Relaying and Cooperation – A System Perspective

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***Abstract*— The paper considers various relaying strategies for wireless networks. We comparatively discuss and analyse direct transmission, conventional "multihop" relaying, and the novel concepts of cooperative relaying from the viewpoint of system level performance. While conventional relaying exploits pathloss savings, cooperative relaying additionally takes two inherent advantages of relay-based systems into account: the ability to exploit the broadcast nature of the wireless medium, and the diversity offered by the relay channel. Following a description of these concepts, we analyse the performance of such systems in an exemplary manner for power-controlled cellular and ad hoc CDMA systems. The resulting power savings and capacity improvements suggest that cooperative relaying may constitute an interesting candidate for future cellular and ad hoc network architectures.**

I. Introduction

Given the constraints imposed by link budget estimates for next generations of wireless networks, relaying has recently emerged as a viable option for challenging the tradeoff between transmission range and end-to-end data rate. Essentially, relays that operate in a store-and-forward manner allow to reduce the end-to-end pathloss between an information source and its destination. In *conventional "multihop" relaying*, each relay in a relay chain thereby usually relies solely on the information sent by its immediate predecessor, and the destination simply listens to the last relay in this chain. See Fig. 1 for an example, where the source communicates with the destination via a single relay along the solid-line arrows.

What could make relaying more appealing are two additional advantages that can be exploited by what is referred to as *cooperative relaying*. First, the relay channel is able to explicitly make use of the *broadcast nature* of the wireless medium as the signal transmitted by the source can in principle be received by the relays as well as by the destination. Second, the relay channel offers *spatial diversity*, as the signals from source and relays propagate to the destination through essentially uncorrelated channels. The idea of cooperative relaying is to profit from these advantages by *combining* the signals from source and relays at the destination. By explicitly taking the signal from the source into account (dashed-line arrow in Fig. 1), the destination extracts useful information from signals that are unnecessarily discarded in conventional relaying (or even regarded as interference).

Viewed more generally, cooperative relaying can be regarded as a step on the way from *point-to-point coding* towards what is referred to as *network coding*.

A considerable number of publications addresses various aspects of conventional relaying; see [1] for an overview. Cooperative relaying has so far been considered primarily at the physical layer. Based on the ideas of *user cooperation diversity* [2], Laneman et al. [3] propose various cooperative protocols for the three-terminal case. It is shown that diversity gains can be achieved; yet, these come at the cost of repetition coding and an increase of the link data rates. The latter is induced by the inability of the relay(s) to receive and transmit simultaneously at the same frequency. It is worth noting that these drawbacks govern conventional and cooperative relaying in the same way. In [4], we proposed and analysed a simple *cooperative decode-and-forward* protocol that simultaneously exploits pathloss reduction, diversity gains, and the broadcast nature of the wireless medium. Finally, the idea of virtual antenna arrays is studied in [5]. To our knowledge, [6], [5] are to date the only publications addressing system-level aspects of distributed relay networks.

In this paper, we aim at contributing by studying the underlying principles and potentials of cooperative relaying at *system level*. We show that the new network coding paradigm has potential for considerable capacity improvements. Following a system description and an analysis in sections II and III, we discuss results and implementation aspects in section IV; the paper concludes in section V.

II. System Model

We start by establishing models for network layout, routing, and resource allocation.

1) Network Model: We study cellular networks and ad hoc networks. For *cellular networks*, we assume that all mobile nodes in the considered cell have traffic destined for the centrally located base station. Besides being a data *source*, a node may support other connections by acting as a *relay* node. The *ad hoc scenario* is characterised by a lack of infrastructure, so that communication between randomly selected pairs must rely on the help of intermediate nodes. In both scenarios, mobile nodes are uniformly placed at i.i.d. random locations in a square area of unit length; once placed, the nodes do not move in our static considerations.

2) Routing: Numerous routing schemes have been proposed [7]. Among them is the prominent class of *link state algorithms*, which target at minimizing a certain metric. For example, Dijkstra's algorithm [8] can be used for finding

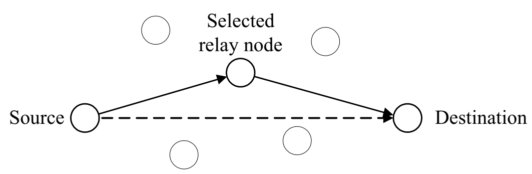

Fig. 1. A possible two-hop relaying scenario. Conventional relaying occurs along the solid arrows. In cooperative relaying, the destination additionally takes the signal sent by the source into account (dashed-line arrow).

