How to Shuffle and Scatter Pieces of a Puzzle Over a Metropolitan Area

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Abstract—We propose a new architecture for broadcasting an enormous amount of information over a large population of users in a typical urban area via multiple base stations for delay tolerant applications. The core idea is that each base station partially broadcasts the information instead of transmitting the whole information. In particular, the large target file is broken into $M$ smaller chunks and is provided to $N$ base stations. Each base station $i$ independently generates $M_i < M$ linear combinations of the chunks using random linear network coding (RLNC) techniques and broadcasts it to the users in its coverage area. Users then code and exchange packets in their possession via their short range communication links (e.g. bluetooth). Thanks to the random nature of human mobility patterns, it is expected that after a while, the placement of the users would be mixed enough so that users can obtain sufficient number of chunks to decode the entire file. The proposed architecture provides a fundamentally bandwidth efficient scheme for delay tolerant broadcast applications and has the potential to be implemented in practice. In particular, the proposed approach is completely opportunistic i.e. it does not require any routing algorithm. We evaluate the performance of the proposed architecture via extensive simulations using a well known human mobility patterns simulator.

I. INTRODUCTION

In the last few decades, the dominant trend in digital communication research and practice has focused on devising fast communication systems, where the delay and/or speed of communication has been critical performance measures. This has been mainly in response to an ever-increasing demand for high data rate communication networks by the users of such systems. However, in the last few years the notion of delay tolerant communication networks and their potential applications have also become the subject of intensive research. We can envisage many applications in which neither the sender(s) nor the receivers are sensitive to delay in the exchange of data. As an example, suppose we want to develop a commercial advertisement system over a wireless cellular network, where a group of business holders wish to send a set of multimedia files to a large number of potential clients who are distributed over a large area. Or imagine when a popular blockbuster movie is first released for mass download on a network. In both cases, even a delay of couple of hours is acceptable for the senders as well as most of the receivers.

In this paper we introduce a new architecture to distribute an enormous amount of data of common interest (such as the previous examples) over a large population of mobile users with random mobility patterns within a typical urban area via multiple base stations in a wireless cellular network. To give a high-level image of the proposed architecture, we can define different stages of transmission as follows:

- The large target file is broken into $M$ smaller chunks and is provided to $N$ base stations.
- Each base station $i$ independently generates $M_i < M$ linear combinations of the chunks using random linear network coding (RLNC) techniques [1] and broadcasts them to the users in its coverage area for $i = 1, \ldots, N$.
- Each user generates combination(s) of what it has already received and broadcasts them to its neighbors when it is chosen to transmit using an appropriate local distribution algorithm.

The assumption is that due to the random nature of human mobility patterns, it is very likely that users with different knowledge backgrounds meet each other sometime, somewhere, in such a way that at least one of the users can transmit an innovative packet for the other ones, i.e. a new packet which increases the amount of information held by others. It is expected that after a while the placement of the users would be mixed enough to exchange information with each other. In this paper we use actual human mobility patterns generated by [2] which is a compatible model with the statistical studies over human mobility patterns [3]–[6].

The key advantages of the proposed algorithm from the service provider point of view are as follows:

- The proposed architecture dramatically improves the bandwidth efficiency. This would be at the cost of delay imposed to a user to collect enough chunks of data to be able to retrieve the intended information.
- Furthermore, coding at the base stations provides freedom to the designer to allocate arbitrary rates\(^1\) to different base stations. Base stations may potentially differ by the rates allocated to each one. The rate allocation can be done based on the population and behavior statistics of the users or other system parameters.
- The proposed system is opportunistic in nature and does not need any routing algorithm or complicated network

\(^1\)In this paper, by rate we simply refer to the number of linearly coded chunks $M_i$ sent by base station $i$. 

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topology formation. This will enable a practical and simple implementation.

In general it is challenging to convince people (as users of a network) to cooperate with each other to achieve a common goal. In our case, the benefits of cooperation for users is tied with the financial incentives provided by the applications which use the proposed architecture. In the advertisement example, this can be a bidirectional procedure: The business holders send their interactive advertisements to the users which is run over a standard software platform, and the users can send service requests to the business holders. The system can be connected to a central database managed by the network service provider to ease this process (e.g. the payment processes, etc.), or GPS can provide the location of the user to be served. Moreover, users can download large multimedia files while their mobile devices are idle in their pockets.

