Mode selection schemes for unicasting device-to-device communications supported by network coding

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Summary
Device-to-device (D2D) communication in a cellular spectrum increases the spectral and energy efficiency of local communication sessions, while also taking advantage of accessing licensed spectrum and higher transmit power levels than when using unlicensed bands. To realize the potential benefits of D2D communications, appropriate mode selection algorithms that select between the cellular and D2D communication modes must be designed. On the other hand, physical-layer network coding (NWC) at a cellular base station—which can be used without D2D capability—can also improve the spectral efficiency of a cellular network that carries local traffic. In this paper, we ask whether cellular networks should support D2D communications, physical-layer NWC, or both. To this end, we study the performance of mode selection algorithms that can be used in cellular networks that use physical-layer NWC and support D2D communications. We find that the joint application of D2D communication and NWC scheme yields additional gains compared with a network that implements only one of these schemes, provided that the network implements proper mode selection and resource allocation algorithms. We propose 2 mode selection schemes that aim to achieve high signal-to-interference-plus-noise ratio and spectral efficiency, respectively, and take into account the NWC and D2D capabilities of the network.

KEYWORDS
cellular networks, device-to-device communications, network coding, radio resource management

1 | INTRODUCTION

Device-to-device (D2D) communication in a cellular spectrum assisted by a cellular network enables direct communication between user equipments (UEs) that are in the proximity of one another.¹,² The objective of supporting D2D communication in a licensed spectrum assisted by cellular networks is to exploit the so-called reuse and proximity gains¹ of UEs when engaged in proximal communication sessions such as social aware communications,³ vehicle- or machine-type communication, or proximity-based services.³ However, the current release of the 3rd Generation Partnership Project (3GPP) standards suite only supports broadcasting at the physical and medium access control layers, which does not allow a D2D transmitter to adjust its transmit parameters to an intended peer receiver.

An early version of this article was presented at the European Wireless conference in May 2014.¹
When proximate communication opportunities exist, unicasting D2D communication has advantages over the traditional cellular communication mode that routes local traffic through the cellular base station and uses both uplink (UL) and downlink (DL) resources. Indeed, D2D communication increases the spectral efficiency not only because of the proximity gain in terms of improved link budget but also because of the so-called spectrum reuse gain and hop gain. A necessary technology component of D2D is mode selection (MS), which selects the cellular or direct communication mode for a D2D pair based on factors such as the large- or small-scale fading between the communicating devices, as well as between the devices and the cellular base station, traffic load, and interference level. Recognizing the potential of unicasting D2D, previous works have proposed efficient MS, resource allocation, and power control algorithms that help realize the proximity, reuse, and hop gains of local communications, while protecting both the cellular and D2D layers from interference that arises because of the tight spectrum reuse.

Recognizing the high potential of D2D communications, the 3GPP has recently included control plane and measurement support for physical-layer broadcasting-based D2D communications. The 3GPP is currently studying the necessary physical-layer enhancements for introducing physical-layer unicast support for D2D communications in the future releases of Long-Term Evolution (LTE) and New Radio networks. Indeed, physical-layer unicast—that is, the D2D transmitter being aware of the intended receiver, as opposed to the currently supported broadcast communication—is needed to fully realize the gains expected from introducing D2D communications in a cellular spectrum.

Studies have shown that when local (proximal) communication opportunities exist in a cellular network, physical-layer network coding (PNC) improves the spectrum efficiency by enabling resource reuse by multiple transmissions and cancelling harmful interference using advanced signal processing techniques. Despite the large differences between D2D communications assisted by a cellular network and using various forms of network coding (NWC), their ultimate objective of improving the spectral efficiency and increasing the network capacity by enabling tighter reuse of resources is comparable.

Since both technologies have similar objectives, it is natural to ask whether the joint application of D2D and NWC would result in further spectral or energy efficiency gains in a network that supports only one of these techniques. This question—initially raised in Fodor et al—is motivated by the realization that introducing D2D and NWC could be costly in terms of UE capabilities, measurement reports, and control plane support.

Therefore, we aim in this article to answer the following questions:

- Does PNC provide gains in cellular networks that support unicasting D2D communication, that is, when a D2D transmitter is aware of its intended receiver?
- Does unicasting D2D provide gains in a cellular network that uses PNC?

Thus, the contribution of our work is that it identifies the possible joint D2D and NWC schemes and—using system simulations—provides insights into the potential benefits of using them separately or jointly. We also believe that the idea of using an NWC-aware MS scheme in D2D-capable cellular network is an important contribution. To this end, we structure the remainder of the paper as follows. Section 3 discusses the possible transmission modes in an integrated D2D-cellular network that can use different forms of NWC. Section 4 develops a system model and discusses the key performance aspects. In Section 5, we propose MS and resource allocation schemes applicable in the integrated D2D-NWC environment. Section 6 discusses numerical results, and Section 7 summarizes our findings.

## 2 RELATED WORKS AND CONTRIBUTION

While many papers are closely related to D2D communications in cellular networks, MS, and NWC facilitated by D2D communications, our literature survey shows that there have not been any previous studies of mode selection algorithms taking into account both D2D communications and NWC. In particular, the question formulated at the end of Section 1 (do combined NWC and D2D schemes provide gains over systems using only one of these techniques) remains unanswered in the literature. We seek an answer to this question, since modern cellular networks are increasingly required to support local (proximity) communications using D2D communications or NWC or combined schemes.

