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Performance Analysis of Network Coding-Based Content Delivery in Dual Interface Cellular Networks

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***Abstract*—We consider a group of mobile users, in closed proximity, who are interested in downloading a common content (e.g., a video file). We address a cooperative solution where each mobile device is equipped with both cellular and Wi-Fi interfaces. The users exploit the cellular link to download different shares of the content from the based-station and leverage on Wi-Fi link to exchange the received data. In order to expedite content delivery, the base-station transmits random linear network-coded data to users. This paper presents an analytical study of the average completion time, i.e., the time necessary for all devices to successfully retrieve the data. We propose an analytical model to address the effect of random access MAC as well as the correlation among the received coded packets on the performance of content delivery. In our model, a p-persistent carrier sense multiple access approximation for IEEE 802.11 MAC is considered. We also derive the probability of a newly received packet to be innovative, where the coding coefficients are selected randomly and uniformly from $GF(q)$. Our simulations confirms the theoretical analysis.**

***Index Terms*—Network coding, content delivery, device-to-device communication, dual interfaces, IEEE 802.11 MAC**

I. Introduction

Device-to-device (D2D) communication is a promising paradigm to improve the service quality of cellular networks. D2D communication enables the cellular users within a close proximity to directly communicate with each other without mediating of the base-station. Several use-cases of D2D communication include content-distribution, cellular offloading and cellular relaying [1]. Long Term Evolution - Advanced (LTE-A) standard as well as 5G cellular network support D2D communication [2].

In this paper, we focus on content delivery among a cluster of mobile users within the proximity of each other. The users are interested in a common content (e.g., watching the same video from the internet at nearly the same time). The mobile devices (MDs) are equipped with two network interfaces: the cellular link to download different shares of the content from the internet and the Wi-Fi link to cooperatively exchange the data content over a short-range wireless network, as depicted in Fig. 1. It is worth noting that LTE provides conventional multicast scheme (CMS) service to multicast a shared content to a group of users [3]. However, the performance of CMS is limited by the user with the poorest channel condition, as the modulation and coding scheme (MCS) is selected according to users in the group with the worst channel in the radio cell. Hence, leveraging on short-range technology in combination with cellular network is an interesting alternative solution to enhance the performance of a multicast content delivery service [4], [5]. Network coding improves the performance of communication networks over traditional routing by allowing each device to encode the incoming packets and transmit a combination of its stored data as coded packets [6]. Random linear network coding (RLNC) is an efficient and fast approach to implement network coding, where the coding coefficients are selected randomly and independently among users from a

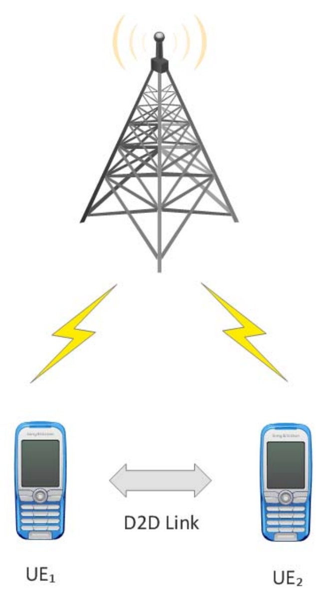

Fig. 1. A dual-interface cellular network. Users in closed proximity cooperate via short-range Wi-Fi links to acquire a common content.

finite field and the coded data is a linear combination of the incoming packets [7]. Network coding is able to facilitate the content dissemination by exchanging the coded data instead of native ones. The coded data is more likely to be innovative which benefits the receivers to recover the interested content faster. In other word, a single transmission of a coded packet can help more devices to retrieve the content.

