Matroid Theory based Broadcast Retransmission in Distributed Storage Network

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***Abstract*—In conventional distributed storage networks, backbone firstly sends the packets that needed by the users randomly to existed servers. Then backbone broadcasts the packets uncoded to the users. This phase is defined as systematic transmission phase. Due to channel distortion and noise, different users may lost different packets. Thus, each user needs to feedback its packet loss state and could constitute a state feedback matrix (SFM) in the side of the backbone. After this, instead of retransmission by the backbone, the binary network coded or original packets are sent from servers to the users, and each user can only receive a packet from one server within a time slot. In this paper, we consider backbone network only sends the packets to the servers after receiving the SFM from all users, and we assume that the time needed for the transmissions from backbone to the servers can be ignored. According to the matroid theory, we propose an algorithm that decide the set of packets that needed to send to the different servers in order to decrease the server resource consumption and utilize the servers to further decrease the number of retransmissions.**

***Index Terms*—Distributed storage networks, matroid theory, resource consumption, number of retransmissions.**

I. Introduction

Because of its high spectral efficiency, wireless broadcast is widely used in our daily life, e.g. safety warning messages, weather information and emergency information. However, when the base station broadcasts data packets to multiple users, different users will have different packet loss patterns due to the different channel erasure rates between the base station and all the users. Thus the base station needs to retransmit the lost packets of each user. In fact, in [1]-[6], it had been shown that finding the optimal solution of the network coding problem base on the state feedback matrix (SFM) is NP-hard. [7] proposed a Deterministic Linear Network Coded (DLNC) [8]-[10] retransmission scheme to minimize the number of coded retransmissions based on the matroid theory [11], [12]. It is known that the lower bound of the number of retransmissions equals to the Wmax (Wmax is defined as the maximum number of lost packets to all the users). And according to the simulations in [7], the minimum number of coded retransmissions obtained is almost no more than Wmax+1 for a small number of users. However, the performance of this scheme is deteriorated in the case of a large number of users due to the fact that the SFM becomes more complex.

In recent years, distributed storage networks (DSNs) [13], [14] become more and more popular. With the massive requirements for content from base station, it is becoming more and more limited for the base station to meet the needs of a large number of users at the same time. Thus, it is necessary to place more than one server to reduce the pressure of the base station. Especially in 5G cellular networks, if we let users to request video or some business that have high demand for traffic from the servers instead of the base station, the base station could have more spectrum resources for other purpose. And it is worth noting that the server is generally cheaper. In the retransmission phase, servers only send an uncoded packet in a time slot traditionally. This scheme is not efficient because it does not consider the side information (one user may know the information for the other user) [15] that the users already had.

In fact, servers could send binary Exclusive OR (XOR) packet which can be efficient for the purpose of improving throughput. It operates in the encoding and decoding processes simply which is known as Instantly Decodable Network Coding (IDNC) [16], [17]. Consider a situation there exists some servers and each server has some resources needed by the users. The resources are sent randomly in advance by the base station. In the retransmission phase, if each server only operates its IDNC strategy according to the resources it has, then the users may receive information from multiple servers which will cause conflict and waste resources. [18] proposed a scheme in which each server could also implement IDNC. And this scheme can avoid the conflict, since it considers the whole system according to the SFM instead of a single server. That is to say, each user can only receive information from one server in one time slot. However, due to the fact that the resources in each server are random, the practice of IDNC strategy is limited to a certain extent. And the servers also buffer some resources that are unnecessary for users. Thus it causes wastage in terms of server size. What is more, although each user can only receive resources from one server in a time slot, but each user may also switch its frequency to another server for the purpose of obtaining its desired resources in next slot. It also cause more complexity and power consumption for users.

In this paper, we apply the matroid theory to address the broadcast retransmission problem in distributed storage networks. And the retransmission phase is still implemented by the servers existed in the networks. According to the matroid theory, we propose an algorithm in order to further decrease the number of coded retransmissions. At the same

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time, we avoid the unnecessary frequency switch for all users and the needless resources wastage for all servers. We find that, compared to backbone network, when it comes to broadcasting retransmission problem, it indeed reduces the number of retransmissions with the help of servers. With the increasing of the number of servers, the number of coded retransmissions is more and more approaching the Wmax.