### 2.1 Papers related to physical-layer network coding

The seminal paper by Louie et al gives an in-depth performance analysis and comparison of the 2-, 3-, and 4-time slot PNC schemes in terms of the received signal-to-noise ratio, outage probabilities, and bit error rates. That paper assumes
perfect channel state information knowledge and does not consider any interference at the receivers. Channel estimation errors and the impact of power allocation on the performance of traditional as well as PNC are examined in Tabataba et al. That paper proposes simple power allocation techniques that are well suited to both perfect and imperfect channel state information conditions and high and low signal-to-noise ratios (in interference-free scenarios) and rely on channel statistics. The impact of co-channel interference on the performance of the 2-way relay system including the 2- and 3-time slot schemes is studied in Yang et al. More recently, Yadav and Upadhyay investigated the impact of outdated channel estimates on 2-way PNC-based relaying without interference. Although the results and methodologies developed in these papers provide valuable insights, they do not easily generalize to scenarios in which multicell interference is present and both cellular and D2D modes are available for proximity communications.

2.2 Papers related to mode selection for D2D communications

Both academia and industry have studied transmission MS for D2D communications underlaying a cellular network (see, for example, previous studies). In those publications, the transmission mode refers to the D2D mode where 2 D2D UEs communicate directly over the air or to the cellular mode where 2 D2D UEs communicate via the base station (BS), as in traditional cellular networks. However, as mentioned in Lei et al., the definition of the transmission mode can also be more complex and reflect more design alternatives in D2D communications, including how spectrum sharing is managed between the cellular and D2D users (orthogonal or overlapping resources) and the time scale over which the resources are assigned to D2D users. However, none of these studies include the PNC schemes that are included in the definition of the transmission mode in the present paper. Therefore, these MS schemes are not applicable in D2D networks that combine D2D capability with PNC.

2.3 Papers related to D2D communications using network coding

Using NWC in cellular network–assisted D2D communication is straightforward and appealing, since the cellular base station can act as a relay between the 2 communicating UEs. Recognizing the applicability of NWC in D2D communications, several papers have investigated the performance benefits of NWC specifically in D2D communication scenarios. The results reported in Rodziewicz indicate that direct D2D communication with NWC can use more resources than D2D communication without NWC (depending on the specific NWC scheme), and its application can be beneficial in terms of link quality and communication range. Physical-layer NWC–aided 2-way D2D communication is considered in Zhao et al. In that paper, the D2D system is modeled as a coalition game, and a distributed resource allocation algorithm based on coalition formation is proposed. Pahlevani et al advocate the use of NWC as an enabling technology for enhanced security and communication efficiency. However, MS schemes are beyond the scope of these papers.

2.4 Contributions of the present paper

In this paper, we develop a model for D2D networks that support 2-slot and 3-slot (with/without maximum ratio combining [MRC]) NWC, in addition to traditional cellular communication and D2D communication without NWC. By implementing this model in a realistic multicell system simulator, and analyzing numerical results, we address 2 research questions:

- What are the performance gains in terms of the achieved signal-to-interference-plus-noise ratio (SINR) of combined D2D and NWC schemes as compared with a cellular system that supports only one of these schemes?
- What transmission MS algorithms should be used in systems that support both D2D and NWC?

This study contributes to the existing literature through the 2 proposed MS algorithms and engineering insights offered by the associated numerical results. We believe that these results are useful for the research and especially for the standardization community in developing D2D technology enablers that are useful in practice.

3 USING D2D AND NWC TO SUPPORT LOCAL TRAFFIC

To understand the similarities and differences between D2D- and NWC-based operation, consider Figure 1. In the scenario of Figure 1, the D2D-capable UE1 and UE2 are served by the same base station (eNB) while exchanging data with...
One another. Unicasting D2D capability enables direct communication without involving the serving eNB, in which case a bidirectional exchange of signals $x_1$ and $x_2$ requires 2 orthogonal resources.* For example, when using time division duplexing on the D2D link, $x_1$ and $x_2$ are exchanged in subsequent time slots (TS-1 and TS-2).

Alternatively, in a cellular network in which the eNB uses PNC, 2 time slots are sufficient for the exchange of $x_1$ and $x_2$. That is, using PNC or 2 time slot (2-TS) NWC, UE1 and UE2 transmit on the same resource (TS-1), while the eNB uses TS-2 to transmit the network coded data $f(x_1, x_2)$ to UE1 and UE2 at the same time.\textsuperscript{13,14} UE1 and UE2 use cellular links to receive $f(x_1, x_2)$ and decode $x_1$ and $x_2$, respectively.

As an alternative to the 2-TS NWC scheme, the 3-TS NWC scheme uses orthogonal resources (time slots) to transmit $x_1$ and $x_2$ to the eNB, while the eNB uses a single time slot (TS-3) to transmit the network coded data of $f(x_1, x_2)$. When UE1 and UE2 are in the proximity of one another, and the eNB supports the 3-TS NWC scheme, it is possible to use D2D and NWC jointly (Figure 1). In this joint NWC-D2D mode, UE2 uses D2D communications to receive the direct transmission from UE1 (in the UL time slot TS-1) and the network coded transmission from the eNB (in the DL time slot TS-2). To properly decode the data transmitted by the peer UE, UE2 can then use signal processing (for example, MRC with maximum likelihood detection, as illustrated by Figures 2 and 3) to separate the own transmitted packet from the packet transmitted by UE1.

