京都大学教育研究振興財団助成事業
成　果　報　告　書

平成20年9月20日

財団法人京都大学教育研究振興財団
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事 業 区 分	平成20年度・ 長期派遣助成	
研 究 課 題 名	コグニティブ無線を用いた周波数資源制御技術の研究	
受 入 機 関	アメリカ合衆国ラトガース (Rutgers) 大学WINLAB	
渡 航 期 間	平成20年8月26日　～　平成21年9月4日	
成 果 の 概 要	タイトルは「成果の概要／報告者名」として、A4版2000字程度･和文で作成し、添付して下さい。「成果の概要」以外に添付する資料　□ 無　■有(発表論文2件)	
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	使用した助成金額	255万円
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成果の概要 / 新熊亮一

2009 年 9 月 20 日

1. はじめに

アメリカ合衆国ニュージャージ州立 Rutgers 大学は 1766 年に設立されたアメリカで 8 番目に古く，州では 2 番目に古い大学である．Rutgers 大学はニュージャージ州で最も大きく，New Brunswick 市と Piscataway 市にまたがって，4 つのキャンパスを有している．報告者が研究を行った WINLAB (Wireless Information Network Laboratory) は，通信ネットワーク工学に関する大学所属の研究所としては世界でも最大規模の研究所である．約 20 人の教授陣と約 10 人のスタッフで研究教育体制を整えている．教授陣は所長の Raychaudhuri 教授をはじめとするネットワークのエキスパートから，アルゴリズム，数理モデル，セキュリティ，電波伝搬のエキスパートまで無線通信の研究を行うのに必要なエキスパートがそろっており，プロジェクトごとにチームを組んで研究開発を遂行している．現在の主なプロジェクトは，Dynamic Spectrum Access 技術をはじめ，Future Internet 技術，ワイヤレスセキュリティ技術，車々通信技術である．また，WINLAB は 400 という数の無線基地局をグリッド上に並べた ORBIT と呼ばれる汎用無線テストベッドを有しており，コンピュータ上の評価では見ることのできない現象をとらえることを目的としながらも，シミュレータのような操作で考案した方式を組み込むことも可能にしている． また，20～30 人の博士課程の学生が在籍しておりプロフェッショナルな意識で勉学と研究に取り組んでいる．

2. 研究成果 1「Bandwidth Exchange： コグニティブ無線環境におけるユーザ協力中継のためのインセンティブメカニズム」

無線ネットワークにおいて, ユーザ協力中継は有効な通信品質改善手法の 1 つとして期待されている. しかし, ユーザが他ユーザのデータを中継するインセンティブは保証されていない. 従来の仮想通貨や評判システムなど近代経済を模擬したメカニズムには複雑さの点で問題があった．そこで原始的な「物々交換」に着目し，無線ネットワークにおいて周波数帯域を交換する Bandwidth Exchange (BE)を提案した．公平なインセンティブを保証するため，交渉ゲーム理論の最適解であるナッシュ交渉解（NBS）を導入し，それに基づいた協力中継のアルゴリズムとプロトコルの設計を行った[1]．その際，3 人以上の交渉が複雑化する問題を回避するため，2 人 1 組の交渉アルゴリズムを 3 人以上に適用できるよう拡張した．また，Altruistic（利他的），Myopic（近視的）という人の自然な行動をベースに比較方式を考案した．これらの方式をシミュレーションに実装し，比較評価の結果から，提案方式が，高い周波数利用効率を保ちながら公平にインセンティブを割り当てられること, さらに BE なしの場合に比べ 6dB（4 倍）もの送信電力の低減を実現することを示した[2]. なお, BE は, 第 4 世代携帯電話（4G）で使用される予定の OFDMA や SC-FDMA といった直交周波数分割方式をプラットホームとして実現可能で，4G での採用も視野に入れた実装実験が ORBIT を用いて始められている．

3. 研究成果 2「コグニティブ無線ユーザのためのコンテンツ配信システム」

WINLAB の提唱する CNF（Cache-aNd-Forward）ネットワークは，モバイルユーザが Opportunistic に断続的接続を繰り返すコグニティブ無線環境でのコンテンツ配信に最適化された，インターネットに代わる新世代のアークテクチャである．その特徴は End-to-End ではない Hop-by-Hop の転送とルータによるネットワークキャッシングであり，これらによって断続接続するユーザに対し低転送コストで大容量コンテンツを配送する．我々は特に，モバイルユーザが受信完了前に切断してしまう問題を取り上げ，有効なコンテンツキャッシング法について検討した[3]．また，ここで扱うコンテンツはユーザ固有のコンテンツである．共有コンテンツについては，人気度に基づいた手法がすでに多く提案されている．固有のコンテンツを前提としているため，新たなコンテンツが到着すると，LRU (Least Recently Used)にしたがって最も古いものが捨てられる．このようなキャッシュメカニズムでは，ルータごとのコンテンツ保持時間（キャッシュから廃棄までの時間）の情報を活用しやすい．まず，我々は，断続接続ユーザの転送コストの最小化を最適化問題として定式化した．その定式を基に，コンテンツ保持時間情報を用いた複数のヒューリスティック手法を提案し，比較評価からそれらの有効性を示した．さらに，このようなキャッシュが限られた資源であることを指摘し，通信帯域と同様，キャッシュ容量もが課金されるモデルの提案を行った[4]．キャッシュ容量を仮想通貨で価格付け（Pricing）し，多く仮想通貨を支払うユーザほど転送コストの大きな削減を期待できるサービスを考案し，ヘッダ構造まで含めたアーキテクチャを設計した．また，価格付けポリシーがネットワークに与える影響についても調査した．以上の技術は CNF ネットワークのみならず，Hop-by-Hop を前提とした現行の CDN（Content Delivery Network）や Web にも広く適用可能である．

謝辞

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発表文献

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Bandwidth Exchange for Enabling Forwarding in Wireless Access Networks

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***Abstract*—Cooperative forwarding in wireless networks has shown to yield benefits of rate and diversity gains, but it needs to be incentivized due to the energy and delay costs incurred by individual nodes in such cooperation. In this paper we consider an incentive mechanism called Bandwidth Exchange (*BE*) where the cooperating nodes flexibly exchange the transmission bandwidth (spectrum) as a means of providing incentive for forwarding data. The advent of cognitive radios with the ability to flexibly change their carrier frequency as well as their transmission bandwidth makes this form of incentive particularly attractive compared to other incentive mechanisms that are often based on abstract notions of credit and shared understanding of worth. Specifically, we consider a N-node wireless network and use a Nash Bargaining Solution (*NBS*) mechanism to study the benefits of *BE* in terms of rate and coverage gains.**