The reminder of this paper is organized as follows. Section II illustrates the system model. Section III illustrates the problem about retransmissions via the base station. Section IV illustrates the problem about retransmissions via the servers. The simulation results are presented in Section V. Section VI concludes the paper.

II. System Model

In this paper, a network with one base station, M servers, K packets and N users is used. Server i denoted by b_i and the set of all servers is $\mathbf{b} = \{b_1, b_2, ...b_M\}$. Packet k is denoted by f_k and the set of all packets is $\mathbf{f} = \{f_1, f_2, ...f_K\}$. User n is denoted by u_n and the set of all users is $\mathbf{u} = \{u_1, u_2, ...u_N\}$. Time is slotted, and one packet is sent in each slot. Channel erasure rate between the sender and each user is assumed to be independent and memoryless.

In systematic transmission phase, the base station broadcasts K uncoded packets to all users using K time slots. After that, all users provide feedback to the base station about the packets they have lost or received. The complete states of users and packets, referred to as a reception instance, can be captured by an $N \times K$ state feedback matrix $\mathbf{S}$ (SFM), where $s_{n,k} = 0$ if u_n has received f_k and $s_{n,k} = 1$ otherwise. The set of Has_i consists of the packets that user i has received successfully and the set of $Wants_i$ consists of the packets that user i failed to receive and still wants.

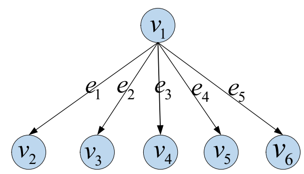
After systematic transmission phase, the base station sent data packets to the servers according to the SFM, we assume that the time used for it can be ignored. Instead of retransmit by the base station, retransmission phase is implemented by the servers. In this phase, each server has its working frequency that different from others. Consider the cost of switching frequency of all users, we limit that each user can only receive the information from one server assigned to it during the whole retransmission phase. And the base station should arrange the different set of packets to different servers in order to reduce redundancy of all servers. That is, each server only receives the packets it needs for its users from the base station.

III. Retransmission via The Base Station

Now we first assume that retransmission phase is implemented by the base station. Consider there is a $N \times K$ SFM collected by the base station after the systematic transmission phase. Then we start the iterative process according to matroid theory. There are total K iterations. Firstly, there are 2 vertexes v_1, v_2 and no edge in the matroid graph. We define the number of vertexes after k-th iteration as N_k. In the $k+1$-th iteration, we first remove the forbidden locations of e_k (e_k represents f_k) which are independent to e_k from the collection of all the

	f_1	f_2	f_3	f_4	f_5
u_1	1	1	1	1	0
u_2	0	1	1	1	1
u_3	1	0	1	0	1
u_4	1	1	0	1	1
u_5	1	1	1	0	1

(a) $\mathbf{S}$



	e_1	e_2	e_3	e_4	e_5
~~c_1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~
c_2	q-1	0	0	0	0
c_3	0	q-1	0	0	0
c_4	0	0	q-1	0	0
c_5	0	0	0	q-1	0
c_6	0	0	0	0	q-1

(b) graphic matroid & matrix matroid $\mathbf{W}$

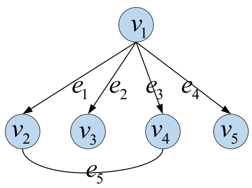
Fig. 1. DLNC solution of a reception instance via graphic matriod (via the base station).

$N_k(N_k-1)/2$ possible edge locations and denote the set of allowable locations by O. If O is empty, then we add a new vertex to the matroid graph and allocate e_k to $v_{(1,N_{k+1})}$. If O is not empty, then we allocate e_k to the smallest location in O. Update N_k to N_{k+1}. From the matroid graph, we can see that there are total N_K vertexes, which means that minimum number of coded retransmissions equals to $N_K - 1$ (the number of vertices to be subtracted from 1 is the minimum number of coded retransmissions). And we can get the matrix matroid according to the matroid graph [4]. First, we generate an all-zero $V \times E$ matrix $\mathbf{W}$, where V equals to the number of vertexes and E equals to the number of edges in the matroid graph. After this, for each column e_k, let $w_{i,k} = 1$ and $w_{j,k} = q - 1$ (q is the coefficient of deterministic network coding) if v_i and v_j are incident to e_k in the graph and $i < j$. Remove the first row of $\mathbf{W}$, the resulting $\mathbf{W}$ is the final solution from which we can obtain all coded packets.

