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Green Mobile Clouds: Network Coding and User Cooperation for Improved Energy Efficiency

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***Abstract*—This paper highlights the benefits of user cooperation and network coding for energy saving in cellular networks. It is shown that these techniques allow for reliable and efficient multicast services from both a user and network perspective. The working principles and advantages in terms of energy and spectrum usage is explained for user cooperation, network coding and a combination of both. For multicast services it is shown that the proposed approaches can save as much as 90% of the energy on the user side and 66% on network provider side for the topologies under investigation. One interesting finding is that user cooperation can be beneficial for the network operator even if some users refuse to cooperate.**

I. Introduction

Green communication is a new research paradigm with focus on reducing energy consumption and CO_2 emissions. In cellular network additional motivations for going green are the big energy bills that network providers face and the energy limitations of battery driven devices. Gartner has estimated that Information and Communication Technology is responsible for two percent of the global CO_2 emissions [1]. As an example, during the New Year's Eve 2007-2008, 43 billion SMS was exchanged worldwide with an estimated energy consumption of 30 MWh. The use of electricity in this context is manifold; powering network equipment, cooling the network equipment, and powering radio transmitters. The energy consumption of mobile clients is important as the number of mobile devices is very large, as of May 2011 there exists approximately 5.6 billion mobile phones worldwide. Furthermore, the size of the battery in a mobile device is limited due to design issues, and battery technology is currently developing at a relatively slow pace.

Thus, the goal is to improve energy efficiency on both the network and the user side. If the wireless links can be exploited more efficiently the transmissions can be completed faster and energy can be conserved. There exists many solutions that aim at conserving spectrum and energy [2]. Here we consider two interesting techniques that are evaluated from the energy efficiency standpoint, namely Network Coding (NC) and user cooperation. Additional the combination of these techniques is considered. Here the use case is that of multicast delivery in mobile communication networks is considered to demonstrate the energy saving potential. Specifically, as illustrated in Fig. 1, one service provider that conveys a multicast service over one Base Station (BS). The BS serves N mobile nodes over a cellular broadcast channel. Additionally the nodes may enable an orthogonal local wireless interface which they can use to form local mobile clouds. As each mobile device is connected to the BS via an error prone wireless link an error recovery mechanisms must be applied to ensure reliability.

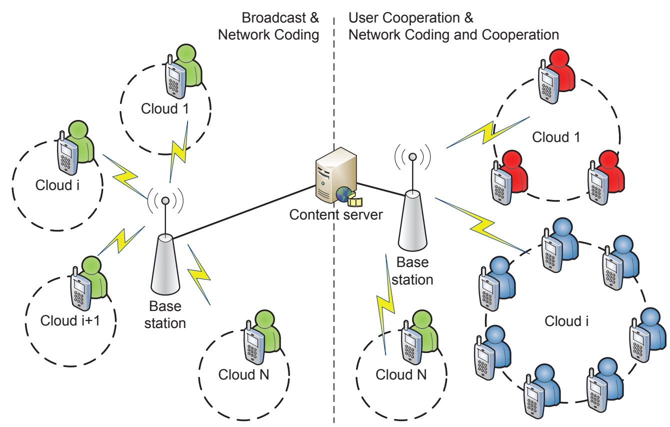


Fig. 1: Scenario under investigation where data is distributed to groups of users .

NC was proposed in [3] where the authors showed that the capacity determined by the Max-Flow Min-Cut theorem can be achieved in any point-to-point network when NC is used. Several codes and approaches have been suggested NC [4]–[8] noticeably Random Linear Network Coding (RLNC) [9], [10]. We apply RLNC to code packets that are conveyed from the BS to the mobile devices, as well as in combination with user cooperation. User cooperation rely on the fact that mobile devices that are close to each other are able to form cooperating clusters also referred to as mobile clouds [11], [12]. The devices are connected directly using short-range links, e.g. WiFi, while the cellular link can be realized with UMTS, LTE or other technologies. By forming a mobile cloud the channel becomes more than a point-to-point connection, as the nodes in each cloud operate jointly and thus act as one virtual antenna array.

In Section II the scenario, the different strategies, and the basis for the performance evaluation is explained. In Section III results for the simplest scenario are presented in order to illustrate the strategies and methods exploited. Section IV and Section V extends the results for two more advanced scenarios. The final conclusions are drawn in Section VI.

II. Scenario and Strategies

The considered strategies are evaluated by forming Markov chains for each node and cluster based on erasure probabilities and code performance. Thus we can calculate the expected number of packets that the BS sends until all nodes or clouds have successfully received the data. Likewise we can calculate how many packets the nodes must receive and send, both via the cellular and local link. We assume that; all clouds internally are fully connected, that erasures are independent, and that erasures occur on the links between the BS, that a error free instantaneous orthogonal feedback channel exists, and the nodes and inside each cloud with a probability of 20%. To calculate the energy consumption we use the values obtained in [13].

The four strategies; broadcast, pure coding, user cooperation, and network coding plus user cooperation shown in Fig. 1 utilize the links of the mobile devices differently, which is summed up by Table I.

TABLE I: Cellular and local link usage for the schemes.