To summarize, the key contribution of this paper is to introduce a distributed and scalable bandwidth-efficient solution that capitalizes on the multicast (or broadcast) nature of a cellular wireless network for delay tolerant applications. Each base station can transmit only a small portion of the data instead of the entire information. Then the clients can carry the information in their mobile devices and exchange it with others while they are in contact. Coding at the base stations increases the randomness in the network to ensure that any of the clients regardless of their mobility pattern is likely to meet someone with innovative packets. More importantly, coding at the base station gives the freedom to the designer to allocate arbitrary portion of transmission to each base station. Clearly, the strategy of the rate allocation will affect the overall performance of the system as well as the quality of service observed by the individuals.

II. RELATED WORK

In this section, the contributions of this paper is clarified among the research body available in the literature. In [7] network coding is applied to a torrent-based peer-to-peer network. Network coding is resilient to node churns resulting in a considerable improvement in performance. [8] considers a broadcast scenario among a set of $n$ wireless mobile nodes, where each node is the source of one packet and at each round of transmission each node transmits a random linear combination of the packets it has already received. They show that network coding can result in a gain of order $\mathcal{O}(\log n)$ compared to non-network coded system. This problem can be generalized to the case that each node initially holds a random subset of the entire set of packets where [9]–[12] try to investigate different aspects of this problem and to obtain the optimal solution for static networks with fixed/stationary nodes. [13] considers the case of mobile nodes and propose an energy-efficient scheme for delay tolerant applications.

The aforementioned works are concerned with the gains of network coding and how the nodes should cooperate. The manner information is initially provided to these nodes is the subject of many recent papers regardless of using network coding or not. In particular, [14] discusses the advantages of an approach called data seeding in terms energy consumption and throughput, where each chunk of data is transmitted to specific clients and the recipient nodes would be in charge to transmit those chunks to others. [15] uses a genetic algorithm to find an efficient method for cluster head selections. Recently, this work has been extended to the case of mobile nodes in WANs [16].

It is important to mention the key points that differentiate the current work from the previous ones: Firstly, our proposed method considers delay tolerant applications, so each base station can freely broadcast an arbitrary number of packets and then the clients can carry the information in their devices and exchange where there is an opportunity. Secondly, unlike [14], [15], [17], the base station broadcasts the information to all the clients in its coverage area. This makes the proposed approach scalable in terms of the number of users and results in faster propagation of information. The third point is that we encode the chunks of information at the base stations using RLNC, which provides more randomness in the way the clients hold the contents and increases the chance of meeting people with innovative packets specially in the initial rounds of transmission. Moreover, coding gives the designer the freedom to arbitrarily allocate the number of packets transmitted by each base station. We can claim that the main targets of data seeding approaches and the current work are different. We consider broadcasting popular contents of common interest over a large population of users and over an urban area where data seeding is not easily scalable.

The idea of pocket switching networks (PSN) has been extensively studied in [18], [19], etc, which means that humans can play the role of relays while they are moving by carrying the information in their mobile devices in their pockets and transfer it to another when they are in touch together.

III. System Model

In this section we provide the notations, model and problem definition.

- **Initial setting**: We consider a wireless cellular network consisting a set of $N$ base stations $B = \{b_1, \ldots, b_N\}$, where each base station $b_i$ has a coverage area denoted by $A_i$. We assume $A_i \cap A_j = \emptyset$ for $i \neq j$. We have a set of $k$ clients $C = \{c_1, \ldots, c_k\}$. The system is observed at discrete times $t = 0, 1, \ldots, T$.

- **Transmission processes**: There are two types of transmission processes in our system. The first one is the transmissions by the base stations. We denote the number of packets transmitted by the station $b_i$ at time slot $t$ by $\Omega_i(t)$. The second type of transmissions is the transmissions by the clients to exchange packets. The number of packets transmitted by client $c_j$ in time slot $t$ is denoted by $\Gamma_j(t)$. We denote the set of clients under the coverage of base station $b_i$ at time slot $t$ with $\mathcal{N}(i)^t$. Also we assume two clients $c_u$ and $c_v$ are neighbors if their Euclidean distance $d(c_u, c_v) < r$. The set of neighbors of the client $c_j$ at time slot $t$ is denoted by $\mathcal{N}(j)^t$. We assume that both the downlink channel between each base
station and the clients in its coverage area and the short range transmission channel between clients are erasure channels. That is, client \( c_j \in C_i^n \) will receive a packet transmitted by the base station \( b_j \) at time slot \( t \) with a probability \( p_b \) and client \( c_u \in N_u^{(t)} \) will receive a packet transmitted by client \( c_v \) with a probability \( p_c \).

- **Data structure:** Our final goal is to deliver a large file \( f \) to as many users as we can. The file \( f \) is divided into \( M \) chunks. Each chunk is denoted by \( x_i \) where \( i = 1, \ldots, M \).