Example 1. In our setting, as depicted in Fig. 1(a), there exists a 5×5 SFM in the base station after the systematic transmission phase. Now let us see how matroid theory could apply to the DLNC scheme for retransmission. First, we define 2 vertexes v_1, v_2 in the graphic matroid. And there are no edges initially. According to the SFM, in the 1st iteration, e_1 is allocated to location $v_{(1,2)}$. In the 2nd iteration, since f_2 is independent to f_1, the only edge location $v_{(1,2)}$ is forbidden to e_2. Thus we insert a new vertex v_3 and allocate e_2 to $v_{(1,3)}$. In the 3rd iteration, since f_3 is independent to $f_1, f_2, \{f_1\ , f_2\}$, then we insert a new vertex v_4 and allocate e_3 to $v_{(1,4)}$. In the 4th iteration, since f_4 is independent to $f_1, f_2, f_3, \{f_1\ , f_2\}, \{f_1\ , f_3\}, \{f_2\ , f_3\}$, thus we insert a new vertex v_5 and allocate e_4 to $v_{(1,5)}$. In the 5th iteration, since f_5 is independent to f_1, f_2, f_3, f_4, $\{f_1\ , f_2\}, \{f_1\ , f_3\}, \{f_1\ , f_4\}, \{f_2\ , f_3\}, \{f_2\ , f_4\}, \{f_3\ , f_4\}$. Thus we insert a new vertex v_6 and allocate e_4 to $v_{(1,6)}$. At this point, the iteration is completed, we can get the final matroid graph, as depicted in Fig. 1(b). We can determine

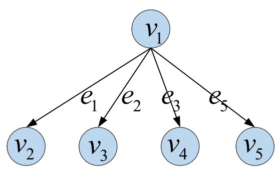
	f_1	f_2	f_3	f_4	f_5
h_1	1	1	1	1	0
h_2	0	1	1	1	1
h_3	1	1	1	0	1
h_4	1	1	0	1	1
h_5	1	0	1	0	1

(a) $\mathbf{S}*$



	e_1	e_2	e_3	e_4	e_5
c_1	1	1	1	1	0
c_2	q-1	0	0	0	1
c_3	0	q-1	0	0	0
c_4	0	0	q-1	0	q-1
c_5	0	0	0	q-1	0

(b) via server 1



	e_1	e_2	e_3	e_5
c_1	1	1	1	1
c_2	q-1	0	0	0
c_3	0	q-1	0	0
c_4	0	0	q-1	0
c_5	0	0	0	q-1

(c) via server 2

Fig. 2. DLNC solution of a reception instance via graphic matriod (via two servers).

the final matriod matrix, define it as FRM, depicted in Fig. 1(b). In Fig. 1(b), the coefficients of the packets (coded or uncoded) in the retransmission phase are c_2, c_3, c_4, c_5, c_6. And the number of the packets equals to Wmax+1 (Wmax equals to 4 according to the SFM).

[7] obtained the conclusion that the designed FRM is efficient in the problem of minimizing the number of coded retransmissions with the help of the matriod theory in the situation that there are small scale users. In fact, when the number of users becomes larger, we could divide them into t parts with the assistance of t servers. In IV, we will introduce the method to divide all users in the scenery that the retransmission phase is executed by the servers.

