# Cooperation in 4G
# – Hype or Ripe? –

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***Abstract***: With increasingly congested frequency bands and an ever-growing demand for higher data-rates, innovative approaches are needed to increase the spectral efficiency and hence cost per bit/s/Hz over the wireless link. Cooperative systems and radios, which are capable of intelligently forming mutually cooperative entities, are a promising way to achieve this increase in capacity. First technological and then social barriers, however, have prevented us so far from having technologies, systems or users jointly cooperate. We will hence try to answer in this article, whether time is ripe for a technology which has recently received so much hype. We will commence by explaining the technological implications of cooperative systems, as well as their state-of-the art and status quo. We will then dwell on the socio-technical implications of such systems, be it due to the new way of cooperative thinking or the impact of the higher system capacity. Finally, we will wrap up and issue a personal stance on required future cooperative 4G developments and trends in the area of cooperative systems.

***Index Terms:*** cooperative radio, relaying technology, 4G systems

# 1. Introductory Note on Cooperation

## 1.1. Introduction

It would be foolish to believe that the capacity offered by the wireless medium is limited. With thousands of THz of electromagnetic spectrum known, auctioning some MHz of bandwidth for several Billion Euros on the grounds of scarce spectrum seems to lack rationale. It could be compared to somebody sitting in a small shelter on earth and claiming there is not enough space in the universe.

Such an auction, however, has happened and it marked the beginning of an era which is generally referred to as 3G. It also marked the beginning of an era where we have only just begun to understand what freedom of information means, where we have grasped the idea of having access to any information anywhere, anyhow, at any cost – but where we have only started to explore ways of delivering this information.

There is a long path to pace until we are entitled to call the development of wireless technologies to be mature. There is little we can predict at this stage, except that the way the electromagnetic spectrum and the data flow itself are handled has to change. First steps are currently being undertaken in this direction with the emergence of, e.g., cognitive radios and – being focus of this paper – cooperative relaying techniques and technologies.

Cooperative, distributed relaying systems have received significant attention in the past decade and – due to their theoretically infinite design degrees of freedom – a large body of highly useful but also often confusing and contradicting research papers has emerged. In this paper, we hence aim at responding to the question whether such a technology is ripe for deployment or only the result of an academic hype.

To this end, we will briefly dwell on important historic milestones in the area of relaying systems, give some useful definitions which shall level understanding prior to technical exposures in subsequent sections, and summarise the design building blocks necessary to facilitate the proper functioning of a relaying communication system.

## 1.2. Academic Milestone Contributions

The method of relaying, i.e. a canonical form of cooperation, has been introduced in 1971 by van der Meulen in [1]. A first rigorous information theoretical analysis of the relay channel has been exposed by Cover in [2]. In these contributions, a source mobile terminal (MT) communicates with a target MT directly and via a relaying MT. In [2], the maximum achievable communication rate has been derived in dependency of various communication scenarios, which include the cases with and without feedback to either source MT or relaying MT, or both. The capacity of such a relaying configuration was shown to exceed the capacity of a simple direct link. It should be noted that the analysis was performed for Gaussian communication channels only; therefore, neither the wireless fading channel has been considered, nor have the power gains due to shorter relaying communication distances been explicitly incorporated into the analysis.

Only in the middle of the 90s, the idea of utilising relaying to boost the capacity of infrastructure-based wireless networks revived, thereby leading to the concept of opportunity driven multiple access (ODMA) [3]. Here, the power gains due to the shorter relaying links have been the main incentive to investigate such systems to reach MTs out of base station (BS) coverage. The emphasis of the study was its applicability to cellular systems, as well as a suitable protocol design.

Interesting milestones into the above-mentioned theoretical studies have been the contributions by Sendonaris, Erkip and Aazhang, which date back to 1998 [4]. In their study, a very simple but effective user cooperation protocol has been suggested to boost the uplink capacity and lower the uplink outage probability for a given rate. Moreover, they show that cooperation can reduce the MT's power consumption. The designed protocol stipulates a MT to broadcast its data frame to the BS and to a spatially adjacent MT, which then re-transmits the frame to the BS. Such a protocol certainly yields a higher degree of diversity because the channels from both MTs to the BS can be considered uncorrelated. The simple cooperative protocol has been extended by the same authors to more sophisticated schemes, which can be found in their subsequent excellent publications.

The contributions by Laneman in 2000 [5] are a conceptual and mathematical extension to [4], where energy-efficient multiple access protocols are suggested based on decode-and forward and amplify-and-forward relaying technologies. It has been shown that significant diversity and outage gains are achieved by deploying the relaying protocols when compared to the direct link. The case of distributed space-time coding has been analysed by Laneman in his PhD dissertation. In his thesis, information theoretical results for distributed single-input-single-output (SISO) channels with possible feedback have been utilised to design simple communication protocols taking into account systems with and without temporal diversity, as well as various forms of cooperation. He has demonstrated that cooperation yields full spatial diversity, which allows drastic transmit power savings at the same level of outage probability for a given communication rate.

Gupta and Kumar were the first to statistically analyse the information theoretically offered throughput for large scale relaying networks [6]. They showed that if the $M$ terminals and associated traffic distributions are random, then the capacity per terminal decreases in the order of $1 / \sqrt{(M \log M)}$. The analysis in [6] has later been extended by the same authors to more general communication topologies, where the interested reader is referred to the landmark paper [7].

Whilst above milestone contributions concentrated on the simple relaying case, the concept of distributed cooperative relaying systems, also termed Virtual Antenna Arrays, with application to cellular networks has been introduced in February 2000 by Dohler [8]. The generalisation of the concept to distributed-MIMO multi-stage communication networks with application of distributed space-time codes has been introduced shortly after and consequently patented by M-VCE in June 2001 [9].

Other excellent research in these areas has been performed thereafter, all of which led to the currently flourishing research area of cooperative wireless communication networks. These long historical developments have led to numerous independent terminologies, some of which we wish to harmonise below.

