complex Rayleigh fading channel coefficient for the wireless link/path between source node S_i and intermediate node r_l. Then, the combined signal received at node r_l over all N carrier frequencies is:

$$\mathbf{Y} = [\mathbf{y}_1 \quad \mathbf{y}_2 \quad \dots \quad \mathbf{y}_n \quad \dots \quad \mathbf{y}_N] + \mathbf{z}_r \tag{6}$$

$\mathbf{z_r}$ is a vector of N AWGN components, each with zero mean power and unit variance.

The intermediate node r_l broadcasts the combined signal $\mathbf{Y}$, using one of the following two NSC modes. The low-complexity NSC *forward* (*NSC-F)* mode simply forwards the combined signals $\mathbf{Y}$. A disadvantage of this scheme is the accumulation of noise in the case of multi-relay (intermediate node) communications. The signal received at destination node t_p from r_l, is given by:

$$\mathbf{Q}_l = \beta_l \mathbf{Y} + \mathbf{z}_t \qquad (7)$$

where β_l is the cumulative complex Rayleigh fading channel coefficient for the wireless link/path (which can consist of one or more hops) between node r_l and destination node t_p. $\mathbf{z}_t$ is a vector of cumulative AWGN components each with zero mean power and unit variance.

From equations (4) – (7), and in the absence of noise, with knowledge of the fading channel profile, the destination node could decode by finding the inverse of the global encoding matrix $\mathbf{G}^{(i)}$ using Gaussian elimination (as in NC). However, the orthogonality requirement of CC sequences enables the receivers to decode/despread signals simply by multiplying received vectors by spreading sequences and then summing the results for all N frequencies (see [12] for more details).

The more robust NSC *despread-and-forward* (*NSC-DSF*) mode, overcomes the noise accumulation problem of NSC-F by enabling each intermediate node to de-spread the received signals, make a decision on and de-spread the incoming symbols, and then spread these again before sending. Results obtained in [11] showed a better bit-error-rate (BER) performance for the system using NSC-DSF compared to those using NSC-F. However, this improvement is at the cost of extra complexity at the intermediate nodes.

The described NSC systems share the same key idea of NC: combining/mixing incoming signals multiplied by encoding vectors (CC sequences) into an output sequence, and providing the receiver with just enough combinations of input symbols in order to decode. However, a fundamental difference to NC lies in the use of binary orthogonal CC sequences, which requires N frequency or time slots for signal-combining.

2.2 Example

The operation of the system is explained through an example shown in Fig. 1, where S1 and S2 attempt to multicast two binary streams $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ of length four symbols to destination nodes $\{t_3, t_4\}$ and $\{t_1, t_2\}$, respectively. Since there are two sources, CC sequences of length K=4 are used. Thus, $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ are encoded using two different encoding vectors $\mathbf{G}^{(1)}$and, $\mathbf{G}^{(2)}$ into $\mathbf{C}^{(1)}$ and $\mathbf{C}^{(2)}$, respectively, that get combined in the shared wireless channel as $\mathbf{C}^{(1)}+\mathbf{C}^{(2)}$ (with added noise and fading) at intermediate node r. For τ =1, each node sends information at the rate of 14 chips per 4 symbols on both carrier frequencies (R_n = 14/4). Node r then performs one of the two NSC modes: (i) NSF-F by simply forwarding $\mathbf{C}^{(1)}+\mathbf{C}^{(2)}$ (together with the added noise) to all destination nodes $\{t_1,\ldots,t_4\}$, which perform despreading to reconstruct $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$, (ii) NSF-DSF by despreading the received signal (to remove added noise and fading), then spread again (to $\mathbf{C}^{(1)}+\mathbf{C}^{(2)}$ assuming no decoding errors) and broadcast.

For the NSF-F scheme, at node r the combined incoming data streams are relayed to the destination nodes at effectively double the rate; i.e., node r transmits at rate of 14 chips per 8 source symbols on two carrier frequencies. Each destination node now applies standard CC despreading to recover its information.

Note that without network coding, i.e., standard spreading only, node r would send 14 chips to $\{t_1, t_2\}$, and 14 different chips to $\{t_3, t_4\}$. Thus, 28 chips would be needed per 8 source symbols. Thus, the NSC scheme reduces the required bandwidth in the downlink channel by 50%.