IV. Retransmission via The Servers

Now we assume that retransmission phase is implemented by the servers. There exists K packets, N users and M servers previously defined and M is often smaller than N. Thus we design the algorithm 1 according to the following rules:

$$\min(\max(num_1, num_2, ..., num_M)) \quad (1)$$

$$\min(num_1 + num_2 + ... + num_M) \quad (2)$$

where num_i referred to the final minimal number of coded retransmissions of server i according to its matroid graph. Rule (1) has higher priority because our purpose is to reduce the number of coded retransmissions. Once rule (1) is met, we will aim at reducing the total transmission power for the purpose of saving energy (transmission power is proportional to the $num_1 + num_2 + ... + num_M$).

Thus, now we discuss about how to design an efficient algorithm. Initially, after obtaining the SFM $\mathbf{S}$, we first rearrange the rows of the SFM. The row that has the maximum number of 1 in $\mathbf{S}$ is rearranged as the first row, and one by one from large to small order. If the number of 1 in some rows is equal, then the order between them is not required. We define the renew matrix as $\mathbf{S}*$. And h_m defines as the m-th user after the rearrangement. If user h_m receives the information from server i in the whole retransmission phase, we consider user h_m is arranged to server i. Before arranging user h_{m+1}, we define the set of the servers that users were arranged as H_m, and the number of servers in H_m as $size(H_m)$. We also define the minimum number of coded retransmissions needed by server i after user h_m were arranged as the num_{im}.

Algorithm 1 The Proposed Arrangement Strategy

Input: Update matrix $\mathbf{S}$ to $\mathbf{S}*$, arrange h_1 to b_1.
for $m = 2$ To N **do**
  while $\exists num_{im-1}$ (i belongs to H_{m-1}) $= num_{im}$ **do**
    arrange h_m to $b_{min(i)}$
  end while
  while $\forall num_{im-1}$ (i belongs to H_{m-1}) $\neq num_{im}$ **do**
    if $\forall num_{im-1}$ = constant **then**
      arrange h_m to $b_{size(H_{m-1})+1}$ ($size(H_{m-1}) < M$) or b_1 ($size(H_{m-1}) = M$)
    else
      arrange h_m to b_i ($num_{im-1} < num_{i-1m-1}$)
    end if
  end while
  renew H_{m-1} to H_m
end for

In fact, the core of the algorithm is how to optimize the arrangement for all users to meet the rules (1) and (2). The algorithm is carried out by N iterations. First we arrange h_1 to server 1. In the m-th iteration,

Case(I): If the minimum number of coded retransmissions equals to a constant for all servers in H_{m-1}, then we divide it into four subcases:
(a)$size(H_{m-1}) < M$, $\exists num_{im-1} = num_{im}$
(b)$size(H_{m-1}) < M$, $\forall num_{im-1} \neq num_{im}$
(c)$size(H_{m-1}) = M$, $\exists num_{im-1} = num_{im}$
(d)$size(H_{m-1}) = M$, $\forall num_{im-1} \neq num_{im}$ and arrange h_m to $b_{\min(i)}$, $b_{size(H_{m-1})+1}$, $b_{\min(i)}$, b_1, respectively.

Case(II): If the minimum number of coded retransmissions is not equal to a constant for all servers in H_{m-1}, then we divide it into three subcases:
(a)$\exists \max(num_{im-1}) = num_{im}$
$(b)\exists \min(num_{jm-1}) = num_{jm}$, $\forall \max(num_{im-1}) \neq num_{im}$
$(c)\forall \min(num_{im-1}) \neq num_{im}$, $\forall \max(num_{im-1}) \neq num_{im}$
and arrange h_m to $b_{\min(i)}$, $b_{\min(j)}$, b_i ($num_{im-1} < num_{i-1m-1}$), respectively.