Each base station holds the entire set of chunks. The base station generates combinations of the chunks it holds using the well-known random linear network coding techniques [1], i.e. in the form of

\[
P = \sum_{\ell=1}^{M} \alpha_{\ell} x_{\ell}
\]

where \( \alpha_{\ell} \in \mathbb{F}_q \) is the coding coefficient randomly chosen from a finite field with a sufficiently large size \( q \). Each client \( c_i \) keeps the packets received either from a base station or a neighbor in its memory. Let us define matrix \( K_i^{(t)} \) to represent the knowledge space of a client \( c_i \) at round \( t \). The coding coefficients \( \alpha = [\alpha_1, \ldots, \alpha_M] \) of any packet received by the client \( c_i \) are added as the new rows to matrix \( K_i^{(t)} \). In general, the coding coefficients of a coded packet generated by the client \( c_j \) at time slot \( t \) is a linear combination of the rows of \( K_i^{(t)} \) with coefficients chosen at random from \( \mathbb{F}_q \). It is possible to break large files to multiple segments and apply network coding on the chunks within the same segment to reduce the complexity of decoding, but for simplicity we ignore this in this paper.

- **Mobility model:** In this paper, we consider a realistic model of human mobility patterns using the SLAW model [6]. Many research works have been carried out to analyze and understand different aspects of human mobility and its statistical behavior. For instance, different studies show that the lengths of human flights [3], [4], the pause time distributions of human walks and the inter-contact time between two specific people follow truncated power-law distributions. In [3], Gonzalez et al. calculate the probability that a person return to the same location where they have shown any individual is more likely to be found in her favorite place. Also [6] infers from the GPS traces of human walks that the way-points of humans can be modeled by fractal points which shows that people are usually attracted to hot spots. Surprisingly, the model introduced in [6] is able to capture all the mentioned characteristics together and more importantly generate synthetic human walk traces. We have used this model to generate the human mobility traces using the simulator developed by the authors of [6], which can be found in [2].

- **Objective function:** Many different candidates for the objective function can be envisaged depending on the application. For instance, one reasonable candidate is the time it takes to deliver the entire file to all clients (or a large fraction of the clients) subject to a set of constraints over the total number of transmissions by each base station.

IV. THE PROPOSED ARCHITECTURE

In this section we provide the details of the proposed architecture. To clarify the strategy used in our system, we need to define the two transmission processes mentioned earlier. It should be noted that many possibilities can be proposed for the base stations and clients transmission strategies. Here we introduce a simple strategy, however it should be noted that more complicated strategies can be developed according to statistical behavior of the users and objective functions. By the transmission strategies we mean how \( \Omega_i^{(t)} \) and \( \Gamma_i^{(t)} \) are allocated. In this paper we assume that all the transmissions by the base stations are done at the beginning (\( t = 1 \)), and then the cooperative data exchange phase among the clients starts. Furthermore, we assume all the base stations transmit the same number of packets denoted by \( \tilde{M}_b \). Also at each time slot \( t > 1 \), each client is able to transmit at most one packet to its neighbors. More formally,

\[
\Omega_i^{(t)} = \begin{cases} 
M_b, & \text{if } t = 1, \\
0, & \text{if } t > 1
\end{cases}
\]

As discussed earlier, an important factor in our system is the number of packets transmitted by each base station. For the proposed setting in this paper, where all the clients the same number of packets at the beginning, we can define a new parameter called coding rate denoted by \( \rho \) which shows the ratio of packets initially transmitted by each base station to the total number of packets needed to be delivered to the clients:

\[
\rho = \frac{M_b}{\tilde{M}}
\]

Clearly \( \tilde{M}_b N \geq M \), otherwise some part of the information would be missed by all the clients. and for the clients \( c_i \), \( i = 1, \ldots, k \),

\[
\Gamma_i^{(t)} = \begin{cases} 
0, & \text{if } t = 1, \\
\gamma \in \{0, 1\}, & \text{if } t > 1
\end{cases}
\]