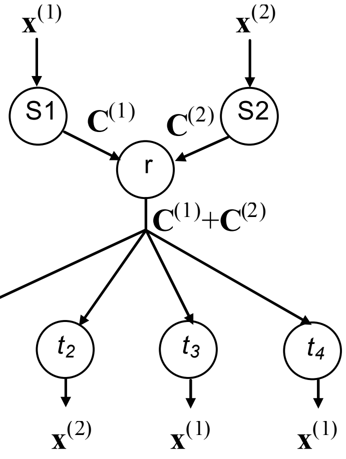

Fig.1: Example of the proposed multi-session multicast system. Two-session multicast between source nodes S1 and S2, and destination nodes $\{t_1,t_2\}$and $\{t_3,t_4\}$, respectively using the proposed scheme

2.3 Properties

The proposed MS-NSC scheme possesses the following desirable properties. Firstly, due to its “offset stack” (OS) encoding technique [12], the MS-NSC scheme is inherently capable of distributed encoding and multi-rate transmission when nodes are multicasting at varying transmission rates or receivers are downloading at different capacities. Secondly, intermediate/receive nodes do not need to know encoding vectors since they can be tagged as the packet header. Thirdly, in contrast to NC, which operates under strict synchronization conditions, MS-NSC using CC encoding vectors does not require any synchronization at the intermediate nodes prior to forwarding because destination nodes are able to separate asynchronously mixed signals. Fourthly, MS-NSC is inherently resilient to security threats, such as “Byzantine attacks” [15] which occur when malicious nodes inject a junk packet into the network. In MS-NSC, authentic signals are assigned orthogonal CC encoding vectors, and any malicious signals are treated as noise, even if the malicious packets are spread with a genuine CC vector – in this case, only signals encoded with the same CC vectors are corrupted.

Finally, one major problem with NC is that the loss of single information (symbol) could affect many other symbols. For example, in Fig. 2 (a) a source S is forwarding four bits a, b, c and d, to three receivers t_1, t_2, and t_3 via intermediate nodes r_1, r_2, and r_3. Node S transmits bits a and b to node r_1, bits c and d to node r_2 and finally the modulo-2 additions a+c and b+d to node r_3. In order for destination node t_3 to recover bits a and b, it requires the reception of c, a+c, d, and b+d. The loss of c during transmission means that t_3 will fail to recover successfully a even if the bit combination a+c reaches t_3 successfully. Furthermore, t_3 considers the encoded combination a+c invalid.

In contrast to NC, the proposed NSC scheme is robust to such loss. Indeed, Fig.2 (b) shows an equivalent network with a source S, four bits (a, b, c, d) that are encoded using CC sequences of length K= 4 chips and chip-shift τ =1 into 14 chips. S sends the 14 chips (compared to 4 bits in case of NC) over two links to only two intermediate nodes r_1 and r_2 to destination node t_1, t_2, and t_3. From Fig 2(b) it is obvious that the NSC scheme is able to deliver the 14 chips to node t_3, successfully, even for the case of total failure with node r_1 and loss of the 14 chips. Eventually, t_3 decodes the 14 chips and recovers the four bits a, b, c, and d. This reflects the robust performance of the NSC scheme.

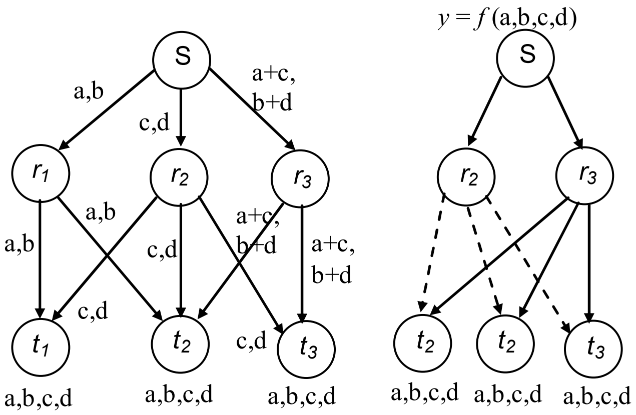

Fig. 2: Loss of a packet in (a) the traditional NC scheme [16], (b) the robust NSC scheme.

3. SIMULATION RESULTS

In this section we report our experimental results for different wireless channels and both the proposed MS-NSC-F and MS-NSC-DSF modes. In all our simulations we use the following:

- The source rate is set to 1 Mbit/sec.
- Two multicast scenarios with the system set-up shown in Fig. 1: (i) single-session multicast for the 2source–2destination nodes - (2,2) setup, (ii) and the two-session multicast for the 2source–4destination nodes - (2,4) setup.
- CC element sequences of length K=4.
- Two source nodes are used and N=2 carrier frequencies.
- Results are averaged over 10^6 bits transmitted per source.
- Two sources transmit independent data streams either synchronously or asynchronously (simulated by an inter-node shift of one chip) to the relay node r, which sends combined streams to the destination nodes using the NSC-F mode or the NSC-DSF mode.
- Transmission rates at the intermediate node r are 14/8 or 14/4 Mchip/sec.
- Two types of channel models are simulated: AWGN (Fig. 3), and AWGN with flat Rayleigh fading (Figs. 4 and 5).