To understand the combined operation of PNC at the eNB and MRC at the UE2, consider Figures 2 and 3. To be able to combine the received signal on the direct D2D link ($y_1$) and the network coded data on the DL ($y_2$), UE2 continuously maintains the corresponding channel estimates $h_{12}$ (D2D link) and $h_2$ (DL). The received D2D and DL signals at UE2 can then be written as

\begin{align}
y_1 & = h_{12} x_1 + n, \\
y_2 & = h_2 f(x_1, x_2) + n,
\end{align}

where $n$ denotes the thermal noise at UE2. The input variables to the maximum likelihood decision unit at UE2 are given as

\begin{align}
\hat{x}_1 & = h_{12}^* y_1 = h_{12}^* h_{12} x_1 + h_{12}^* n, \\
\hat{x}_2 & = h_2^* y_2 = h_2^* h_2 f(x_1, x_2) + h_2^* n.
\end{align}

UE2 uses the maximum likelihood decoding rule to estimate the transmitted symbol by $\hat{x}_i \in \mathcal{X}$, where $\mathcal{X}$ is the symbol alphabet, as

\*In this paper, we do not consider the application of full-duplex communication.
FIGURE 2  Maximum ratio combining at UE2: In the uplink time slot (TS-1), UE1 transmits $x_1$, which is captured by the eNB and UE2. In the subsequent uplink time slot (TS-2), UE2 transmits $x_2$. Finally in the downlink time slot (TS-3), the eNB transmits the network coded data $f(x_1, x_2)$. D2D, device-to-device; UE, user equipment.

$$\hat{x}_1 = \arg \min_{x_1 \in \mathcal{X}} \left( |y_1 - h_{12}x_1|^2 + |y_2 - h_{22}f(x_1, x_2)|^2 \right)$$

FIGURE 3  Details of the maximum ratio combining with maximum likelihood decision at user equipment (UE2): UE2 uses the received signal through the direct device-to-device (D2D) path ($y_1$) and the received network coded data ($y_2$) to estimate the transmitted symbol $x_1 \in \mathcal{X}$, where $\mathcal{X}$ is the symbol alphabet.

FIGURE 4  An overview of the available transmission modes for local communications. The fifth transmission mode (3-TS NWC with maximum ratio combining) integrates D2D and NWC in a joint scheme, as illustrated by Figures 2 and 3. D2D, device-to-device; NWC, network coding; TS, time slot.
\[
\hat{x}_i = \arg \min_{x_i \in \mathbb{X}} (|y_1 - h_{12}x_i|^2 + |y_2 - h_{2}f(x_i, x_{\text{own}})|^2) = \\
= \arg \min_{x_i \in \mathbb{X}} (|y_1|^2 + |y_2|^2 + |h_{12}|^2|x_i|^2 + |h_{2}|^2|f(x_i, x_{\text{own}})|^2) \\
- x_i^* \hat{x}_1 - x_i^* \hat{x}_1 \hat{x}_2 f^*(x_i, x_{\text{own}}) - \hat{x}_2^* f(x_i, x_{\text{own}}) .
\]

Note that using the locally available channel estimates and (3) and (4), all 6 terms that are needed in the maximum likelihood decoding above are available at UE2, since UE2 substitutes its own transmitted symbol \(x_2\) into \(x_{\text{own}}\) and the NWC function \(f(\cdot, \cdot)\) is known by UE2.

Figure 4 illustrates the possible transmission modes that are available for local (proximity) communications by the traditional cellular, unicasting D2D, and PNC schemes. Notice that the traditional cellular transmissions (without D2D and NWC capabilities) of \(x_1\) and \(x_2\) require 4 time slots (4-TS), since transmitting each requires a UL and a DL time slot. \(^{13}\)

### 4 PERFORMANCE ASPECTS

Investigating the performance of the available local communication schemes (Figure 4) analytically is difficult because of the random positions of the UEs and the resulting interference situation at each receiver. Therefore, in this paper, we resort to a realistic system simulator to analyze system performance. The performance indicators of interest include the end-to-end SINR, the total transmit power needed for the bidirectional transmissions \((P_A + P_B + P_R)\), and the resulting spectral efficiency as a function of the achieved SINR and the number of required time slot.

#### 4.1 Signal models

The signal models for the NWC-based and D2D-based transmissions are shown by Figure 5, where the aggregate interference affecting both the end devices (UE1 and UE2) and the relaying equipment (eNB) is also illustrated. In this figure, \(h\) and \(g\) denote the complex channel coefficients, while \(n\) denotes the additive Gaussian noise.

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**FIGURE 5** Signal models for network coding (NWC) and device-to-device (D2D) transmissions. Source A transmits signal \(x_A\) with power \(P_A\) while source B transmits signal \(x_B\) with power \(P_B\). NWC transmission involves a relay node (in this case is the base station) while D2D transmission does not. The relay transmits with power \(P_R\).
4.1.1 Network coding

As indicated in the upper part of Figure 5, when NWC is used, the communication is assisted by a relay node that forwards the information from source A to source B and vice versa. In a local communication session, it is assumed that sources A and B are UEs while the relay node is the base station (eNB).

Each node receives additional Gaussian noise $n_A, n_B, n_R \sim \mathcal{CN}(0, \sigma^2)$ and experiences interference from other transmitters using the same resource.

Notations $h_U, g_U, h_D, g_D, i_{A_k}, i_{R_k},$ and $i_{B_k}$ represent channel gains. In our model, the UL and DL channels can have different channel gains.

4.1.2 D2D communication

The signal model for a unicasting D2D communication session is illustrated by the lower part of Figure 5. In this case, the UEs communicate with one another through the direct D2D links, and there is no relay node (eNB) assisting the information exchange.

4.2 SINR analysis

The SINR analysis for the physical NWC schemes is based on Louie et al. The notations $x_A, x_B,$ and $x_{i_k}$ represent data symbols transmitted by source A, source B, and interferer $k,$ respectively. The transmit power levels of source A, source B, the relay, and interferer $k$ are denoted as $P_A, P_B, P_R,$ and $P_{i_k}$, respectively. Furthermore, we define $P_{i_k}^{(1)}, i_{A_k}^{(1)}, i_{R_k}^{(1)},$ and $i_{B_k}^{(1)}$ as the transmit power, channel gains, and data symbols associated with interferer $k$ in time slot $t$.