I. Introduction

Cooperative forwarding is an essential technique to enhance connectivity and throughput for wireless networks. However, forwarding always incurs some sort of cost – either real costs like energy and power, or opportunistic cost like delay. To circumvent the above difficulties, we have recently proposed Bandwidth Exchange (*BE*) as an incentive for forwarding. Specifically in [1], we have considered a two-node network where each node is endowed with orthogonal frequency resources and shown that a Nash Bargaining Solution (*NBS*) based mechanism can provide incentive for forwarding. In this paper we consider the extension of *BE* to a N-node network, i.e., whenever a node asks another node for cooperation, it delegates a portion of its frequency resource to the forwarder as immediate compensation for the forwarder's cost. A similar *NBS*-based cooperation strategy for a two-node network was also discussed in [2]. Recent advances in cognitive radio have made this approach feasible. In particular, OFDMA (Mobile WiMAX) [3] and SC-FDMA (LTE) [4] technologies allow nodes to flexibly acquire and relinquish a number of the subcarriers/subchannels. Such spectrum agility achieved in radio technology has great promise to cope with the forwarding incentive problem that is studied in this paper.

II. System Model and Bandwidth Exchange

Consider N nodes (labeled $1, 2, \ldots, N$) communicating to an access point (*AP*, labeled as node 0) as shown in Fig. 1. Each node is assigned a nonoverlapping, hence orthogonal bandwidth W_i. The transmission power P_i^{t} for each node is fixed. The minimum required rate for each node is $R_i^{\min}$. We assume an ergodic fading model where the transmission is slotted and the channel gain ρ_{ij} $(= \rho_{ji})$ in each slot is quasi-static and is an independent realization of a random variable (with marginal distribution $p(\rho_{ij})$). To avoid confusion, subscript ij always implies the direction from i to j. If such a subscript is used in a transmission scheme, it is understood that i is the source and j is the forwarder (or the *AP* if $j = 0$).

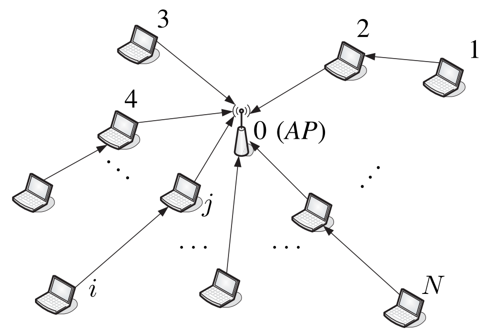


Fig. 1. Nodes connect to *AP* through cooperative forwarding.

In every slot a node i first attempts to transmit directly to the *AP*. If the direct link is under outage, i.e., the link capacity is smaller than the minimum required rate of node i, it tries to find a node j which could help forward its data to *AP*, by means of *BE*. During transmission, node i makes use of its available bandwidth up to W_i as dictated by *BE*. The instantaneous direct link capacity R_{ij}^{ins} from node i to node j in a slot is a function of node i's available bandwidth and ρ_{ij} with transmission power P_i^{t} a fixed parameter. We assume there is no flow splitting and every forwarder serves at most one source.

The basic idea of cooperation through *BE* is the source delegating a portion of the frequency band to the forwarder in exchange for cooperation that guarantees the minimum required rate of the source. When node i transmits to the *AP* directly, the resulting (noncooperation) rate is denoted as $R_i^{\mathrm{n}} = R_{i0}^{\mathrm{ins}}(W_i, \rho_{i0})$. When node j forwards data for node i through *BE*, the resulting rate for j is denoted as R_{ij}^{r} and R_{ij}^{s}

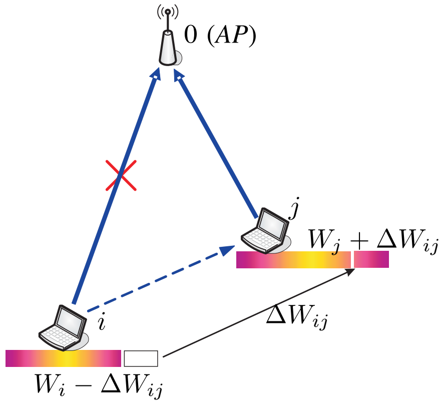


Fig. 2. When the direct link is under outage, node i tries to solicit cooperation by delegating ΔW_{ij} to node j.

for the source node i. Note that $R^{\text{s}}_{ij} = R^{\text{min}}_i$ since a source only seeks to maintain the minimum required rate to connect to *AP*. Therefore, as shown in Fig. 2, the source node i can withhold $W_i - \Delta W_{ij}$ and delegate ΔW_{ij} to the forwarder j such that

$$R^{\text{min}}_i = R^{\text{ins}}_{ij}(W_i - \Delta W_{ij}, \rho_{ij}). \tag{1}$$

Node j, in addition to guaranteeing R^{min}_i for node i, uses the remaining capacity achieved with increased bandwidth $W_j + \Delta W_{ij}$ for its own data,

$$R^{\text{r}}_{ij} = R^{\text{ins}}_{j0}(W_j + \Delta W_{ij}, \rho_{j0}) - R^{\text{min}}_i. \tag{2}$$

Equations (1) and (2) define the basic mechanism of *BE* as described in [1] – instead of raising transmission power, cooperation is achieved by autonomously reallocate bandwidth resources among the nodes. Note that they also describe the relationship of the rates (R_{ij}) and bandwidth portion (ΔW_{ij}) to the link gain ρ_{ij}. For simplicity in notation, we suppress the explicit dependence. Link ij is considered as under outage when it is too weak,

$$\Delta W_{ij} < 0 \tag{3}$$

or when it leads to outage for the forwarder,

$$R^{\text{r}}_{ij} < R^{\text{min}}_j. \tag{4}$$

In either case, we also say the request from i is not *supportable* at j.

III. Cooperation Forwarding Incented by *BE*

In a fading environment, the role of a node as a forwarder or source can change from slot to slot. The decision made in a slot should take the consequences it entails in future slots into consideration. This situation is better modeled with an infinitely repeated game [1] [5], each slot corresponding to a stage game. A node i under outage in a slot will request for cooperation through *BE*; a potential forwarder j has to make a decision from a binary strategy space, i.e., to cooperate or not. Node j will make a *trivial decision* to simply reject cooperation if the request is not supportable. Otherwise node j will choose to cooperate with a nonzero probability to be discussed shortly.

