A Heuristic Approach for Overlay Content-Caching Network Design in 5G Wireless Networks

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***Abstract*—With a wide variety of mobile applications and social networks, there is a growing demand for anytime, anywhere access to high quality video and other multimedia content. Fifth generation wireless networks are aiming to keep up with user demands by incorporating new spectrum bands at high frequencies, which results in shrinking of cell sizes and eventually leads to small cells. Dense deployment of small cells and base stations open up new opportunities for faster and energy-efficient access to content. Content caching at small cell base stations, for the purpose of reducing delay, has been studied in several previous works. In our previous work, we used Integer Linear Programming (ILP) models to show that content caching can also reduce energy consumption of User Equipment (UE). In particular, selecting a subset of small cell base stations to cache the content, reduces uplink energy budget, cuts down caching energy budget and simplifies management of distributed caches. Yet, ILP based methods are powerful for obtaining benchmark results but they are computationally intensive for large size problems. In this paper, we propose a particle swarm optimization (PSO) based scheme to deploy an overlay small cell content-caching network with the aim of reducing UE energy consumption. We show that PSO is computationally efficient while it slightly increases energy consumption with respect to the ILP-based methods.**

***Index Terms*—Content caching, heterogeneous networks, particle swarm optimization, small cell networks, wireless networks.**

I. Introduction

With the increasing popularity of social networks, mobile applications, and advances in smartphone hardware, users are demanding high quality video, or other rich multimedia content, on-the-go. According to the mobility report of Ericsson, 70% of all mobile data traffic is forecasted to be online video by 2021 [1]. In modern mobile connected devices, wireless networks are the bottleneck for content delivery. This means 5G wireless networks should aim to enhance data rates and reduce latency to meet the ever increasing user demands. However, increasing the wireless capacity cannot solve the core problem of content delivery which is that the user traffic is outpacing the increases in the transmission rates of modern networks [1].

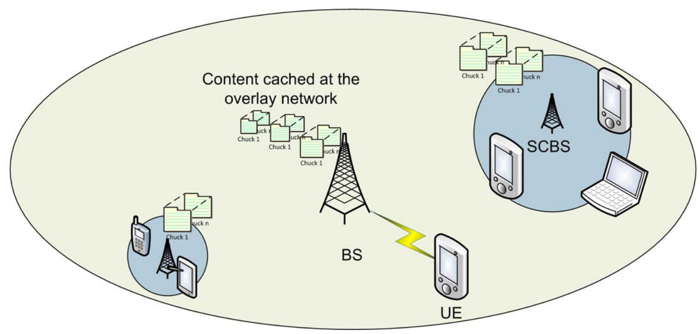

Fig. 1. Illustration of content caching at small cell base stations.

One particular source of inefficiency occurs when multiple users access the same content from similar geo-locations. Delivering content each and every time, wastes network resources and can even congest the upcoming 5G systems. At the same time this user behavior allows a unique optimization. Mobile network operators (MNOs) can deploy the well-known Internet solution of Content Delivery Networks (CDNs). In a CDN, popular contents are stored in multiple servers that are geographically dispersed. This approach naturally brings contents closer to the user and reduces latency [2]. CDNs have been used successfully as part of the Internet when computers were the mass content consumers. Today mobile devices already dominate content consumption.

5G systems are expected to be rolled out by the year 2020. It is anticipated that the heterogenous network (HetNet) architecture will be part of the landscape. HetNets consist of a macro cell and multiple small cells and/or relays. Small cells allow spatial reuse and so they can increase significantly capacity and coverage. For 5G in particular, when millimeter Wave (mmWave) channels are used, smaller cell sizes are inevitable due to pathloss constraint. Thus, densely deployed base stations covering small areas are expected to prevail in 5G. As the cost of unit memory is decreasing, utilizing those base stations as content servers opens up new opportunities. This approach is sometimes referred to as caching in the air

[3], cache at relay [4] and caching at the edge [5]. This also allows effective utilization of network resources since user demands do not travel all the way up to the content servers located in the core of the Internet. An illustration of content caching at small cell base stations is given in Fig. 1.

