Cost-Effective Broadcast in Cellular Networks

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ABSTRACT

In recent years, video-related services such as YouTube and Netflix have generated huge amounts of traffic and the network neutrality debate has emerged as a major issue. In this paper, we consider feasibility of using a hybrid of unicast and broadcast in cellular networks for high-traffic services (e.g., video streaming), from the perspective of cost effectiveness. To reflect spatial characteristics of base stations (BSs) and mobile users (MUs), we use the stochastic geometry approach where BSs and MUs are modeled as independent homogeneous Poisson point processes (PPPs). With these assumptions and results, we show how to cope with the trade-off between broadcast and unicast for providing the service with affordable cost levels and reduced network load. Moreover, we propose the so called periodic broadcasting service, where popular video contents are periodically broadcast over cellular networks. This service will make a positive impact on the network neutrality debate by stimulating cooperation between mobile network operators (MNOs) and content providers (CPs).

Categories and Subject Descriptors
C.2.1 [Computer-Communication Networks]: Network Architecture and Design—Wireless communication

1. INTRODUCTION

A Cisco report predicts that global mobile data traffic will increase 26-fold between 2010 and 2015 [1]. This traffic explosion drives mobile network operators (MNOs) to invest more in their networks (upgrading infrastructure and purchasing more spectrum). On the other hand, MNOs suffer from the decrease of average revenue per user (ARPU) and severe financial problems. For this reason, MNOs insist that content providers (CPs) should shoulder the extra cost for their huge amounts of traffic, which gives rise to the network neutrality debate.

Video-related services such as YouTube and Netflix generate huge amounts of traffic, which already surpassed non-video traffic in 2010 [1]. Naver, a major Internet portal site in South Korea, provides the live broadcasting service of Korean baseball game. At the beginning, the service was offered through any access network, including both wired and wireless. Recently, however, the service over cellular networks has been terminated due to its huge amounts of traffic and service quality degradation.

The 3rd Generation Partnership Project (3GPP) has introduced the Multimedia Broadcast/Multicast Service (MBMS) [2]. An interesting issue is to find an efficient method for supporting the MBMS. Broadcast (or multicast) in cellular networks can be a cost effective way to deliver information to all interested users, by allowing radio resources to be shared. On the other hand, if the interested users are few, then it will become a wasteful use of radio resources. This trade-off is the motivation and a starting point of our study.

In this paper, we consider a hybrid of unicast and broadcast in cellular networks for high-traffic services (e.g., video streaming), from the perspective of cost effectiveness. The cost effectiveness depends on spatial characteristics of base stations (BSs) and mobile users (MUs). For reflecting this, we use the stochastic geometry approach, where BSs and MUs can be modeled as independent homogeneous Poisson point processes (PPPs) [3]-[6]. This PPP modeling for cellular networks has been strengthened through theoretical and empirical validation in [3].

Using a distribution of the number of MUs per cell [6], we derive some useful metrics for quantifying the wasteful use of radio resources in unicast and broadcast respectively. With these results, we evaluate the economic feasibility of broadcast in cellular networks for video streaming services from cost effectiveness perspective. Besides, we propose periodic broadcasting service in cellular networks to increase efficiency, where popular video contents are periodically broadcast over cellular networks. This service will make a positive impact on the network neutrality debate by stimulating cooperation between MNOs and CPs.

2. SYSTEM MODEL

Consider a cellular network where BSs and MUs are distributed as independent PPPs \( \Phi_b \) and \( \Phi_u \) with density \( \lambda_b \) and \( \lambda_u \), respectively. Each MU is assigned to the nearest BS. Then, the cell area (i.e., coverage) of each BS forms a

\[ \lambda_b \]

Many previous studies on cellular networks assumed that BSs are positioned regularly. However, this regular model tends to overestimate the performance of cellular networks due to the perfect geometry of BSs and the neglect of weak interference from outer tier BSs. For this reason, the PPP modeling for cellular networks has recently been suggested in [3].
The value and the process of MUs subscribing to the content is an independent PPPs with $\lambda_u = 3\lambda_b$. Blue triangles and red dots denote BSs’ and MUs’ locations, respectively. The cell area of each BS forms a Voronoi tessellation and the border lines among Voronoi cells are denoted by blue lines.

Voronoi tessellation [2] as in Figure 1. A video content will be streamed over the cellular network. We assume that the audience rating (i.e., popularity) of the content is $\alpha \in [0, 1]$, and the process of MUs subscribing to the content is an independent thinning of $\Phi_u$ with the thinning probability $\alpha$. The value $\alpha$ is close to 1 when the the content is very popular and a lot of MUs subscribe to it. In the other extreme ($\alpha = 0$), all MUs do not subscribe to the content.

There are two types of video streaming services; buffered video streaming service and live video streaming service. In the buffered video streaming service such as YouTube and Netflix, already-produced video contents are streamed over the cellular network. On the other hand, in the live video streaming service, video contents are live generated and streamed over the cellular network. The live video streaming service is synchronized among its subscribers but the buffered video streaming service is not. In the next section, we focus on the live video streaming service and mathematically analyze the trade-off between unicast and broadcast.