This work was supported by Vodafone Group Research and Development.

paths with a *minimum hop count* or a *minimum end-to-end pathloss*. While this algorithm requires central knowledge of the link metrics (states), distributed implementations are likewise available [7]. For cellular operation, a viable option is to limit the number of hops from a node to the base station in order to reduce the drawbacks induced by repeated emission of essentially the same signal. Allowing two hops and taking the pathloss *reduction* as a metric leads to an algorithm presented in [9] which we refer to as the "two-hop max gains" scheme. We use this method for the cellular scenario and the minimum hop count metric for ad hoc networks [10]. Conventional and cooperative relaying deploy the same routing scheme, so that communication proceeds along identical paths.

3) Relaying Models:

a) Direct Transmission: For the cellular scenario, direct transmission to the base station constitutes the reference case. For ad hoc scenarios with limited transmit powers, direct transmission is in general not possible.

b) Conventional Relaying: This store-and-forward operation is performed in classical multihop scenarios. Each receiver along the established paths exploits solely the copy of the information that has been sent the preceding transmitter, while it discards emissions from other transmitters in the chain. In power-controlled CDMA networks, the power of each transmission is adjusted such that the desired target SINR is achieved at the intended receiver.

c) Cooperative Relaying: Cooperative relaying proceeds along the same routes as those used for conventional relaying. In contrast to conventional relaying, however, each receiver along the chain combines the signals it receives from previous transmissions in this chain. As a special case, we refer to *cascaded two-hop cooperative relaying* if combining takes only the previous *two* transmissions in the chain into account. This constitutes a tradeoff between the advantages of cooperative relaying on the one hand and the challenges of combining complexity, resource allocation, and scheduling on the other hand.

4) Resource Assignment: We refer to a resource as a time slot or a frequency; both are equivalent for our considerations. For relay systems, having all nodes transmit and receive at the same resource implies that nodes are able to transmit and receive simultaneously on one frequency. Due to RF impairments, small terminals cannot do so, which is often referred to as the *orthogonality constraint*.

Consequently, *orthogonal resources* must be assigned for reception and transmission, where orthogonality can be achieved by allocating either different frequencies or different time slots. In any case, such resource assignment should obey the following constraints and criteria: *(i)* no node may transmit and receive at the same resource, *(ii)* resources should be spatially reused, *(iii)* the total number of resources should be kept at a minimum as available bandwidth and allowed delay are limited.

This problem of resource assignment corresponds to a graph colouring problem [11]; for the problem at hand we have chosen to solve it using the so-called smallest-last ordering algorithm [12]. The algorithm's outcomes for a cellular two-hop scenario is depicted in Figs. 2. We will later

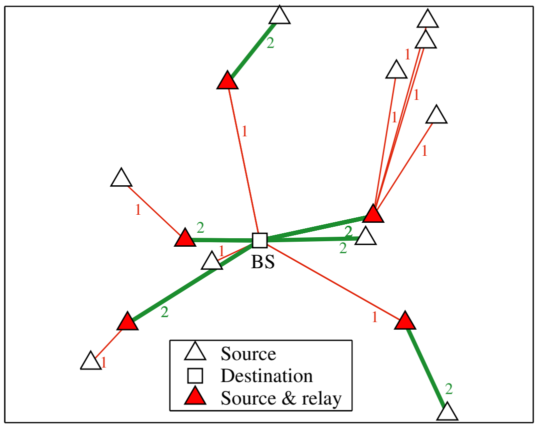

Fig. 2. Example of a cellular network with 15 nodes and a central base station. Two-hop max gains routing. Resources (time slots or frequencies) are indicated with different line colors, thicknesses and labels.

discuss that assigning orthogonal resources also calls for an increased spectral efficiency of the individual transmissions.