### 1.3. Some Useful Definitions

Often occurring in the exposures of relaying-related work is the concept of *infrastructure*. An infrastructure – be it physical or logical – can:

- be available prior to deployment (e.g. cellular networks or WLANs); or
- emerge after deployment or simply remain unavailable (e.g. ad hoc networks).

The former is also referred to as infrastructure-based, whereas the latter as infrastructure-less. The infrastructure can be managed in the following fashions:

- centralised (eg cellular network); or
- decentralised (eg WLAN mesh network).

Note that one may have a decentralised infrastructure-based system (e.g. systems with decentralised RRM) or a centralised infrastructure-less system (e.g. clustering).

Another key-concept is related to the *information flow* from source to destination/target. As shown in Figure 1, the information flow can be:

- point-to-point (traditional);
- point-to-multipoint (broadcast);
- multipoint-to-point (multiple access);
- multipoint-to-multipoint (general).

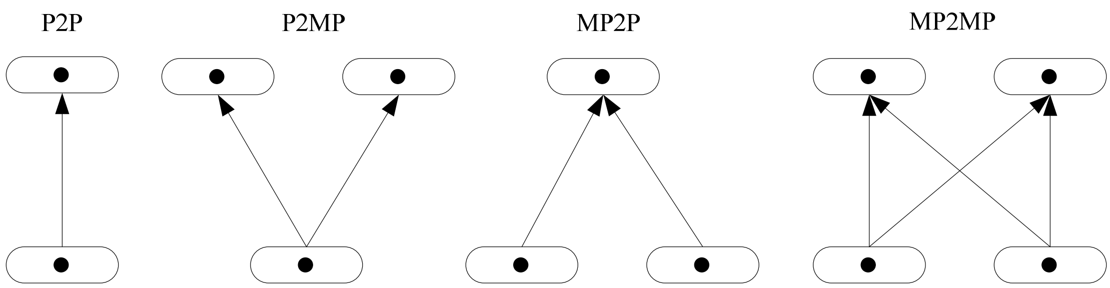


**Figure 1:** Possible information flows from source towards sink/target.

As exposed in Figure 2, such *information flows can be realised* by means of:

- direct links (no relays between source and target);
- relaying links (at least one relay between source and target);
- relaying stages (clusters where information passes approx. the same time).

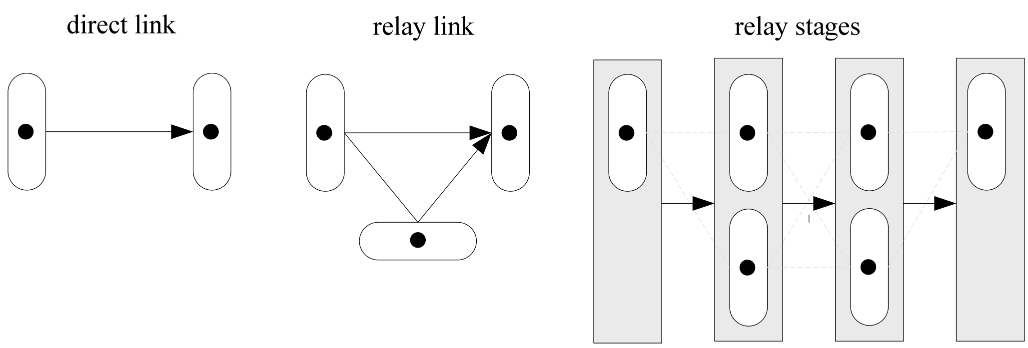


**Figure 2:** Possible realisation of information flows.

From Figure 3, each of the involved nodes in the network can have the following behaviour:

- egoistic (no help);
- supportive (unidirectional help);
- cooperative (mutual help).

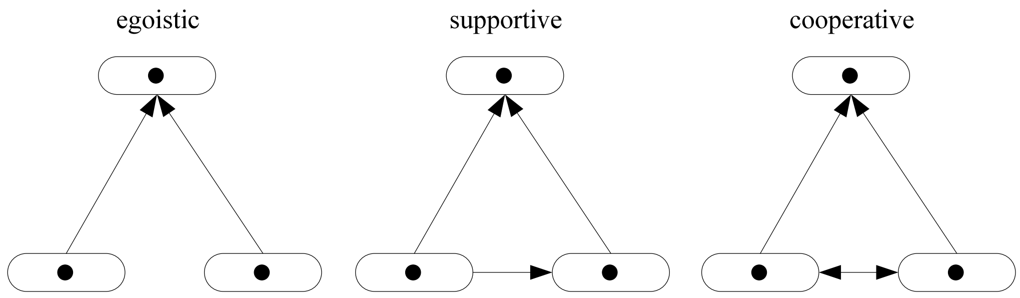


**Figure 3:** Examples of node behaviour.

The *relaying process* itself can be:

- transparent (retransmission of originally received analogue signal); or
- regenerative (retransmission of digitally modified received signal).

The former is seemingly simple as it usually only involves some form of frequency translation and amplification of the received signal, whereas the latter comprises some baseband processing but is generally known to outperform transparent techniques.

As an operator, we are clearly interested in designing an infrastructure-based system, for which we would like to quantify both financial and performance gains – if any – due to relaying and cooperation, as well as establish the optimum choice of relaying techniques and technologies.

### 1.4. Design Building Blocks

Designing a properly function wireless communication system – be it cooperative or non-cooperative – is an arduous task, which requires structural and modular design approaches to be invoked. To this end, a typical operator-internal approach is presented in Figure 4. The main design driver is the business case, which then leads to a set of requirements which translate into technological and implementation design approaches, supported by performance analyses. These building blocks are, of course, interconnected and interrelated and hence require iterative approaches to be taken to guarantee near-optimum solutions.

The core of the business case is the to-be-supported services, such as high-speed data access, IP-telephony, etc. To introduce these services, some survey and advertisement campaigns need to be run, licences paid, and technology needs to be researched, designed, optimised and deployed – leading to some capital expenditure (CAPEX). To maintain these services, some customer services need to be provided, technology maintained and faulty elements replaced – leading to some operational expenditure (OPEX). Estimated CAPEX and OPEX are deduced from projected service revenues, only after which it is decided if it is worthy to go ahead with the given service/technology pair or if another service/technology needs to be used.