Scheme	Cellular	Local
Broadcast (B)	Broadcast	None
Pure Coding (PC)	RLNC	None
User Cooperation (UC)	Broadcast	Broadcast
Network Coding plus User Cooperation (CC)	RLNC	RLNC

Table II provides the notation used in the following sections.

TABLE II: Notation.

Notation	Description
N	Total Nodes
M	Total Clusters
ϵ	Erasure probability of the link
i	Cluster number
j	Node number
n_i	Nodes in cluster i
m_i	Nodes in cluster i with a cellular connection
c	Transmissions on the cellular link
C	Expected total transmissions on the cellular link
l	Transmissions on the local link
L	Expected total transmissions on the local link
q	Field size used for RLNC
g	Generation used for RLNC

A. Broadcast

With simple broadcasting the BS retransmit a packet until all nodes have received it. For those devices that have lost the packet a retransmission is beneficial, but for the other devices a retransmission equals wasted time and energy. The probability that a packet is lost, ϵ, defines the transition matrix for node j, $\boldsymbol{B}_j$, which describe the probability that the packet is received.

$$\boldsymbol{B}_j = \begin{bmatrix} \epsilon & 0 \\ 1-\epsilon & 1 \end{bmatrix} \tag{1}$$

The pmf of the number of received packets at node j as a function of the number of transmissions, c, is thus given by $\boldsymbol{B}_j^c \cdot \boldsymbol{s}$. The vector $\boldsymbol{s}$ is the starting condition, where initially a node have received no packets and thus in this case$\boldsymbol{s} = [1; 0]$. Elements x in the resulting pmf express the probability that node j has received x packets, we denote this probability $P(j_{\text{recv}} = x)$. The probability that all devices have received all data can then be found by multiplying the probabilities that each node is done. To calculate the expected transmissions on the cellular link, C_B, simply calculate and sum the probabilities that another transmission is necessary.

$$C_B = \sum_{c=0}^{\infty} \left(1 - \prod_{j=1}^{N} P(j_{\text{recv}} = 1 | \boldsymbol{B}_j^c \cdot \boldsymbol{s}) \right) \tag{2}$$

B. Pure Coding

To improve the erasure recovery, coding can be used at the BS. We use RLNC [9], as described in [14], [15], see [16] for an introduction. Other rateless codes could also be used in a similar way, but we later consider the combination of RLNC and user cooperation, where end-to-end codes are not applicable. Thus the BS can encode the original data into coded packets, which can be recoded and/or decoded at the receiving nodes. The main advantage of NC over the simple repetition scheme in broadcasting, is that packets encoded at the BS can, with high probability, be used to repair erasures at all nodes that have not yet received the full original data. In this way the BS only needs to send packets until the nodes have collected approximately the number of original packets, instead of the exact original set of packets.

Some important parameters of a RLNC scheme are the field size and generation size [15]. The field size is the size of the finite field over which all coding operations are performed. A high field size improves the performance of the code as the probability that a coded packet is useful at a node increases. However, a high field size also increases the computational complexity and thus the energy consumed during encoding, recoding and decoding. We assume that the smallest field size of two is used, as it can deliver acceptable code performance in most cases while being computational undemanding [14]. The generation size defines the number of packets over which coding is performed. For the code to perform well the generation size should be large, but a large generation size also result in a higher computationally complexity. Furthermore, increasing the generation size increases the decoding delay of the received data which can be problematic for delay sensitive services. Here we consider a relatively small generation size of 64. Given the field size q and generation size g the probability that a received packet is linearly dependent at node j is given by $\boldsymbol{D}_j$ [14], [15].

$$\boldsymbol{D}_j = \begin{bmatrix} \frac{1}{q^g} & 0 & \cdots & 0 \\ (1-\frac{1}{q^g}) & \frac{1}{q^{g-1}} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & (1-\frac{1}{q^1}) & 1 \end{bmatrix} \tag{3}$$

Additionally the probability that a packet is lost due to a link erasure must be included which gives $\boldsymbol{E}_j$ in Equation (4). Thus we can calculate C_{PC} similar to Equation (2).

$$C_{PC} = \sum_{c=0}^{\infty} \left(1 - \prod_{j=1}^{N} P(j_{\text{recv}} = g | \boldsymbol{E}_j^c \cdot \boldsymbol{s}) \right) \tag{6}$$

We note that in a practical system it would be beneficial to use systematic code which would significantly reduce the workload needed to encode and decode, but in most cases would not impact the expected number of transmitted packets.

C. User Cooperation

As given in Fig. 1 some mobile devices in close proximity can communicate with each other via a secondary air interface and form a cooperative cluster or a mobile cloud. As the nodes in each cloud cooperate they do not necessarily all have to keep their cellular interface open. We refer to nodes that receive data via their cellular interface as heads. If there is only one head in a cloud it must subsequently forward the data to all other nodes in the cloud. Thus all nodes except the head conserve energy as they do not receive data over their cellular interface. To distribute the load equally the role of the cloud head can be changed in a round robin fashion.