In this paper, we address network coding-based content delivery in dual-interface mobile network. The MDs receive randomly coded parts of a common content from a base-station using cellular links. They broadcast the received data to other users cooperatively based on IEEE 802.11 MAC protocol to retrieve the demanded content. The paper's main contribution is to provide an analytical solution to approximately compute the average completion time of the content delivery process. In the analysis, we consider the correlation among the transmitted coded packets as well as the average time the MDs contend to successfully transmit a packet. To the best of our knowledge, the previous analytical works in this area do not consider these factors together. In this regard, we derive the probability that a newly received coded packet is innovative (i.e., it is linearly independent from the set of previously received packets). Moreover, in order to include the collision of transmitted packets in the completion time, we adopt a p-persistent CSMA approximation for IEEE 802.11 MAC protocol.

In our previous work [8], we analyzed content distribution in a single-hop VANET and provided a theoretical framework to calculate the average content distribution delay. We employed two network coding schemes: RLNC over a large finite field and random XORed network coding. In the present paper, we extend the analytical framework developed in [8] in twofold. First, we assume an arbitrary coding field size. This generalization is important since it contributes to make a good balance between network coding overhead and coded packet innovative probability (see Section III for more detail). Second, in analytical model presented in [8], the number of coded packets depends on the number of users, which limits the application of the model. In this paper, we extend the model in order to consider a broader range of network scenario (more detail will be provided in Section III).

The reminder of the paper is organized as follows. Section II presents a summery of related works. We provide the network scenario in details in Section III. We analyze the expected completion time in Section IV. The numerical results are presented in Section V. Finally, we conclude the paper in Section IV.

II. Related Works

The effectiveness of D2D-assisted cellular communications in LTE-A networks in term of throughput and energy efficiency is shown in [2], [4]. Network coded content delivery with the aid of cooperative device-to-device communications has recently been investigated in the literature. In this respect, the authors in [9] considered a group of mobile devices which cooperatively disseminate a common content exploiting D2D connections. They proposed an instantly decodable network coding (IDNC) scheme which reduces the completion time as compared to no network coding scenario. The authors in [10] considered a multicast scenario using RLNC and provided an analytical framework to calculate throughput and energy gain from cooperation among devices. A cooperative network coding-based MAC protocol for bidirectional communication was proposed in [11], where MDs leverage on Wi-Fi links to exchange the received packets from eNodeB. They provided an analytical model to quantify the throughput. The authors in [12] considered a dual-interface mobile network and addressed minimizing the content delivery delay. They developed a framework based on graph theory. [13] proposed a cooperative system for video streaming to a group of mobile device users. They formulated the problem as a network utility maximization framework, and provided a distributed solution. They also implemented a prototype on an Android application. [14] investigated D2D-based video streaming. They implemented RLNC on the CoopStreaming system. Their experiential results showed that RLNC can enhance the quality and robustness of streaming service.

III. Network Scenario

We consider a cellular network with one base-station (eNodeB) and N mobile devices. The devices are within the proximity of each other, which have the same demand for a common content (e.g., a video). The devices utilize two interfaces: the cellular link to connect to the base station, and the Wi-Fi link to exchange the received data via device to device (D2D) communication. The base station divides the content into G pieces, called data generations. As an example, data generation may represent different frames of a video. Each data generation is further split into M blocks (hereafter referred as data packets). Data packets are linearly combined to form $C > M$ coded packets. The coding coefficients are selected randomly and uniformly from $GF(q)$.

In order to facilitate the transmission of a large file, it should be divided into several small packets. On the other hand, it is not practical to perform network coding among a large number of elements. Because, it will increase the overhead of network coding as well as decoding delay. Hence, network coding is employed among data packets of the same generation. By adjusting the number of data generations, the number of data packets at each generation is regulated. Packets are transmitted such that data generations are retrieved sequentially. Hereafter, we focus only on data dissemination of a single data generation.