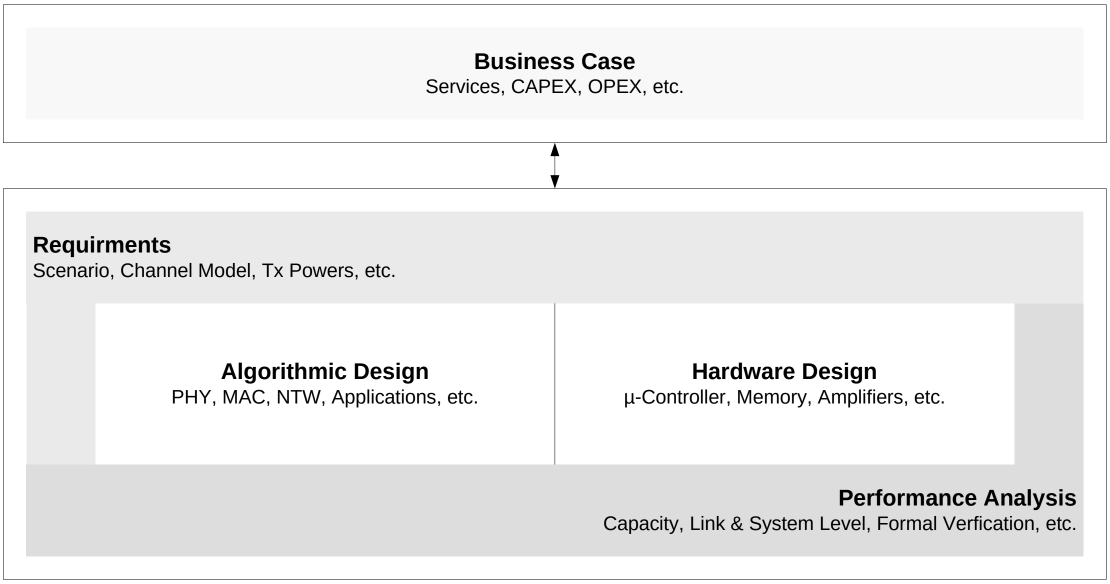


**Figure 4:** Essential blocks and their interrelation for designing wireless communication systems.

To support above decision and/or to deploy the chosen service/technology pair given it had been deemed worthwhile, a set of requirements is deduced. These include, e.g., some set of typical scenarios, the type of wireless channel, transmission powers, user distributions and speeds, service distributions, etc.

Said requirements are then used to facilitate the technological design, traditionally including a separate design of, e.g., physical (PHY), medium access control (MAC), network (NTW) and application (APL) layers. However, for networks constrained in some parameters – such as energy, latency, jitter – cross-layer design approaches have lately been successfully pursued.

Once these technological design blocks have been realised, these need to be implemented by means of a performance-optimised hardware design of radio front-ends, microcontrollers, logic, memory, power supply, etc. Here lie traditionally the biggest constraints, which often need to be fed-back to the technological analysis and underlying requirements.

Finally, various performance analysis tools can be used to optimise the design process, to determine the link or system performance, or to establish the gap between the developed real-world algorithms and theoretical capacity bounds. Another important tool is the formal verification of designed algorithms, which verifies that the states a complete system can enter are not of catastrophic or loop nature. This guarantees that developed system will operate under any of the envisaged situations.

# 2. State-of-the-Art of Cooperative Technologies

From previously discussed building blocks, applied to the cooperative relaying case, we deem issues related to the wireless relaying channel, characterisation of link and system capacity, as well as the various OSI layers of grand importance and hence briefly dwell on their state-of-the-art.

### 2.1. Characterisation of Relaying Channels

Channel models are vital in the design process of wireless systems, because they influence power budget dimensioning, transceiver design, performance behaviour, etc. Channel models are multiplicatively composed of pathloss, shadowing and fading.

Without going into greater details due to space limitations, we expose the general channel tendencies in Figure 5. Compared to their narrowband counter-part, wideband communication systems manage to reduce the fading margin due to the additionally injected frequency diversity. Cooperative systems, in addition, have the advantage of reducing the shadowing margin due to a high spatial diversity. Such a reduction constitutes a serious advantage, as the performance of today's communication systems is dominated by the shadowing effect.