In this paper, we propose a Particle Swarm Optimization (PSO)-based overlay network design for HetNets with content-caching capability. The goal of the heuristic method is to reduce the energy consumption of UEs while accessing content cached on small cell base stations. Our optimization selects the base stations for inclusion in the overlay topology, which allow content download and servicing as a CDN overlaid on the existing physical deployment of Small Cell Base Stations (SCBSs). In our previous work [4], we proposed ILP-based solutions to minimize uplink energy when content is cached at relays. However, the time complexity of the ILP-based solution increases with the number of base stations, UEs, and contents. In this paper, we use the previous energy-efficiency oriented schemes as a baseline, and compare it with the proposed PSO-based scheme. We show that PSO has significantly lower runtime than the ILP model at the cost of slightly higher energy consumption. The benefits of such a scheme are significant since it allows the creation of overlay caching topologies with low computational complexity and overhead while offering a significant performance boost.

The rest of the paper is organized as follows. In Section II, we summarize the related works in content-caching at wireless networks with a brief background on CDNs. In Section III, we provide the system model and in Section IV, we present the proposed PSO-based overlay formation scheme and give a short description of the corresponding ILP-based model that is used in performance comparison. In Section V we discuss the performance of the proposed scheme. Section VI concludes the paper with a summary of findings, future directions and planned work.

II. Related Work

Traditional CDNs and Peer-to-Peer (P2P) networks rely on replicating content on distributed servers which are likely to be closer to a group of users. CDNs are implemented in core networks for the purpose of reducing delay when accessing contents and consuming fewer network resources [6], [7]. There has been a significant interest recently to cache contents closer to mobile users [8], [9]. One of the initial works that considered caching at the Radio Access Network (RAN) has been presented in [10]. In [11], the authors considered caching at femtocells as well as device-to-device cooperation to minimize latency. In [12], the authors studied the delivery of content via Cooperative Multi Point (CoMP) transmission and caching at relays to minimize redundant transmissions from the Macro cell Base Station (MBS). These works do not focus on energy efficiency aspects of the overall system. Several other earlier works have studied energy efficiency issues for mobile and cached content delivery in arbitrary wireless ad hoc networks [13]. In more recent works, the authors in [14] investigated the interplay between energy and caching in the context of small cells. The center of this later study was the energy-efficiency of the base station and more specifically the wireless transmit power. Reducing the energy consumption at the SCBS/MBS reduces the rate and overall experience of cached content delivery. In another recent work, the authors in [15] presented a framework that jointly optimizes the energy cost at the SCBSs and the file delivery delay for the users.

In this work, we also consider the presence of cache-endowed small cells. We augment the literature by focusing on the energy-efficiency of the UEs rather than BSs, an aspect that has been previously neglected. Energy efficiency is critical for UEs because the majority of the smart phones today are left with drained batteries at the end of a day when video applications are intensively used. We propose a heuristic-based approach that creates an overlay between cache-enabled small cell base stations that allows minimization of the UE energy when downloading videos. We had initially explored caching for improving energy efficiency in [4], [16], [17]. In those works, we proposed three Integer Linear Programming (ILP) models where the first model selected the optimal set of relays given that relay locations and cached contents are known. The second model studied optimal content placement and the third model jointly minimized the number of relays serving as content holders and the uplink power of the UEs. This later model was named as Place Relay (PREL). PREL addressed the trade off between relay deployment cost and uplink energy budget. In the present paper, PREL acts as a benchmark ILP-model that provides the lower bounds for the proposed heuristic method.