The base station transmits $\Gamma = C/N$ coded packets to each mobile device through the cellular link (*receive phase*). MDs constitute a Wi-Fi ad hoc network to exchange the received parts and retrieve the required content in a cooperative way (*exchange phase*). We suppose a single-hop network of N devices, where each device is in the transmission range of the others. Cooperative devices broadcast the downloaded data in the Wi-Fi network, based on IEEE 802.11 medium access protocol. Hence, active devices (which have packets to transmit) contend for the channel access to transmit one coded packet at a time. We ignore all physical channel non-idealities and consider the collision as the main hindering factor. Hence, a successfully transmitted packet is received by all the devices. In our analysis, we model the MAC protocol as a p-persistent CSMA. In this model, the exponential back-off process is approximated by a geometric distribution. Before transmitting a packet, a device senses the channel for a free time slot and transmits a packet with probability p, if the channel is not busy. Otherwise, it sends the packet with the same probability in the next free time slot. If the transmission probability, p, is carefully selected, the p-persistent CSMA model is a good approximation for IEEE 802.11 MAC protocol [15]. The parameter p is selected such that the mean of back-off interval is equal to the window-based back-off mechanism, that is, $p = 2/(1 + E(CW))$, where $E(CW)$ is the average contention window size.

At the beginning of the exchange phase, all devices are active and compete for acquiring the channel. A device is deactivated (until the next exchange phase), if it succeeds to send all its packets successfully. A device will not initiate transmitting data packets from a new generation until finishing the exchange of the previous generation. This leads to reducing the collision probability and shortening the time of retrieving a data generation. *Completion time* is defined as the total time to finish the exchange phase of a single data generation. An exchange phase is finished if either all devices succeed to recover the data generation, using the received packets, or all devices are deactivated. A successful exchange phase is defined as the one that all devices succeed to retreive the data generation, at the end of the exchange phase.

Correlation among the transmitted packets affects the success of content delivery process. If the coding coefficients are selected from $GF(q)$, the overhead is $M \log_2(q)$ bits. The larger the field size, the more innovative are the coded packets. Hence, the completion time is shorter. On the other hand, performing network coding over a smaller field size, reduces the computational complexity on the MDs as well as the coding overhead. Since the received packets are generally not independent, the successful exchange phase may need more than M successful transmissions. If the set of C coded packets contain M innovative packets, the exchange phase will be successful. The list of the most important symbols used in our analysis is summarised in Table I.

In this paper, we extend the analytical framework devised in [8] as we assume that each device has Γ initial coded packets (rather than one, i.e. $\Gamma = 1$). $\Gamma = 1$ limits the number of data blocks (M) in a data generation, since M should be less than or equal to N for a successful exchange phase. This can be a limiting factor when the number of devices is small. Moreover, the exchange phase is more likely to be successful if Γ is increased. This is because the devices can exchange the coded packets from a larger set ($C = \Gamma N$). In addition, the Markov chain representing the system is multi-dimensional which is more difficult to solve compared to the two-dimensional Markov chain presented in [8].

IV. Analysis of Completion Time

In this section, we analyze the completion time, expected time to finish an exchange phase of a single data generation.

TABLE I
Description of Symbols

Symbol	Description
N	Number of mobile devices in a cluster
M	Number of packets in a data generation
G	Number of data generations
n	Number of active devices
k	Number of successfully received innovative packets
Γ	Number of initial coded packets at a device
q	Coding coefficients are selected from $GF(q)$
δ	Slot size
L	Length of data in the number of slots
D	Length of DIFS in the number of slots
L'	Length of DIFS plus data in the number of slots
p	Probability of packet transmission
CW	Contention window size
α_i	Number of remaining packets to transmit at device i

Completion time is determined by the time required to successfully transmit a packet, determined by the MAC protocol, as well as the innovation probability of the received coded packets.