Note that routing and resource assignment form a joint optimization problem [13], which eventually might lead to different solutions for conventional and cooperative relaying. For simplicity, and in order to demonstrate the commonality of conventional and cooperative relaying, we conventionally decoupled routing and resource allocation.

III. Analysis

The following analysis targets at determining the *transmit powers* as a primary performance indicator in CDMA networks, which will then allow to draw further conclusions.

A. Introduction

From the viewpoint of network information theory, the inherent beauty of cooperative relaying stems from a simple fact: a transmission from a node is not intended for a single receiver in the relay chain, but it may contribute to reception at multiple nodes. As a consequence, the network does not consist of a collection of certain point-to-point links, but it is formed by a *collection of transmissions and receptions*.

B. Analysis of Transmit Powers

Each node in the network may transmit more than one signal as it may be part of more than one multihop path. In CDMA networks, this is accomplished using multi-code transmission. The total number of transmissions is therefore larger than the number of nodes. Let L denote the total number of transmissions in the system, which is equal for cooperative and conventional relaying as both schemes rely on the same routing mechanism. Each of these transmissions is characterised by a transmit power P_l and a spreading factor g_l $(0 \leq l \leq L-1)$.

One finds that these transmissions are received L times, i.e. the number of transmissions matches the number of receptions. Each reception l is based on a set of contributing transmissions $\mathfrak{C}_l$, while the remaining $L - |\mathfrak{C}_l|$ transmissions potentially interfere. Note that the relay schemes differ in the number of contributing transmissions. While there is only a single contributing transmission $(|\mathfrak{C}_l| = 1)$ for direct transmission and conventional relaying, cooperative relaying can extract useful signal energy from more than one transmission in the relay chain ($|\mathfrak{C}_l| > 1$), thereby exploiting broadcast advantages and diversity benefits as well as reducing effective interference.

Each *reception* requires that a target signal-to-noise ratio γ_l be achieved. Assuming that all transmissions take place at the same resource, this SNR condition is stated as

$$\gamma_l = \frac{\sum_{c\in\mathfrak{C}_l} a_{c,l} \cdot g_l \cdot P_c}{\sum_{i\notin\mathfrak{C}_l} a_{i,l} \cdot P_i + N_l} \quad \forall\, l = 0, \ldots, L-1\,. \qquad (1)$$

In this equation, $a_{i,j}$ is the path gain from the node that emits transmission i to the node that receives reception j, which we model for a distance $d_{i,j}$ and a pathloss exponent α as $a = d_{i,j}^{-\alpha}$. N_l denotes the thermal noise power of the considered reception l. For direct transmission and conventional relaying, i.e. for $|\mathfrak{C}_l| = 1$, eqn. (1) reduces to the well-known CDMA condition for point-to-point links [14].

Reordering (1) yields

$$\gamma_l N_l = \sum_{c\in\mathfrak{C}_l} a_{c,l} \cdot g_l \cdot P_c - \gamma_l \sum_{i\notin\mathfrak{C}_l} a_{i,l} \cdot P_i \quad \forall l\,. \qquad (2)$$

This system of linear equations can be summarised in matrix form using a *contributor* matrix $\mathbf{C}$ and an *interference* matrix $\mathbf{\Psi}$ as

$$\mathbf{n} = (\mathbf{C} - \mathbf{\Psi})\,\mathbf{P}\,,$$

with $\mathbf{n} = [\gamma_1 N_1, \ldots, \gamma_L N_L]^{\mathrm{T}}$. The matrices are given by

$$[\mathbf{C}]_{l_1,l_2} = \begin{cases} a_{l_2,l_1} g_{l_2} & l_2 \in \mathfrak{C}_{l_1} \\ 0 & \text{otherwise} \end{cases}$$

$$[\mathbf{\Psi}]_{l_1,l_2} = \begin{cases} 0 & l_1 = l_2 \,\vee\, l_2 \in \mathfrak{C}_{l_1} \,\vee\, t(l_2) = r(l_1) \\ a_{l_2,l_1}\gamma_{l_1} & \text{otherwise} \end{cases}$$

In these equations, $[\mathbf{C}]_{l_1,l_2}$ denotes the contribution of transmission l_2 to reception l_1. Likewise, $[\mathbf{\Psi}]_{l_1,l_2}$ represents the degree to which transmission l_2 interferes reception l_1.[1] For the case of direct transmission and conventional relaying, the matrix $\mathbf{C}$ reduces to an identity matrix (assuming appropriate ordering). The transmit powers $\mathbf{P}$ can finally be found from

$$\mathbf{P} = (\mathbf{C} - \mathbf{\Psi})^{-1}\,\mathbf{n}\,. \qquad (3)$$

Equation (3) allows for computing the transmit powers of CDMA relaying systems which use a *universal resource* (e.g. a single carrier) for transmission and reception at all nodes. In the following, we extend the model to the case of resource assignment.