III. System Model

A. Network Model

Let $G = (V, E)$ be a connected graph representing the snapshot of the mobile wireless network within the timeframe δ_t which is equal to the optimization horizon. Also T is the set of UEs and $T \subset V$. A is the set of all small cell base stations where $A \subset V$. Regarding the cardinality of these sets we have $|T| = N_{UE}$ and $|A| = N_{SCBS}$. A_c is the set of base stations included in the overlay network and are enabled to cache content. A_{nc} is the set of base stations that do not cache contents during the given optimization horizon, which means $A_c \cup A_{nc} = A$. Each SCBS $i \in A$ has an identical storage with capacity of St_R bits and identical communication range of D_R meters. UEs within the communication range of a BS can be associated with it. In general, if a UE is covered by more than one UE, strongest Signal to Interference-Noise Ratio (SINR) can be used to determine association. The small cells are deployed within the macro cell coverage area as illustrated in Fig. 1. The communication range of the macro cell BS (MBS) is D_{BS} meters. Regarding user deployment we assume each $n \in T$ is randomly deployed within the cell. Finally, only unicast communication is considered since it is the standard delivery method for Video on Demand (VoD) applications where the content can be cached. For streaming live popular videos such as sports events, only then multicast can be considered but in this case, caching is not convenient.

B. Content and User Demand Model

The content library is denoted as the set $K = \{0, ..., k, ...\}$. We assume that the SCBS caches have been populated with these contents during the prior system operation (typically the caches may change/re-populated with a period of a few days [11], [15], [18]). Also at the start of the optimization horizon user demands are known and are captured through a demand vector. Hence, we study the short-term performance during content delivery and after these caching decisions have been made and the content is fixed for each SCBS $i \in A_c$. Regarding each video content, it can generally be partitioned into chunks[1]. Our model is not restrictive and it allows for these chunks to be stored at different base stations.

C. Power Consumption Model

We aim to evaluate the energy consumption of UEs. The PSO-based scheme and PREL compute the uplink power. Hence, power must be converted to energy. According to the findings of [19], the uplink energy of a UE, E_{UE}, is given by:

$$E_{UE}[mJ] = \frac{P_{UE} * N_d * S_k}{T} \tag{1}$$

where P_{UE} is the uplink power, N_d is the number of contents demanded from a SCBS, S_k is the size of the content and T is the throughput. Uplink power calculation may vary from different UE hardware. We used the derivation in [4], [19] to compute P_{UE}.

IV. Overlay Network Design for Content Caching

In this section, we present first the ILP optimization model which serves as a benchmark. It also allows for a direct comparison with our proposed scheme.

A. Place Relay (PREL) Optimization Model

The ILP model was initially proposed in [4] with the objective of jointly minimizing the number of relays and the uplink power of the UEs. However, minimizing the number of relays is equivalent to identifying the optimal number of SCBSs in the overlay content caching network, an objective of the present paper. This allows us to use the previously developed ILP as a baseline framework for comparisons. An important aspect of PREL was that it involved a tradeoff between energy efficiency and the number of dedicated SCBSs. This can accomplished by introducing a normalizing weight factor denoted as σ. The PREL optimization problem is:

$$\begin{aligned} \min_{\alpha^k_{xy,i}, \Psi^{i,k}_{xy}} \quad & \sigma \sum_x \sum_y R_{xy} P^{coff} \\ & + (1-\sigma) \sum_i \sum_k \sum_x \sum_y P^{tr,SCBS}_{xy,i,k} \Psi^{i,k}_{xy} \\ & \text{subect to } \mathcal{C} \end{aligned} \tag{2}$$

[1]Dynamic Adaptive Streaming over HTTP (DASH) uses chunks with typical sizes of a few Mbytes that are called *segments*.

In the above $\Psi^{i,k}_{xy}$ is a binary optimization variable that is 1 if there is a SCBS at (x, y) and UE i is receiving the k_{th} content from the SCBS located at (x, y).

