On the Need of Network coding for Mobile Clouds

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Publication date:
2011

Document Version
Early version, also known as pre-print

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Abstract. This paper advocates the need of network coding for mobile clouds. Mobile clouds as well as network coding are describing two novel concepts. The concept of mobile clouds describes the potential of mobile devices to communicate with each other and form a cooperative cluster in which new services and potentials are created. Network coding on the other side enables the mobile cloud to communicate in a very efficient and secure way in terms of energy and bandwidth usage. Even though network coding can be applied in a variety of communication networks, it has some inherent features that makes it suitable for mobile clouds. The paper will list the benefits of network coding for mobile clouds as well as introduce both concepts in a tutorial way. The results used throughout this paper are collaborative work of different research institutes, but mainly taken from the mobile device group at Aalborg University.

Keywords: Mobile Networks, Mobile Clouds, Network Coding

1 Introduction

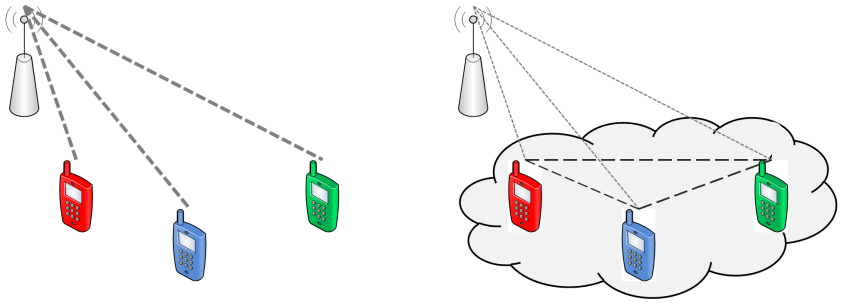
Mobile communication systems undergo a tremendous change from centralized systems to more distributed systems. That trend has several reasons. First of all the voice oriented systems are extended by data communication. Then the mobile domain is offering new ways of creating services. In the very first days the mobile devices were downloading static content from servers. Nowadays the phones themselves are creating the content by individual contributions (see twitter.com or facebook.com) or by accumulating their contextual awareness to create a new service (waze.com). Often these services are labeled cloud services. This paper describes the upcoming trend of mobile devices to connect directly to each other without any or with help of a given overlay network. In underdeveloped countries there is no or insufficient overlay network and services are creating among the peers. But even in the presence of overlay networks the additional communication link among mobile devices wherever possible offers new potential ways to designing novel communication systems. The connection of mobile devices in close proximity to each other is referred to as mobile clouds.

While the communication from a centralized access point with any given mobile device is very easy, the communication among mobile devices that are not fully, but very often only partially connected tends to be very inefficient.

Therefore the paper will introduce a more efficient way how mobile devices might communicate among each other. This technique is referred to as network coding. Before we introduce this technology, we will look into the potential of mobile clouds.

2 Mobile Clouds

Mobile clouds are referring to the concept of cooperating mobile devices to achieve a common or even a different goal. Cooperating devices are connected directly, in a multi-hop fashion or virtually by an overlay network. In [1, 2] different forms of mobile clouds are introduced. Clouds that are established by the same person are referred to as personal or private clouds. Public clouds on the other side are set up by users with at least one dedicated device, where the users might not even know each other.



(a) State of the art cellular networks. (b) Mobile clouds with overlay network.

Figure 1: Comparison of the state of the art and mobile clouds.

One of the most interesting architectures is based on mobile devices that are connected to the overlay network as well as directly with mobile devices in close proximity. Current technologies support this idea as the overlay network might be realized by a 3G link and the direct links are realized by IEEE802.11 as given in Figure 1b. The maximum distances between the mobiles are small compared to the maximum distance of the 3G link. The main idea to introduce this new degree of freedom is motivated by potential new services, increased bandwidth and potential energy savings for the mobile device as well as for the network operators. Compared to the old fashioned cellular connection in Figure 1a, the design of mobile devices for a mobile cloud might be less complex and therefore less expensive for the manufacturer. One example should clarify this argument. As higher data rates become more important even for mobile users, it is much harder to facilitate a given rate for an individual user than for a cooperative cluster of devices. One reason is the diversity of the links towards each user to maintain at least a minimum rate. Another reason is that some services such as IPTV might reduce the data rate per link dramatically. At this point we would like to emphasize that cooperative reception is not limited to broadcast

services, even though that this is the most efficient one. In [3] we have shown the advantage of mobile clouds over state of the art approaches even for unicast traffic, in this case web traffic.