The utility function u^{ins}_{ij} of a stage game for an arbitrary node j, called instantaneous *rate gain*, is defined to be the rate increase achieved in that slot compared to noncooperation. Instantaneous rate gain is closely related to the strategy a node takes. For example, the instantaneous rate gain of node j when it chooses to forward for node i is

$$u^{\text{ins}}_j = u^{\text{ins}}_{ij} = R^{\text{r}}_{ij} - R^{\text{n}}_j, \tag{5}$$

while

$$u^{\text{ins}}_i = R^{\text{min}}_i. \tag{6}$$

The utility function of the repeated game for an arbitrary node j is the average *rate gain*. A *trivial stage game* for node j is one in which every decision involving j, no matter whether it is the source or forwarder, is trivial, then $u^{\text{ins}}_j = 0$ for that stage. Therefore we focus only on nontrivial stage games and disregard, for each node j, those stage games that are trivial to j. In other words, in each nontrivial stage game of j, either j is a source and sends a supportable request to some node i, or j is a potential forwarder and receives a supportable request from some node i.

A. Simplified N-Node Bargaining and Selection Policy

In a two-node network, a nontrivial stage game consists of either node 1 sending a supportable request to node 2, or node 2 sending a supportable request to node 1. Suppose the two events happen with probability P_{12} and P_{21}, respectively. A potential forwarder thus has two possible strategies: C for cooperation and N for noncooperation. The two-node *NBS* (see [1]) tells us the probability P^{c}_{12} that node 2 chooses C and the probability P^{c}_{21} that node 1 chooses C. Let v_1, v_2 denote the average rate gains of node 1 and 2, respectively, in a nontrivial stage game. Further, let $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ denote the mixing probabilities corresponding to joint strategies $\langle N, C\rangle, \langle C, C\rangle, \langle C, N\rangle, \langle N, N\rangle$. The *NBS* is given as

$$\begin{aligned}
\underset{\lambda_1,\lambda_2,\lambda_3,\lambda_4}{\text{maximize}} \quad & v_1 v_2, \qquad (7)\\
\text{subject to} \quad & v_1 = \lambda_1 P_{21} R^{\text{min}}_2 + \lambda_2 (P_{21} R^{\text{min}}_2 + P_{12} u_{12}) \\
& \quad + \lambda_3 P_{12} u_{12} + \lambda_4 \cdot 0, \\
& v_2 = \lambda_1 P_{21} u_{21} + \lambda_2 (P_{12} R^{\text{min}}_1 + P_{21} u_{21}) \\
& \quad + \lambda_3 P_{12} R^{\text{min}}_1 + \lambda_4 \cdot 0, \\
& \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1, \\
& \lambda_i \geq 0, \quad i = 1, 2, 3, 4.
\end{aligned}$$

Then, the desired cooperation probabilities are

$$P^{\text{c}}_{12} = \lambda_1 + \lambda_2, \quad P^{\text{c}}_{21} = \lambda_2 + \lambda_3. \tag{8}$$

In the case of a N-node network, formulating the N-node *NBS* is practically infeasible. One reason is that the strategy space for each node contains an exponentially increasing number of strategies relative to the number of nodes. This prompts us to look for approximate solutions with much lower complexity.

One such solution is based on restricting cooperations to two-hop forwarding. In other words, every node can reach the *AP* via at most one other node. Since we have required one forwarder for one source and no flow splitting, eventually cooperation happens only between a distinct pair of nodes. It is then natural to approximate the N-node bargaining with a series of two-node bargainings, each completely disregarding the existence of other nodes and their influence. Consequently, the simplified N-node bargaining boils down to every node under outage in a slot carrying out independent two-node bargainings with every other node according to the two-node *NBS* given in equation (7).

However, with this simplification, a potential forwarder may receive multiple cooperation requests while a source may receive multiple positive acknowledgements. A natural choice is to dictate that one of the source nodes is chosen by the forwarder with a probability proportional to the corresponding cooperation probabilities calculated from the two-node *NBS* in equation (7). Specifically, suppose the requests from $i_1, i_2, \ldots, i_k$ are all supportable at forwarder j and the corresponding cooperation probabilities calculated from the two-node *NBS* are $P^{\text{c}}_{i_1 j}, P^{\text{c}}_{i_2 j}, \ldots, P^{\text{c}}_{i_k j}$, then j chooses to cooperate with i_ℓ ($1 \leq \ell \leq k$) with probability

$$P'^{\text{c}}_{i_\ell j} = \frac{P^{\text{c}}_{i_\ell j}}{P^{\text{c}}_{i_1 j} + P^{\text{c}}_{i_2 j} + \cdots P^{\text{c}}_{i_k j}}. \tag{9}$$

On the other hand, a source may also receive positive responses from multiple forwarders. The source then randomly chooses one to follow as every forwarder equally guarantees the minimum required rate of the source. It is possible for the forwarders whose offers are turned down to pick up requests from other sources that they can help but we do not pursue this situation and instead simply assume this concludes the bargaining phase of the slot. Nodes then use the remaining time of the slot to either cooperate, or to transmit on their own, or to stay off connection.

IV. Numerical Results

A. Simulation model

Our mechanism is applicable to any multihop network, infrastructured or ad hoc, in a licensed or unlicensed band. For the purpose of illustration, we consider an OFDMA [3] transmission scheme much like the one used in mobile WiMAX [6]. The presence of orthogonal subcarriers in an OFDMA system provides a natural platform for implementing *BE* by exchanging orthogonal frequency bands.

We simulate a slotted system using parameters that are typical to mobile WiMAX. Each node is pre-assigned 20dBm fixed transmit power [7] [8] and 500kHz transmission bandwidth corresponding to 50 subcarriers at 10kHz spacing. When a node delegates bandwidth, it transfers a number of the subcarriers to a forwarder. Since nodes in our network use mutually orthogonal portions of frequency, we model the instantaneous capacity of link ij using its information-theoretic rate

$$R^{\text{ins}}_{ij}(W, \rho_{ij}) = W \log_2\left(1 + \frac{\rho_{ij} P^{\text{t}}_i}{W}\right), \quad i, j = 0, 1, \ldots, N. \tag{10}$$

Links are under independent Rayleigh fading and the link gain in each slot is an independent realization of a Rayleigh random variable. Equivalently, this implies that ρ_{ij} is exponentially distributed

$$p(\rho_{ij}) = \frac{1}{\bar{\rho}_{ij}} \exp\left(-\frac{\rho_{ij}}{\bar{\rho}_{ij}}\right) \tag{11}$$

where the statistical mean $\bar{\rho}_{ij}$ is given by the path loss model

$$\bar{\rho}_{ij} = \kappa d^{-3}, \quad (\kappa = 6 \times 10^6 \text{MHz} \cdot \text{m}^3/\text{mW}). \tag{12}$$

The above simulation model implicitly assumes that the average rate of a transmission is one that is obtained when all the subcarriers used undergo identical fading. This is done for the simplicity of illustration but the idea of *BE* and its applicability to frequency selective OFDMA systems is still valid. The pairwise *NBS* with *BE* in equation (7) is implemented for the above channel model. We simulate for sufficiently many slots to assess the average performance.