$$\Psi^{i,k}_{xy} = R_{xy} \alpha^k_{xy,i} \tag{3}$$

$\alpha^k_{xy,i}$ is a binary variable that is 1 if UE i is downloading content k from the relay at (x, y). P^{coff} is a constant to scale the first term. $P^{tr,SCBS}_{xy,i,k}$ is the uplink power of UE i to download k_{th} content from the base station at (x, y). The constraint set, that will be described shortly, is denoted as $\mathcal{C}$. The optimization variables are related to each other as follows. The set of constraints ensure that the UEs do not download contents in parallel from multiple BSs, there are no redundant relays, geometric constraints are met, and binary variables are linearized. The resulting constraint set is presented below:

$$\alpha^k_{xy,i} \le R_{xy} H^k_i, \qquad \forall x, y, i, k \tag{4}$$

$$\sum_x \sum_y \alpha^k_{xy,i} = H^k_i, \qquad \forall i, k \tag{5}$$

$$\sum_i \sum_k \alpha^k_{xy,i} \ge R_{xy}, \qquad \forall x, y \tag{6}$$

$$\Psi^{ik}_{xy} \le R_{xy}, \qquad \forall x, y, i, k \tag{7}$$

$$\Psi^{ik}_{xy} \le \alpha^k_{xy,i}, \qquad \forall x, y, i, k \tag{8}$$

$$\Psi^{ik}_{xy} - R_{xy} - \alpha^k_{xy,i} \ge -1, \qquad \forall x, y, i, k \tag{9}$$

$$\alpha^k_{xy,i} d_{xy,i} \le D_R, \qquad \forall x, y, i, k \tag{10}$$

$$\alpha^k_{xy,i} = 0, \qquad \forall d_{xy,i} > D_R \tag{11}$$

$$\alpha^k_{xy,i} \le R_{xy} \eta^k_{xy} H^k_i, \qquad \forall x, y, i, k \tag{12}$$

$$\alpha^k_{xy,i} d_{xy,i} \le d_{i,BS}, \qquad \forall x, y, i, k \tag{13}$$

$$\beta^k_{i,BS} + \sum_x \sum_y \alpha^k_{xy,i} = H^k_i, \qquad \forall x, y, i, k \tag{14}$$

The constraints ensure that each UE can download one content from one and only one relay and if there is a relay at (x, y) at least one UE downloads at least one content from that relay. Coverage constraints and linearization of the binary variable Ψ^{ik}_{xy} is also included in the constraint set.

B. Heuristic Method based on Particle Swarm Optimization

The main contribution of this paper is the use of particle swarm optimization (PSO) for selecting the most energy-efficient set of SCBSs for inclusion in the overlay network. The goal of the overlay network design is to minimize energy consumption of UEs. PSO uses a number of particles where each particle represents a solution in an N-dimensional space. Particles constitute a swarm moving in the search space looking for the optimal solution. The best solution the particle has reached so far is denoted by $pbest$. The search of the overall swarm gives a global optimal solution which is denoted by $gbest$. The aim of the proposed approach is to find the optimal overlay caching network layout that minimizes the energy consumption of UEs by including an optimal number of

Algorithm 1 —Location Update Algorithm

1: {Input: $p \in S^N$, $pbest \in S^N$, $gbest \in S^M$}
2: {Output: $p \in S^N$ located at new location}
3: **for** $j = 1$ to $min(N, M)$ **do**
4: `Get` R `with` $r = j$ `from` $gbest$ `and` $pbest$
5: `Update location of` R_j^p `according to` $R_j^g best$ `and` $R_j^p best$ `using eqn (1)`
6: `Get` R `with` $r = j$ `from` $gbest$ `and` $pbest$
7: **if** $N > M$ **then**
8: `Eliminate` R `with` $r > M$
9: **end if**
10: **end for**

SCBS in the overlay network. Note that, each additional SCBS brings in caching cost and cache management complexity. The overlay content-caching network evolves in time.

In the PSO-based scheme, at each iteration, particles update their search location according to their previous moving direction, $pbest$ and $gbest$ according to the following equation:

$$V_i^{k+1} = \omega V_i^k + w_1 r_1 (pbest - p_i^k) + w_2 r_2 (gbest - p_i^k) \quad (15)$$

where, V_i^k is the velocity of the particle i at the iteration k, ω is a weighting function and w_1, w_2 are weighting factors, r_1, r_2 are uniformly distributed random numbers between 0 and 1, and p_i^k is the position of the particle i at iteration k.