Algorithm 1 shows the procedure applied to the clients after the base stations transmitted the packets at \( t = 1 \). More precisely, it defines \( \Gamma_i^{(t)} \) to choose the transmitting nodes at each time slot. We have used a voting mechanism to choose a set of qualified clients at each time slot which is based on the connectivity degree of the nodes to increase the energy efficiency and throughput: At each round of transmission, each client broadcasts a message including \( u_t \) which is the number of times it has been transmitting so far. By receiving this message each client infers how many neighbors it has. Each client broadcasts the number of detected neighbors in another message. Now each client decides to vote for one of the clients which has the maximum number of neighbors and if there are multiple nodes with the same number of neighbors...
it votes for the one with minimum $u_j$ (including herself). The benefit of announcing $u_j$ is to maintain a balance among the number of transmissions among the clients to be as fair as possible. Finally if a node receives votes from more than half of its neighbors it starts transmitting a coded packet. Since our approach is delay tolerant and opportunistic we do not consider retransmission processes and allow collisions (As some of the neighbors who have not voted for a specific client may suffer from collisions). However, designing the optimal MAC layer for such kind of architectures can be a challenging problem and is beyond the scope of this paper.

Algorithm 1 The Proposed Architecture

$t \leftarrow 1$
$\forall c_j \in C : u_j \leftarrow 0$

while $\exists c_j \in C : \text{Rank}(K^{(t)}_j) < M$ or $t < T$ do
$\forall c_i \in C : c_i$ broadcasts $u_i$
if $c_i$ receives $u_j$:
$N^{(t)}_i \leftarrow N^{(t)}_i \cup c_j$
end if
$\forall c_i \in C : c_i$ broadcasts $\mu_i = |N^{(t)}_i|$
$M^{(t)}_j = \{\mu_i : c_i \in (N^{(t)}_i \cup \{c_j\}) , \mu_i = \max_{\mu_i} \}$
$\forall c_j \in C : v_j \leftarrow 0$
if $c_j \in M^{(t)}_i : u_j = \min_{\mu_i} \{u_i : c_i \in M^{(t)}_i\}$
ci votes for $c_j$, $v_j \leftarrow v_j + 1$
end if
if $v_j > \frac{M}{2}$
cj transmits a packet with coefficients $\alpha_j$, $u_j \leftarrow u_j + 1$
if $c_i \in N^{(t)}_j$ receives the packet $K^{(t)}_j \leftarrow [K^{(t)}_j : \alpha_j]$
end if
end if
$t \leftarrow t + 1$

V. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed architecture. It is crucial to have a realistic model of human mobility patterns to give a realistic estimation of how, when and for how long the people meet each others in an urban area. This motivated us to use an advanced model for mobility patterns. To generate the human walk traces we have used the simulator available at [2] as discussed earlier which works based on the SLAW model. This model initially requires a set of parameters which varies from one city to another depending on the social behaviors, population, urban structure, etc. However, a typical range of acceptable parameters is known for typical urban areas. Clearly the performance of our proposed system depends on this parameter settings. We have chosen our parameters within the reasonable range of parameters (We have used the default settings of the simulator for most of the parameters except those ones mentioned here).

We ran the experiments for a set of $k = 5000$ mobile clients over an urban area of $5km \times 5km$ and 4000 way-points (visiting points) has been defined. We divided the area to 20 sectors (In practice, each sector can be a geographical unit since a base station would be able to transmit distinguished sets of packets to different sectors). We have defined the sector areas based on the distribution of the way-points. We identified the areas that the way-points are concentrated using a clustering algorithm (Simply starting from a subset of random nodes and adding the proximity nodes step by step to the cluster). A central point is assigned to each cluster, and finally the borders of the sectors are obtained by the corresponding Voronoi diagram. We have observed the system for 10 hours and each time slot is 5 minutes. We assume that $r = 20m$, $p_b = 0.85$ and $p_c = 0.9$.

Fig. 1 shows the evolution of the average rank of the clients for different values of $\rho$. Clearly, when $\rho$ is larger, it means that each client has initially received more packets and will obtain the entire set faster. Fig. 2 gives the cumulative number of clients has achieved full rank by the time $t$ for different values of $\rho$. Similar discussion is applied to this figure. Since we assumed at each round of transmission each client will receive at most one packet, there would be an inevitable time period that none of the clients can achieve full rank.

Another interesting metric to understand the behavior of this system is the the time elapsed between two successful receptions. By a successful reception, we mean receiving a packet which increase the rank of a client by one. This parameter can roughly give an estimation of how likely is to meet a new person with useful information. The distribution of the elapsed time is given in Fig. 3 for $\rho = 0.2$.

VI. CONCLUSION AND FUTURE TRENDS

In this paper, we introduced a new cooperative architecture for broadcasting hot information where a large number of network clients are interested in. The main idea is to break the information to smaller parts and broadcast it via multiple base stations using RLNC. This will result in a dramatic bandwidth efficiency in comparison to other possible alternatives (For
broadcasts a number of descriptions to the users under its coverage.

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