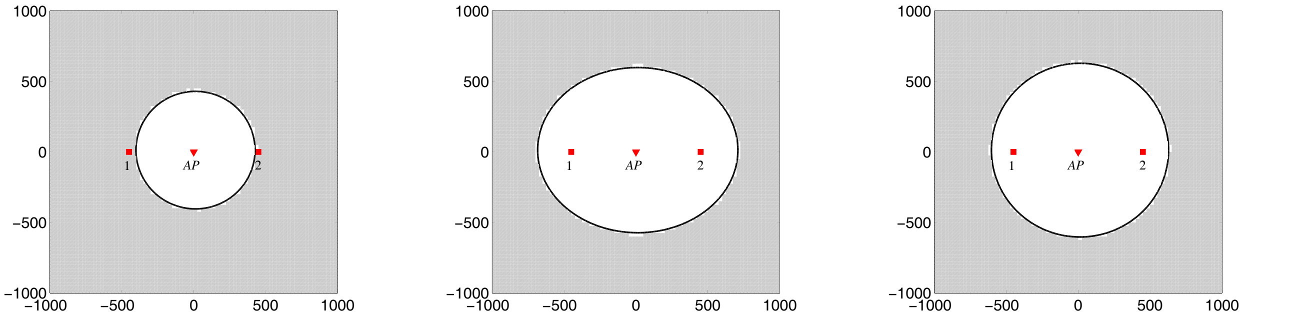
B. A Three-Node Example

We first present a three-node example to show the power of *BE* with *NBS* in improving coverage and rate. Suppose node 1 is fixed at (-450m, 0) and node 2 at (450m, 0). Node 3 is allowed to vary its location in a 2000×2000m^2 region as shown in Fig. 3.

If we set the minimum required rate for each node to 700kbps and the tolerable outage probability to 10%, Fig. 3(a) shows coverage area for node 3 without cooperation. Fig. 3(b) shows the improvement in coverage area achieved when using *BE* with *NBS* for the same level of outage. Fig. 3(c) shows a comparable coverage area for node 3 in the absence of cooperation. However, the minimum required rate now has to be lowered to 300kbps to generate an identical level of outage. This simple illustration indicates that *BE* can be used to either increase coverage, or increase the supported rate.

C. Performance Evaluation in a N-Node Network

In this section, we present a comparative evaluation of *BE* with *NBS* with noncooperation, as well as with a simple heuristic cooperative forwarding scheme. Specifically, the simple heuristic requires that in each slot, every potential forwarder tries to cooperate with a supportable source (see equations (3) and (4)) randomly and the source also randomly follows a cooperating forwarder. This is equivalent to setting $P^{\text{c}}_{ij} = P^{\text{c}}_{ji} = 1$ in the *NBS*. Recall that every node has its own bandwidth. When a node under outage cannot get any cooperation its bandwidth will go unused in that slot. The simple heuristic is a straightforward measure to reduce, if not minimize, such waste. Therefore it serves as a good benchmark for the average rate gain and spectral efficiency to be addressed.



(a) (b) (c)

Fig. 3. Improvement in coverage and rate – $P_3^{\rm out} < 0.1$ in the white area. (a):noncooperation, $R_i^{\rm min} = 700$kbps; (b):*BE* with *NBS*, $R_i^{\rm min} = 700$kbps; (c):noncooperation, $R_i^{\rm min} = 300$kbps; $i = 1, 2, 3$.

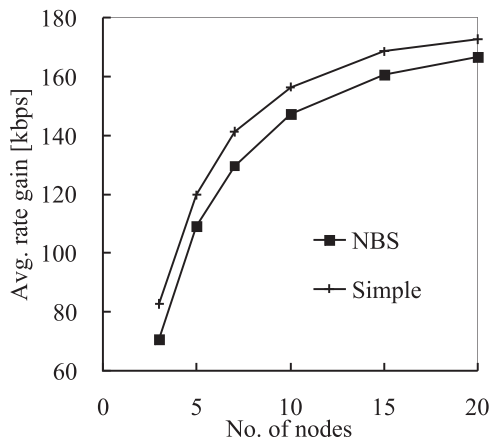


Fig. 4. Average rate gain in a cell consisting of varied number of nodes.

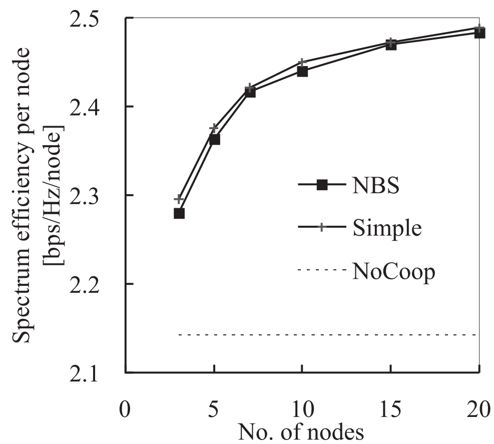


Fig. 5. Spectrum efficiency per node.

As mentioned earlier, we simulate a slotted system that uses parameters typical to mobile WiMAX. We consider up to 20 nodes randomly placed in a cell with a radius of 1000m. Our results are obtained by averaging over multiple time slots and location instantiations of mobiles. Specifically, we look at the metrics of average rate gain, spectrum efficiency and fairness as a function of the number of nodes in the system.

1) Average Rate Gain: Fig. 4 shows the average rate gain available to any node in a cell when the minimum required rate is set to 700kbps. No matter which algorithm is used, the average rate gain is an increasing function of the number nodes in the system, illustrating the benefits of user cooperation diversity. The simple heuristic exhibits the best performance thanks to its generous nature, though only the nodes far away from the *AP* are the real beneficiaries while nodes close to the *AP* usually suffer substantial loss while forwarding for others.

2) Spectrum Efficiency: Fig. 5 shows the spectrum efficiency averaged over the number of nodes to illustrate the effect of user cooperation diversity when the minimum required rate is set to 700kbps. Note that in our model, nodes are employing orthogonal subcarriers and hence do not interfere with each other. However, the spectrum efficiency per node increases with the number of nodes. Noncooperation performs well below the two cooperative strategies. It is noteworthy that *BE* with *NBS* has almost the same spectrum efficiency with the very generous simple heuristic algorithm.