It is worth noting that, as we can see in Case(I) (a), in the m-th iteration ($2 \leq m \leq N$), there exist servers which are in

$H_{\mathrm{m}-1}$ and have same number of coded retransmissions and other servers which are not in $H_{\mathrm{m}-1}$. If h_m is arranged to the server in $H_{\mathrm{m}-1}$ and it do not change the number of coded retransmissions, then the servers which are not in $H_{\mathrm{m}-1}$ are prohibited for h_m in order to decrease the transmission power. Although the number of coded retransmissions is not change when h_m is arranged to the server unused. As we can see in Case(I) (d), due to the fact that M is often smaller than N, there may exist that M servers are all in $H_{\mathrm{m}-1}$ and the number of coded retransmissions of them are same in m-th iteration ($2 \leq m < N$), thus the number of coded retransmissions may increase in $m+1$-th. However, compared to the approach that retransmission is carried by the base station, the number of coded retransmissions by the servers is always smaller. In Case(II) (a), we arrange h_m to the server which has larger number of coded retransmissions in $H_{\mathrm{m}-1}$ instead of the server with smaller number of coded retransmissions for the purpose of making full use of each server. The arrangement for Case(I) (b), (c) and Case(II) (b), (c) are easy to understand, we omit here.

Example 2. Consider the situation that there exist a base station, two servers and five users. Now we determine the users that receive packets from the server 1 and other users that receive packets from the server 2. We first arrange h_1 to server 1, that is h_1 can only receive packets from server 1 in the whole retransmission phase, thus we can see that server 1 has to provide at least 4 time slots (minimum number of coded retransmissions) in order to make h_1 successfully get all the packets it needed. Next we arrange h_2 to server 1 and see whether the obtained minimum number of coded retransmissions still equal to 4 or more than 4 according to the matroid graph which can be obtained through a 2×5 matrix that constituted by the first two rows in $\mathbf{S}*$. From the matroid graph, we can see that the total vertexes still equal to 5, that is to say, minimum number of coded retransmissions still equal to 4, then arrange h_2 to server 1. For h_3, now pay attention to the 3×5 matrix that constituted by the first three rows in $\mathbf{S}*$. From its matroid graph, e_1, e_2, e_3, e_4, e_5 are all independent to each other, that is to say, there are 6 vertexes in the graph. Thus minimum number of coded retransmissions equals to 5, then we arrange h_3 to server 2.

We arrange h_m in turn. After m-1-th iteration, if both server 1 and server 2 have the same number of coded retransmissions, then we arrange h_m according to following principle: in the case that arranging h_m to server 1 or server 2 will always increase their minimum number of coded retransmissions according to their matroid graph, then we arrange h_m to the server 1; if server 1 or server 2 will keep the invariant number of coded retransmissions after arranging h_m, then we arrange h_m to the corresponding server. If server 1 and server 2 has different number of coded retransmission after m-1-th iteration, then we arrange h_m according to the following principle: in the case that arranging h_m to the server that has larger number of coded retransmissions will increase its number of coded retransmissions, then we arrange h_m to another server; if the server which has larger number of retransmissions in m-1-th iteration will keep the invariant number of coded retransmissions after it accepted h_m, then

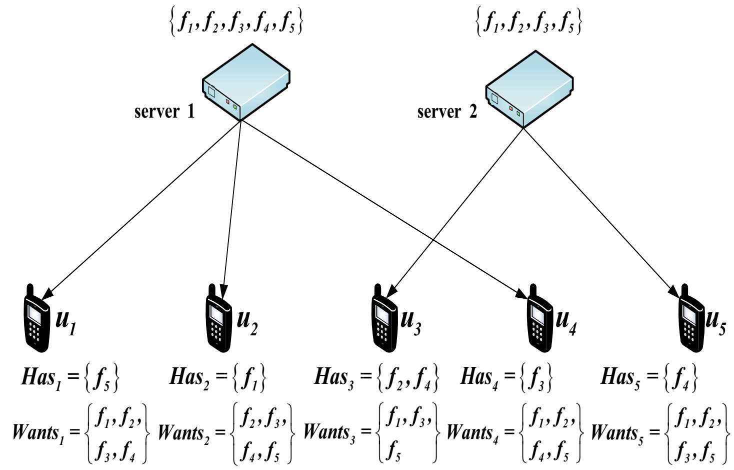


Fig. 3. Two servers model.

we arrange h_m to it.