The time is divided into slots. Each data packet transmission prolongs L slots. The average time between two consecutive successful transmissions is defined as virtual transmission time (VTT), which generally comprises a successful slot as well as possibly some idle and collision slots. Let $T_{VTT}(n)$ denote the expected time of VTT, provided that there are n active devices in the system. $T_{VTT}(n)$ is derived (see [16])

$$T_{VTT}(n) = \frac{L' - (L' - 1)(1 - p)^n}{np(1 - p)^{n-1}} \delta \tag{2}$$

where $L' = L + D$. D and δ denote the length of DCF Interframe Space (DIFS) in the unit of time slot and size of a time slot, respectively. It is worth noting that the number of active devices changes during the exchange phase. At the beginning of an exchange phase, each device has Γ coded packets which is willing to exchange with the others. During the exchange phase, devices succeed to share some of their packets with the others. We model the system at the end of each successful transmission with a multi-dimensional Markov chain $(\boldsymbol{\alpha}, k)$. Here, $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \ldots, \alpha_N)$, where α_i represents the number of remaining packets to transmit at device i. Also, k represents the number of successfully received innovative packets. Correlation among the received coded packets affects the process of exchange phase. If a recently transmitted packet is innovative, it contributes to complete the exchange phase. Let $p_{new}(j; i, k, q)$ denote the conditional probability of j innovative coded packets (over $GF(q)$) among next i successfully transmitted ones, provided that k innovative packets have been received so far. $p_{new}(j; i, k, q)$ is derived from the following lemma:

Lemma 1. *$p_{new}(j; i, k, q)$ is given by :*

$$p_{new}(j; i, k, q) = \frac{R(j; i, k, q)}{(q^M - 1)^i} \tag{3}$$

where $R(j; i, k, q)$, defined in Appendix A, is given by the recursive relation (1).

$$R(j;i,k,q)=\begin{cases}(q^{k+j}-q+1)R(j;i-1,k,q)+(q^{M}-q^{k+j-1}+q-2)R(j-1;i-1,k,q) & i,j>1\\ (q^{k}-q+1)R(0;i-1,k,q) & i>1,j=0\\ q^{k}-q+1 & j=0,i=1\\ q^{M}-q^{k}+q-2 & j=1,i=1\end{cases} \quad (1)$$

Proof. see Appendix A. □

Theorem 1. *Let $T(\boldsymbol{\alpha},k;M)$ denote the expected time to finish the exchange phase starting from state $(\boldsymbol{\alpha},k)$, provided that totally M innovative coded packets are necessary to retrieve the data. $T(\boldsymbol{\alpha},k;M)$ is calculated by the following recursive equation*

$$T(\boldsymbol{\alpha},k;M)=T_{VTT}(n) + \sum_{i=1}^{N}\sum_{j=0}^{1}\Pr(\boldsymbol{\alpha},\boldsymbol{\alpha}-\boldsymbol{e}_i)T(\boldsymbol{\alpha}-\boldsymbol{e}_i,k+j;M)P_{new}(j;1,k,q) \quad (4)$$

where, n is the number of active devices which equal to zero-norm of $\boldsymbol{\alpha}$, i.e., $\|\boldsymbol{\alpha}\|_0$, $\boldsymbol{e}_i$ is the i^{th} row of identity matrix and

$$\Pr(\boldsymbol{\alpha},\boldsymbol{\alpha}-\boldsymbol{e}_i)=\frac{sign(\alpha_i)}{n}. \quad (5)$$

Proof. We start from state $(\boldsymbol{\alpha},k)$. Therefore, the number of active devices is n and k innovative packets have been successfully transmitted and received by all other devices. Among all active devices, the active device i succeeds to transmit a coded packet with probability $\frac{1}{n}$. On average, it takes $T_{VTT}(n)$ to successfully transmit a packet. After that, two events may occur. a) The transmitted packet is linearly independent of k innovative packets that have been received so far, with probability $p_{new}(1;1,k,q)$. Hence, the system enters the state $(\boldsymbol{\alpha}-\boldsymbol{e}_i,k+1)$. The mean residual of completion time is $T(\boldsymbol{\alpha}-\boldsymbol{e}_i,k+1;M)$. b) The transmitted packet is not innovative, with probability $p_{new}(0;1,k,q)$. Consequently, the system enters the state $(\boldsymbol{\alpha}-\boldsymbol{e}_i,k)$ and the mean residual completion time is $T(\boldsymbol{\alpha}-\boldsymbol{e}_i,k;M)$. Consequently, (4) infers. □