3) Geometric Mean of Rate Gains: The *NBS* does not take average rate gain or spectrum efficiency as an explicit optimization objective. Rather, it provides a proportionally fair rate allocation, i.e., it tries to maximize the product of rate gains, or equivalently, the geometric mean of rate gains. In this sense, the geometric mean of rate gains can be regarded a measure of the average amount of individual incentive that a node has for cooperation when *BE* is used with *NBS*. Let $\mathcal{I}$ denote the fairness metric defined as

$$\mathcal{I} = \left(\prod_{i=1}^{N} \max(u_i, 0) \right)^{1/N}. \quad (13)$$

The implication is that for fair cooperation schemes, the average rate gains are always positive and equation (13) reduces to the canonical geometric mean as an average amount of individual incentive. When the average rate gains for some nodes are negative, then equation (13) indicates $\mathcal{I} = 0$, i.e., the

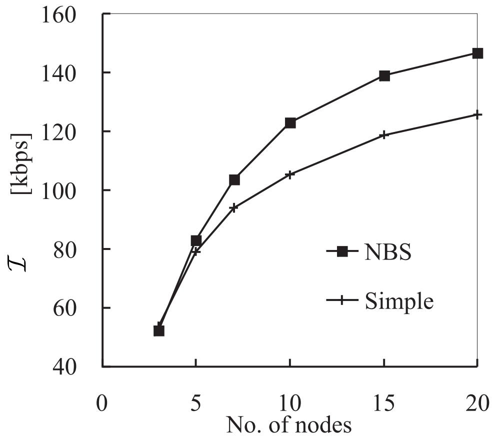


Fig. 6. Geometric mean of rate gains as a measure of fairness.

scheme is unfair. Fig. 6 shows $\mathcal{I}$ as a function of the number of nodes when the minimum required rate is set to 700kbps. We observe that, as a proportionally fair cooperating scheme, *BE* with *NBS* performs desirably and the average amount of individual incentive increases with the number of nodes. This observation is consistent with user cooperation diversity increasing with the number of nodes. On the contrary, the noncooperation scheme has $\mathcal{I} = 0$. The simple heuristic can be unfair as well. In fact, our experiments reveal in roughly 20% of simulation trials, one or more nodes experience negative rate gains.

V. Conclusion and Discussions

In this paper we discussed a cooperative forwarding incentive mechanism called Bandwidth Exchange where relay nodes forward data in exchange for bandwidth that is delegated by source nodes. The advent of cognitive radios with the ability to flexibly change their carrier frequency as well as their transmission bandwidth makes this form of incentive particularly attractive. Further, the use of OFDMA or SC-FDMA based access allows for the flexible exchange of frequency bands among the nodes. Compared to other incentive mechanisms such simple bandwidth delegation provides more tangible and immediate incentive. Specifically, we considered a N-node wireless network and used a Nash Bargaining Solution to study the benefits of *BE* in terms of rate and coverage gains. Further, the *NBS* also assured that the rate allocations were proportionally fair.

While the results presented here showed the benefits of *BE* as an incentive mechanism, an interesting and important aspect of *BE* is the need for a distributed protocol for implementing the *NBS* strategy in a N-node network. The choices of selection policies as well as other heuristic *BE* based incentive mechanisms also need to be considered. These will be discussed in an upcoming paper [9].

Acknowledgement

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Network Caching Strategies for Intermittently Connected Mobile Users

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***Abstract*—This paper presents an evaluation of in-network caching strategies for efficient delivery of content to mobile devices that are intermittently connected to the network. Placement of content into in-network caches is formulated as an optimization problem that minimizes access latency under certain cost constraints. Several heuristic solutions (longest lifetime, split & longest lifetime and proportional probability to lifetime) are investigated via numerical examples and simulations. The results show that the proposed methods offer significant performance improvement over random caching and can approach the performance of exhaustive caching at every node with reduced storage cost.**

I. Introduction

Mobile content delivery is an important technical challenge for the next decade as more and more applications move from desktop computers to portable devices. Content delivery to mobile devices is more difficult because of fundamental limitations in coverage and bit-rate of the mobile/wireless access network. Conventional services over cellular networks are feasible but suffer from capacity limitations and corresponding high cost of delivery [1]. This has motivated the use of opportunistic/hybrid networking in which users may migrate between different radio access technologies such as cellular and WiFi and may also be entirely disconnected at times. Delivery of content to intermittently connected wireless users has been proposed in earlier work on Infostations [2], and more recently in context of DTN's [3] and clean-slate mobile internet solutions such as CNF [4]. Use of such opportunistic/disconnected networking techniques offers significant cost/performance advantages over conventional cellular service and is expected to become increasingly important as mobile data applications continue their rapid growth.

Content caching is a key enabling technology for the opportunistic mobile data delivery scenario under consideration. In-network caching has been shown to provide large performance gains in the wired Internet [5], and is even more important when designing a system for mobile data. Intermittent network access implies that the point of attachment of a mobile end user may vary widely with time, so that placement of the cache needs to consider mobility patterns as well as the anticipated latency and capacity. Particularly we need to deal with situations in which the end user becomes disconnected while the content is in transit. In this paper, we focus on the specific problem of optimizing cache locations for mobile data where the requester has been disconnected before delivery of the content is completed. The system model under consideration is based on reliable hop-by-hop transport between in-network caches rather than on end-to-end TCP streaming of the content file. This model corresponds to an overlay cache network as in CDNs [6] or integrated in-network caching as in the cache-and-forward (CNF) architecture [4]. Under hop-by-hop transport, a file that is enroute to a mobile is temporarily cached at all nodes along the route. So, our goal in this paper is to determine an appropriate cache placement strategy which takes into account *content-lifetime*, which is defined as the time duration from the time the content is cached until it is discarded from the cache. Content lifetime may be calculated at every node as a historical moving average of the time difference between caching and discarding contents at the node. Earlier work on content caching algorithms has focused on web caching, P2P content sharing and ad hoc networks[7][8], but much of the discussion has been limited to placement of content based on popularity rather than to serve future access by a temporarily disconnected mobile user.

In the rest of this paper, we briefly review the system architecture and give our model assumptions. We then formulate the content placement problem as an optimization problem. When the mobile becomes disconnected, the key question is which nodes along the route should continue to keep the content. The key idea is to use content-lifetime information. Then, we propose three heuristic strategies using estimated content-lifetime information. Numerical performance evaluation results are given to show that the proposed heuristics achieve excellent performance relative to random caching and also closely approach the performance of exhaustive caching at every node along the route.