We conduct this process until the last user is arranged. According to this principle, we should arrange h_1, h_2, h_4 to server 1, and arrange h_3, h_5 to server 2, where h_1, h_2, h_3, h_4, h_5 represents u_1, u_2, u_5, u_4, u_3, respectively. Fig. 2(b), (c) denote the matriod graph and FRM about server 1 and server 2, respectively. From two FRM, we can see that the number of retransmissions equals to Wmax (Wmax equals to 4). Fig. 3 depict the final implementation process, that is to say: after the systematic transmission phase, five users having the following contents and requests:

$Has_1 = \{f_4\}, \mathrm{Wants}_1 = \{f_1, f_2, f_3, f_5\}.$
$Has_2 = \{f_1\}, \mathrm{Wants}_2 = \{f_2, f_3, f_4, f_5\}.$
$Has_3 = \{f_2, f_4\}, \mathrm{Wants}_3 = \{f_1, f_3, f_5\}.$
$Has_4 = \{f_3\}, \mathrm{Wants}_4 = \{f_1, f_2, f_4, f_5\}.$
$Has_5 = \{f_4\}, \mathrm{Wants}_5 = \{f_1, f_2, f_3, f_5\}.$

Through the SFM we can see that the packets that the base station needed to send to server 1 and server 2 are $\{f_1\ , f_2, f_3, f_4,\ f_5\}$, and $\{f_1\ , f_2, f_3,\ f_5\}$ respectively according to the arrangement mentioned above. And server 1 serves u_1, u_2, u_4, server 2 serves u_3, u_5. Through the arrangement, each user only receives information from one determined server in the whole retransmission phase, which can avoid frequency switching that could cause power consumption and complexity to some extent.

V. Simulation Results

In this section, we use numerical simulations to verify our claim. K data packets are broadcast to N users via the base station and M servers through wireless channels with i.i.d. packet erasure probability of Pe. The proposed algorithm is applied to divide the SFM according to its rows after the systematic transmission phase. The resulting minimum number of coded transmission is compared with Wmax, i.e., the lower bound.

The results in Fig. 4 under $K = 15$, $N \in [10, 110]$, and Pe = 0.2. Fig. 4 compares minimum number of coded retransmissions (we conduct 100000 simulations) via servers and the base station with Wmax (lower bound), respectively.

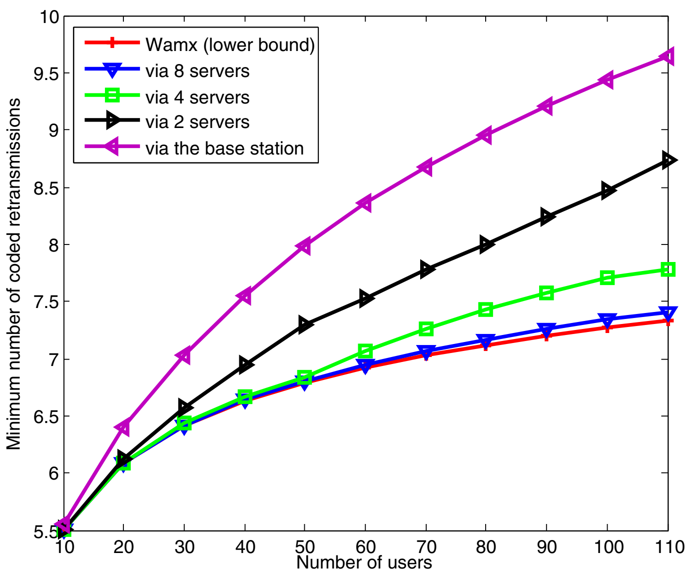


Fig. 4. Compares the two schemes with Wmax versus number of users in term of minimum number of coded retransmissions. $K = 15$, $N \in [10, 110]$, Pe = 0.2.