Note that if $\sum\alpha_i = 1$ and $k < M$, then $T(\boldsymbol{\alpha},k;M) = T_{VTT}(1)$. Hence, staring from this point, other terms can be calculated recursively from (4). It is worth noting that successful transmission of M innovative packets is sufficient to finish the exchange phase. Since each device already has Γ coded packets, it may be able to retrieve the data using part of the transmitted packets. In other words, a device may be able to recover the content before successful exchange of M innovative packets. However, simulations show that the time to successfully transmit M innovative packets is an accurate estimation for completion time (see Section V). Hence, an estimation on the completion time is obtained by calculating the expected time to successfully transmit M innovative packets, i.e., $T(\boldsymbol{\Gamma},0;M)$, where $\boldsymbol{\Gamma}=(\Gamma,\Gamma,\ldots,\Gamma)$.

V. Numerical results

In this section, we evaluate our analytical framework by simulation. In the simulations, we adopt 802.11 MAC protocol with binary exponential back-off. The contention window size is initiated by CW_{min} and duplicated each time a packet is collided. Whenever a node successfully transmits a packet, the contention window size is reset to CW_{min}. The simulations are performed in MATLAB environment.

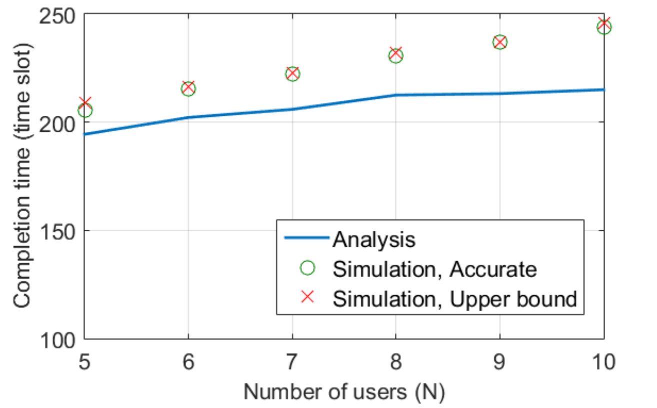

Fig. 2. Completion time versus the number of devices. $M=8, q=2, \Gamma=3, CW_{min}=16$.

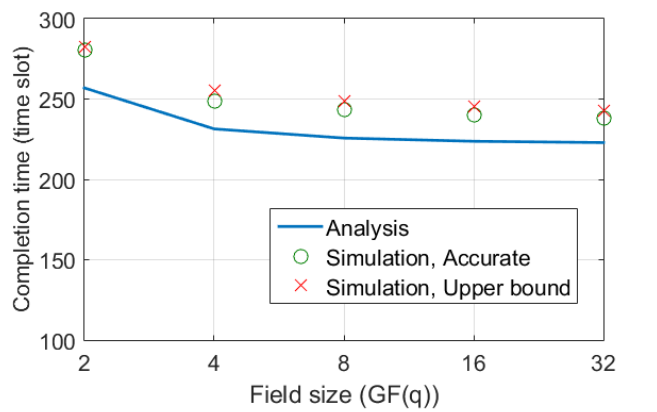

Fig. 3. Completion time versus the field size of coding coefficients. $N=8, M=10, \Gamma=3, CW_{min}=16$.