Large weighting function ω lead to better results in global search and small values gives better results in local search. A small value of ω will lead the particle toward $pbest$ and $gbest$ faster, and that gives the ability to faster approach to the local minimum, which is most likely located in the neighborhood of $pbest$ and $gbest$. By linearly decreasing ω from a relatively large value to a small value gives better convergence than fixed ω, as expected.

Let S^N be the solution with N number of SCBSs, the location update works as follows:

- For the particle $p \in S^P$ where P is number of particles, each SCBS $R \in p$ will have its own fitness which is the utilization of that SCBS. r denotes the rank for each SCBS where $r = 1, ..., N$. (1 for highest utilization and N for lowest utilization).
- Updating the location of the particle means that for each SCBS $R \in p$, the location is updated according to the same rank of SCBS $pbest$ and $gbest$.
- If $gbest \in S^M$ with $M < N$, only SCBS with $r \leqslant min(N, M)$ will be updated and SCBS with $r > min(N, M)$ will be eliminated.
- If $gbest \in S^M$ with $M > N$, SCBS with $r \leqslant min(N, M)$ will be updated with no addition to match $gbest$.
- That implies that rank of $pbest^k \leqslant pbest^{k-1}$.

Location update is summarized in Algorithm 1.

The overlay network design uses the location update algorithm, and at each iteration, establishes the connections and computes the control parameters, utilization, uplink energy and fitness of the distribution of each particle. If a better solution is attained, $gbest$ and $pbest$ are updated, in addition to updating the particle locations. This process is repeated until the minimum budget of iterations is reached. The overlay network formation scheme is given in Algorithm 2.

Algorithm 2 —Overlay Caching Network Formation Algorithm

1: {Input: A (Set of SBCS), T (Set of UEs)}
2: {Output: A_c (Set content caching SBCSs)}
3: `Initialize swarm with` $p \in S^N$`, UE is the user equipment distribution map`
4: `Create two vectors;` V_R `contains` K `different solution for SBCS distribution map, and` V_{UE} `contains` N `copies of UE`
5: **for** $k = 1$ to $maximum\_budget$ **do**
6: **for** $j = 1$ to K **do**
7: `Connect` V_R^j `to` V_{UE}^j
8: `Find utilization (rank) of each` $R \in V_R^j$
9: `Find uplink power and fitness for` V_R^j
10: `Update` $pbest$ `and` $gbest$
11: `Update location using algorithm 1`
12: `Reset connections between` V_R^j `and` V_{UE}^j
13: **end for**
14: **end for**
15: `Repeat 1 to 3 for different swarm with different UE distribution map`
16: `Mask` $gbest$ `from all swarms and find the optimal`

V. Performance Evaluation

The proposed PSO-based scheme is implemented in MATLAB while the ILP optimization model is solved using the CPLEX optimizer with the same settings. We consider a single macrocell with a radius of 1km. We assume SCBSs are deployed densely enough to cover minimally each grid point. Overlay network members are selected from the existing SCBSs. The range of an SCBS is set to 200m which is close to the maximum achievable range for real-life outdoor base stations [20], [21]. We assume the number of UEs that download video varies from 20 to 100 and they are randomly deployed within the cell. Our results are averaged over 10 runs.

Our performance metrics are uplink energy, overlay network size and runtime complexity. We also show the intermediate iterations of PSO to illustrate the overlay network. In Fig. 2 and in Fig. 3, we present two iterations of the proposed PSO-based scheme. Each UE requests a video chunk, and to receive it establishes a connection to the nearest SCBSs (green triangle) that have the chunk. The green circles represent the coverage range for each SCBS. Through the iterative execution