Interesting will be the motivation of users to cooperate. There are different scenarios where motivating them is easier than for others. In nature we have seen several ways of cooperation and derived the most important ones for the mobile devices. The basic rule for cooperation is to illustrate each participating entity the potential goal by cooperating. This is condensed by the statement *real egoistic behavior is to cooperate*. As long as there is a gain by cooperating everybody will join the collaborative effort. Most cooperative approaches rely on altruism or slavery, especially the work present for multi-hop systems. Here and hereafter we are looking into egoistic users, that are selfish and will carefully evaluate whether to cooperate or not. If we solve this problem, other forms based on altruism or friendship is easy to solve. A second rule derived from nature is the need to detect and to eventually punish free riders or cheaters. Another rule refers to the payoff tolerance. A rule that deals with the time that can be used to pay back a received benefit by cooperating with other devices to those involved devices. The interested reader is referred to [1] where those rules are derived with more care. Upcoming social networks might become a main driver behind mobile clouds as the cooperativeness might increase when it is reported back to the community. In combination with social networks the mutual benefit can be given just by listing it in certain communities.

At this point we would like to present one small example for showing the benefits by joining a mobile cloud. We assume users that are interested in a video service e.g. a soccer match. For comparison reason let's first look at a standalone user. The user will consume a certain amount of energy by receiving the desired service. The energy consumed is based on the power level of the air interface used and the time the air interface is active. Here we assume that each user can easily switch on and off the air interface as needed. Cooperative users on the other side have two air interfaces. As the standalone user, the overlay network air interface is used to retrieve information. But this time not the full information need to be downloaded. Only partial information from the overlay network will be retrieved. The partial information is than exchanged over the second air interface among the members of the mobile cloud. It is important that the cooperating devices are retrieving disjointed information in order to be able to retrieve the full information. In terms of energy for the overlay network less energy is consumed as we are less time active. That is obvious. The energy that we will use on the second air interface should be less than getting the remaining information over the overlay network to enable cooperation at all. As shown in [4] this is often the case as the second air interface is using less time to exchange the information whereas the power levels for the two air interface are the nearly the same [5]. The reason that the second air interface is less active is based on the fact that the data rate on the secondary one is larger than the overlay network [5]. The energy involved to exchange data in the mobile cloud will increase if the cooperating devices are not connected directly. For multi-hop clusters the energy increases and that would reduce the benefit and willingness

to cooperate. In order to make the inner cloud communication more efficient new techniques are needed. One of those techniques is network coding.

3 Network Coding

The main breakthrough of network coding came with the work presented in [6] by Ahlswede. Since that work, network coding is always introduced by the famous butterfly example, which is given in Figure 3. At this point we would like to make clear that network coding is not limited to this kind of topology, but can be used in any arbitrary network topology. The scenario includes seven nodes that are connected in a certain way as shown in Figure 2. The aim of source node A is to send two packets a and b to the destination nodes F and G over the given network topology. Each link has the same capacity and able to convey either packet a or b. As it can be easily seen in Figure 2 node D becomes the bottleneck of this topology as it receives both packets but is only able to forward either a or b. Based on the decision of node D one of the destination nodes will get both packets and the other one will only get one packet.

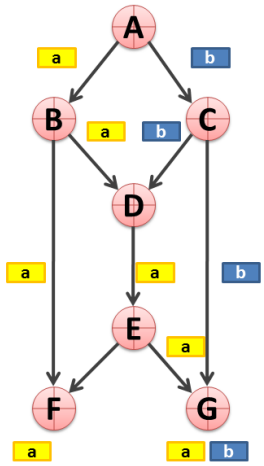


Figure 2: Butterfly network without network coding.

In Figure 3 the same network is given but now the nodes are able to perform network coding. Actually the most interesting node is node D again. As before it receives two packets and the outgoing capacity is only large enough to forward only one packet. But here network coding kicks in. Node D performs a coded version of packet a and b. For illustration purpose we paint packet a and b with the color yellow and blue, respectively. A coded version of both packets could

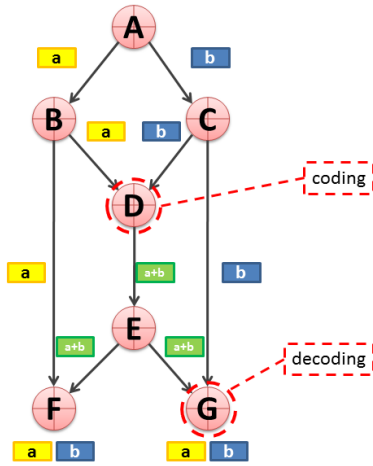


Figure 3: Butterfly network with network coding.