Alternatively all nodes in the cloud could receive from the BS, we refer to such a cloud as all heads. Such a cloud is able to receive packets from the BS faster compared to an one-head cloud due to the low probability that all nodes in the cloud experience an erasure. However, this can have a negative impact on the energy consumption at the cellular interfaces of all nodes consume energy. As a hybrid solution we can enable two, three, or more heads in each cloud. This provides the possibility to trade a reduction in the packets sent from the BS with a reduction in the energy consumption by the nodes.

$$\boldsymbol{F}_i = \begin{bmatrix} \epsilon^{m_i} & 0 \\ 1 - \epsilon^{m_i} & 1 \end{bmatrix} \tag{7}$$

To determine the number of cellular transmissions, needed to ensure that the nodes in each cluster combined have received all data. The probability that a cluster have received all packets is given by $\boldsymbol{F}$. From this we can determine the number of cellular transmissions necessary to satisfy all clusters.

$$C_{UC} = \sum_{c=0}^{\infty} \left(1 - \prod_{i=1}^{M} P(i_{\text{recv}} = 1 | \boldsymbol{F}_i^c \cdot \boldsymbol{s}) \right) \tag{8}$$

Simultaneously we update the Markov chains for all individual nodes similar to the broadcast case. For the $n_i - m_i$ in a cloud that have disabled their cellular connection no update is necessary, alternatively we can say that $\epsilon = 1$ for these nodes. After the first phase where the BS broadcast is complete, we consider each cluster as a case of the broadcast scenario.

$$L_{UC} = \sum_{l=0}^{\infty} \left(1 - \prod_{j=1}^{N} P(j_{\text{recv}} = 1 | \boldsymbol{B}_j^l \cdot \boldsymbol{B}_j^{C_{UC}} \cdot \boldsymbol{s}) \right) \tag{9}$$

D. Network Coding plus User Cooperation

In this case user cooperation is enhanced with the use of RLNC. The BS sends RLNC packets and subsequently the devices in the cloud cooperate similar to the user cooperation strategy but instead transmit recoded packets.

The probability that each cluster has received all packet can be extended in the same way as broadcasting was extended in the user cooperation strategy, which result in the transition probabilities in Equation (5).

$$C_{CC} = \sum_{c=0}^{\infty} \left(1 - \prod_{i=1}^{M} P(i_{\text{recv}} = g | \boldsymbol{F}_i^c \cdot \boldsymbol{s}) \right) \tag{10}$$

Similar to the user cooperation strategy the expected local transmissions can be found by considering each of the clusters as a case of pure coding, but with modified starting conditions.

$$L_{CC} = \sum_{l=0}^{\infty} \left(1 - \prod_{j=1}^{N} P(j_{\text{recv}} = g | \boldsymbol{G}_j^l \cdot \boldsymbol{G}_j^{C_{CC}} \cdot \boldsymbol{s}) \right) \tag{11}$$

$$\boldsymbol{E}_j = \begin{bmatrix} 1 - (1-\epsilon)(1 - \frac{1}{q^g}) & 0 & \cdots & 0 \\ (1-\epsilon)(1 - \frac{1}{q^g}) & 1 - (1-\epsilon)(1 - \frac{1}{q^{g-1}}) & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & (1-\epsilon)(1 - \frac{1}{q^1}) & 1 \end{bmatrix} \tag{4}$$

$$\boldsymbol{G}_i = \begin{bmatrix} 1 - (1-\epsilon^{m_i})(1 - \frac{1}{q^g}) & 0 & \cdots & 0 \\ (1-\epsilon^{m_i})(1 - \frac{1}{q^g}) & 1 - (1-\epsilon^{m_i})(1 - \frac{1}{q^{g-1}}) & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & (1-\epsilon^{m_i})(1 - \frac{1}{q^1}) & 1 \end{bmatrix} \tag{5}$$

III. A Single Cloud

First we consider the case of a single cloud, which also serves the purpose of illustrating the approach used to analyze the remaining scenarios. A BS distributes data to N nodes that is varied between one and 32 and which form a single cloud. The reported number of packets is in all cases the expected number of packets needed for each node, when a single packet is conveyed from the BS to each of the nodes.

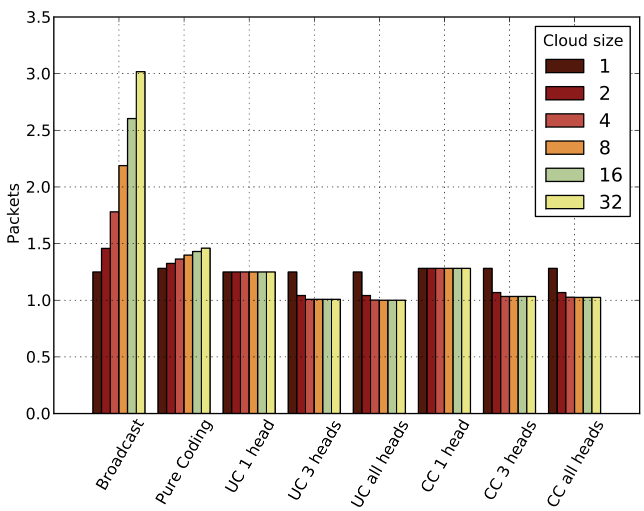
The expected number of packets sent from the BS via the cellular link are shown for the different schemes in Fig. 2a. Fig. 2b shows the expected number of packet received via the cellular link for each node. In Fig. 2c the number of packets sent from a node via the local connection is show and Fig. 2d shows the number of packets received via the local link. In Fig. 2c and 2d schemes where no packets are transmitted locally are omitted. In each figure the values for each scheme are grouped and marked on the x-axis. The y-axis denote the number of packets.