It is important to realize that the SINR used in this context is different from the traditional single-link SINR. Specifically, we use end-to-end SINR that accounts for both the source-to-relay and the relay-to-destination SINRs to better characterize the different transmission schemes. The expressions of all transmission schemes listed in Figure 4 are given below, while the derivations are given in the Appendix.

4.2.1 Two-time slot (2-TS) network coding

For the 2-TS NWC scheme, the end-to-end SINR values at sources A and B are calculated as follows.

$$\gamma_A = \frac{G^2 P_R |h_D|^2 |P_B|^2 |g_U|^2}{G^2 P_R |h_D|^2 \psi_2 + \sum_k P_{i_k}^{(2)} |i_{A_k}^{(2)}|^2 + \sigma^2},$$

$$\gamma_B = \frac{G^2 P_R |g_D|^2 |P_A|^2 |h_U|^2}{G^2 P_R |g_D|^2 \psi_2 + \sum_k P_{i_k}^{(2)} |i_{B_k}^{(2)}|^2 + \sigma^2},$$

$$\psi_2 = \left( \sum_k P_{i_k}^{(1)} |i_{R_k}^{(1)}|^2 + \sigma^2 \right).$$

$G$ is the gain by which the received signals from the sources are amplified at the relay. For 2-TS NWC, $G$ is given by

$$G = \sqrt{\frac{1}{P_A |h_U|^2 + P_B |g_U|^2 + \sigma^2}}.$$

4.2.2 Three-time slot (3-TS) network coding

As a unique property of the 3-TS NWC, the transmit power at the relay is characterized by power allocation factors $a_A$ and $a_B,$ which must be known at both sources. These power allocation factors are determined such that $a_A^2 + a_B^2 = 1.$ For the 3-TS NWC, $G$ is given as follows.

$$G = \sqrt{\frac{1}{P_A |h_U|^2 + P_B |g_U|^2 + \sigma^2}}.$$
The end-to-end SINRs for the 3-TS NWC are then calculated as follows.

\[ \gamma_A = \frac{G^2 P_R |h_D|^2 \alpha^2 P_B |g_U|^2}{G^2 P_R |h_D|^2 \psi_3 + \left( \sum_k P_k^{(3)} |l_k^{(3)}|^2 \right) + \sigma^2}, \]  
(11)

\[ \gamma_B = \frac{G^2 P_R |g_D|^2 \alpha^2 P_A |h_U|^2}{G^2 P_R |g_D|^2 \psi_3 + \left( \sum_k P_k^{(3)} |l_k^{(3)}|^2 \right) + \sigma^2}, \]  
(12)

\[ \psi_3 = \alpha^2_B \left( \sum_k P_k^{(1)} |l_k^{(1)}|^2 + \sigma^2 \right) + \alpha^2_A \left( \sum_k P_k^{(2)} |l_k^{(2)}|^2 + \sigma^2 \right). \]  
(13)

### 4.2.3 3-TS network coding with MRC

As shown in Figures 2 and 3, the 3-TS NWC scheme with MRC takes advantage of the direct links provided by unicasting D2D communications in a 3-TS NWC operation. In the first time slot, source A transmits to both the relay node and node B. The transmission to source B is done through the D2D link. Similarly, in the second time slot, source B transmits to both the relay node and node A. In the third time slot, network coded data are transmitted to both receiving nodes by the relay node. As a result, each destination node receives the information twice: first through the D2D link and then from the relay, and can, therefore, take advantage of receiver diversity.

Assuming that nodes A and B support MRC, the received SINR at A and B in the case of 3-TS NWC with MRC can be approximated as

\[ \gamma_{A,3-TS,MRC} \approx \gamma_{A,3-TS} + \frac{P_B |g_{U,\text{direct}}|^2}{\left( \sum_k P_k^{(2)} |l_k^{(2)}|^2 \right) + \sigma^2}, \]  
(14)

\[ \gamma_{B,3-TS,MRC} \approx \gamma_{B,3-TS} + \frac{P_A |h_{U,\text{direct}}|^2}{\left( \sum_k P_k^{(1)} |l_k^{(1)}|^2 \right) + \sigma^2}, \]  
(15)

where \( \gamma_{A,3-TS} \) and \( \gamma_{B,3-TS} \) are the received SINR in the traditional 3-TS scheme as calculated in (11) and (12). Channels \( h_{U,\text{direct}} \) and \( g_{U,\text{direct}} \) are direct channels from A to B and B to A, respectively.

### 4.2.4 Four-time slot (4-TS) network coding

In the 4-TS NWC, there are 2 distinct relay gains \( G_A \) and \( G_B \) that are given as follows.

\[ G_A = \frac{1}{P_B |g_U|^2 + \sigma^2}, \]  
(16)

\[ G_B = \frac{1}{P_A |h_U|^2 + \sigma^2}. \]  
(17)
The end-to-end SINR values at sources A and B are calculated accordingly:

$$\gamma_A = \frac{G_A^2 P_A|h_D|^2 P_B|g_U|^2}{G_A^2 P_A|h_D|^2 \psi_{4,A} + \sum_k P_A^{(3)} |i_k^{(3)}|^2 + \sigma^2}.$$  (18)

$$\gamma_B = \frac{G_B^2 P_B|g_D|^2 P_A|h_U|^2}{G_B^2 P_B|g_D|^2 \psi_{4,B} + \sum_k P_A^{(2)} |i_k^{(2)}|^2 + \sigma^2}.$$  (19)

$$\psi_{4,A} = \left( \sum_k P_A^{(3)} |i_k^{(3)}|^2 + \sigma^2 \right),$$  (20)

$$\psi_{4,B} = \left( \sum_k P_A^{(2)} |i_k^{(2)}|^2 + \sigma^2 \right).$$  (21)