3. TRADE-OFF BETWEEN UNICAST AND BROADCAST IN CELLULAR NETWORKS

Assume that MUs can be offered the live video streaming services through unicast or broadcast in the cellular network. In the unicast mode, MUs are independently served by using each radio resource even though they subscribe to the same video content at the same time. On the other hand, in the broadcast mode, a live video content is shared by using one radio resource, where all interested MUs can subscribe to the content simultaneously. If $k$ MUs subscribe to the content in a cell, then $k - 1$ radio resources will be saved by broadcasting. However, if there is no subscriber (i.e., $k = 0$) in the cell, then one radio resource will go to waste. We denote the average numbers of saved and wasted radio resources per cell by $\bar{N}_s$ and $\bar{N}_w$, respectively.

To derive $\bar{N}_s$ and $\bar{N}_w$, we start with the probability density function (fX(x)) of the size of a typical Voronoi cell [8]:

$$f_X(x) = \frac{3.5^3.5}{\Gamma(3.5)} \lambda_b^{3.5} e^{-3.5\lambda_b x} x^{2.5},$$  (1)

where $X$ denotes the size of a typical Voronoi cell and its average value is $E[X] = 1/\lambda_b$. Using the distribution of the number of MUs per a typical Voronoi cell [6], we get a useful probability mass function in the following:

$$P[K = k] = \frac{3.5^3.5 \Gamma(k + 3.5)(\alpha\lambda_u/\lambda_b)^k}{\Gamma(3.5)k!(\alpha\lambda_u/\lambda_b + 3.5)^{k+3.5}},$$  (2)

where $K$ denotes the number of MUs who subscribe to a live video content with the audience rating $\alpha$ in a typical Voronoi cell. With the law of total probability, we can calculate $E[K]$ as follows:

$$E[K] = E[E[K|X]] = E[\alpha\lambda_u X] = \frac{\alpha\lambda_u}{\lambda_b}$$  (3)

Then, we can derive $\bar{N}_s$ and $\bar{N}_w$ in the following propositions:

**Proposition 1**: If a live video content with the audience rating $\alpha$ is broadcast in the cellular network, then the average number ($\bar{N}_s$) of saved radio resources in a typical Voronoi cell is

$$\bar{N}_s = \frac{\alpha\lambda_u}{\lambda_b} + (1 + 3.5^{-1}\alpha\lambda_u/\lambda_b)^{-3.5} - 1.$$  

**Proof.** If there are $K$ MUs subscribing to the content in a typical Voronoi cell, then $k - 1$ radio resources will be saved by broadcasting. Therefore, we can get the following equation:

$$\bar{N}_s = \sum_{k=2}^{\infty} (k - 1) P[K = k]$$
$$= \sum_{k=2}^{\infty} kP[K = k] - \sum_{k=2}^{\infty} P[K = k]$$
$$= (E[K] - P[K = 1]) - (1 - P[K = 0] - P[K = 1])$$
$$= E[K] + P[K = 0] - 1$$
$$= \frac{\alpha\lambda_u}{\lambda_b} + (1 + 3.5^{-1}\alpha\lambda_u/\lambda_b)^{-3.5} - 1.$$  

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**Proposition 2**: If a live video content with the audience rating $\alpha$ is broadcast in the cellular network, then the average number ($\bar{N}_w$) of wasted radio resources in a typical Voronoi cell is

$$\bar{N}_w = (1 + 3.5^{-1}\alpha\lambda_u/\lambda_b)^{-3.5}.$$  

**Proof.** If there is no subscriber in a typical Voronoi cell (i.e., $K = 0$), then one radio resource will be wasted by
Proposition 3: If the audience rating $\alpha$ of a live video content satisfies the following condition;
\[
\alpha > \frac{\lambda_b}{\lambda_u} \left( \frac{c_b}{v_r} + 1 \right),
\]
then the average amount of cost reduction (CR) by broadcasting the content over the cellular network is;
\[
CR = v_r (\frac{\alpha \lambda_u}{\lambda_b} - 1) - c_b.
\]

Proof. By broadcasting a live video content over the cellular network, the average value $v_r \bar{N}_s$ is saved but the average value $v_r \bar{N}_w$ is wasted. Moreover, there is an additional cost $c_b$. With Propositions 1 and 2, the average amount of cost reduction $CR$ can be calculated as follows:
\[
CR = v_r \bar{N}_s - v_r \bar{N}_w - c_b = v_r \left( \frac{\alpha \lambda_u}{\lambda_b} - 1 \right) - c_b. \tag{5}
\]
By re-arranging Equation (5), we can find the audience rating condition for making $CR$ positive. \hfill \square

Considering the value of radio resources increased in these days, Proposition 3 show that the cost reduction gain by broadcasting over the cellular network will be high in practice. Proposition 3 is derived under an implicit assumption that all MUs subscribing to a live video content will immediately switch to the broadcasting channel. In practice, however, some MUs might prefer unicast if there is no economic incentive in broadcast, and the average amount of cost reduction (Proposition 3) will decrease. In this case, the service price discount on broadcast may be an attractive option for the MUs. Proposition 3 is not applicable to the buffered video streaming service because there will be less MUs subscribing to the same buffered video content concurrently. More details are described in the next section.