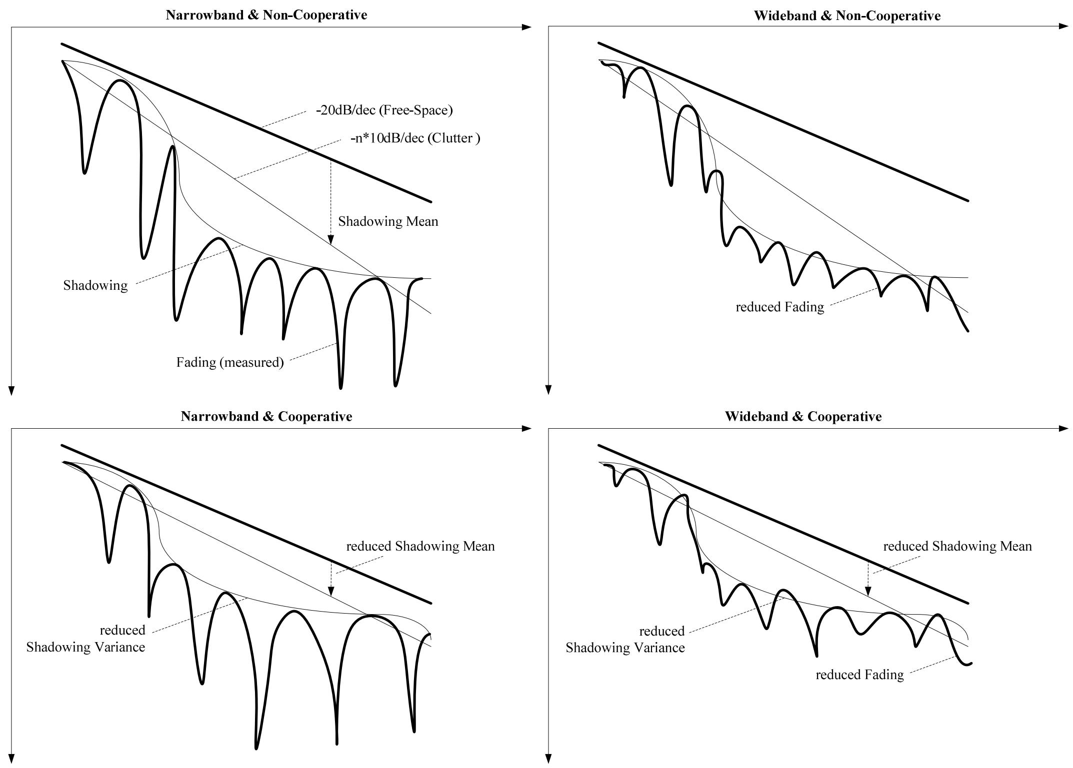


**Figure 5:** Cooperative relaying channel tendencies for narrow and wideband systems.

As for the *regenerative relaying channel*, each individual cooperative relaying segment counts differently, thereby leading to point-to-point channel models. Since cooperative relaying systems are often composed of a cellular link from an elevated BS towards a relaying terminal as well as some non-elevated cooperative links among nodes, both obey different channel statistics which are summarised in [10].

As for the *transparent relaying channel*, [11] has studied the statistical properties of a one-hop amplify-and-forward cooperative relay channel. It has been shown that under given conditions the end-to-end channel (source-relay-destination) envelope is a modified Bessel function of zeroth order. It is interesting to point out that the temporal autocorrelation is a product of three first-order Bessel functions. This leads to a faster decrease in correlation compared to the classic single relay channel, thereby complicating channel estimation procedures but aiding channel code performance.

### 2.2. Physical Layer Algorithms

At PHY layer, we distinguish three canonical relaying techniques, which can be used in conjunction with simple relaying or cooperative diversity relaying:

- amplify-and-forward;
- compress-and-forward; and
- decode-and-forward.

In the *amplify-and-forward* approach – being equivalent to *transparent relaying* – the cooperative relay down-converts the received analogue signal, amplifies it and up-converts it to another frequency band prior to re-transmitting it. The amplification requires some power constraints to be respected, where fixed or variable gain amplifications can be implemented. Note that this protocol suffers from severe performance losses at low signal-to-noise ratios (SNRs), because noise at the relay is also amplified. Furthermore, the analogue signal cannot be stored and hence requires immediate frequency translation; this implies two oscillators, two frequency bands and two fairly good filters – not necessarily making it a cheaper technology with respect to below relaying techniques.

The *compress-and-forward* approach is an extension of the amplify-and-forward method, where the analogue signal is sampled, quantised, compressed and re-transmitted. The advantage of doing so is to be able to temporarily store the signal or to relay it using a different communication standard. For instance, a 3G terminal could relay its received signal in compressed form via Bluetooth to adjacent terminals.

Finally, the *decode-and-forward* approach decodes the received signal and re-encodes it with a potentially different codebook prior to re-transmission. This clearly adds some complexity but at low SNR it exhibits a better performance than the amplify-and-forward approach. However, when the source-relay link is bad, this leads to a bottleneck for the transmission system since the relay is assumed to decode correctly the source message. Relay selection procedures are hence needed to overcome this problem and to increase the protocol's diversity order [12]. Information theoretically, such a processing permits to adapt the relaying rate to the relay-destination capacity.

The requirement of two frequency bands and the inability to store the relayed signal makes, in our opinion, the amplify-and-forward a less likely deployment candidate when compared to the decode-and-forward protocol. We will hence concentrate on the latter, for which repetition based, channel code based, and space-time code based relaying methods are available. As depicted in Figure 6, the first method repeats the received codeword (known to be sub-optimum from a code design point of view); the second method relays some parity information; and the third method constructs a space-time codeword between the source (s) and relaying (r) partners, thereby creating a distributed antenna array with obvious performance gains [13, 14].

All three methods require the source codebook to be known at the cooperative relaying node, so that it can successfully decode the message. However, repetition and channel code based methods require only a fairly loose synchronisation at frame level between source and relay terminals, whereas the space-time code based relaying method requires a fairly tight synchronisation at symbol level. This has lately been relaxed with the design of synchronisation-robust space-time codes [15].

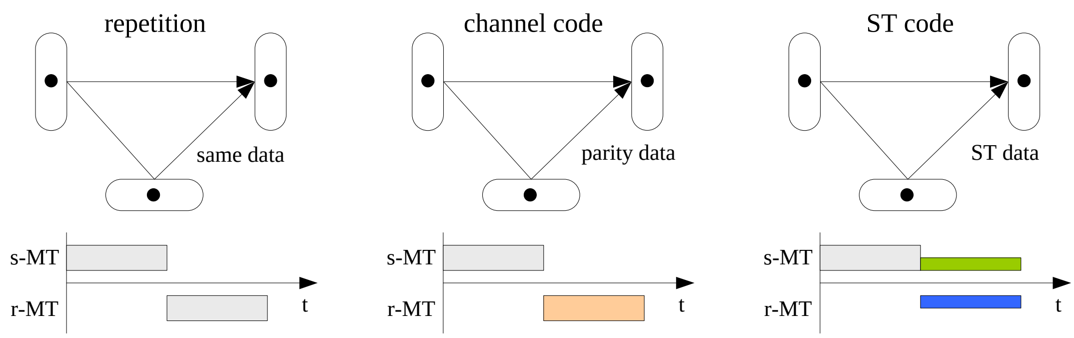


**Figure 6:** Decode-and-forward relaying methods.

### 2.3. Medium Access Control Mechanisms

Conflicts occur when more than one wireless link is active in a system. These conflicts are managed by the medium access control (MAC), which chooses:

- resources, i.e. which resources a link may use (e.g. specific time-slot);
- duplex method, i.e. whether the same frequency or different; and
- contention protocol, i.e. how each link gets access to the wireless medium.