C. Impact of Resource Assignment

Recall that taking the *orthogonality constraint* into account calls for assigning orthogonal resources for transmission and reception at the nodes. This in turn requires a split of the available bandwidth or, alternatively, a subdivision into certain time slots. For limited total bandwidth and delay, this consequently leads to a higher required spectral efficiency of the individual links, which we model here by reducing the processing gains g_l of the transmissions. On the other hand, this split into orthogonal resources also has a positive effect: interferences are reduced as the effective number of interfering transmissions per resource is lowered.

For the case of direct transmission and conventional relaying, there is only a *single contributing transmission* for each reception ($|\mathfrak{C}_l| = 1$). Hence, in the denominator of (1) only those transmissions must be considered that interfere at this specific resource, and (3) remains applicable accordingly.

For cooperative relaying, however, we combine transmissions from various resources. This is done by means of maximum ratio combining (MRC) of the contributions from all resources:

$$\gamma_l = \sum_{s=1}^{S} \gamma_l^{(s)}\,, \qquad (4)$$

where $\gamma_l^{(s)}$ is the SINR received on resource s. In this case, one finds that the set of equations (1) becomes nonlinear, thus preventing from computing a simple solution for the transmit powers. Nevertheless, the existing unique solution can be found using numerical techniques. A particularly attractive approach is to simulate a *distributed power control* algorithm, which not only helps in determining the transmission powers, but also demonstrates the feasibility of power control mechanisms in cooperative networks. Towards this end, we have used the distributed power control algorithm presented in [15].

D. Pole Capacity, Processing Gain, and Data Rate

We proceed by establishing the baseline case for comparison for cellular networks. For *direct transmission* from all nodes to the central base station, the number of transmissions is equal to the number of nodes, $L = M$, and $|\mathfrak{C}_l| = 1\,\forall\, l$.

For such a system, the concept of pole capacity can be readily applied [14]. To this end, and in order to further simplify our analysis of the reference case, we assume in the sequel that the parameters of all transmissions are equal, i.e., $\gamma_l = \gamma_0$, $N_l = N$ and $g_l = g_0$ for all l. Note that choosing equal processing gains ($g_l = g_0$) implies that all transmissions operate at the same data rate. We assume furthermore that power control adjusts the same *receive* power $P_r = a_{i,j}P_j$ for all links. For M mobile nodes, equation (2) then reads

$$\frac{\gamma_0 N}{g_0} = P_r - (M-1)\frac{\gamma_0}{g_0}P_r\,.$$

Solving for M and allowing unlimited transmit powers (so that $P_r \to \infty$) yields the well-known *pole capacity* for an isolated cell of the *direct* CDMA system, $M_{pole} = (g_0/\gamma_0)+1$ for $P_r \to \infty$. Equivalently, we can solve for the minimum required processing gain $g_{pole}(M)$

$$g_{pole}(M) = \gamma_0 \cdot (M-1) \qquad \text{for} \quad P_r \to \infty\,. \qquad (5)$$

That is, $g_{pole}(M)$ is the *minimum processing gain* that is required to serve M users with SINR requirement γ_0 if an unlimited transmit power budget was available. In terms of data rate, $g_{pole}(M)$ is the spreading gain that corresponds to the *maximum data rate* per user that is theoretically achievable given M users with a SINR requirement γ_0. For realistic operation with limited transmit powers, one must choose larger spreading gains.

[1] $[\mathbf{\Psi}]_{l_1,l_2} = 0$ for $t(l_2) = r(l_1)$ simply states that no self-interference occurs at a node; $t(l_2)$ is the node transmitting transmission l_2 and $r(l_1)$ is the node of reception l_1.

