5G Architectures for Small Cells with Wireless Backhaul and Two-Way Communication

Petar Popovski and Elisabeth de Carvalho

Department of Electronic Systems, Aalborg University, Denmark
Email: {petarp, edc}@es.aau.dk

I. Motivation

There is a growing evidence that small cells will play a major role in the upcoming generation of wireless communication systems [1]. This is in line with the trend of wireless network densification, which indicates that the bit rate per unit area will grow immensely. The key element in small cell deployments is the *backhaul connection* that connects the small cell Base Stations (BSs) to the infrastructure. The choice of the backhaul needs to hit the right tradeoff between the connectivity and deployment flexibility/cost. Using wireless backhaul turns the small cell BS into a relay and it offers inherently flexible deployment. However, the use of wireless backhaul or relay within the same radio spectrum has been considered to have a limited applicability for coverage enhancement [1].

Our main observation is that such a view on wireless backhauls is rooted in the spectral efficiency loss incurred when a half-duplex relay is optimized for *one-way communication*. The focus on one-way communication has not been limited to relays only, but it has pervaded the design and the architecture of the wireless cellular systems up to the present, 4G. Namely, the current wireless systems are designed by keeping uplink (UL) and the downlink (DL) largely *decoupled* in terms of design and optimization. One may object to this statement, saying that the DL/UL are coupled, e. g. through the provision of Channel State Information (CSI) or flexible UL/DL allocation in Time-Division Duplex (TDD) systems. Nevertheless, in the current systems, once the UL/DL allocation is made, the signal processing, rate selection, etc. is done through optimization of *one-way communication* in either UL or DL. Clearly, this is only one and not necessarily optimal way to solve two-way wireless communication problems.

Relays have received a fresh research potential with the introduction of two-way relaying (TWR) based on wireless network coding (WNC) [2], as spectral efficiency loss can be regained by simultaneously serving two data flows through the relay. The related research has for a long time been fixed to the specific traffic pattern of TWR, but recently our research group has published series of works [3], [4], [5], [6] contributing to the general question: *What are the system-level implications of WNC and are there other traffic patterns that can benefit from the spectral efficiency gain seen in two-way relaying?* The answer is affirmative: the fundamental implication is that the individual one-way communication problems should be accrued into a joint optimization of the DL/UL transmissions for multiple terminals and BSs. We present the core principles and ideas of the propose two-way communication paradigm in the next section, illustrated with specific examples.

II. Core Principles and Ideas

We use Fig. 1 to recall the main idea of the spectral efficiency gain in TWR. Let BS and MS_1 have two-way traffic to each other, carried via RS. Instead of four phases, as it would be required by decoupling DL/UL, two phases suffice: (a) BS and MS_1 transmit simultaneously, RS receives over a multiple-access channel, but does not need to decode, (b) RS transmits a function of the signal received in phase (a), e. g. by Amplify-and-Forward (AF) and BS (MS_1) decodes the desired signal of MS_1 (BS) by using its transmission from phase (a) as a side information. The mechanism behind TWR can be generalized through the following two principles: (1) simultaneous service of multiple flows over the wireless medium and (2) cancellation of interference based on previously gathered side information. Using these two principles, we devise *transmission building blocks* for traffic patterns that are more general than the specific TWR. We illustrate this with three traffic patterns and end with an example of a more general scenario. The examples are limited to single antenna nodes and AF relaying, but they can clearly be generalized and give rise to new optimization problems. In all examples RS stands for a small cell BS.

The first example is on *Coordinated Direct and Relay (CDR)* transmission, where the basic scenario is: BS, RS and two MSs. MS_1 has a connection to the BS via the relay only, while MS_2 has a direct connection to the BS. For simplicity, we assume that MS_1 and MS_2 are distant from each other and do not interfere (e. g. interference cancellation can be applied when the nodes are equipped with multiple antennas). MS_1 and MS_2 have UL and DL traffic. Following the two principles stated above, we obtain two schemes with coupled UL/DL: CDR1 couples the relayed DL and direct UL traffic (Fig. 1) and CDR2 couples the relayed UL and direct DL traffic (Fig. 2). Decoupling the UL and the DL would required 3 time slots, while CDR1 and CDR2 take two time slots. Detailed analysis of CDR1, CDR2 and other related schemes is given in [3], where large spectral efficiency gains are shown.

The second example (Fig. 3) is *four-way relaying*, where the UL/DL transmission of two small cells, RS_1 and RS_2,

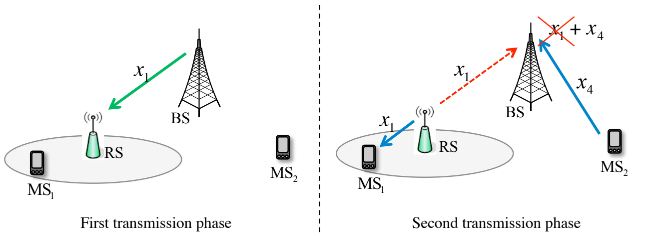

Fig. 1. CDR 1: relayed DL - direct UL. During the first transmission phase, BS transmits DL signal x_1 to the RS. During the second transmission phase, two concurrent transmissions are scheduled: 1) RS transmits x_1 to MS_1 which causes interference at BS and 2) MS_2 transmits x_4 to BS. As BS knows x_1, the interference at BS can be cancelled.