Resources can usually be allocated using, e.g., time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), or orthogonal frequency division multiple access (OFDMA). The available duplex methods are time division duplex (TDD) and frequency division duplex (FDD). Protocols resolving contention are reservation-based MACs for typically centralised applications – in conjunction with, e.g., TDMA; and contention-based MACs for distributed applications – e.g. carrier sensing multiple access (CSMA).

Whilst the MAC is traditionally informed by the network layer about the next-hop destination, it needs to *select one or several suitable relay partner(s)* to facilitate cooperation. Several such protocols, based on different underlying assumptions and design goals, have been proposed in [16].

Since the relay channel is an additional traffic channel, the choice of relaying mechanism will influence the *multiple access protocol*. For instance, amplify-and-forward approaches require FDMA to be implemented at the relay, whereas the other two approaches also allow for TDMA.

The TDMA mode is generally realised by means of two phases. In the first phase, the source broadcasts information to the destination and the relay(s). In the second one, the relay(s) transmit(s) the information towards the destination. At MAC, this can be implemented using an *orthogonal as well as non-orthogonal mode*. For the orthogonal mode, the source does either not transmit in the second phase which reduces interference at the receiver side [12] or uses entirely orthogonal space-time codes [14]. For the non-orthogonal mode, the source also transmits in the second phase, which is known to increase the rate [17]. Several works studied different versions of the two orthogonal and non-orthogonal modes. Their performance is compared using the diversity-multiplexing trade-off [18] introduced for MIMO systems. It is shown in general that the non-orthogonal mode outperforms the orthogonal one, because, for the same diversity order, they achieve higher rates [18]. This has also been extended to broadcast and multicast channels [17].

To facilitate a cooperative MAC from an implementation point of view, two cases need to be distinguished: the *homogenous MAC* cooperation, where one distinct MAC layer is present in the system; and the *heterogeneous MAC*, where MAC protocols from different systems are used for cooperation.

Cooperation using a *homogenous MAC* takes advantage of the inherent properties of the wireless medium, its shared nature as well as the broadcast support of wireless transmissions. In practice, the conventional wireless systems are designed such that any unicast communication involves the two concerned parties only, i.e. the sender and the receiver. Therefore, existing MAC protocols ignore any overheard information from neighbouring nodes that are not involved in the transmission. In a cooperative scenario, this situation leads to a multitude of retransmission and therefore bandwidth waste.

In order to counteract this waste and also improve the system reliability, new wireless medium access control solutions enforce additional collaborative mechanisms at the neighbouring nodes, which can act as relays to improve the transmission reliability. In such a case, we consider three entities: the source, the destination and the relay. The source transmits first its MAC packet data unit (PDU). If the destination successfully receives this PDU, it sends an acknowledgement which will be overheard by both the relay and the source. In the case where the destination does not receive the PDU correctly but the relay node does, the latter transmits the PDU to the destination. If both the destination and the relay fail, the packet gets retransmitted by the source node.

Several practical solutions based on the suggested scheme with some minor variations are proposed in the literature. For instance, in [19], a new MAC protocol called CoopMAC is proposed, which is based on the IEEE 802.11 distributed coordination function (DCF). Another proposal has been put forward for IEEE 802.15.

In the case of *heterogeneous MACs*, we consider the co-existence of several MACs in the system. The cooperative system must take profit of this diversity to improve the effectiveness of the network and shall enable the inter-working between the different solutions. It can work either in handover based mode such that it triggers the hand off between two MAC technologies using a predefined criterion like signal strength, or in a complementary fashion, i.e. the traffic is divided over all the existing links. Many proposals have been made to handle cooperation issues in heterogeneous MAC environments; for instance, IEEE 802.21 or the unlicensed mobile access (UMA).

Research on cooperation mechanisms at MAC layer should also ensure that no user misbehaves. For example, in the IEEE 802.11 DCF, all participating nodes adhere to the backoff protocol to ensure – in the absence of hidden nodes – a fair share of the bandwidth for each node. A selfish node might want to obtain more than its fair share of the channel bandwidth [20] by selecting smaller backoff values or using a different retransmission strategy, such as not to double the contention window value after a collision. Such a selfish behaviour seriously degrades the throughput of the fair/no-selfish nodes. To deal with this issue, protocols where changes to the backoff calculation are sought. In [20], the authors propose some modifications to the IEEE 802.11 DCF with the supposition of the presence of a trusted base station that can identify sender misbehaviours.

## 2.4. Network Layer Protocols

Cooperation from a network viewpoint concerns the design of an efficient routing protocol that enables effective network resource management. Interestingly, from the higher level perspectives, the wireless network is represented as a set of wireless nodes that attempt to increase the system’s quality of service (QoS) via cooperation. It is worth mentioning that an effective cooperation at network level implies the usage of cooperative transmission at both MAC and PHY layers. The problem to alleviate at the routing level considering a multihop path is how to select the best cascaded relay set from a source towards the destination.

We find in the literature numerous protocols that deal with the proper selection of multihop paths in a wireless environment. However, only a few routing protocols exist that really consider the existence of cooperative terminals along the route.

In [21], the authors advocate the use of opportunistic relaying as a practical scheme for cooperative solutions. A distributed path selection mechanism is proposed where the best relay is selected by the source using instantaneous wireless channel conditions, i.e. signal-to-interference-and-noise ratio (SINR) measurements, and then used to realise the cooperation between the source and the destination. The simplicity of the solution facilitates the coordination between the cooperative entities and bounds the overall signalling overhead.

In [22], the authors combine both cross-layer optimisation and spatial diversity by investigating the performance of a link/network layer diversity routing protocol. The process of packet delivery is as follows: iteratively, at each hop and for each packet, a “candidate forwarder” is selected by the source node from its one hop neighbour nodes and prioritised based on their proximity, in terms of number of hops to the destination. Therefore, the node with the highest priority will relay the received packet, whereas the other candidate forwarders transmit only the unacknowledged packets. Such an approach was shown to outperform traditional routing, typically increasing the overall throughput by a factor of two.