Fig. 2 illustrates the completion time versus the number of devices. Increasing the number of users results in more interference which in turn contributes to larger completion time. In this figure, upper bound on simulation results show the expected time to successfully transmit (broadcast) M innovative coded packets over Wi-Fi links. Since all devices has Γ initial packets some devices may able to retrieve the required content before receiving M innovative coded packets. However, the simulation results show that the time it takes to successfully transmit M innovative coded packets (i.e., "simulation, upper bound") is very close to completion time ("simulation, accurate"). This is useful in developing analytical

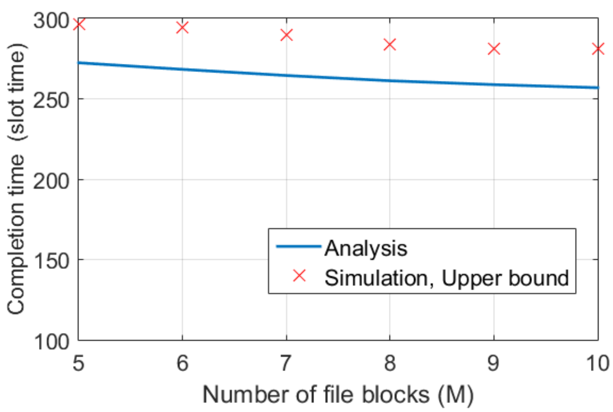

Fig. 4. Completion time versus the number of file blocks (M). $N = 8$, $\Gamma = 3, q = 2, CW_{min} = 16$.

model, since quantifying the accurate completion time requires the joint correlation between the successfully transmitted coded packets via Wi-Fi shared link and initial set of coded packets all users has received via cellular connections. Comparison between analytical and simulation results show the validity of our analysis. However, the approximated modelling of 802.11 MAC protocol results in a small difference (5% to 12%) between simulations and analysis.

The effect of field size on completion time is depicted in Fig. 3, where the coding coefficients are selected randomly from $GF(2^m), 1 \leq m \leq 5$. Increasing the field size expedites the exchange phase, since the transmitted coded packets are more innovative. This effect is more significant between $GF(2)$ (i.e. randomly XORed network coding) and $GF(4)$. On the other hand, coding complexity increases with the field size. Hence, there is a compromise between the complexity of network coding and completion time.

We also investigate the role of the number of file blocks (M) on completion time in Fig. 4. On the one hand, increasing M necessitates more innovative coded packet transmission, since each device requires M innovative coded packet to retrieve the original content. On the other hand, by increasing M, the packet size (L) deceases since we assume a fixed data generation size (L = data generation size$/M$). Hence, increasing the number of file blocks contributes to smaller transmission delay. As discussed in Section III, M should be kept small enough to reduce the network coding overhead as well as decoding complexity and delay. Hence, we can adjust M for a good balance between the completion time and decoding complexity.

VI. Conclusion

In this paper, we addressed network coding-based content dissemination in dual-interface mobile network. The users constituted a single-hop wireless network to cooperatively exchange the received coded packets from the base-station via the Wi-Fi links. We devised an analytical framework to approximately compute the average time to compute the exchange phase. The accuracy of our theoretical framework was validated by the simulation results.

Our results showed that performing network coding over a large field size expedites the content delivery process. However, there is a compromise between the completion time and coding complexity.

Appendix A
Proof of Lemma 1

A coded packet can be represented with a vector comprised of elements from $GF(q)$ and of length M. We denote Ω as the set of these vectors (excluding the all-zero vector). Assuming that k innovative packets have been received so far, the probability of existing j innovative packets within the i transmitted packets, i.e., $p_{new}(j; i, k, q)$, can be derived by counting the ways we can select i vectors $V_1, \ldots, V_i \in \Omega$, among which exactly j vectors are linearly independent from a specific k linearly independent vectors. Let $R(j; i, k, q)$ denote the number of these ways. Clearly, by this definition p_{new} is derived from (3). $R(j; i, k, q)$ is equivalent to the number of $(i+k) \times M$ matrices with rank $j+k$ with given k independent rows.

We can construct the aforementioned matrix by one of the two following ways: (a) add a dependent row to a $(i+k-1) \times M$ matrix with rank $j+k$. (b) add an independent row to a $(i+k-1) \times M$ matrix with rank $j+k-1$. A non-zero vector linearly dependent with the given $j+k$ independent vectors is selected in

$$(q-1)\binom{k+j}{1} + (q-1)^2\binom{k+j}{2} + \ldots + (q-1)^{k+j}\binom{k+j}{k+j} \tag{6}$$

ways which equals to $q^{k+j} - (q-1)$, using binomial expansion.