A. Broadcast

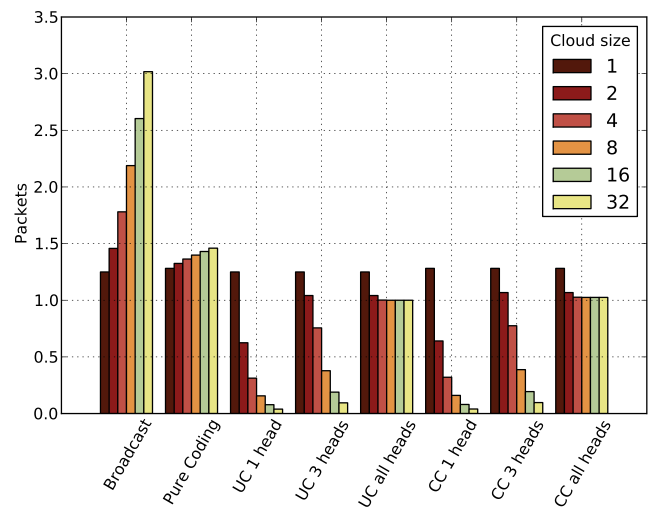
In the broadcasting case the number of packets sent from the BS increases significantly as the number of receiving nodes increases, see Fig. 2a and 2b. As the cloud size increase the BS must overcome the packet erasures at all receivers before transmission is completed. However, the necessary transmissions serve a higher number of receivers and only approximately three times more transmission are used in order to served 30 nodes compared to serving a single node.

B. Pure Coding

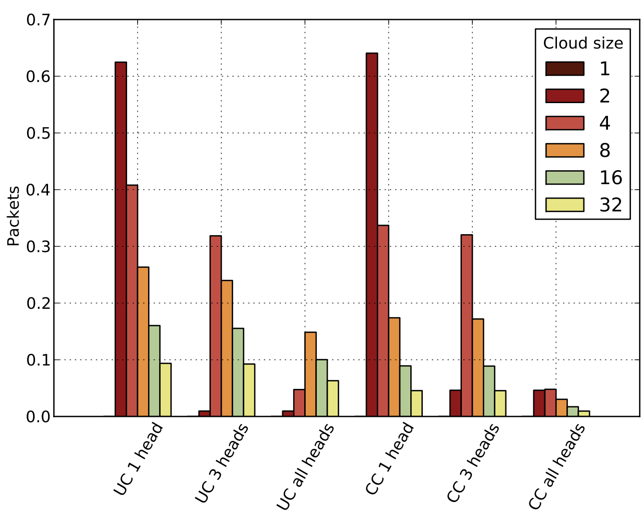
When coding is used, the BS only approximately needs to overcome the erasure probability to ensure that all nodes receive the data reliably. The expected number of sent packets increases slightly as the number of nodes increases, as seen in Fig. 2a and 2b due to the chosen parameters of the code. The highest reduction in cellular traffic compared to broadcasting is 50% and obtained when the cluster is biggest, see Fig. 2a.



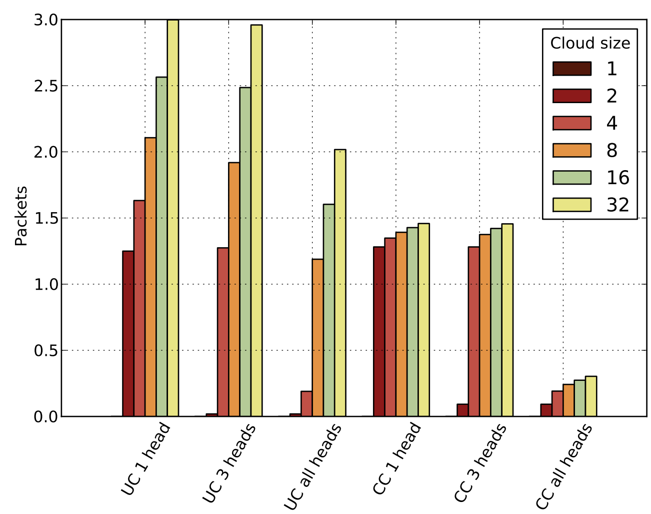
(a) Packets sent by the BS.



(b) Packets received from the cellular link.



(c) Packets sent within the mobile cloud.



(d) Packets received from the mobile cloud.

Fig. 2: Expected transmissions for one node in the scenarion of a single cloud.