II. System model

Our system model is illustrated as Fig 1, in which each node is assumed to have a large storage cache that can be used to store files in transit, as well as to offer in-network caching of common content. Each content file transported is carried in a strictly hop-by-hop fashion. The file is transported reliably between data stores at each node before being prepared for the next hop towards its destination. This network corresponds to an infrastructure part of CNF [4] and an optional form of the overlay CDN proposed in [6]. The recent reduction

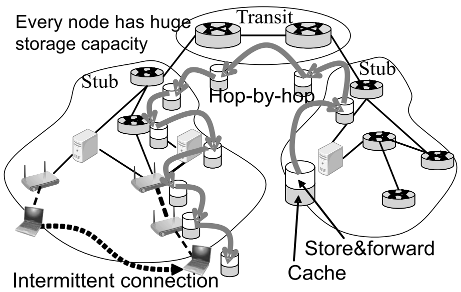


Fig. 1. System model.

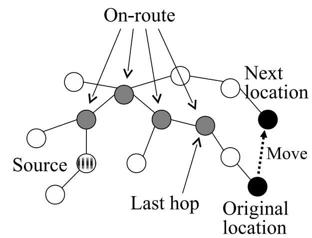


Fig. 2. Problem model

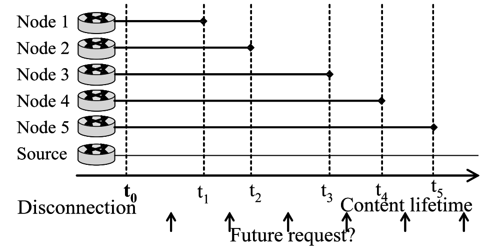


Fig. 3. Nodes sorted in ascending order of content lifetime.

of storage cost has made this type of architecture with in-network storage feasible. Such a network can be built on top of IP using overlay content delivery routers connected by IP tunnels, or as a clean-slate implementation such as CNF described in [4]. In both cases, content delivery routers will have additional protocol support for naming and resolution of content files, as needed to support storage and caching functions. In the CNF architecture, this is achieved by the "content name resolution service (CNRS)" protocol which maintains the mapping between content ID's and the storage locations within the network. In such a network, when a user requests a particular content ID, the query is resolved by the CNRS (which in general, returns multiple router and server addresses), and the content is then fetched from the nearest location according to the routing metric. In order to deal with user mobility, an additional concept of "post-office (P.O.)" is introduced. The P.O. is responsible for maintaining pointers to content in transit being delivered to a mobile device during disconnections. Overall, these content management protocols make it possible to support caching of both popular content and content addressed to individual mobile users. In the rest of this paper, we focus on content caching algorithms with the understanding that in-network storage and retrieval is supported by a suitable protocol similar to CNRS used in the CNF architecture.

III. Model assumptions

Figure 2 illustrates the model we assume in this paper. Each node has cache function with storage capacity and serves wireless connectivity to user terminals. The problem scenario of this paper is described as follows:

1) The requester (user terminal) requests a file from the source node. We assume that the requested file here is always low popularity common content or unique personal content for the requester. We do not take into account popular content which has already been considered in earlier work.

2) The file is transferred hop-by-hop along the routed path from the source to the requester. Every enroute node keeps the file in its temporary storage space.

3) Before the content reaches the requester, the mobile user moves away from its original location and disconnects. The last hop in Fig. 2 is the node that detected the requester's disconnection.

4) We limit our caching scheme to 'enroute caching'; the cached nodes are chosen from the last-hop node and the nodes between the source and the last-hop node.

5) The enroute nodes selected as cached nodes move the content data into their cache spaces, while the other enroute nodes discard the file from the temporary storage space.

6) The requester tries to retrieve the same content at a next location. We assume that the retrieval request time and location are random. The renewed request for content is first directed to the pointer function like P.O. in CNF which maintains a pointer to the current location(s) to the cached data.

Other than enroute caching, we could use a predictive caching approach as an alternative solution [9],[10]. The problem in such an approach is that significant extra cost is required for content replacement and mobility prediction.

IV. Problem formulation

We now formulate the problem of enroute caching for the mobile requester. Suppose that we ideally know the content lifetime t_i at each node i, which corresponds to the duration from the time node i caches the content until the time node i discards it. A node may discard certain cached content if the cache is full and it needs to make room for newer content. First, we sort all the enroute nodes in ascending order of t_i. Figure 3 shows an example with five enroute nodes. In this example, the cached content is discarded earliest from the cache of node 1, while node 5 stores the content for longest time among the enroute nodes. At time t_k, node $j(> k)$ still keeps the content in the cache, while node $j(\leq k)$ has already discarded it from the cache. In other words, for time period $[t_k, t_{k+1}]$, node $j(> k)$ is *available* as a candidate of cached nodes.

We are interested in evaluating network cost and latency the requested content experiences after the requester tries to retrieve it at the new location. To simplify the problem, we consider only the number of hopcounts as a metric because our purpose here is to give a fundamental observation rather than to estimate latency or network cost accurately. We could later extend our observation to more realistic models; in the future, we may design a more complex model, where we would compute roundtrip time as a function of queuing delay, bandwidth, and number of hopcounts. The expected shortest hopcounts is given as:

$$\sum_{k=0}^{n-1} C_k P(T \in [t_k, t_{k+1}]) \tag{1}$$

where C_k is the shortest hop distance from the new location to the closest node among the nodes for which the content lifetime is greater than t_k, i.e., the set of nodes in $(k+1, k+2, \cdots n-1)$; $P(T \in [t_k, t_{k+1}])$ is the probability that the request will arrive within period $[t_k, t_{k+1}]$.

Our objective is to find the optimal node set that minimize this metric. To achieve that, we first think of minimizing C_k. C_k depends mainly on which nodes are selected as cached nodes from available nodes for $[t_k, t_{k+1}]$ and the new location of the requester. As long as we can not predict the location, what we can do is to minimize the possible hopcounts. If we know the topology of the global network and it can be illustrated as Fig. 4, in which nodes a to e are available as a candidate of cached nodes, we could ensure the possible number of hopcounts is equal or less than 2 by choosing nodes a, c, and e. However, when we are allowed to pick only two nodes from them, we should choose nodes b and d to minimize the possible hopcounts.