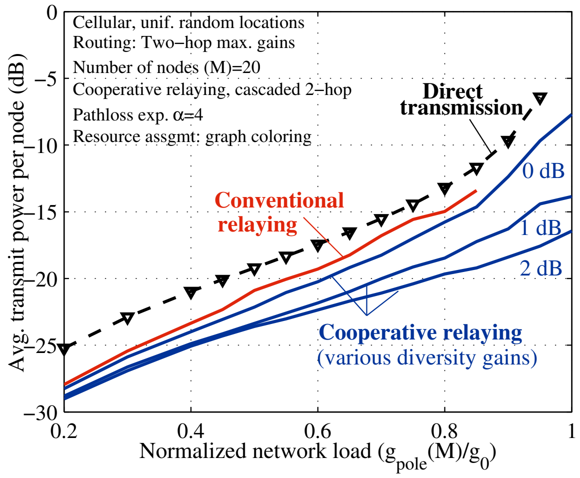

Fig. 3. Average transmit power per node as a function of the normalised network load. Cellular scenario with 20 users per cell.

For the purpose of further exposition, consider the ratio of the pole processing gain to the actually used processing gain,

$$0 \leq \frac{g_{pole}(M)}{g_0} < 1\,. \qquad (6)$$

This ratio represents the *normalised load* with respect to the pole capacity, and is for a fixed number of users solely determined by the employed processing gain g_0. We will use the ratio $g_{pole}(M)/g_0$ to adjust the network load for a fixed number of users M in the cellular case. Note finally that the normalised load $g_{pole}(M)/g_0$ corresponds to the so-called *uplink load*, which is frequently used for admission- and load control in 3G CDMA systems [16].

IV. Results and Discussion

Unless otherwise stated, we assume the following parameters: pathloss exponent $\alpha = 4.0$, target SINR $\gamma_l = 1$, and noise power $N = 1$. Noise power and transmit powers have the same unit, e.g. Watt.

A. Cellular Networks

Transmit Powers: Fig. 3 depicts the average transmit power per node for a cellular scenario with 20 users per cell as a function of the normalised network load. Several thousand snapshots, each characterised by random positions of the mobile nodes, route establishment, resource allocation, and power control, have been considered to obtain a sufficient statistic.

Direct transmission exhibits the typical *load curve*: as the load approaches one, the transmit powers diverge. Compared to this, *conventional relaying achieves a transmit power reduction* from lower end-to-end pathlosses. Cooperative relaying further improves performance by realizing profits from broadcast advantages of the wireless medium. In other words, while the *number of transmissions* is equal for conventional and cooperative relaying, the latter exploits more than one of them by *combining* contributing transmissions from the "relay chain". This combining also enables the exploitation of the inherent *diversity* benefits of relaying systems. For moderate diversity gains of 1 or 2 dB, significant power savings are achieved for cooperative relaying.[2]

TABLE I

Potential capacity improvement over direct transmission in cellular CDMA networks for the studied parameters; reference power level taken at a normalised load of 0.6.

Number of nodes per cell	10	20	30	40
Conventional Relaying	20%	13%	9%	3%
Cooperative R. (Div. gain=1 dB)	38%	40%	22%	14%

Capacity: In classical direct networks, transmit powers increase non-linearly with network load; see Fig. 3. Limited transmit powers of mobile nodes in connection with a desired minimum coverage imply that networks be operated at a network load less than one, i.e. below pole capacity. Admission- and load control in 3G systems typically ensure the network load to stay below 60%-70% for macrocell scenarios [16].

Yet, the main objective is not to limit the network load itself, but instead one intends to stay below a certain transmit power level. This power level should serve as the actual point of reference. As an example, consider Fig. 3. A network load of 60% requires an average power level of -17.4 dB per node for direct transmission. With this power level as a limit, we note that one can achieve a network load of 68% for conventional and 84% for cooperative relaying with diversity gains of 1 dB. Consequently, with an average power budget of -17.4 dB and for the considered parameters, conventional relaying achieves a capacity gain of $(0.68/0.6) - 1 = 13\%$ over direct transmission; cooperative relaying achieves more significant gains of $(0.84/0.6) - 1 = 40\%$. These capacity considerations are quantified more generally in Table I. It summarises the potential capacity gains achieved over a direct system, with the reference power level taken at a network load of 60% in the direct case.