C. User Cooperation

When cooperation is used the number of sent packets from the BS is dramatically reduced compared to the broadcasting case. In the case where there is only one cloud head the BS needs to send the same number of packets as if it was transmitting to a single node. If there are multiple heads the load on the BS is reduced. Thus the performance does not depend on the number of devices in each cloud but on the number of heads. Additionally, if not all nodes in the cloud are heads the number of packets received via the cellular link is also dramatically reduced, as only some of the nodes utilize their cellular interface. However, with user cooperation the nodes also exchange packets locally in the cloud. As the cloud size increases the number of packets received from within the cloud increases, see Fig. 2c. Conversely the number of packets sent decreases as the task of transmitting packets are distributed over an increasing number of nodes, see Fig. 2d. When Fig. 2a-2d are compared it can be seen that the number of heads in the cloud presents a trade-off between the load on the cellular and local link. If only a single node in a cloud is not a head the amount of local packets are increased dramatically compared to when all nodes are heads, see Figure 2d. The reason is that nodes with a disabled cellular connection must receive all data from the cloud. In small clouds this is undesired as the number of nodes that share the burden of transmitting packets locally is small. Thus in such cases all nodes should enable their cellular connection.

D. User Cooperation plus Network Coding

When user cooperation and network coding is used in combination, the best of the two approaches can be obtained. Compared with user cooperation approach the load on the cellular link is similar but the local link usage is reduced.

On the local link the most significant saving is on reception of packets, which is due to the same reasons that cellular transmissions are reduced for the coding approach over broadcasting. The biggest saving is observed when the cluster is big and all nodes are heads, see Fig. 2c-2d. Thus the impact of increasing the cluster size is greatly reduced compared to the user cooperation case. However, if the size of the cloud is very small a small overhead due to the applied code is observed.

E. Energy Consumption

Fig. 2a shows the number of packets sent from the BS. This can be translated into energy consumption at the BS if the energy used to transmit per bit or per packet at the BS is known. A general observation is that if the number of receivers is significantly larger than one, all of the proposed techniques reduces the energy consumed at the BS compared to unicasting. The energy consumption can be reduced by up to 66% in the case where the cloud size is 32, if user cooperation or user cooperation plus network coding is used instead of broadcasting. Thus from the point of view of the network operator, cooperation or cooperation with NC should be used, preferably with multiple heads per cloud.

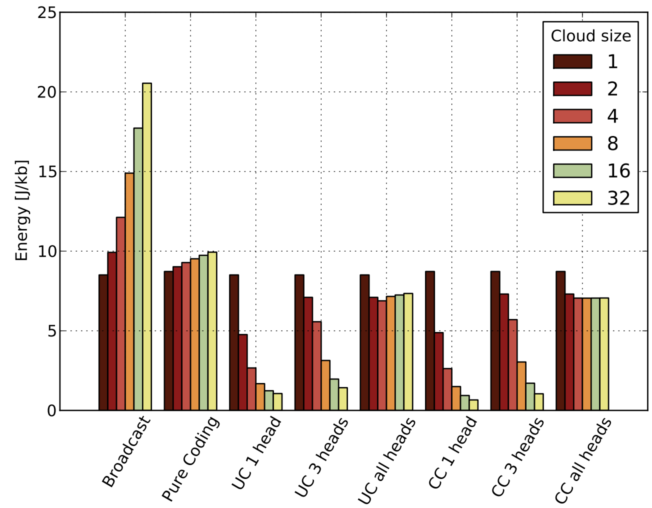


Fig. 3: Node energy usage for a single cloud.

The energy consumption per node in Fig. 3, is calculated from the values in Fig. 2 and the energy consumption per bit [13]. For pure coding the energy consumption is approximately constant for any number of nodes. When cooperation is used the energy consumption is decreased significantly if not all nodes in the cloud are heads. If coding is also utilized the energy consumption is further reduced for the cases where the number of nodes are above two. The highest reduction in energy consumption over broadcasting is 90% and obtained when; user cooperation is combined with network coding, the cloud is big, and only a small number of the nodes are heads.

Depending on the used communication technologies useless retransmission could be ignored by the nodes. This would decrease the amount of received bits and hence reduce the energy consumption, in particular for non-coding approaches where many packets are transmitted that are only useful at some of the receiving nodes.

IV. Multiple Homogeneous Clouds

For this scenario the number of nodes is fixed and the nodes are divided into clouds of the same size, where the cloud size is varied between 1 and 32. This scenario is the simplest in which we can observe the effect of dividing nodes into clouds of different sizes. Note that for a cluster size of 32 there is one cloud.

The amount of packets sent from the BS is significantly lower for the strategies that utilize coding compared to the non-coding strategies, when the clouds have size one and thus no cooperate is possible, see Fig. 4a. As the cloud size increases the amount sent by and received from the BS decreases significantly for the strategies that utilize cooperation. For Cooperation combined with coding both the gain from coding at low cloud sizes, and the gain of cooperation at large cloud sizes is obtained.