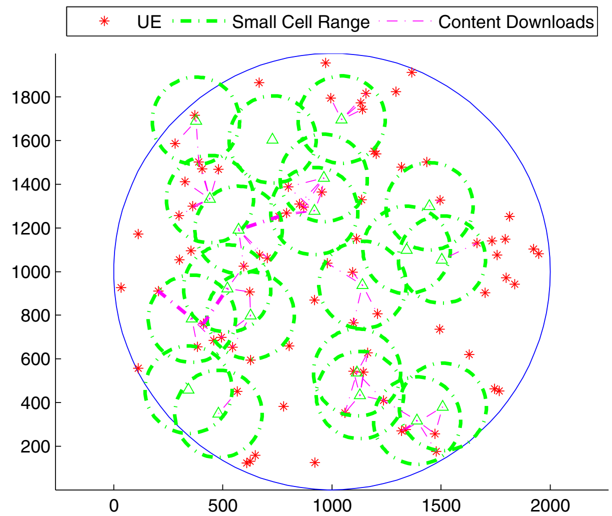

Fig. 2. Overlay content-caching SCBS network and UEs after iteration 15.

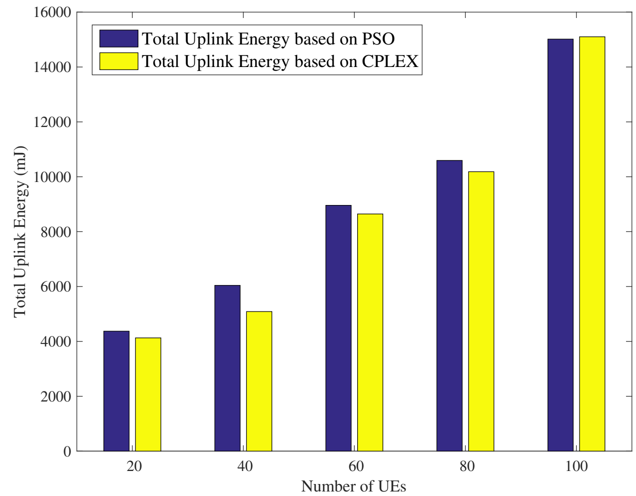

Fig. 4. Uplink energy comparison of the PSO-based scheme and PREL (ILP-based scheme).

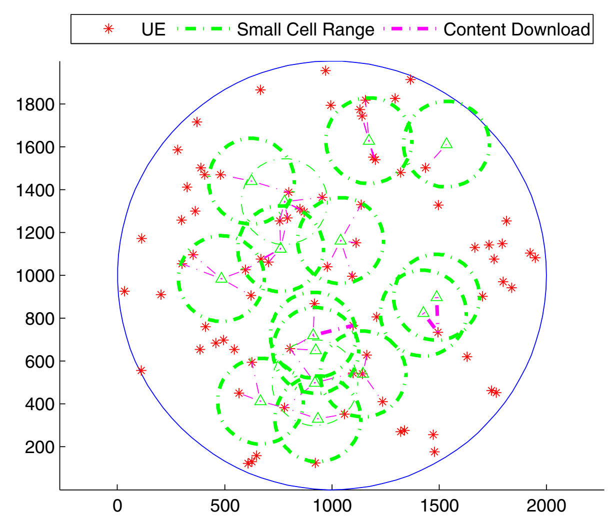

Fig. 3. Overlay content-caching SCBS network and UEs after iteration 30.

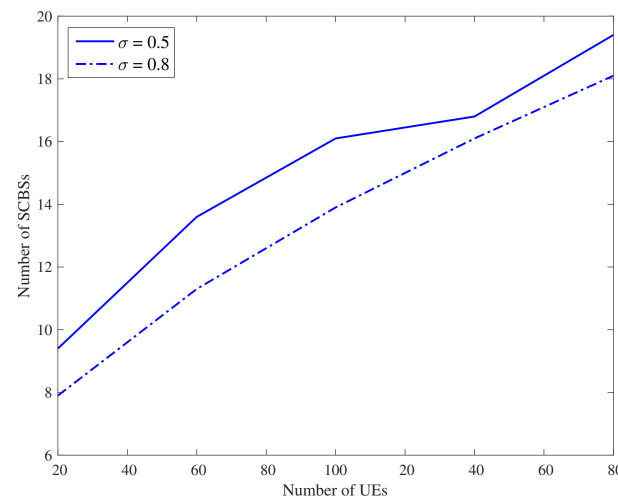

Fig. 5. Overlay network size for weight factor $\sigma = 0.5$ and $\sigma = 0.8$.

of the algorithm, the SCBSs with the optimal location are selected for inclusion in the overlay network.