### 4.2.5 Unicasting D2D communication

Unicasting D2D communications allow the transmitting nodes to be aware of their respective intended receivers and thereby facilitate controlling the transmit power levels such that the SINR at the receiving nodes can be controlled. Because of the direct D2D link, this transmission scheme is a bidirectional direct transmission, without involving infrastructure nodes such as an eNB or relay node. It is assumed that a transmission in one direction requires 1 time slot, which results in 2 time slots needed in total. The transmission from source A to source B takes place in the first time slot. Then, the received signal at source B is given as follows.

$$y_B = \sqrt{P_A h_u x_A} \left( \sum_k \sqrt{P_A^{(1)} |i_k^{(1)}|^2} \right) + n_B.$$  (22)

The transmission from source B to source A takes place in the second time slot. The received signal at source A is given as follows.

$$y_A = \sqrt{P_B g_u x_B} \left( \sum_k \sqrt{P_B^{(2)} |i_k^{(2)}|^2} \right) + n_A.$$  (23)

Taking the ratio of the desired signal’s power over interference and noise power, the SINR values at sources A and B can be calculated as follows.

$$\gamma_A = \frac{P_B |g_U|^2}{\left( \sum_k P_A^{(2)} |i_k^{(2)}|^2 + \sigma^2 \right)},$$  (24)

$$\gamma_B = \frac{P_A |h_U|^2}{\left( \sum_k P_A^{(1)} |i_k^{(1)}|^2 + \sigma^2 \right)}.$$  (25)

### 5 PROPOSED RESOURCE ALLOCATION AND MODE SELECTION ALGORITHMS

#### 5.1 Resource allocation

The resource allocation algorithm proposed in this paper takes into consideration the number of required resources by the different local communication schemes discussed above and makes use of resource utilization counters. The basic idea of the proposed resource allocation and MS schemes is to allocate the resources that are least used and thereby to
avoid assigning a high number of communication links to the same resource. We assume that the eNB has knowledge of which UL and DL resources are used by all UEs within its coverage area. This assumption is realistic, in, for example, LTE networks, in which UEs regularly send measurement reports to their serving eNBs even when operating in D2D mode.

Let us define UL and DL utilization vectors $\rho_U$ and $\rho_D$, and denote $\rho_U(i)$ as the utilization counter of UL resource $i$ and $\rho_D(j)$ as the utilization counter of DL resource $j$. For each communicating UE pair, UE-A and UE-B, the eNB needs to select 2 UL resources and 2 DL resources (denoted by $U_1$, $U_2$, $D_1$, and $D_2$, respectively), which are candidates of allocated resources for a 2-way communication between UE-A and UE-B.

The eNB executes the following procedure. Note that this procedure is fundamentally similar to the scheduling procedure of an LTE eNB but takes into account the specific characteristics of the transmission schemes discussed in this paper.

1. Selects the first UL resource, $U_1$, by choosing a UL resource $i$ randomly or taking into account the instantaneous channel response out of the resources for which $\rho_U(i) = \min(\rho_U)$.
2. Increments $\rho_U(i)$, $\rho_U(i) \leftarrow \rho_U(i) + 1$.
3. Selects the second UL resource, $U_2$, by choosing a UL resource $i$ randomly out of the resources for which $\rho_U(i) = \min(\rho_U)$.
4. Increments $\rho_U(i)$, $\rho_U(i) \leftarrow \rho_U(i) + 1$.
5. Selects the first DL resource, $D_1$, by choosing a DL resource $j$ randomly out of the resources for which $\rho_D(j) = \min(\rho_D)$.
6. Increments $\rho_D(j)$, $\rho_D(j) \leftarrow \rho_D(j) + 1$.
7. Selects the second DL resource, $D_2$, by choosing a DL resource $j$ randomly out of the resources for which $\rho_D(j) = \min(\rho_D)$.
8. Increments $\rho_D(j)$, $\rho_D(j) \leftarrow \rho_D(j) + 1$.

At the end of this resource balancing allocation procedure, 4 resources ($U_1$, $U_2$, $D_1$, and $D_2$) are selected, and the resource utilization counters are updated.

5.2 Mode selection

On the basis of Figure 4 and the signal model, it is clear that there is an inherent trade-off between the number of used time slots, used total transmission power, and the resulting SINR levels and the achieved spectral and energy efficiency. This suggests that we should study 2 MS algorithms that aim at maximizing the achieved SINR (MS-NWC 1) and the spectral efficiency (MS-NWC 2), respectively.

In the proposed MS schemes, the eNB makes a prediction of the end-to-end SINR for all available transmission modes based on the channel knowledge, selected resources, and assuming appropriate eNB and UE transmit power levels (Figure 6). At this prediction stage, all UEs are assumed to transmit with a constant power of $P$, since it can be assumed that the resource allocation and MS take place before power control is performed. For the eNB to be able to make an end-to-end SINR prediction, it uses a mathematical model and computation technique that is characteristic to the specific transmission mode, as described in Section 4.2.

5.2.1 MS-NWC 1 (SINR-maximizing mode selection)

According to the SINR-maximizing MS scheme, the eNB selects the mode that has the highest predicted end-to-end SINR.