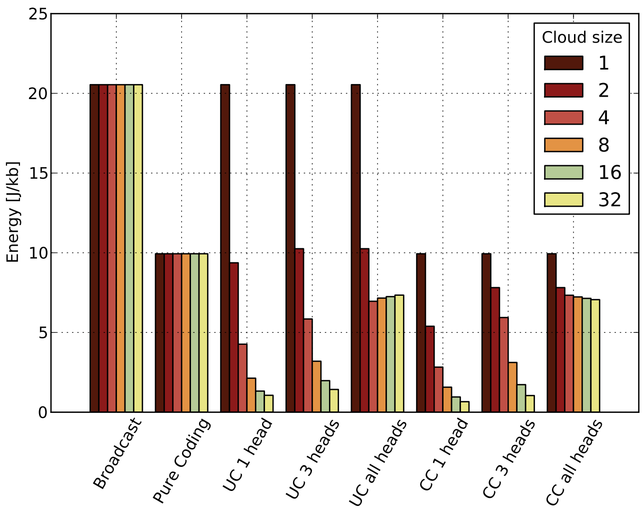
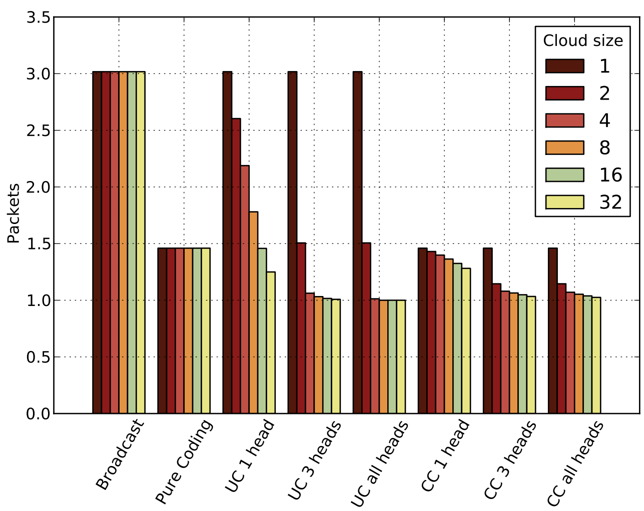


Fig. 5: Node energy usage for multiple homogeneous clouds.

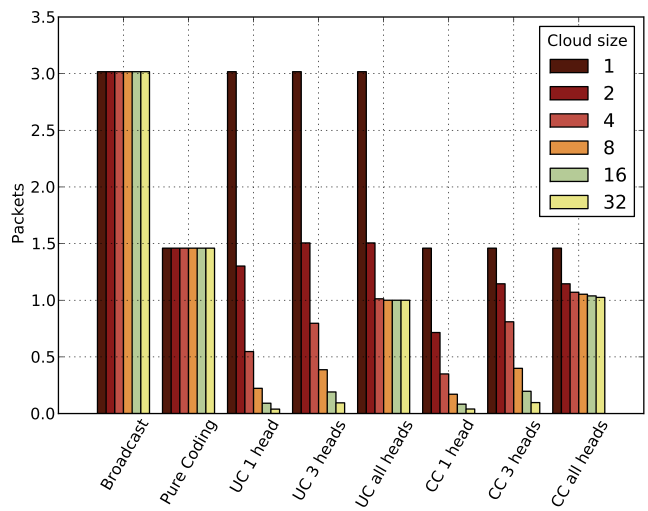
A. Energy Consumption

Fig. 4a shows that the coding strategies result in reduced packets transmitted from the BS when the clouds are small. As the cloud size increase the benefit of the cooperative approaches becomes visible. When coding and user cooperation is combined it reduces the amount of transmitted packets both for small and big clouds. This translates into energy consumption experienced by the network provider as the amount of transmitted bits from the BS is proportional to the energy consumption of the BS.

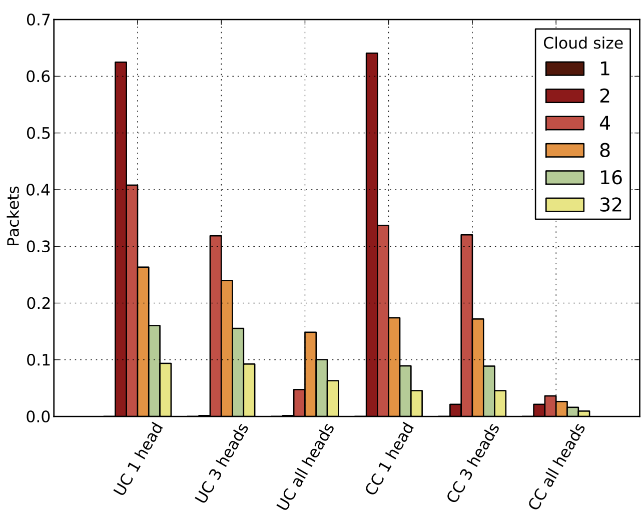
The energy consumption of the nodes in Fig. 5 show a similar trend. However, to conserve most energy at the nodes only a small number of nodes in each cloud should be heads. It should be noticed that the energy consumption for the case of user cooperation and all heads increase when the cluster size is large than four. This is because the nodes receive a constant amount of packets from the cellular network but overhear an increasing number of packets from the local network.