B. Ad hoc Networks

The potential for application of cooperative relaying extends well beyond cellular networks, namely to the class of ad hoc networks. Our ad hoc network model is characterised by *(i)* each transmitting node using fix spreading factor, *(ii)* the network load being defined by the number of connections relative to the total number of nodes, and *(iii)* for each source node, a destination node is chosen randomly from the remaining $M - 1$ nodes.

For 40 nodes in a unit square area and various network loads, we found that a transmit power reduction of 2-3 dB can be achieved by using cooperative instead of conventional relaying (results not shown). However, these achievements come at the cost of an increased number of resources that are required for operating the network. Recall that in conventional relaying, an intermediate node receives a single transmission only and requires a *second* resource for transmission. By contrast, cascaded two-hop cooperative relaying combines

[2] The choice of a diversity gain of 1 dB results from comparing the difference of the mean power levels of our contributing links to the level differences studied in [17]. There, soft handover gains have been determined for selection combining; we focus on the even more advantageous case of maximum ratio combining.

signals received at two different resources, thus calling for a *third* resource to be allocated for transmission. For the considered example, cooperative relaying required in average six resources while conventional relaying called for four resources; the power savings therefore come at the cost of a 50% throughput reduction for limited bandwidth and allowed end-to-end delay.

C. Implementation Aspects

At the physical layer, cooperative relaying calls for *combining* from various resources – as done in ARQ mechanisms where redundancy from different time slots is taken into account. At the MAC layer, resources must be allocated such that reception(s) and transmission take place on orthogonal resources. A simplified resource allocation can be applied in two-hop networks, where conventional and cooperative relaying have identical demands.

We note that the lion's share of challenges, for example routing in mobile environments, is related to relaying itself, not to cooperation. Based on this, a viable strategy might be to *view cooperative relaying as an extension of conventional relaying* – not as a competing technology. Issues such as distributed routing, mobility management, and partly resource assignment, are challenges for both conventional and cooperative relaying, and hence should be tackled jointly. However, provisions should be made towards implementing the above listed cooperative extensions.

Then, to take full benefits from both relaying methods, operation could take place in a supplementary manner: conventional relaying serves as a means of providing coverage in areas where direct communication and cooperative relaying are not viable; for the remaining areas, cooperative relaying is used to improve network performance by lowering transmit powers, reducing interferences, or providing higher data rates.

V. Conclusions

We have comparatively discussed the options of conventional and cooperative relaying at the system level of wireless networks. Both schemes rely on pathloss savings; the cooperative version additionally exploits the broadcast nature of the medium and the diversity offered by independent paths to the destination node.

Our cellular and ad hoc scenarios were characterized by different models for network layout, traffic patterns, routing, and resource allocation. For cellular systems, we discussed a *two-hop option* that limits the number of re-transmissions, simplifies routing, and allows for identical resource allocation for conventional and cooperative relaying.

In cellular and ad hoc networks, cooperative relaying was shown to outperform conventional relaying by achieving power savings for typical network settings. In general, the resulting capacity gains are found to decrease as the node densities increase. For ten nodes per cell, conventional relaying achieves capacity gains of 20%, while for a density of 40 nodes the performance degrades to that of direct transmission. By contrast, cooperative relaying in connection with diversity gains of one decibel *more than doubles these gains*. These figures were obtained under the assumption of strictly limited bandwidth and end-to-end delay for a cellular two-hop scenario in power-controlled CDMA networks.

The advantages of cooperative relaying come at the cost of an increased complexity as combining must take two or more resources into account. For ad hoc networks, the power savings over conventional store-and-forward relaying come at the cost of a throughput reduction as cooperative relaying in multi-hop chains requires more resources to be allocated.

Finally, we have discussed a strategy that views cooperative relaying as an extension of conventional relaying. We believe that operating conventional and cooperative relaying in a supplementary manner constitutes a viable option for future generations of wireless networks.

Acknowledgements

The authors gratefully acknowledge the funding received from Vodafone Group Research and Development [18]. Furthermore, we would like to thank W. Rave for valuable discussions and comments.

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