Finally, w.r.t. [23], the essence of this contribution led to the design and the implementation of the best-select protocol (BSP), which generalises single-path routing with sets of nodes substituting the concept of a single node relay. Consequently, the data are transferred from a given relay-set towards another relay-set. The channel gain information obtained through message exchange between relay-sets is utilised to select the best node within a relay-set as the relay to transmit the data to the next relay-set. The process is reiterated until the destination is reached.

In the context of cooperative communication, it is important to study the node behaviour in the case of infrastructure-less ad hoc networks. In fact, in the case of an existing centralised authority that enforces the overall collaboration, all nodes adhere to the cooperative paradigm. However, in ad hoc networks, where no centralised entity exists, a malicious or self-interested user can misbehave and does not cooperate. A malicious user could inject false routing messages into the network in order to break the cooperative paradigm. However, a self-interested user does not intend to directly damage the overall functioning, but to save its own resources. A user's selfishness is comprehensible as it is often requires to forward packets for the benefit of others, consuming precious resources that they want to save for their own communication. The basic network functions subject to selfishness are broadcasting and routing.

Current approaches to counteract such behaviour and enforce cooperation at network layer can be broadly classified into two categories:

- pricing or credit based schemes; and
- reputation based schemes [24].

*Credit-based schemes* consider packet forwarding as a market model where nodes providing a service are remunerated, whilst nodes receiving a service are charged. Hence, if a node wants to send its own packets, it must forward packets for the benefit of others. However, these schemes require tamper-resistant hardware [25] or infrastructure-dependent credit clearance systems [26] that other nodes can trust.

*Reputation-based schemes* discourage misbehaviour by estimating the nodes reputation and punishing nodes with bad behaviour [27, 28]. The scheme requires each node to rate every other node with which it communicates based on the service received or on observing the behaviour of neighbours by listening to communications in the same transmission range. According to the collected information, the reputation system maintains a value for each observed node that represents a reputation of its behaviour. The reputation mechanism allows avoiding sending packets through misbehaving nodes.

### 2.5. Inter-System Cooperation

Ubiquitous cooperative protocols will likely find their way into standards and deployment with the advent of 4$^{th}$ generation (4G) systems. 4G is likely going to be composed of a heterogeneous plethora of seamlessly interconnected technologies [29]. However, whilst cooperation at various layers between different systems has been in part discussed above, there are no viable state-of-the-art standardisations available. Work only commenced; see, e.g., recent efforts of IEEE P1900 (www.ieeep1900.org).

## 3. Socio-Technical Impact of Cooperation

Cooperation is not a natural characteristics attributed to humans. The typical human horizon is focused on short-term gains, which might be due to our instinct-driven subconscious occupying a grander importance than we dare to admit [30]. Cooperating with other individuals or entities, however, usually means that short-term losses may translate into long-term gains – something children do not yet and adults rarely ever understand. Any cooperative technology depending solely on human decisions is hence *a priori* doomed to fail; history has shown this on numerous occasions. By contrast, if machines only have access to some decision making engines, cooperative schemes become viable communication techniques and are likely to occupy an important place in the technological landscape of the 21$^{st}$ century.

We will briefly dwell on the various failures of past cooperative communication projects and use this to highlight requirements for making cooperative schemes a success. Presuming that cooperation succeeds, we will discuss its direct and indirect impact onto society.

### 3.1. Reasons for Failures

To name a few, some obvious and less obvious failures related to relaying and cooperative systems are the following:

- ad hoc networks in general;
- 3GPP ODMA; and
- Ricochet Networks.

Ad hoc networks often require some peer-to-peer communication via a multihop path. Such a type of network has been researched for more than 30 years; however, no commercially viable civil product has appeared on the market so far. In our personal opinion, although often not depicted as such, that constitutes a serious failure and possibly requires a change in funding, research and deployment policies. The cause for this failure is manifold, mainly however due to the following two reasons. First, the design degrees of freedom have turned out to be too large to reach commercialisation; i.e., a psychological barrier prevailed at the manufacturer and service provider side, which prevented the deployment of such technology that had not even been fully mastered for much simpler cellular systems. And, second, the data relaying process required users to give away battery power and bandwidth, and possibly jeopardise the security of their own data, with no obvious instantaneous gains; i.e., a psychological barrier prevailed at the user side, which – for abovementioned reasons – has turned out to be hardest to break.

The UMTS Concept Group Epsilon proposed ODMA as a potential 3rd generation (3G) candidate solution [3]. The idea was to use – in an opportunistic manner – 3G terminals within a cell to give coverage to terminals out of BS range. Although suitable protocols had been proposed and the overall system gains had clearly been demonstrated, this proposal received a lukewarm reception and was subsequently withdrawn. The prime reasons of lack of success were, again, the fact that users needed to authorise usage of their own resources to facilitate the cooperative relaying process, but also the inability of ODMA to function as a stand-alone, always available, high-capacity 3G system.

A third and fairly prominent example is Ricochet® (www.ricochet.net), a US company which was well ahead of its time by rolling-out a broadband wireless network throughout major US cities more than 10 years ago. They simply formed a mesh network by means of relay-capable nodes attached to lamp-posts. Technology was at its finest, including routing and MAC protocols, but the technology just did not take of back then. The reasons are most likely similar to the ones given above. Today, however, Ricochet has addressed these concerns; for instance, when consulting the company's website today, data security is well advertised. Ricochet has again taken up business in a few US cities and is likely to grow over the upcoming years.

There are many other examples of relaying technology not having worked out. Most of these failures are rooted in the inhibition of users relaying other people's data for no apparent short-term gain and the inability of cooperative systems to guarantee constant and reliable availability.

### 3.2. Requirements for Success

The sheer amount of factors influencing the success or failure of a technology seemingly makes this a binomially distributed random variable. Success can hence not be programmed, even if many factors seem to be favourable and compelling. In fact, only very few technologies were successful – mainly because they appeared at the right time, at the right place, at the right pace, and supported by the right team. Many more technologies, however, did not make it but they exposed lessons to be learned for future projects.