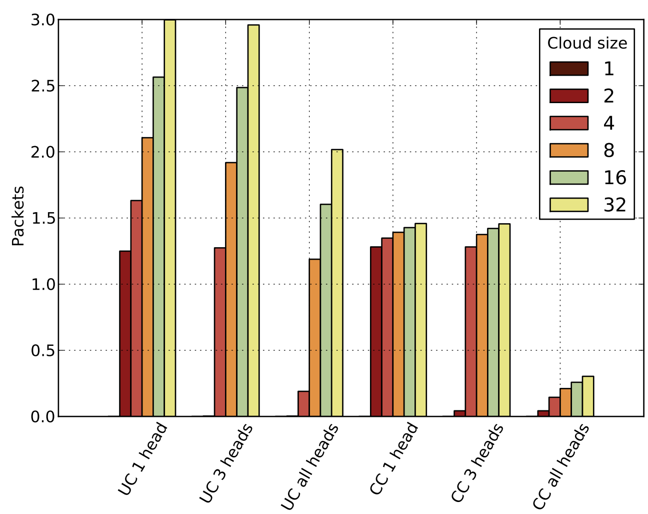
(a) Packets sent by the BS.



(b) Packets received from the cellular link.



(c) Packets sent within the mobile cloud.



(d) Packets received from the mobile cloud.

Fig. 4: Expected transmissions for one node in the scenarion of multiple homogeneous clouds.

V. Multiple Heterogeneous Clouds

In this scenario we consider clouds of different sizes and how this impacts performance. Initially we have a single cloud and then adds clouds of size; 2, 4, 8, 16, and 32 nodes respectively. Thus we first consider one cloud of size $\{1\}$, then two clouds of size $\{1, 2\}$, respectively, then three clouds of size $\{1, 2, 4\}$ respectively, and so forth until the largest cloud has size 32.

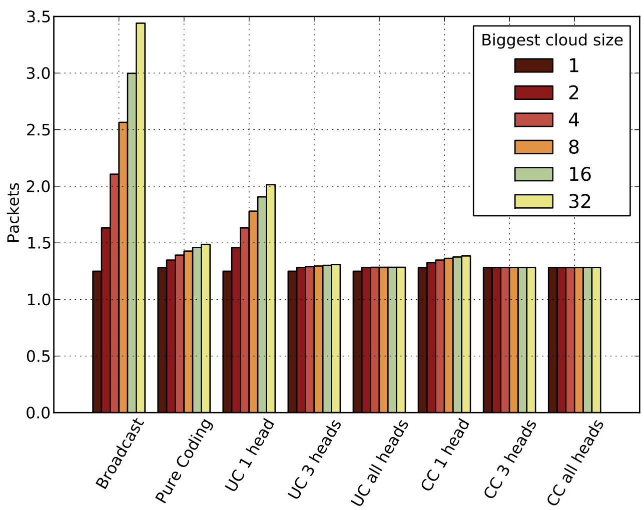
In Fig. 6a the mean number of packets sent from the BS to the mobile devices is shown. In this case the non coding strategies suffer a slight performance degradation as the cluster size is increased. However, if we look at the mean number of packets received by each mobile device, in Fig. 6b, we see that as the cluster size increases the cooperative strategies benefit, as less packets must be received by other devices than the head.

Note that in this scenario the level of cooperation is significantly reduced when all nodes in each cloud are heads. The reason is that the small clouds triggers a high level of retransmissions from the BS. Thus there is no need for the nodes in the bigger clouds to cooperate as they receive most necessary data from the BS directly. When not all nodes in each cloud are heads cooperation operates similar to the previous scenarios.

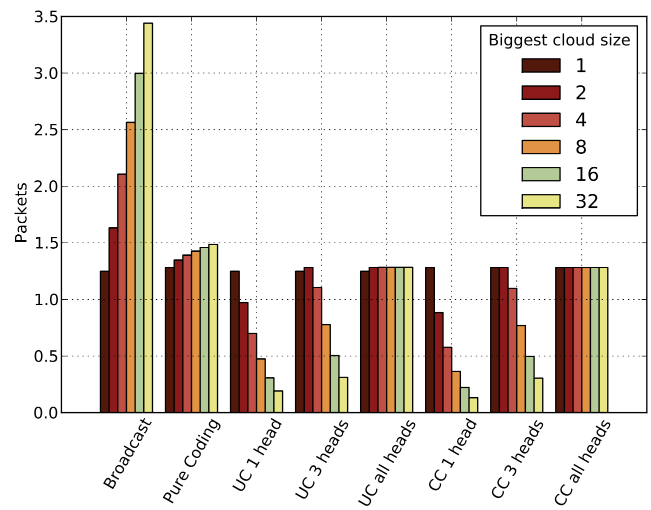
A. Energy Consumption

In Fig. 6a we can observe that the energy reduction at BS is reduced compared to the homogeneous scenario, in particular for multiple heads. This is due to the single non-cooperation node which increases the transmissions from the BS. However, the cooperative and coding approaches still provide significant energy reduction over broadcasting.