5.2.2 MS-NWC 2 (spectral efficiency–maximizing mode selection)

According to the spectral efficiency maximizing MS scheme, the eNB selects the mode that has the highest predicted spectral efficiency, $\hat{S}$. This prediction takes the end-to-end SINR prediction ($\hat{\gamma}_{\text{mode}}$) as well as the number of consumed resources ($\tau_{\text{mode}}$) into account.

$$\hat{S}_{\text{mode}} = \frac{\log_2 (1 + \hat{\gamma}_{\text{mode}})}{\tau_{\text{mode}}}.$$  (26)

In (26), $\tau_{\text{mode}}$ is equal to 4 for cellular mode, 3 for classical PNC and NWC with MRC modes, and 2 for the 2-TS PNC and D2D modes.
FIGURE 6  The proposed mode selection algorithms and their interplay with resource allocation. The mode selection algorithms take the predicted end-to-end SINR and the required resources per mode as its basic input and select the mode that yields the highest expected SINR or highest spectral efficiency. D2D, device-to-device; DL, downlink; MRC, maximum ratio combining; NWC, network coding; SINR, signal-to-interference-plus-noise ratio; TS, time slot; UE, user equipment; UL, uplink

6 | NUMERICAL RESULTS

6.1 | Simulation setup and operation modes

Mode selection in a multicell environment is a complex problem that can be advantageously studied by system level simulations.18,22 To obtain numerical results, we use a realistic system level simulator called the Rudimentary Network simulator30 that was enhanced to support NWC, unicasting D2D communications, and the proposed MS schemes. We consider a 7-cell network and collect statistics using Monte Carlo simulations. In each Monte Carlo experiment, a cellular system is generated with 7 hexagonal cells, a fixed number of locally communicating UE pairs per cell, and a fixed number of radio resources (resource blocks) per cell. The UEs are dropped randomly within the cell with uniform distribution. Additionally, we consider both low traffic and high traffic scenarios. The simulation parameters are listed in Table 1.

We assume that the system uses LTE open-loop fractional path loss compensation power control with path loss compensation factor $\alpha_{FPC}$ given in Table 1. Power control is assumed to be done taking into account the selected resources, as proposed in Fodor et al.8

To compare the performance of the communication schemes discussed in this paper, 7 operating modes are considered in our simulations.

| TABLE 1  | Simulation parameters |
|-----------|------------------------|
| System bandwidth | 5 MHz |
| Carrier frequency | 2 GHz |
| Gain at 1 m distance | −37 dB |
| Path loss coefficient | 3.5 |
| Log normal shadow fading $\sigma$ | 6 dB |
| Number of Monte Carlo iterations | 100 |
| Number of cells | 7 |
| Number of UE pairs per cell | 4 (low traffic), 8 (high traffic) |
| Number of radio resources per cell | 8 |
| Cell radius | 500 m |
| Power allocation numbers $(\alpha_A, \alpha_B)$ | $\sqrt{0.5}$ (both) |
| eNB transmit power | 40 dBm |
| Path loss compensation $(\alpha_{FPC})$ | 0.8 |
| Assumed constant UE power for mode selection $(P)$ | −10 dBm (MS-NWC 1), 20 dBm (MS-NWC 2) |

Abbreviations: MS, mode selection; NWC, network coding; UE, user equipment.
1. **2-TS NWC**: All UE pairs use the 2-TS NWC scheme.
2. **3-TS NWC**: All UE pairs use the 3-TS NWC scheme with MRC.
3. **4-TS NWC**: All UE pairs use the 4-TS NWC scheme (traditional cellular mode).
4. **D2D–No NWC**: All UE pairs are forced to communicate in unicasting D2D mode.
5. **MS-NWC 1**: End-to-end SINR-maximizing MS where it is possible to choose any of the transmission schemes in Figure 4.
6. **MS-NWC 2**: Spectral efficiency maximizing MS where it is possible to choose any of the transmission schemes in Figure 4.
7. **MS without NWC**: An MS strategy where it is possible to choose either D2D or cellular (4-TS mode). Network coding is not supported. The selection is based on a simple channel gain comparison, i.e., if the channel between the transmitting UE and the receiving UE has higher gain than the channel between the transmitting UE and the eNB, D2D mode is selected. Otherwise, cellular mode is selected.

### 6.2 Numerical results and discussion

#### 6.2.1 Behavior of the mode selection algorithm

Figure 13 and Table 2 show the transmission modes selected by the MS algorithm in 2 different traffic scenarios. We can observe that the SINR-maximizing MS tends to choose a transmission scheme that consumes more resources in an

![End-to-end SINR](image)

**FIGURE 7** End-to-end SINR performance of the available local transmission schemes, low traffic scenario (4 user equipment pairs per cell). CDF, cumulative distribution function; D2D, device-to-device; MS, mode selection; NWC, network coding; SINR, signal-to-interference-plus-noise ratio; TS, time slot

| Mode selection | Low traffic | High traffic |
|----------------|-------------|--------------|
| **MS-NWC 1**  | 3-TS NWC: 24% | D2D mode: 19% |
| (SINR maximizing) | 4-TS NWC: 76% | 2-TS NWC: 16% |
|                |             | 3-TS NWC: 12% |
|                |             | 4-TS NWC: 52% |
| **MS-NWC 2**  | D2D mode: 19% | D2D mode: 21% |
| (Spectrum efficiency maximizing) | 2-TS NWC: 81% | 2-TS NWC: 72% |
|                |              | 3-TS NWC: 1% |
|                |              | 4-TS NWC: 6% |
| **MS without NWC** | D2D mode: 19% | D2D mode: 20% |
|                | Cellular: 81% | Cellular: 80% |

**TABLE 2** Mode selection outputs in low and high traffic scenarios

Abbreviations: D2D, device-to-device; MS, mode selection; NWC, network coding; TS, time slot
attempt to reduce interference, while the spectral efficiency maximizing MS chooses recourse-efficient modes (2-TS NWC or D2D mode) most of the time.