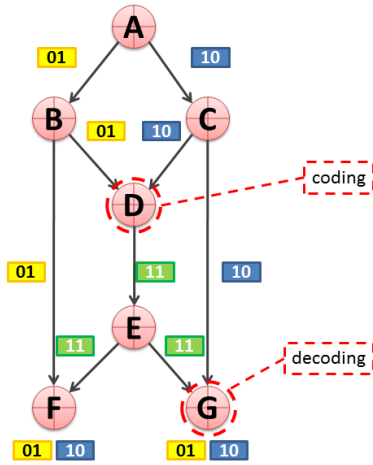


Figure 4: The binary butterfly examples.

be represented by the green color referring to the mixing of blue and yellow. A green packet, having the same size of either a or b, would be forwarded to node E which will then forward that packet to both destination nodes. Each destination node will receive two packets, namely one original packet (either a or b) and a coded packet. The coded packet alone is useless, but in combination with one original packet decoding can be done. In case of node F packet a is received from node B and the coded version from node E. To retrieve the original packet, node F decodes the green packet. As it already has a yellow packet it assumes that only a blue packet would make the coded packet green. Leaving this illustrative example a more technical description of the coding is given in the following. Coming back to node D the binary representation of packet a and b is coded by a bitwise XOR operation as given in Figure 4. So a bitwise operation of packet a (represented by 01) and packet b (represented by 10), would end up in a packet with the same size represented by 11. As we will see later a coded packet would need also additional information which packets are coded together in order to perform the decoding. This allows the usage of network coding in any arbitrary network topology and it is not limited to the butterfly example.

The use of this simple form of coding was applied to wireless meshed networks in [7] by Katabi et al. introducing the COPE mechanism. COPE is not only the XOR type of packet coding it also deals with implementation towards the IEEE802.11 standard. The main outcome of the work was an increase in capacity for the wireless meshed network using network coding compared to a non-coded system. In [8] the authors applied similar COPE mechanism to the Nokia N810 platform. In [9] a video shows how this approach works and gives some insights about the potential gain.

Referring to the example given in Figure 5, the advantage of network coding over standard approaches for mobile clouds is highlighted shortly. Therefore we assume an overlay network introducing two packets a and b into a mobile cloud. The mobile cloud is based on three mobile devices that are partially connected. As given in Figure 5 one node is fully connected to the other two nodes, while the outer nodes need the middle node to communicate. This topology is often referred to as *Alice and Bob* scenario.

If the standard approach is used to exchange two packets between the outer nodes, four transmissions are needed as shown in Figure 5. The outer nodes send their packets to the middle node, which is relaying it to the final destination. Using network coding as introduced beforehand, the number of overall transmission is reduced to three. The reduction is based on the network coding procedure at the middle node. Two packets that arrive will be coded (e.g. using XOR) and the coded version is broadcasted at the same time to two destinations. Once again for the ease of illustration we are using the three colors (blue/yellow/green) in Figure 5.

At this point we would like to emphasize that a new field at network coding is looking into the possibility to do the coding on the physical layer. In the example beforehand the coding was performed on layer 3 (network layer) referring to the ISO/OSI protocol layer design. But physical layer network coding exploits the

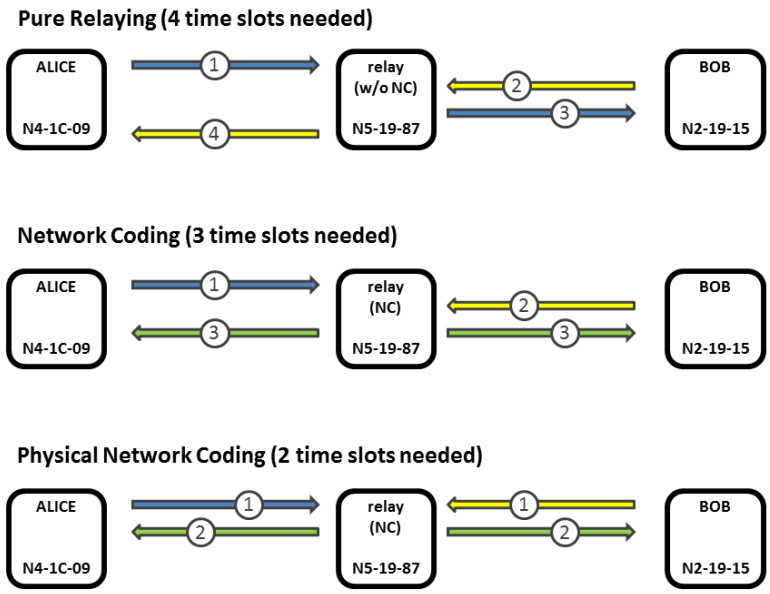


Figure 5: Alice and Bob scenario for pure relaying, layer 3 network coding, and physical layer network coding.