For offered services, where the end-user had the last word, many failed technologies were simply either far ahead of time (i.e. the user was psychologically not prepared to accept the new technology and got around it by using another – possibly worse – technology) or lagged behind time (i.e. the user was already saturated with similar technologies and saw no reason – particularly for incremental gains – to change technologies). Prior to introducing cooperative techniques to these type of services, a thorough and sound survey hence needs to be conducted, which will determine whether time is ripe for such technologies to be exposed to the habit-driven end-user.

Given that cooperative relaying technology is affordable, another means for a company to secure revenues is to profit from government supported initiatives related to homeland security, emergency applications, etc. A prominent example is PacketHop (www.packethop.com), which capitalises on the fact that, on one hand, relaying technology today is not very expensive, reliable, robust and well understood and, on the other hand, security needs are constantly rising.

The revenue equation, however, changes immediately once a company is exposed to market forces alone and is not supported by government initiatives anymore. Such is the case for an integrated operator, like ourselves, who needs to make a strategic decision whether cooperative technologies are a worthwhile investment. We are bound by agreements to provide a certain degree of QoS to the end-user and hence need to dimension our networks appropriately. This greatly diminishes the possibility to use mobile terminals as cooperative relays, mainly because their availability is unreliable. An attractive notion is hence the use of fixed relays [31], which are clearly cheaper than BSs but still more expensive than using the users' terminals for relaying. The loss-benefit equations hence need to be redrafted when dimensioning a cellular system with the availability of such fixed relays. Interestingly, [32] has demonstrated that, with the current state of technology, using such fixed relays does not yield significant cost benefits. He also quantified the costs a fixed relay has to obey if such an approach is to bring benefits to the operator.

Furthermore, in our opinion, cooperative techniques will likely survive in scenarios which are independent of government or user, i.e. machine-to-machine applications. An example is wireless sensor networks (WSNs), where cooperation benefits data reliability, energy savings, network longevity, etc [33]. Indeed, a sensor group-behaviour by means of cooperation can greatly increase the average network lifetime. For instance, cooperation at PHY layer can reduce transmission powers; cooperation at MAC layer can reduce idle listening times; cooperation at application layer can use data aggregation to reduce the traffic to be relayed; etc.

On a more long-term prognosis, cooperative schemes not falling in any of the above approaches will need to develop suitable incentive schemes. That means that users who sacrifice their resources to cooperatively aid other users are credited and users who benefit from cooperation are charged. Whilst long-term benefits have been demonstrated analytically and by means of simulations for a variety of cooperative schemes, the challenge will be to develop crediting schemes which seem advantageous already over a short to medium-term horizon; a good starting point are schemes exposed in [24-28].

Finally, likely facilitators of cooperative technologies are the software defined and opportunistic radio, which are in position to sense the radio context and knowledgeably draw a decision whether cooperation is beneficial and which steps have to be taken to set up a cooperative scheme. Such radios would also allow for nodes to learn about appropriate decisions related to cooperation and hence constantly improve the performance of such systems.

### 3.3. Impact onto Society

The momentum of cooperative technologies in the context of current and forthcoming 4G systems is very large and it commences finding its input into various standardisation bodies, such as IEEE P1900. It is hence safe to assume that this technology – in one way or another – will be part of the future wireless arena. Assuming that it is deployed, its impact onto the academic, industrial and general society shall be discussed below.

*Academia*, playing a dominant part in a modern society, had already felt a strong impact due to cooperative schemes. Compared to a decade ago, thousands of conference, journal and white papers have appeared – virtually any university department works on cooperative schemes in one way or another. This strongly influences funding policies and hence also has a significant impact onto other research areas, which may or may not be equally important. This obvious imbalance needs to be addressed, where we need to find some measures to quantify the usefulness of conducted research and exposed results. Shannon’s communication bounds proved very useful in the communications theory, because it potentially prevented Millions of Euros to be poured into the enhancement of wireless transceivers which operated at the theoretically achievable bounds anyway already. An example of pouring funding into research areas without any quantified limits are ad hoc networks – indeed, whilst many contributions in this area are of highest importance and certainly aid the design of future ad hoc type systems, the large body of published results are fairly incremental and the funds used to support this work would probably have been better off elsewhere.

*Industry*, being the main driver in technological developments and deployments, obey the same rules. As a matter of fact, the same as above applies to funding strategies within R&D departments of manufacturers and service providers. The biggest challenge within companies today, however, is to find a suitable synergy between research, development and business units. This may mean that the research departments need to synthesise and simplify the large degrees of freedom of cooperative systems, so that these are being picket up by development departments. These, in turn, need to develop a compelling technology to coerce business units.

*Government and policy makers* also have an important impact onto society. For instance, spectrum allocations are negotiated every 4 years at the world radio conferences (WRCs). The specific decision to re-farm spectral bands in the sub-GHz TV band region, e.g., triggered an upsurge in research into opportunistic radios and hence influenced funding flows. With respect to infrastructure-less cooperative techniques, it is interesting to note that these are unlikely to have an impact onto spectrum allocation policies. The main reason is that spectrum allocations are based on offered guaranteed services, which – as said before – cooperative relaying techniques cannot support with 100 % reliability.

Finally, as for the *everyday end-user*, cooperation should ideally go unnoticed – underlying technologies should make their own knowledgeable decisions in a transparent fashion. For instance, being an example of loose cooperation between two technologies, France Telecom's UNIK service allows seamless handovers between its cellular GSM technology and its home Livebox WLAN once in communication range. This has also been extended to the case where any user with suitable GSM/WLAN terminal can use any reachable WLAN or cellular technology to facilitate communication. In none of these cases, the instantaneous decision of switching between technologies is left to the user. This is mainly because of reasons outlined in Section 2, but also due to the delay incurred by such decision making.