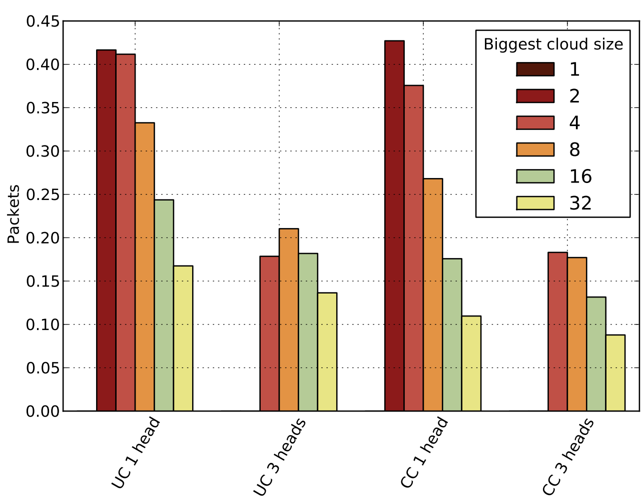
The energy consumption at the nodes are still significantly reduced in particular for the cases where not all nodes are heads. The effect of single non-cooperating nodes does not significantly impact the energy consumed in the large cooperating cluster. Even though the nodes in these clusters receives



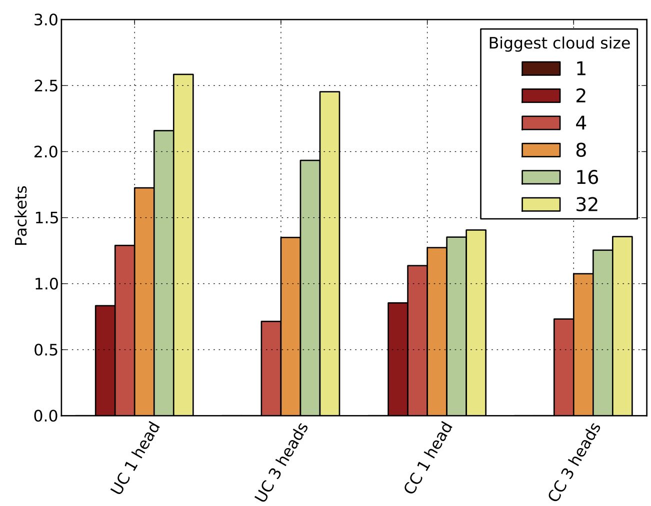
(a) Packets sent by the BS.



(b) Packets received via the cellular link.



(c) Packets sent to the mobile cloud.



(d) Packets received from the mobile cloud.

Fig. 6: Expected transmissions for one node in the scenarion of multiple heterogeneous clouds.

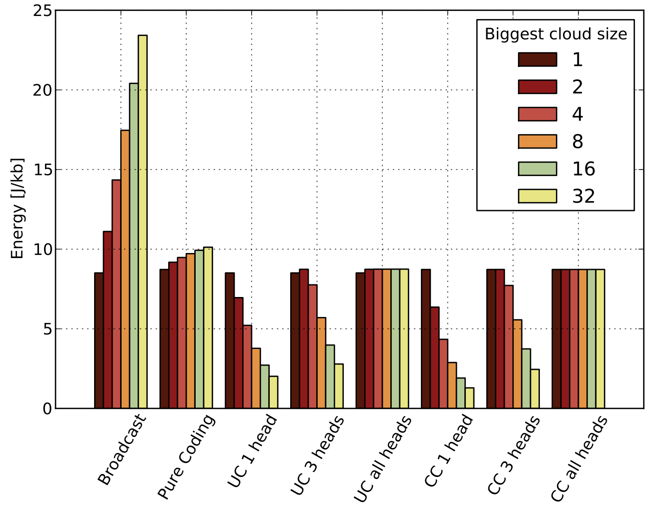


Fig. 7: Node energy usage for multiple heterogeneous clouds.

slightly more via the cellular link, this is not significant when it is distributed between all nodes in the cloud. Thus the only nodes that does not experience a reduced energy consumption are those that choose not to cooperate. This is an important observation as this provide each individual node with a strong motivation for entering the cooperation of a cloud.

VI. Conclusion

In this paper we have investigated the benefits of using green mobile clouds to allow energy savings on both the network and user side. The presented results shows the benefit of coding and cooperation over broadcasting solutions on the network and user side. The gain of user cooperation depended highly on the scenario and provides the largest gains when the clouds where large. Coding is less sensitive towards the scenario and provided gains even when the cloud sizes was small. By combining the two approaches, both their respective benefits can be obtained which broadens the range of scenarios where the spectral and energy efficiency is improved.

The highest reduction in energy consumption at the BS compared to broadcasting was 66% and observed when network coding was combined with cooperation and all nodes was heads. Similar performance was observed for all cooperation strategies with more than one head in each cloud. The highest reduction in energy consumption for the nodes compared to broadcasting was 90% and observed when network coding was combined with cooperation and one node was head. Similar performance was observed for all cooperation strategies where more only a few nodes was heads. Thus the number of heads present a parameter that can be tweaked to distribute the energy consumption between the BS and the nodes. Additionally many heads conserve the most cellular bandwidth. We note that introducing a single non-head node into a cluster increases the local transmissions significantly. This presents an extreme case of the "crying baby" problem [17], and should be avoided. Noticeably cooperation was shown to be highly beneficial even if a subset of nodes declined to cooperate.

As a final remark applying coding significantly reduces the implications of assuming an orthogonal feedback channel. For coding based schemes the amount of necessary feedback is reduced to a single bit, which is the indication that decoding has been successfully completed. This benefit is particularly important in partially connected networks where the network topology can be significantly more complex.

Acknowledgment

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