possibility to perform the XOR coding directly in the air. For our example the outer nodes should send their two original packets at the same time. The middle node would receive a combinatorial version of both packets. This combination will then be broadcasted to both destination nodes. Physical layer network coding would reduce the amount of overall transmissions to two.

Let's compare these three approaches. Both network coding approaches yield better results in terms of used time slots for packet transmissions compared to the standard approach. While the network layer network coding is adding only little complexity, the physical layer network coding is currently harder to implement. Furthermore it has to be noted that the role of the middle node is different for both approaches. With network layer network coding the middle node is a full member of the mobile cloud as it receives all information. In case of the physical layer network coding the middle nodes is degraded to a simple relay, which is not possible to use the relayed information for itself. The later one is beneficial with respect to security if the outer nodes would not like the middle node to understand. But for the operation of the mobile cloud it is of utmost importance to show each member a clear benefit in participation (see rules of cooperation above).

Currently the research community is looking into layer 3 network coding as well as physical layer network coding. As explained above the expected gain for that given example is 25% as we reduce the number of transmitted packets

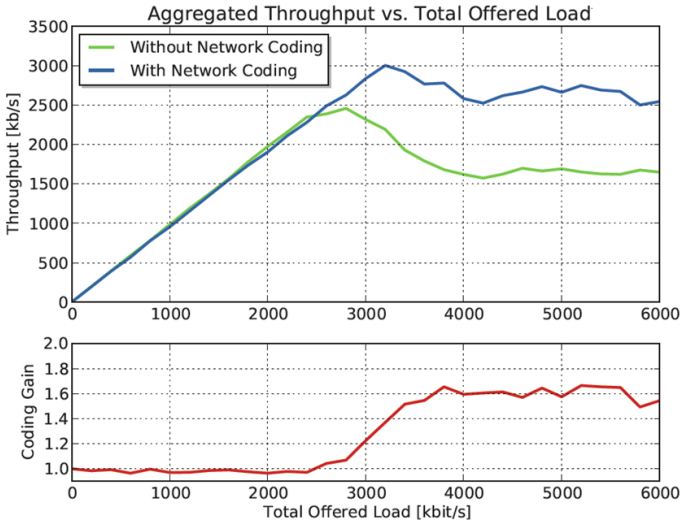


Figure 6: Throughput and coding gain versus the offered load for pure relaying and network coding investigating the Alice and Bob scenario.

from 4 to 3. But if we consider the medium access as well then the results will differ. Figure 6 shows throughput of the system versus the offered load from both entities [10]. So we are assuming symmetric traffic. Two approaches are compared with each other, namely the pure relaying and the use of network coding. With an increasing load the pure relaying performs worse than network coding. Interestingly the coding gain exceeds the 25% reaching values up to 60%. First let's look at the working point where both approaches yield the same performance (below 2500 kbit/s). Even if the throughput is the same, from the energy perspective the relay node has to transmit twice as much and this might cause problems if the relay node would be battery driven. Increasing the offered load shows impact in the system throughput. The reason behind this is the way the MAC works. IEEE802.11 is providing a fair share between all nodes. IEEE802.11 has not information nor interest that the relay node is doing the hard work for Alice and Bob and therefore should provide more capacity for the middle node. Loosely speaking Alice and Bob are shooting into their own foot by "stealing" the capacity from the middle node. In case a perfect MAC would have been designed in favor for the relaying node, the coding gain would not exceed the 25% for the given scenario. But currently the WLAN world is dominated by IEEE802.11.

The simple form of network coding using the XOR functionality has some drawbacks. While the simplicity allows quick implementation, the nodes performing network coding needs to understand which packets need to be coded in order to be efficient. If this is achieved by signaling the performance will

be degraded. Therefore a huge milestone in history of network coding was introduced by Kötter and Medard [11] with the idea of random linear network coding. In this approach a linear combination of all packets are transmitted all the time. Each packet gets a random coefficient for the linear combination in contrast to a systematic code where the coefficients are designed. Figure 7 shows the difference between no coding, binary and RLNC in order to explain the differences.