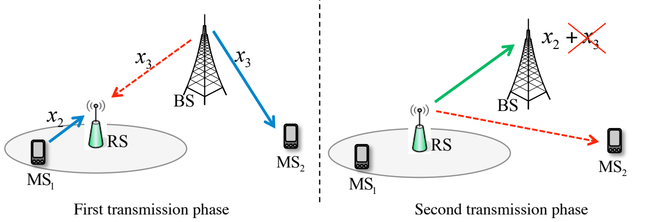

Fig. 2. CDR 2: relayed UL - direct DL. During the first transmission phase, two concurrent transmissions are scheduled: 1) MS_1 transmits UL signal x_2 to RS and 2) BS transmits x_3 to BS which causes interference to RS. During the second transmission phase, RS transmits a signal containing x_2 and x_3 to BS (denoted generically as $x_2 + x_3$). As BS knows x_3, the interference at BS can be cancelled.

are coupled. Each MS is connected to the RS. The two small cells are selected such that they do not interfere with each other (e.g. situated in two different buildings). Decoupling the UL/DL in the two cells would require 8 time slots. If TWR is applied independently for each small cell, then 4 time slots are required. Four-way relaying only takes 2 time slots and [4] has shown that it offers superior spectral efficiency compared to the reference schemes.

In the talk we will address the general problem, that consists of multiple BSs, RSs, and MSs, with each MS having a two-way traffic. The question that we can ask for the general scenario is: *Given a set of two-way data flows, what is the best way to serve them, using building blocks as the ones described in the examples above?* As an example, the solution could include time division between four-way relaying and CDR, using them as building blocks. We are not aware of all possible building blocks that could be employed general scenarios, but it is important to note that the transmission schemes of the decoupled DL/UL are "yet other building blocks" and in the proposed framework we will always achieve better rates than the standard design with decoupled DL/UL. In the talk we will provide further examples and elaborate on the optimization problems that arise in that setting.

III. Conclusion

From the principles and ideas presented in the previous section, it is clear that the transmission methods and optimization problems considered in a traditional one-way setting are special cases of the methods and problems that arise in the two-way setting. The objective of this talk is to present a new architectural/algorithmic paradigm of designing two-way

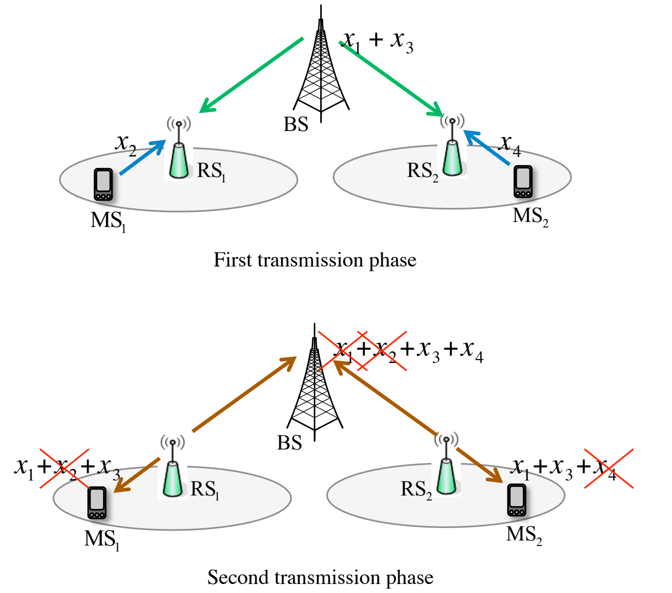

Fig. 3. Four-way relaying. During the first transmission phase, four transmissions are scheduled: BS broadcasts DL signals x_1 and x_3 using superposition coding while MS_1 transmits UL signal x_2 and MS_2 transmits UL signal x_4. Interference is created at each RS. During the second phase, RS_1 transmits a signal containing x_1, x_2 and x_3 (denoted $x_1 + x_2 + x_3$), while RS_2 transmits a signal containing x_1, x_3 and x_4. As BS knows x_1 and x_3, the interference at BS can be cancelled: the resulting transmission is equivalent to a multiple access channel at the BS. As MS_1 knows x_2, it cancels the interference caused by x_2 and decodes the resulting signal $x_1 + x_3$ as superposition decoding dictates. A similar procedure is performed at MS_2.

wireless communication systems that feature small cells with wireless backhaul. In that sense, we have not solved the ultimate optimization problem of two-way communication, but we are opening the research/development space for designing new transmission methods and solving new optimization problems.

References

[1] J. Andrews, "Seven ways that hetnets are a cellular paradigm shift," *Communications Magazine, IEEE*, vol. 51, no. 3, pp. 136–144, 2013.

[2] P. Popovski and H. Yomo, "Physical network coding in two-way wireless relay channels," in *Communications, 2007. ICC '07. IEEE International Conference on*, 2007, pp. 707–712.

[3] C. D. T. Thai, P. Popovski, M. Kaneko, and E. de Carvalho, "Multi-flow scheduling for coordinated direct and relayed users in cellular systems," *Communications, IEEE Transactions on*, vol. 61, no. 2, pp. 669–678, 2013.

[4] H. Liu, P. Popovski, E. de Carvalho, Y. Zhao, and F. Sun, "Four-way relaying in wireless cellular systems," *Wireless Communications Letters, IEEE*, vol. 2, no. 4, pp. 403–406, 2013.

[5] F. Sun, E. De Carvalho, P. Popovski, and C. D. T. Thai, "Coordinated direct and relay transmission with linear non-regenerative relay beamforming," *Signal Processing Letters, IEEE*, vol. 19, no. 10, pp. 680–683, 2012.

[6] F. Sun, T. M. Kim, A. Paulraj, E. de Carvalho, and P. Popovski, "Cell-edge multi-user relaying with overhearing," *Communications Letters, IEEE*, vol. 17, no. 6, pp. 1160–1163, 2013.

[7] Y. Lin and W. Yu, "Fair scheduling and resource allocation for wireless cellular network with shared relays," *Selected Areas in Communications, IEEE Journal on*, vol. 30, no. 8, pp. 1530–1540, 2012.