The number of linearly independent non-zero vectors with the given $j+k-1$ independent vectors will be

$$q^M - 1 - (q-1)\binom{k+j-1}{1} - (q-1)^2\binom{k+j-1}{2} - \ldots - (q-1)^{k+j-1}\binom{k+j-1}{k+j-1} \tag{7}$$

which is equal to $q^M - q^{k+j-1} + q - 2$. Hence, (1) immediately infers.

References

[1] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[2] A. Asadi and V. Mancuso, "Network-assisted outband D2D-clustering in 5G cellular networks: Theory and practice," *IEEE Transactions on Mobile Computing*, vol. 16, no. 8, pp. 2246–2259, 2017.

[3] R. O. Afolabi, A. Dadlani, and K. Kim, "Multicast scheduling and resource allocation algorithms for OFDMA-based systems: A survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 1, pp. 240–254, 2013.

[4] L. Militano, M. Condoluci, G. Araniti, A. Molinaro, A. Iera, and F. H. P. Fitzek, "Wi-Fi cooperation or D2D-based multicast content distribution in LTE-A: A comparative analysis," in *2014 IEEE International Conference on Communications Workshops (ICC)*, 2014, pp. 296–301.

[5] Z. Xia, J. Yan, and Y. Liu, "Cooperative content delivery in multicast multihop device-to-device networks," *IEEE Access*, vol. 5, pp. 6314–6324, 2017.

[6] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung, "Network information flow," *IEEE Transactions on Information Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[7] T. Ho, M. Medard, R. Koetter, D. Karger, M. Effros, J. Shi, and B. Leong, "A random linear network coding approach to multicast," *IEEE Transactions on Information Theory*, vol. 52, no. 10, pp. 4413–4430, Oct. 2006.

[8] M. H. Amerimehr and F. Ashtiani, "Performance analysis of network coding-based content distribution in vehicular ad-hoc networks," *IET Communications*, vol. 8, no. 9, pp. 1447–1458, 2014.

[9] Y. Keshtkarjahromi, H. Seferoglu, R. Ansari, and A. Khokhar, "Content-aware network coding over device-to-device networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 8, pp. 2147–2158, 2017.

[10] N. J. Hernndez Marcano, J. Heide, D. E. Lucani, and F. H. P. Fitzek, "Throughput, energy and overhead of multicast device-to-device communications with network-coded cooperation," *Transactions on Emerging Telecommunications Technologies*, vol. 28, no. 2, pp. e3011–n/a, 2017.

[11] E. Datsika, A. Antonopoulos, N. Zorba, and C. Verikoukis, "Cross-network performance analysis of network coding aided cooperative outband D2D communications," *IEEE Transactions on Wireless Communications*, vol. 16, no. 5, pp. 3176–3188, 2017.

[12] M. S. Karim, A. Douik, P. Sadeghi, and S. Sorour, "On using dual interfaces with network coding for delivery delay reduction," *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3981–3995, 2017.

[13] A. Le, L. Keller, H. Seferoglu, B. Cici, C. Fragouli, and A. Markopoulou, "Microcast: Cooperative video streaming using cellular and local connections," *IEEE/ACM Transactions on Networking*, vol. 24, no. 5, pp. 2983–2999, 2016.

[14] L. Aymen, B. Ye, and T. M. T. Nguyen, "Offloading performance evaluation for network coding-based cooperative mobile video streaming," in *7th International Conference on the Network of the Future (NOF)*, Nov. 2016, pp. 1–5.

[15] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Transactions on Networking*, vol. 8, no. 6, pp. 785–799, Dec. 2000.

[16] K. Yedavalli and B. Krishnamachari, "Enhancement of the IEEE 802.15.4 MAC protocol for scalable data collection in dense sensor networks," in *WiOPT*, Apr. 2008, pp. 152 –161.