In Fig. 4, we show the uplink energy consumption of UEs for the PSO-based and ILP-based schemes. Our results show that the total uplink energy for both schemes is similar, while in PSO it tends to be slightly higher because the algorithm may be trapped occasionally in a local minimum. In our performance evaluation, we calculate the uplink energy using an uplink data rate of 8Mbps. Uplink power is translated into energy following the approach in [19]. PREL is executed with $\sigma = 0.5$ which means selection of relays and energy-efficiency have equal importance.

In Fig. 5 we present the size of the overlay network size when the proposed scheme was used, for different weighting factors σ. We notice that with a higher value for σ the optimization tends to find the optimal point with fewer number of SCBSs.

Finally, in Fig. 6 we compare the runtime of the proposed scheme with PREL. Our results indicate that the PSO-based scheme can find the optimal solution faster than the ILP-based scheme (PREL). This performance difference increases when the number of UEs increases.

VI. Conclusion

5G wireless networks are expected to embrace a wide variety of techniques to meet the ever-increasing mobile data traffic. Overlay content-caching network formation, similar

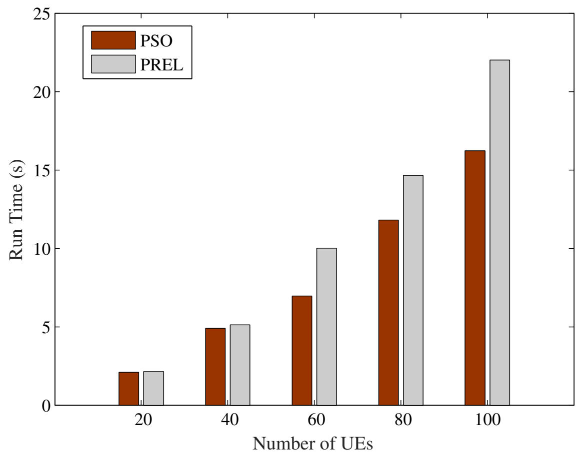

Fig. 6. Run time for PSO and ILP-based scheme (PREL).

to Internet CDNs, brings in several advantages including reducing delay, better usage of network resources and reducing energy consumption. In this paper, we propose a heuristic for overlay network design that reduces the uplink energy of UEs. The proposed scheme is based on Particle Swarm Optimization (PSO) where the energy-minimizing set of small cell base stations (SCBSs) is determined with an iterative algorithm. This approach is compared to a previously proposed ILP-based scheme, namely Place Relays (PREL). PREL jointly minimized the number of selected relays and energy consumption of UEs. Our results indicate that the proposed scheme can form an overlay topology in shorter run-times while approaching the performance of PREL. We plan to extend this work to integrate energy efficiency of downlink, energy efficiency of BSs and jointly improving latency and throughput performance. In addition, video content awareness can be incorporated to provide a more effective distribution of video partitions over the distributed BS storage.

References

[1] P. Cerwall (ed.), "Ericsson Mobility Report", November 2015. [Online] http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-nov-2015.pdf.

[2] G. Pallis, A. Vakali, "Insight and perspectives for content delivery networks," Communications of ACM, vol. 49, no. 1, January 2006, pp. 101-106.

[3] X. Wang, M. Chen, T. Taleb, A. Ksentini, V. Leung, "Cache in the air: exploiting content caching and delivery techniques for 5G systems," IEEE Communications Magazine, vol.52, no.2, pp.131-139, February 2014.

[4] M. Erol-Kantarci, "Cache-At-Relay: Energy-Efficient Content Placement for Next-Generation Wireless Relays," International Journal of Network Management (Wiley), vol. 25, no 6, pp. 454-470, Nov./Dec. 2015.