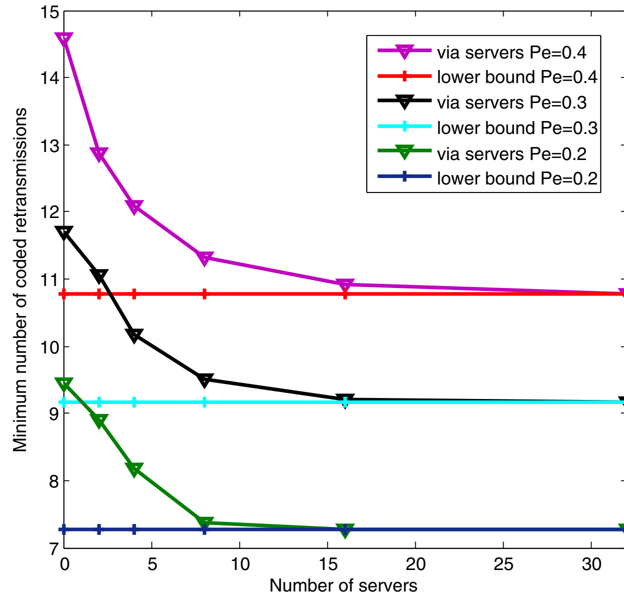


Fig. 5. Comparison of numerical simulation results with Wmax on minimum number of coded retransmissions. $K = 15$, $N = 100$, $M \in [0, 32]$.

When the retransmission phase is implemented via servers or the base station, we can see that the gap between minimum number of coded retransmissions and Wmax gets smaller for the former, and when M increases, the gap between the former and the latter becomes greater, because the feedback matrix could be divided into M parts according to its rows by the aid of M servers and each part is more simple than the complete SFM. With the increasing of the number of servers, minimum number of coded retransmissions is more and more approaching Wamx. In this case, minimum number of coded retransmissions is only a little bit larger than Wmax when number of servers equals to 8.

The results in Fig. 5 under $N = 100$, $M \in [0, 32]$, and $K = 15$. In Fig. 5, it is obviously that minimum number of coded retransmissions is more approaching Wmax when the number of servers becomes larger. When Pe increases, number of servers needs to be expanded for the purpose of approaching Wmax. In this case, number of servers is roughly equal to 8, 16 and 32 when Pe equals 0.2, 0.3, and 0.4, respectively.

The results in Fig. 6 under $N = 100$, $K \in [15, 85]$, and Pe = 0.2. We can see that minimum number of coded retransmissions increase linearly with the number of packets. The increasing of minimum number of coded retransmissions are more and more slow when number of servers increases. In this case, minimum number of coded retransmissions is almost equal to Wmax when number of servers equals to 8.

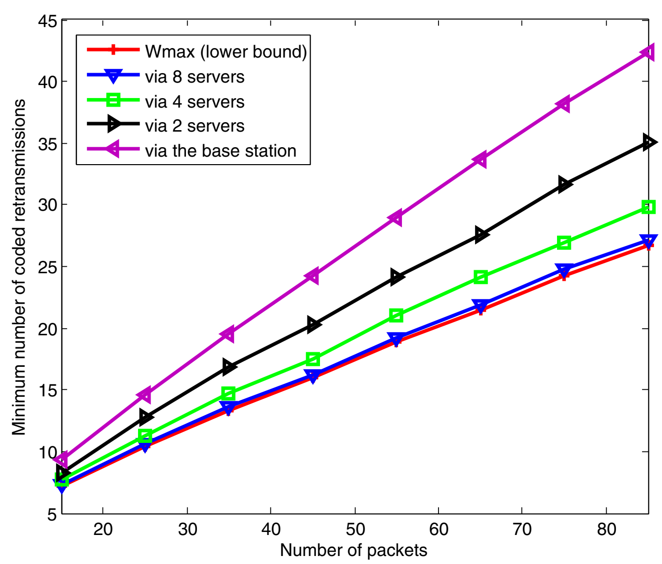


Fig. 6. Compares the two schemes with Wmax versus number of packets in term of minimum number of coded retransmissions. $N = 100$, $K \in [15, 85]$, Pe = 0.2.

VI. Conclusion

In this paper, we employed matroid theory to address the problem of minimizing the number of coded retransmissions in distributed storage networks. Simulation results show that with the help of servers, minimum number of coded retransmissions can be decreased through the proposed scheme. And number of coded retransmissions is more closed to Wamx when number of servers is large. Compare to [7], servers resource utilization is greatly improved. And each receiver in the whole retransmission phase only receives information from one definite server, which also reduces unnecessary frequency switching of each user to a certain extent.

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