On the other hand, the number of selectable nodes should be determined by a constraint of the storage cost because the requested content here is low popularity common content or unique personal content for the requester. When node i consumes storage cost s_i to cache the content into its cache, the total storage cost for period $[t_k, t_{k+1}]$ needs to satisfy $\sum_{i \in \mathcal{I}_k} s_i < \theta_k$, where $\mathcal{I}_k$ and θ_k indicate a set of the nodes determined as cached nodes and a threshold for period $[t_k, t_{k+1}]$, respectively. Finally, we could obtain a set of the selected nodes over the entire period $\mathcal{I}$ from $\mathcal{I}_0 \cup \mathcal{I}_1 \cup \mathcal{I}_2 \cup \mathcal{I}_3 \cup \cdots \mathcal{I}_{n-1}$. However, the storage constraint should be considered for the entire period rather than each period, meaning that the total consumed storage-cost has to satisfy $\sum_{i \in \mathcal{I}} s_i < \theta$, where θ is a threshold for the entire period. Another factor that makes this problem difficult is $P(T \in [t_k, t_{k+1}])$ in Eq. (1), which is the probability that the retrieval request arrives during period $[t_k, t_{k+1}]$. To minimize the objective function defined by this equation, we need to make C_k smaller as $P(T \in [t_k, t_{k+1}])$ is larger.

To motivate the above problem formulation, we draw a representative network in Fig 4. We find two time intervals $[0, t_v]$ and $[t_v, t_q]$ such that $0 < t_v < t_q$ and $P(T \in [0, t_v])$ = $P(T \in [t_v, t_q])$ = 0.5. We assume that nodes a to c and d to e have cached copies with lifetime t_q and t_v, respectively, and the requester's position can be limited only to leaf node L_j (j = 0 to 5). The shortest hopcount to a cached location C_k when the requester connects at points L_0 at time intervals $[t_0, t_v]$ and $[t_v, t_q]$ are $[1, 2]$. Therefore the expected shortest hopcount is obtained from the formulation (1) as 3/2. The expected shortest hopcounts for all locations L_0 to L_5 are $[3/2, 6/2, 4/2, 2/2, 2/2, 4/2]$. Our objective is to select a subset of nodes from this set such that the storage cost does not exceed a fixed threshold and the expected hopcount is minimized. For this example we choose a storage threshold

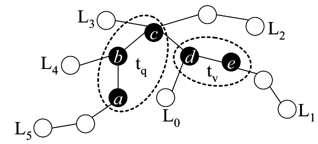


Fig. 4. An example of cached-node selection.

of two nodes. Given the storage constraints, the optimal cache locations are nodes a and c.

V. Heuristic strategies using content lifetime information

In the previous section, we gave a mathematical formulation of the caching issue for intermittently connected mobile users based on the content lifetime concept. In reality, the optimization based on this formulation seems to be impractical because we need to pick the node set minimizing the objective defined by Eq. (1) with taking into account the global network topology, available nodes at each period, $P(T \in [t_k, t_{k+1}])$, and storage constraint. However, Eq. (1) tells us that we should take into account content lifetime to choose cached nodes because nodes with longer content lifetime can reduce C_k for many possibilities of $P(T \in [t_k, t_{k+1}])$. Furthermore, to reduce C_k, we need to take into account geometric position of nodes in the network as demonstrated using an example in Fig. 4 in the previous section: it is obviously ineffective to choose the set of neighboring nodes like a and b or d and e. These observations motivated us to propose the following three proposed strategies based the estimated content lifetime:

Strategy 1: Longest lifetime (LT)
Step 1 Initialize: set i=1 and s=0.
Step 2 Pick node with i-th longest lifetime and add it to $\mathcal{I}$.
Step 3 $s = s + s_i$. s_i denotes consumed storage cost by node selected at Step 2.
Step 4 If $s < \theta$, $i = i + 1$ and back to step 2. Otherwise terminate algorithm.

Strategy 2: Split & longest lifetime (SLT)
Step 1 Initialize: set M=1.
Step 2 Set s=0 and split enroute network to M sub-networks with approximately equal number of nodes in each sub-network. Let set of split networks denote $\mathcal{M}$.
Step 3 For every sub-network $m \in \mathcal{M}$
1) Pick node with 1st longest lifetime in sub-network m and add it to $\mathcal{I}$.
2) $s = s + s_m$. s_m denotes consumed storage cost by selected node from network m.
Step 4 If $s < \theta$, $M = M + 1$ and back to step 2. Otherwise terminate algorithm.

Strategy 3: Proportional probability to lifetime (PLT)
Step 1 Initialize: set M=1.
Step 2 Pick M nodes from enroute nodes. Node i is chosen with probability $P_i = t_i$ / $\sum_{j=1}^{n} t_j$; nodes are chosen with probability proportional to their content lifetimes. Add the chosen nodes to $\mathcal{I}$.
Step 3 Set s=0. For every chosen node $i \in \mathcal{I}$, $s = s + s_i$.
Step 4 If $s < \theta$, $M = M + 1$ and back to step 2. Otherwise terminate algorithm.

We could say that LT is one of the optimal strategies because it maximizes the expected number of remaining cached nodes.

SLT and PLT are expected to reduce the expected number of hopcounts from the new location of the requester to the nearest cached node. In the example of Fig. 4, LT would select two nodes from the set $[a, b, c]$, SLT would select a node from the set $[a, b, c]$ and one from $[d, e]$ and PLT would select two nodes from $[a, b, c]$ with higher probability compared to $[d, e]$. Therefore, in this example, LT is closest to optimal while SLT and PLT follow closely. In order to implement these strategies, at least one node needs to know the information of the estimated content-lifetime and the estimated storage cost for every enroute node. One implementation strategy is for every enroute node to attach its own estimated content-lifetime and storage cost to the transferred data. This additional information is very small compared to the data size. Therefore, the overhead is insignificant. The last-hop node would then have the necessary information to execute the heuristic strategy. Content lifetime may be calculated at every node as a historical moving average of the time difference between caching and discarding contents at the node.

VI. Numerical evaluation model

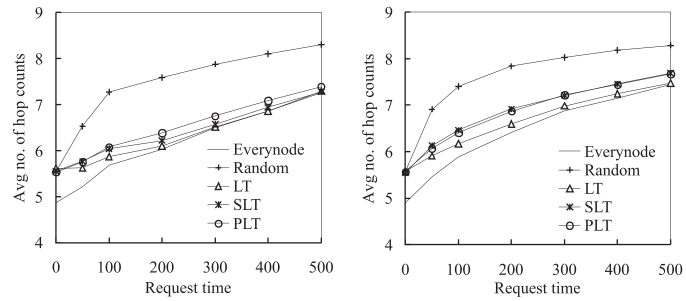
In this section, through a numerical evaluation, we provide a fundamental observation for the caching issue under intermittent connectivity. Our interest here is to evaluate the decrease in experienced cost with the proposed heuristic strategies when user movement happens. Generally speaking, to investigate caching schemes, we would need to introduce query model, cache replacement policy, content-size distribution, and link capacity model [8]. However, if we incorporate specific models to our evaluation, the existences of alternative models and parameters might cause loss of generality. Hence, we came up with a general model of the caching issue for intermittently connected mobile users described as follows:

1) Generate a network consisting of a few hundreds nodes
2) Choose randomly a node as the source
3) Choose randomly the last-hop node (see Fig. 2)
4) Set the content lifetime in each cached node . Note that the content lifetime in the source is set to infinity.
5) Apply one of the heuristic strategies to the enroute nodes and determine cached nodes
6) Choose a node as the (future) location of the requester
7) Set the request time manually
8) Pick the cached nodes whose content lifetime is NOT older than the request time
9) Measure the minimum hop distance from the requester location to the nodes picked at the previous step

This model allows us to clearly capture how the proposed strategies work when the requester's movement occurs without using any specific query and mobility models. However, it remains an issue how to appropriately model the content lifetime of each node. We came up with a simple model, which is represented as:

$$t_i = \bar{N}_i / \lambda_i \tag{2}$$

where $\bar{N}_i$, λ_i, and t_i are the number of content files node i can store, how many contents arrive at node i per time unit, and the expected lifetime of a content cached in node i. This model is based on the assumption that nodes get an opportunity to replace their caches every time a new content arrives at them. This is a reasonable assumption whatever replacement policy we use. For example, suppose that we adopt the least-recently-used (LRU) policy [7]. The newly cached content will be discarded at earliest after $\bar{N}_i$ new contents additionally arrive at node i. In our evaluation, we set $\bar{N}_i$ uniform and content arrival rate λ_i for node i proportional to how many shortest paths between two nodes pass through the node. This setting is also reasonable because nodes with higher centrality such as transit and junction nodes are more likely to receive contents in enroute caching.



(a) Fixed content lifetime (b) Exponential distribution

Fig. 5. The average number of hopcounts between the closest cached node and the requester as a function of the request time.

VII. Numerical results

In this section, we compare the performance of our strategies with a simple random strategy, in which cached nodes are randomly chosen from the enroute nodes, and the 'every-node' strategy, in which every enroute node is chosen as cached nodes without any constraint. The latter is a lower bound to assess the optimality of strategies. As illustrated in Fig. 1, the content-delivery network consists of the Transit domain and the Stub domains like the current internet. To generate this model, we used Georgia Tech Internetwork Topology Model (GT-ITM) [11]. We generated a simple network with two transit nodes in one transit network, 100 nodes in each of two stub networks. The average and maximum of shortest distance between two nodes are 8.8 and 19. The average and maximum numbers of degrees per node are 3.2 and 11. Although, due to space limitations, we just show the results using this topology, we have experimented with several other topologies and found essentially the same results.

Figure 5(a) shows the number of hopcounts measured at step 9 in the previous section, which was averaged over 5000 trials. Suppose that three nodes are selectable as cached nodes in addition to the source under a storage constraint. The horizontal axis indicates when the retrieval request arrives after the disconnection happened at time 0. The retrieval request time is represented using the relative value to the maximum content lifetime which is set to 1000. In Fig. 5(a), the later the retrieval request arrives, the larger number of hopcounts

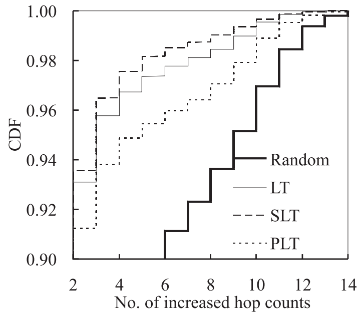


Fig. 6. The cumulative distribution function of the number of increased hopcounts compared with the Every-node strategy. The request time is 20.

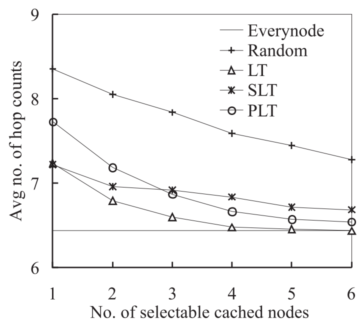


Fig. 7. The average number of hopcounts vs. the number of selectable nodes. The request time is 200.

is observed. This is simply because the number of cached nodes decreases as time passes. The proposed strategies are much better than the Random strategy and comparable with the Every-node strategy. Note that the worst number of hopcounts here should be 8.8, which is equivalent to the average of the shortest distances between two nodes. The best one is 4.9, which we can observe when Every-node is used and the request time is zero. The horizontal axis is scaled so as to cover this range.

In our previous result, the content lifetime was given as modeled in the previous section. We change this model in the following evaluations so that the content lifetime for node i follows the exponential distribution with mean of $\bar{N}_i/\lambda_i$. As shown in Fig. 5(b) even using such probabilistic lifetime model, the proposed strategies work well. In both Figs. 5(a) and 5(b), the LT strategy is the best among the three proposed strategies. This is simply because LT maximizes the expected number of remaining cached nodes.

To capture the benefits of SLT and PLT against LT, we plot how many hopcounts were increased compared with the Every-node strategy in Fig. 6. We here set the request time to 20 units of time. The result shows that when request arrives very early, there is a one hop improvement in the performance of SLT with respect to LT. Why the improvement was so limited is because, as the request is earlier, the number of remaining cached nodes is larger, which makes the difference between the two schemes small. On the other hand, when the retrieval request arrives late, the number of remaining cached nodes reduces, resulting in the loss of the benefit of SLT.

Finally, we evaluate the average number of hopcounts as a function of the number of selectable nodes shown in Fig. 7. As the number of selectable cached nodes increases, all the strategies become closer to the Every-node strategy as we could easily predict. We observe that the superiority of SLT to PLT decreases as the number of the selectable nodes increases. LT minimizes the number of hopcounts regardless of the number of selectable nodes.

VIII. Conclusion

In this paper, we have discussed network caching strategies for intermittently connected mobile users. We showed the problem formulation and then proposed heuristic strategies based on the content lifetime concept. Through a numerical evaluation, the proposed heuristic strategies were shown to provide significant performance improvement over random caching and also approach the lower bound for enroute caching. Considering the complexity, we could conclude that complexity of an optimization solution is unnecessary. Furthermore we observed the LT strategy, which simply chooses the nodes with the longest lifetime, minimized the hopcounts because this is the optimal solution to maximize the expected number of remaining cached nodes for the future retrieval request. Since we have given a general performance study in this paper, future work should include consideration of more specific network, traffic and mobility models. We could further extend our discussion to predictable mobility and request time though we assumed only unpredictable ones in this paper. Prototyping of mobile content caching algorithms is also under consideration at WINLAB using the ORBIT radio grid testbed [12] as the experimental platform.

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