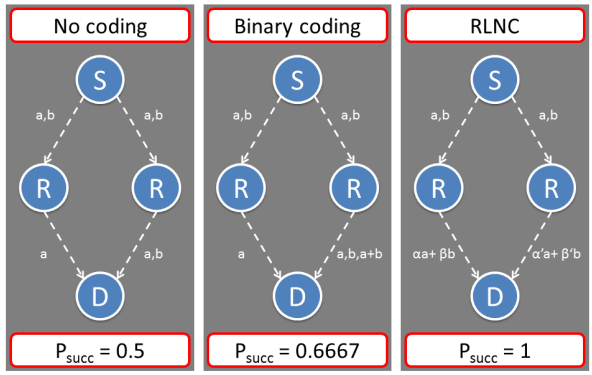


Figure 7: Comparison between no coding, binary coding and RLNC

The figure shows the example of two relay nodes (R) that receives information from the source node (S) and are willing to forward those information to the destination node (D). We consider only two packets a and b and investigate the probability to send those two packets in two time slots. If both packets are received successfully from the source, the relays should forward those packets. The question arises which packets should be forwarded by which relay. In the presence of no coding, the relays might forward the same packet with probability 50%, which will be very inefficient. In order to not send the same packet the relays should overhear each other. An assumption that does not always hold as the link between the relays might be error prone but more importantly packets will be queued in order to achieve transmission slots (as for IEEE802.11) and no decision can be made after the queuing.

In case of binary coding there is one additional packet that can be sent for the relay. Besides the original packets a and b, there is one linear combination of both packets. That improves the probability to send both original packets in to time slots to 66%. With RLNC the probability increases nearly to 100% as there are a large number of random linear combinations. In our prior work [12, 13, 14] we have shown that the implementation of RLNC on mobile devices is feasible.

4 Conclusion

This paper has motivated the combination of mobile clouds and network coding. Mobile clouds will offer new services for less complex mobile devices, while network coding is changing the world we will design communication networks of the future. With respect to mobile clouds network coding can ease the operation in many ways.

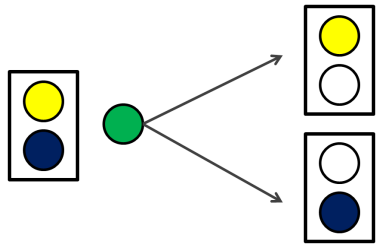


Figure 8: Network coding solving the collector's problem.

1. Exchange of information within mobile clouds: The exchange of information within mobile cloud needs to be as efficient as possible in order to motivate a large number of users to cooperate. With network coding the number of packets can be reduced significantly. For multi-hop networks this is obvious as explained by the butterfly example. But even for a fully meshed network, network coding helps to reduce the number of transmissions. E.g. if one mobile device wants to transmit a number of packets to neighboring devices, in case of losses, coded packets can repair different losses at several devices at the same time. In Figure 8 the example is given for one device that conveys a coded packet (green) to two destination devices. Those two devices have already received different information but with the reception of a broadcasted coded packet, both losses can be healed.

2. Introduction of information into the mobile cloud: From the network perspective network coding eases the information seeding into the mobile cloud. Without network coding the loss pattern across the mobile devices matters. A simple example should illustrate this. In order that the mobile cloud is able to start local retransmission, all information from the network has to be received at least once at one mobile device. As long as this state is not reached the network will constantly insert more information. This will end up in more resource usage if no perfect feedback channel from all mobile devices is available compared to case where network coding is applied.

3. Distributed Storage: An inherent feature of network coding is the possibility to store data in a distributed way. That can be done locally among the devices in the mobile cloud as well as different places within the Internet. The mobile device would need to code the original data and store the coded data on different places.

4. Security: As given in Figure 1b data will be retrieved from the overlay network as well as from the neighboring devices. This caused some discussion whether this kind of information is secure. Using network coding the data is inherently save as all coded packets are needed to recover the data. Furthermore the splitting of the encoding vectors from the coded data would increase security if the encoding vectors are solely transmitted via the overlay network.

Acknowledgment

This work was partially financed by the CONE project (Grant No. 09-066549/FTP) granted by Danish Ministry of Science, Technology and Innovation, and the ENOC project in collaboration with Renesas, Oulu. Furthermore we would like to thank Martin Hundebøll and Jeppe Ledet-Pedersen for the provision of Figure 6 from [10].

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