Fig. 3 shows the performance of NSC-F obtained as bit-error-rate (BER) averaged over the four destination nodes, versus the channel SNR over an AWGN channel. All channels from the two sources to the relay node and from the relay node to the destination nodes are simulated with the same SNR. We observe: (i) for both synchronous and asynchronous transmission and the same receiving rate (14/8 or 14/4), the system maintains the same BER regardless of the number of active destination nodes (2 or 4 nodes) involved in the two-session multicast, (ii) as expected, for both synchronous and asynchronous transmission, doubling the data rate to 14/4 Mchip/sec offers 3dB improvement in system performance, (iii) a slight degradation of roughly 1 dB exists between the asynchronous and synchronous communications.

Fig. 4 demonstrates the BER versus SNR performance of the proposed system using the NSC-F scheme over a fading channel, with different destination node speeds of 3, 30 and 120km/h. All channels from the two sources to the relay node and from the relay node to the destination nodes are simulated with the same SNR and independent fading. It is observed that for the same node speed and transmission rate, there is almost no performance loss with increased number of destination nodes. However, a degradation of almost 3 dB and 5 dB is experienced when the node speed is increased from 3km/h to 30 km/h, and from 3km/h to 120km/h, respectively. Similar to results obtained in Fig.3, doubling the data rate offers 3dB improvement in system performance, e.g., the proposed system achieves BER = 10^{-3} at SNR = 21 dB and 18 dB and rate 14/8 and 14/4 Mchip/sec, respectively.

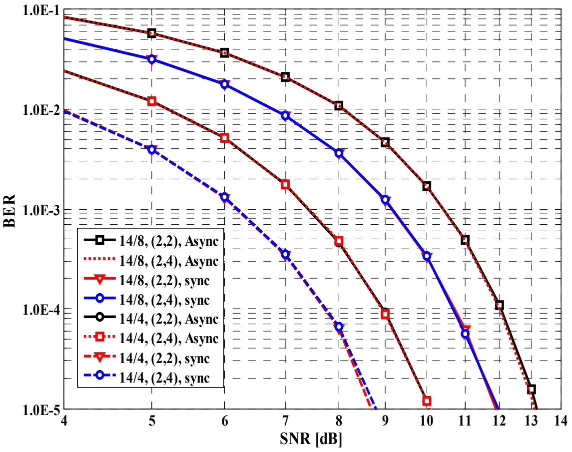

Fig.3: BER vs SNR performance for both asynchronous and synchronous NSC-F scheme with combined rate 14/4 or 14/8 under AWGN channel.

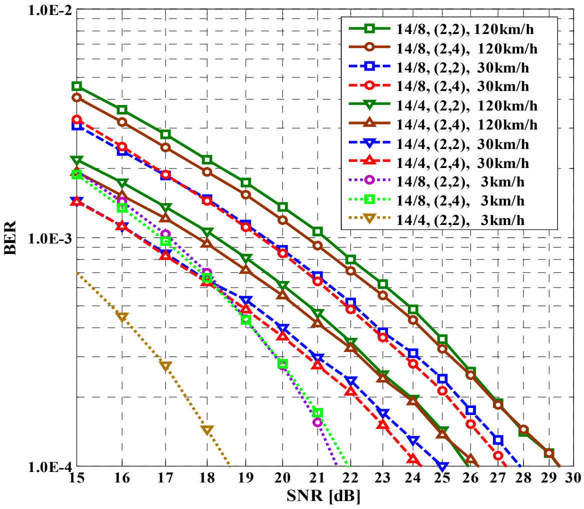

Fig.4: BER vs SNR performance for the asynchronous NSC-F scheme at combined rate 14/4 or 14/8 and under a flat fading channel with relative node speed of 3, 30, and 120 km/h.

Observations for Fig. 5 are similar to those in Fig. 4; however, the system using the NSC-DSF scheme outperforms, by roughly 3dB, the system using the NSC-F scheme for the same node speed and rate.