6.2.2 End-to-end SINR

Figure 7 compares the SINR performance of the transmission schemes of Figure 2, when using the proposed MS algorithms that support both NWC and D2D (MS-NWC 1 and MS-NWC 2) and MS in an integrated D2D-cellular network (MS without NWC). As expected, the SINR is maximized when using MS-NWC 1. On the other hand, the gain of using NWC in an integrated cellular and D2D network in terms of SINR is negligible.

However, as shown in Figure 8, MS-NWC 1 performs poorly when the interference level is high. This is caused by inaccurate SINR prediction resulted from assuming constant power for all UEs. In high traffic situation, it is better to use MS-NWC 2 because the inaccuracy of SINR prediction is suppressed by logarithmic function in the MS criterion. In any
case, Figures 7 and 8 prove that an integrated D2D-NWC-cellular network can always achieve high end-to-end SINR with a proper MS.

### 6.2.3 Spectrum efficiency

As Figure 9 shows, however, NWC leads to significant spectral efficiency increase if the MS scheme of MS-NWC 2 is used. This clearly suggests that the main benefit of introducing NWC into an integrated D2D-cellular network is further improving the spectral efficiency. MS-NWC 2 also outperforms other MS strategies in the high traffic scenario as shown in Figure 10.

### 6.2.4 Invested transmit power

Finally, as suggested by Figures 11 and 12, this high spectral efficiency can be obtained even at low power consumption when using proper MS (see MS-NWC 2 column). These results indicate that a network that supports both D2D and NWC is more energy-efficient than a network that supports NWC only. In other words, the expected gain that D2D brings in a cellular network using NWC is energy efficiency (Figure 13).

![Spectral Efficiency](image1.png)

**FIGURE 10** Spectral efficiency of the transmission schemes under study, high traffic scenario (8 user equipment pairs per cell). CDF, cumulative distribution function; D2D, device-to-device; MS, mode selection; NWC, network coding; TS, time slot

![Average Power Consumption](image2.png)

**FIGURE 11** Average power consumption of the transmission schemes under study, low traffic scenario (4 user equipment pairs per cell). D2D, device-to-device; MS, mode selection; NWC, network coding; TS, time slot
7 | CONCLUSIONS

In this paper, we asked whether unicasting D2D and NWC schemes can or should be used together in scenarios in which local (proximate) communication opportunities exist. This question is particularly opportune when standardization bodies, such as the 3GPP, are considered introducing unicasting D2D communications support in the upcoming releases of LTE networks. We have shown that introducing NWC in integrated D2D-cellular networks can provide significant spectral efficiency gain. On the other hand, introducing unicasting D2D in a cellular network that uses NWC reduces the invested transmit power. Our results show that D2D and NWC can complement each other and be advantageously used jointly, provided that the network applies a proper MS algorithm. Our planned future work includes aspects that are beyond the scope of this paper, including the modeling of the impact of channel state information imperfections, as well as the modeling of other imperfections, such as synchronization errors or scheduling delays.
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APPENDIX A: DETAILED SINR ANALYSIS

A.1 | Two-time slot (2-TS) network coding

The signal received at the relay in the first time slot is expressed as follows.

\[ r = \sqrt{P_A h_U x_A} + \sqrt{P_B g_U x_B} + \left( \sum_k \sqrt{P_k^{(1)} R_k x_k^{(1)}} \right) + n_R. \]  

(A1)

After receiving signals from both sources, the relay transmits its network coded signals to sources A and B. The signal received at each source in the second time slot is expressed as follows:

\[ y_A = G \sqrt{P_R h_D} r + \left( \sum_k \sqrt{P_k^{(2)} R_k x_k^{(2)}} \right) + n_A, \]  

(A2)

\[ y_B = G \sqrt{P_R g_D} r + \left( \sum_k \sqrt{P_k^{(2)} R_k x_k^{(2)}} \right) + n_B. \]  

(A3)

We assume that \( h_U \) and \( h_D \) are known to source A, \( g_U \) and \( g_D \) are known to source B, while G and \( P_R \) are known to both sources and each source also knows its own data symbols. As a consequence, the interference terms whose components are known to the receiver can be excluded in the SINR calculation. Substituting (A1) into (A2) and (A3) gives

\[ y_A = G \sqrt{P_R h_D} \sqrt{P_A h_U x_A} + G \sqrt{P_R h_D} \sqrt{P_B g_U x_B} \] 

known by source A + desired signal

\[ + G \sqrt{P_R h_D} \left( \sum_k \sqrt{P_k^{(1)} R_k x_k^{(1)}} \right) + G \sqrt{P_R h_D} n_R + \left( \sum_k \sqrt{P_k^{(2)} R_k x_k^{(2)}} \right) + n_A, \]  

(A4)

\[ y_B = G \sqrt{P_R g_D} \sqrt{P_A h_U x_A} + G \sqrt{P_R g_D} \sqrt{P_B g_U x_B} \] 

desired signal known by source B

\[ + G \sqrt{P_R g_D} \left( \sum_k \sqrt{P_k^{(1)} R_k x_k^{(1)}} \right) + G \sqrt{P_R g_D} n_R + \left( \sum_k \sqrt{P_k^{(2)} R_k x_k^{(2)}} \right) + n_B. \]  

(A5)

Taking the ratio of desired signal’s power over interference and noise power, while excluding the known signals from the interference, end-to-end SINR values at sources A and B are written according to (6), (7), and (8).
A.2 | Three-time slot (3-TS) network coding

In the first time slot, source A transmits its signal to the relay. Signal received at the relay in the first time slot can be expressed as follows.