5. PERIODIC BROADCASTING SERVICE FOR BUFFERED VIDEO CONTENTS

In the buffered video streaming service, already-produced video contents are streamed over the cellular network and MUs can subscribe to the contents whenever they want. This means that broadcasting the content is very inefficient. To tackle this inefficiency, we propose periodic broadcasting service for buffered video contents, where some buffered video contents are periodically broadcast in the cellular network. If economic incentives such as price discount are offered, the service can bring a cost reduction effect.

In this service, it is very important to determine what and how video contents are played. For this, we suggest two simple schemes; scheduled play and real-time voting and play.

Figure 3: Scheduled play, and real-time voting and play.
In the scheduled play scheme, video contents are sorted by the popularity (e.g., the cumulative number of views on YouTube or Netflix) and top-n video contents are played repeatedly. Figure 3 shows two examples of the scheduled play scheme, where the top-5 video contents are played with an equal weight (A) and with a different weight (B). The scheduled play scheme is simple but it cannot reflect the real-time changing of user demand. On the other hand, in the real-time voting and play scheme, MUs vote for their favorite contents during a certain period and a video content receiving the most votes is played in the next period (Figure 3).

For the success of periodic broadcasting services, MNOs can go into business in partnership with CPs. These services can reduce inefficiency in the video content delivering and can create additional revenues by advertising, which will eventually give a positive effect on the network neutrality debate.

6. CONCLUSIONS

In this paper, we consider broadcast in cellular networks for video streaming services and analyze its cost effectiveness reflecting spatial characteristics of BSs and MUs. Using the stochastic geometry approach, we derive average numbers of saved and wasted radio resources in a typical Voronoi cell respectively, and show there is the trade-off between broadcast and unicast. With these results, we evaluate the economic feasibility of broadcast in cellular networks for live video streaming services. Moreover, we propose periodic broadcasting service for buffered video contents. Even though our analytic results are derived under a simple model for mathematical tractability, it will provide engineering and economic insights for managing huge amounts of video traffic in cellular networks.

In recent years, the network neutrality debate has been emerging as a major issue. Moreover, the mobile data explosion causes the spectrum shortage and the data usage polarization among users, which will eventually lead to the decrease of user welfare. For this reason, in our previous work [10], we have proposed a data subsidy scheme where the regulator offers spectrum price discount to MNOs in return for providing a predefined data amount to users without any charge, and have showed that it can increase user welfare even further without MNOs’ profit loss. Broadcasting service in cellular networks for live and buffered video contents can be directly applied to the data subsidy, which will generate a significant synergy effect on both solving the mobile data explosion and improving user welfare.

7. REFERENCES

[1] Cisco, “Cisco visual networking index: Global mobile data traffic forecast update, 2010-2015,” Cisco white paper, 2011.
[2] 3GPP TS 25.346 V8.3.0. Technical Specification Group Radio Access Network, Introduction of the Multimedia Broadcast Multicast Service (MBMS) in the Radio Access Network (RAN), Stage 2 (Release 8).
[3] J. G. Andrews, F. Baccelli, and R. K. Ganti, “A tractable approach to coverage and rate in cellular networks,” IEEE Transactions on Communications, vol. 59, no. 11, pp. 3122-3134, 2011.
[4] H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, “Modeling and analysis of k-tier downlink heterogeneous cellular networks,” IEEE Journal on Selected Areas in Communications, vol. 30, no. 3, pp. 550-560, 2012.
[5] B. Blaszczyszyn, M. K. Karray, and H.-P. Keeler, “Using Poisson processes to model lattice cellular networks,” to appear in Proceedings of IEEE INFOCOM, 2013. Available: http://arxiv.org/abs/1207.7228
[6] S. M. Yu and S.-L. Kim, “Downlink capacity and base station density in cellular networks,” to appear in Proceedings of IEEE WiOpt Workshop on Spatial Stochastic Models for Wireless Networks (SpaWiN), 2013. Available: http://arxiv.org/abs/1109.2992
[7] A. Okabe, B. Boots, and K. Sugihara, Spatial Tessellations: Concepts and Applications of Voronoi Diagrams. 2nd ed. John Wiley and Sons Ltd, 2000.
[8] J.-S. Ferenc and Z. Neda, “On the size distribution of poisson voronoi cells,” Physica A: Statistical Mechanics and its Applications, vol. 385, no. 2, pp. 518-526, 2007.
[9] M. Cha, H. Kwak, P. Rodriguez, Y.-Y. Ahn, and S. Moon, “Analyzing the video popularity characteristics of large-scale user generated content systems,” IEEE/ACM Transactions on Networking, vol. 17, no. 5, pp. 1357-1370, 2009.
[10] S. M. Yu and S.-L. Kim, “Guaranteeing user welfare in network service: comparison of two subsidy schemes,” ACM SIGMETRICS Performance Evaluation Review, vol. 40, no. 2, pp. 22-25, 2012.