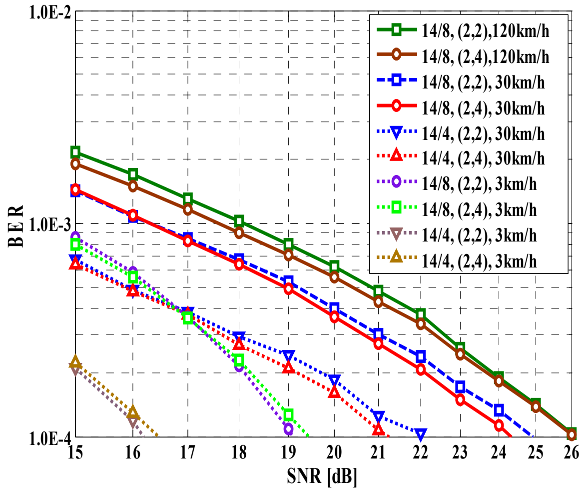

Fig.5: BER vs SNR performance for the asynchronous NSC-DSF scheme at combined rate 14/4 or 14/8 and under a flat fading channel with relative node speed of 3, 30, and 120 km/h.

In summary, the proposed system using either the NSC-F or NSC-DSF scheme achieves almost the same BER performance for both single and multi-session multicast scenarios, regardless of the data rate, communication channels conditions, or node speed.

4. CONCLUSIONS

In this paper, we extend the single-source Network Spread Coding (NSC) scheme to the more general MS-NSC scheme. Results obtained demonstrate the ability of the proposed NSC–F and NSC-DSF modes to achieve similar BER performance for both single and multi-session multicast in wireless networks operating under fading channel conditions and interference. Furthermore, flexible trade-off among the mode complexity, the required channel bandwidth and the recovered signal quality can simply be achieved by modifying the combined rate.

Future work will focus on developing practical systems for wireless multimedia multi-session multicast using the MS-NSC scheme.

REFERENCES

[1] R. Ashlswede, N. Cai, S.-Y.R. Li, and R. W. Yeung, “Network information flow,” IEEE Trans. Inform. Theory, vol. 46, pp. 1204-1216, July 2000.

[2] P. A. Chou and Y. Wu, “Network Coding for the Internet and wireless networks,” IEEE Signal Processing Magazine, to appear, available as Microsoft Research Technical Report TR-2007-70, June 2007.

[3] Y. Wu, P.A. Chou, Q. Zhang, K. Jain, W. Zhu, and S.-Y. Kung, “Network planning in wireless ad hoc networks: a cross-layer approach,” IEEE JSAC, vol. 23, pp. 136-150, Jan. 2005.

[4] Y. Wu, P.A. Chou, and S.-Y. Kung, “Information exchange in wireless networks with network coding and physical-layer broadcast,” CISS-2005, Baltimore, MD, March 2005.

[5] C. Fragouli, J.-Y. Le Boudec, and J. Widmer, “Network coding: An instant primer,” ACM Computer Communication Review, vol. 36, pp. 63-68, 2006.

[6] J. Widmer and J. -Y. Le Boudec, “Network coding for efficient communication in extreme networks”, Proc. ACM SIGCOMM Workshop on Delay-tolerant Networking and Related Networks (WDTN -05), Philadelphia, PA, Aug. 2005.

[7] Y. Wu, V. Stankovic, Z. Xiong, and S. Y. Kung, “On practical design for joint distributed source and network coding,” Proc. NetCod-2005, Riva del Garda, Italy, April 2005.

[8] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, “XORs in the air: Practical wireless network coding,” Proc. ACM SIGCOMM, Pisa, Italy, Sept. 2006.

[9] S. Zhang, S. – C. Liew, and P. P. Lam, “Hot topic: Physical layer network coding,” Proc. MobiCom2006, LA, USA, Sept.2006.

[10] S. Katii, S. Gollakota, and D. Katabi, “Embracing wireless interference: Analog network coding,” ACM SIGCOMM, Aug. 27 – 31, Kyoto, Japan.

[11] C. Khirallah, V. Stankovic, L. Stankovic., D. Poutouris, “Network Spread Coding,” Proc. Netcod-2008, Hong Kong, Jan. 2008.

[12] H. H. Chen, Y. Xiao, J. Li, and R. Fantacci, “The OCC-CDMA/OS for 4G wireless,” IEEE Vehicular Technology Magazine, vol. 1, no. 3, pp. 2–3, 2006

[13] C. Khirallah, P. Coulton, H. Rashvand, and N. Zein, “Multi-user MIMO CDMA systems using complete complementary sequences,” IEE Proc. Commun., vol. 153, pp. 533-540, Aug. 2006.

[14] R. W. Yeung, S.-Y. R. Li., N. Cai, and Z. Zhang, *Network Coding Theory*, now publishers, 2005.

[15] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, and M. Medrad, “Resilient network coding in the presence of Byzantine adversaries,” IEEE INFOCOM, 2007.

[16] T. Noguchi, T. Matsuda, and M. Yamamoto, “Performance evaluation of new multicast architecture with network coding,” IEICE Trans. Commun, vol. E86-B, pp. 1788-1975.