Taking decisions on cooperation away from the conscious end-user will allow machines to communicate more reliably and at higher data-rates. This in turn will increase the population's trust in a particular technology, as well as technologies in general. Once a trust threshold will be passed and the technology will have reached sufficient roll-out densities, users will not mind giving away resources on the short-term horizon, knowing that the long-term gains can be significant.

A likely beneficiary from accepting such technology is the intelligent transportation system (ITS) for road safety and driver information. Car-to-car cooperation can significantly improve the efficiency and safety of modern transportation systems. For example, vehicles can communicate detour, traffic accident, and congestion information with nearby vehicles early to reduce traffic jam near the affected areas. This cooperation could be used for cooperative driving, passing assistance, security distance warning, and coordination of cars entering a lane or in blink traffic lights.

Furthermore, using cooperative technologies – be it via relaying or distributed space-time techniques – will facilitate reliably high data rates to be provided in areas which currently suffer from connectivity problems. For instance, cooperative mesh networks could provide in-home voice, data and TV in sparse residential areas, which predominantly occur in Northern Europe, Eastern Russia, Africa and large parts of the Americas. This will significantly change life styles, business patterns and hence political protocols in these regions.

Finally, a likely beneficiary is also the *environment*. Cooperative techniques allow for great savings in energy needed to transmit and support communications. This, in turn, translates directly to less use of batteries, less transmission power, less number of BSs, less pollution when deploying these BSs, as well as less spectral pollution. These impacts may not directly be measurable today, but certainly have an influence on the environment and hence on humanity on the long run.

### 3.4. Quo Vadis Cooperation?

Algorithms to facilitate cooperation at a local scale seems to be ripe, technology allows users to be kept out of the decision loop as much as possible and sufficient funds seem to be available to support developments in this area – the question hence arises, which direction this technology will be going in the forthcoming years?

In our personal opinion, within a few years, cooperative mechanisms will be found in diverse forms within wireless and wireline communication systems. 4G will most likely be a single cooperative entity composed of various standardised and possibly non-standardised heterogeneous systems. The latter might be the result of the ITU releasing more frequency bands for which spectral masks only are defined, hence – with the dawn of reconfigurable radios – triggering competition into superior radios.

Since a single standard could not hold this promise, we hope that one day cooperative systems will facilitate the creation of a wirelessly connected community as large as the Internet and hence seamlessly extend it to the wireless world, thereby finally realising the dream of being connected anywhere, anytime and anyhow.

Before this dream can be put into reality, however, design concerns and design constraints of such large-scale cooperative networks will need to be understood. A first step towards these quantitative descriptions of cooperative systems, as we have alluded to before, various scaling laws constitute a handy tool [34].

For instance, Kumar and Gupta's throughput scaling law quantifies theoretical network capacity limits in a network where everybody talks with everybody [6,7]. As said before, they established that the network throughput scales with $1 / \sqrt{(M \log M)}$, where *M* is the number of terminals; hence, no matter what we try, we cannot design a scalable protocol and topologies different from pure ad hoc have to be invoked. This has recently been considered in [35], in which it has been proven that network capacity can increase linearly (and hence per-node capacity remains constant) for an increasing number of nodes by using cooperative communication hierarchies; this tendency had originally motivated [14].

With this in mind, Odlyzko and Tilly's value scaling law can be used to quantify the value of a network, where everybody has circles of friends with decreasing importance. This is, for instance, useful if entities in a network do not cooperate with everybody but only with important partners. The law, if properly applied, quantifies the increase in network value if cooperative clusters are used [36].

As for practical test-runs, more initiatives similar to the EASY-C project (www.easy-c.de) are needed. In this first large-scale testbed worldwide, to be rolled-out in Dresden in Germany, innovative transmission techniques for next generation mobile communications systems will be demonstrated. This includes cooperative relaying techniques hopefully facilitating strong coverage and fairness improvements.

More work on this, however, is needed to understand the theoretical and practical limits of cooperative systems under various constraints. In our personal opinion, we should invest into this now to gain directive insights for the future, so that the impact of cooperative technologies can be maximised to everybody’s benefit.

# Glossary

| | |
|---|---|
| 3G | 3$^{rd}$ Generation (Mobile System) |
| 3GPP | 3$^{rd}$ Generation Partnership Project |
| 4G | 4$^{th}$ Generation (Mobile System) |
| APL | Application (Layer) |
| BS | Base Station |
| BSP | Best-Select Protocol |
| CAPEX | Capital Expenditure |
| CDMA | Code Division Multiple Access (Protocol) |
| CSMA | Carrier Sensing Multiple Access (Protocol) |
| DCF | Distributed Coordination Function |
| FDD | Frequency Division Duplex |
| FDMA | Frequency Division Multiple Access (Protocol) |
| GSM | Global System for Mobile Communications |
| ITS | Intelligent Transportation System |
| ITU | International Telecommunications Union |
| MAC | Medium Access Control |
| MHz | Mega Hertz |
| MIMO | Multiple-Input-Multiple-Output |
| MT | Mobile Terminal |
| M-VCE | Mobile Virtual Centre of Excellence |
| NTW | Network (Layer) |
| ODMA | Opportunity Driven Multiple Access |
| OFDMA | Orthogonal Frequency Division Multiple Access (Protocol) |
| OPEX | Operational Expenditure |
| OSI | Open Systems Interconnection (Reference Model) |
| PDU | Packet Data Unit |
| PHY | Physical (Layer) |
| QoS | Quality-of-Service |
| R&D | Research and Development |
| RRM | Radio Resource Management |
| SISO | Single-Input-Single-Output |
| SINR | Signal-to-Interference-and-Noise Ratio |
| SNR | Signal-to-Noise Ratio |
| TDD | Time Division Duplex |
| TDMA | Time Division Multiple Access (Protocol) |
| THz | Terra Hertz |
| TV | Television |
| UMA | Unlicensed Mobile Access |
| UMTS | Universal Mobile Telecommunications System |
| WLAN | Wireless Local Area Network |
| WRC | World Radio Conference |
| WSN | Wireless Sensor Networks |

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