[5] B. Perabathini, E. Bastug, M. Kountouris, M. Debbah, A. Conte, "Caching at the Edge: a Green Perspective for 5G Networks," In Proc of ICC.15, London, UK.

[6] J. Llorca, A.M. Tulino, K. Guan, J. Esteban, M. Varvello, N. Choi, D.C. Kilper, "Dynamic in-network caching for energy efficient content delivery," IEEE Proceedings of INFOCOM, pp.245,249, April 2013.

[7] Wang, Y.; Li, Z.; Tyson, G.; Uhlig, S.; Xie, G., "Design and Evaluation of the Optimal Cache Allocation for Content-Centric Networking," in Computers, IEEE Transactions on , vol.65, no.1, pp.95-107, Jan. 1 2016.

[8] L. Dong, D. Zhang. Y. Zhang, D. Raychaudhuri, "Optimized content caching and request capture in CNF networks," Annual Wireless Internet Conference (WICON), pp.1,9, 1-3 March 2010.

[9] Poularakis, K.; Iosifidis, G.; Sourlas, V.; Tassiulas, L., "Exploiting Caching and Multicast for 5G Wireless Networks," in Wireless Communications, IEEE Transactions on , vol.PP, no.99, pp.1-1.

[10] J. Erman, A. Gerber, M. Hajiaghayi, D. Pei, S. Sen, O. Spatscheck, "To Cache or Not to Cache: The 3G Case," IEEE Internet Computing, vol.15, no.2, pp.27,34, March-April 2011.

[11] N. Golrezai, A. F. Molisch, A. G. Dimakis, and G. Caire, Femtocaching and Device-to-Device Collaboration: A New Architecture for Wireless Video Distribution, IEEE Comm. Mag., vol. 51, issue 4, 142-149, 2013.

[12] A. Liu, V. K. N. Lau, "Cache-Enabled Opportunistic Cooperative MIMO for Video Streaming in Wireless Systems" CoRR abs/1306.2701, 2013.

[13] P. Nuggehalli, V. Srinivasan, and C.-F. Chiasserini, "Energy-efficient caching strategies in ad hoc wireless networks," in *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking &Amp; Computing*, ser. MobiHoc '03. New York, NY, USA: ACM, 2003, pp. 25–34.

[14] X. Wang, Y. Bao, X. Liu, Z. Niu, "On the design of SCBS caching in cellular networks for energy efficiency," IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp.259,264, 10-15 April 2011.

[15] K. Poularakis, G. Iosifidis, A. Argyriou, and L. Tassiulas, "Video delivery over heterogeneous cellular networks: Optimizing cost and performance," in *IEEE Infocom*, 2014.

[16] M. Erol-Kantarci, "Content Caching in Small Cells with Optimized Uplink and Caching Power," IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, USA, 2015.

[17] M. Erol-Kantarci, "Uplink Power Optimized In-Network Content Caching for HetNets," International Conference on Computing, Networking and Communications (ICNC) - Workshop on Computing, Networking and Communications (CNC), Anaheim, CA, USA, 2015.

[18] M. Maddah-Ali and U. Niesen, "Fundamental limits of caching," in *ISIT*, July 2013, pp. 1077–1081.

[19] B. Dusza, C. Ide, L. Cheng, C. Wietfeld, "An Accurate Measurement-Based Power Consumption Model for LTE Uplink Transmissions," IEEE Infocom 2013.

[20] T. Wirth, V. Venkatkumar, T. Haustein, E. Schulz, R. Halfmann, "LTE-Advanced SCBSing for Outdoor Range Extension," IEEE Vehicular Technology Conference Fall (VTC 2009-Fall), pp.1,4, 20-23 Sept. 2009.

[21] J. Gan, Z. Guo, F. Rui, L. Weihong, W. Hai, K. Sandlund, J. Liu, X. Shen; G. Liu, "LTE In-Band SCBS Prototype and Field Measurement," IEEE Vehicular Technology Conference (VTC Spring), pp.1,5, 6-9 May 2012.