\[ r_A = \sqrt{P_A h_U x_A} + \left( \sum_k \sqrt{P_k^{(1)} I_k^{(1)} x_k^{(1)}} \right) + n_R^{(1)}. \]  
(A6)

In the second time slot, source B transmits its signal to the relay. Signal received at the relay in the second time slot

\[ r_B = \sqrt{P_B g_U x_B} + \left( \sum_k \sqrt{P_k^{(2)} I_k^{(2)} x_k^{(2)}} \right) + n_R^{(2)}. \]  
(A7)

In the third time slot, the relay simultaneously transmits network coded signals to sources A and B. Signals received at sources A and B in the third time slot are expressed as follows.

\[ y_A = G \sqrt{P_R h_D (\alpha_B r_A + \alpha_A r_B)} + \left( \sum_k \sqrt{P_k^{(3)} I_k^{(3)} x_k^{(3)}} \right) + n_A, \]  
(A8)

\[ y_B = G \sqrt{P_R g_D (\alpha_B r_A + \alpha_A r_B)} + \left( \sum_k \sqrt{P_k^{(3)} I_k^{(3)} x_k^{(3)}} \right) + n_B. \]  
(A9)

Substitution of (A6) and (A7) into (A8) and (A9) yields the following expressions.

\[ y_A = G \sqrt{P_R h_D a_B \sqrt{P_A h_U x_A}} \]
known by source A

\[ + G \sqrt{P_R h_D a_B} \left( \sum_k \sqrt{P_k^{(1)} I_k^{(1)} x_k^{(1)}} \right) \]

\[ + G \sqrt{P_R h_D a_B n_R^{(1)}} + G \sqrt{P_R h_D a_A \sqrt{P_R g_U x_B}} \]
desired signal

\[ + G \sqrt{P_R h_D a_A} \left( \sum_k \sqrt{P_k^{(2)} I_k^{(2)} x_k^{(2)}} \right) \]

\[ + G \sqrt{P_R h_D a_A n_R^{(2)}} + \left( \sum_k \sqrt{P_k^{(3)} I_k^{(3)} x_k^{(3)}} \right) + n_A, \]  
(A10)

\[ y_B = G \sqrt{P_R g_D a_B \sqrt{P_A h_U x_A}} \]
desired signal

\[ + G \sqrt{P_R g_D a_B} \left( \sum_k \sqrt{P_k^{(1)} I_k^{(1)} x_k^{(1)}} \right) \]

\[ + G \sqrt{P_R g_D a_B n_R^{(1)}} + G \sqrt{P_R g_D a_A \sqrt{P_R g_U x_B}} \]
known by source B

\[ + G \sqrt{P_R g_D a_A} \left( \sum_k \sqrt{P_k^{(2)} I_k^{(2)} x_k^{(2)}} \right) \]

\[ + G \sqrt{P_R g_D a_A n_R^{(2)}} + \left( \sum_k \sqrt{P_k^{(3)} I_k^{(3)} x_k^{(3)}} \right) + n_B. \]  
(A11)

Taking the ratio of desired signal’s power over interference and noise power, while excluding the known signals from the interference, end-to-end SINR values at sources A and B are calculated as written in (11), (12), and (13).
A.3 | Four-time slot (4-TS) network coding

The first and second time slots are allocated for communication from source A to source B. In the first time slot, source A transmits $x_A$ to the relay, and the relay received $r_A$.

$$r_A = \sqrt{P_A} h_U x_A + \left( \sum_k \sqrt{P_k^{(1)} k_k} x_k^{(1)} \right) + n^{(1)}_R. \quad (A12)$$

In the second time slot, the relay amplifies $r_A$ by gain $G_B$ and transmits to source B. The received signal at source B is expressed as follows.

$$y_B = G_B \sqrt{P_{gD}} r_A + \left( \sum_k \sqrt{P_k^{(2)} k_k} x_k^{(2)} \right) + n_B. \quad (A13)$$

The third and fourth time slots are allocated for communication from source B to source A. In the third time slot, source B transmits $x_B$ to the relay, and the relay received $r_B$.

$$r_B = \sqrt{P_{gU}} x_B + \left( \sum_k \sqrt{P_k^{(3)} k_k} x_k^{(3)} \right) + n^{(3)}_R. \quad (A14)$$

In the fourth time slot, the relay amplifies $r_B$ by gain $G_A$ and transmits to source A. The received signal at source A is expressed as follows.

$$y_A = G_A \sqrt{P_h} d_{DR} r_B + \left( \sum_k \sqrt{P_k^{(4)} k_k} x_k^{(4)} \right) + n_A. \quad (A15)$$

Substitutions of (A12) into (A13) and (A14) into (A15) result in the following expressions.

$$y_A = \underbrace{G_A \sqrt{P_h} d_{DR} \sqrt{P_{gU}} x_B}_{\text{desired signal}} + \underbrace{G_A \sqrt{P_R} h_D \left( \sum_k \sqrt{P_k^{(3)} k_k} x_k^{(3)} \right)}_{\text{interference}} + \underbrace{G_A \sqrt{P_R} h_D n^{(3)}_R + n_A}_{\text{noise}}. \quad (A16)$$

$$y_B = \underbrace{G_B \sqrt{P_{gD}} \sqrt{P_A} h_U x_A}_{\text{desired signal}} + \underbrace{G_B \sqrt{P_{gD}} \left( \sum_k \sqrt{P_k^{(1)} k_k} x_k^{(1)} \right)}_{\text{interference}} + \underbrace{G_B \sqrt{P_{gD}} n^{(1)}_R + n_B}_{\text{noise}}. \quad (A17)$$

Taking the ratio of desired signal’s power over interference and noise power, end-to-end SINRs are calculated as specified in (18)-(20), and (21).