Study of Mobility in Cache-enabled Wireless Heterogeneous Networks

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***Abstract*—Caching popular multimedia content has the potential to take wireless networking to an unprecedented height in terms of user experience. Primary motif behind content caching is to give frequent access to popular content cached at local caches, such as femto access point with finite storage. Although content-caching was initially limited to wired backbone networks, it now being developed for wireless networks. The main difference between these two cases is the potential mobility of the user. We thus investigate the impact of user mobility on the performance of content-caching wireless heterogeneous networks (HetNets). We describe the user mobility by the random waypoint model and characterize the spatial randomness of different types of nodes by using independent Poisson point processes. Using their stochastic properties, we analyze the handover probabilities and evaluate expected download delay as a function of handover probabilities.**

***Index Terms*—HetNet, Mobility, Caching, Wireless Communication**

I. Introduction

Annual mobile traffic growth is greater than 50% [1], and commercial explosion of tablets and mobile devices suggest even greater future growth prospects. Moreover, fifth generation (5G) wireless standards with their unprecedented performance benchmarks require technical breakthroughs. Various innovative technologies are being developed [2]–[4], and cache-enabled content-centric networking is one of the most promising technologies [5]. According to Cisco only a small percentage of data (5-10%) is requested by the majority of users, whereas other data is occasionally requested [6]. Therefore, caching the popular content can significantly help to offloading traffic, increase throughput, and reduce end-to-end latency. Content can be cached at the terminal devices such as femto access points and routers to serve content requests without forwarding them to the server. Golrezaei *et al.* in their seminal paper explored the concept of caching contents at femtocells to improve wireless video streaming experience [7].

However, user mobility is a necessary feature of most wireless systems. In particular, it is essential for cellular networks and the performance impact of user mobility depends on fading and handover requirements. In terms of wireless content caching, we are interested in, for example, how mobility affects the performance and handover probabilities and related questions. For example, content downloading from a femto AP can be greatly affected by user mobility. Due to its smaller coverage area, a user moving out of a femto AP region may happen quickly. This move will result in a handover. Thus, handover probabilities of cache-enabled systems in a mobile environment must be rigorously analyzed. To the best of our knowledge, the study of the effects of mobility in content-caching wireless networks has not been reported. Hence, in this paper we develop a mathematical model to explore the impact of user mobility on the performance of cache-enabled wireless networks. We thuse develop the relations between handover and transition length of the mobile device, cache size of femto access points (APs), size of content universe, and content popularity skewness.

A. Contribution

Specifically, the contributions of this paper are listed as follows:

- We develop a stochastic geometry based analytical framework for content-caching wireless networks. The caching ability at femto APs is finite.
- We consider random waypoint mobility model to analyze the effects of user mobility. To this end, we derive analytical expressions for different handover probabilities. We also develop an expression for expected delay depending on mobility.
- We provide extensive performance results for various caching and mobility parameters. We also analyze the effect of mobility on delay for wireless content-caching networks.

B. Paper Organization

Rest of the paper is organized as follows. We briefly overview the related works in Section II. We discuss the main problem and develop the analytical framework in Section III. Performance evaluation and discussion are given in Section IV. Finally we summarize and conclude in section V.

II. Related Work

Cache-enabled content-centric communication has recently gained significant attention of researchers. Initially applied to wired networks, the content caching concept has now spread to wireless networks. Several works on content-caching networks for wireless medium, without considering mobility are available. For example, Baştuğ *et al.* propose a machine learning based caching strategy for wireless networks [8], however, they did not consider the spatial randomness of the nodes. Considering the spatial randomness of nodes via

Poisson point processes, authors in [9] study optimal caching for cellular networks. An asymptotic analysis of required link capacity for multi-hop cache-enabled wireless networks is analyzed in [10]. However, spatial randomness of nodes is omitted. Overall, the lack of holistic analysis, considering a content-centric mobile wireless network motivates us to write this paper.

Since mobility is a fundamental feature of wireless systems, several analytical models are available [11]–[13]. However, according to [14], human movement has extremely complicated spatial and temporal correlations. Nevertheless, Lin *et al.* developed an analytical model where nodes are initially modeled as Poisson spatial randomness and their mobility is modeled considering transition lengths to be Rayleigh distributed [15]. As the results match well with real-life data, therefore, in this paper we use the model in [15] to analyze the effect of mobility on wireless caching.

Earlier, [16] analyzed the effect of mobility on coverage probability of a device-to-device communication. However, a two file system is assumed, which does not reflect realistic scenario. Therefore, in this paper we develop a generalized analytical framework and analyze handover probabilities and their cumulative effect over delay.

III. MAIN RESULTS

A. Problem Statement

We consider a cellular network with multiple BSs, femto APs, and users. Users are connected to a BS following nearest association rule. BSs are connected to the servers via backbone links and femto APs are connected to the BSs using backhaul links. We also consider that each femto AP has a fixed amount of cache memory and content are temporarily stored there. Content requests are follows popularly modeled with power law distributions such as a Zipfian, Pareto or a Zeta distribution (we use Zipfian). We also assume that requests for content follow an Independent Reference Model (IRM) [17], and the Femto APs follow leave copy everywhere (LCE) [18] caching strategy and least recently used (LRU) cache eviction policy.

Our goal in this paper is to study the effects of mobility when a content request is served by the femto AP. We want to analyze handover schemes when the user is moving out of femto AP's coverage area, and the effect of handover in expected download delay.

B. Network Architecture

We consider the customary cellular architecture where each cell consists of a single base station (BS), multiple femto access points (APs), and users. Each femto AP has a finite memory to cache content. Basic overview of the architecture is given by Figure 1.

We assume the users to connect with the nearest BS, and therefore, the cellular architecture can be modeled using the Poisson-Voronoi tessellation, which is briefly described next.

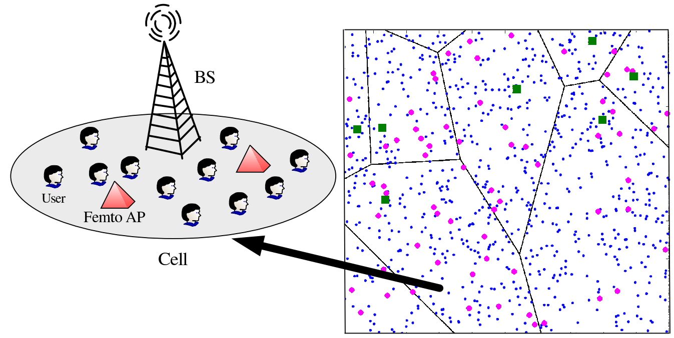


Fig. 1: Network Architecture

Consider the set of BSs to be $\Phi = \{x_i\}$. Hence the Voronoi cell $C_{x_i}(\Phi)$ of point x_i is defined as [19],

$$C_{x_i}(\Phi) = \{y \in \mathbb{R}^2 : \| y - x_i \|_2 \quad \leq \quad \| y - x_j \|_2 \quad , \forall x_j \in \Phi\} \tag{1}$$

Therefore, each BS x_i serves the mobile users within C_{x_i}, which follow the nearest BS association strategy. We will make of point processes to analyze the effects of mobility in content-caching wireless networks.

The common symbols are tabulated in Table I.

TABLE I: Notations and Descriptions

Notation	Description
K	Content universe
α	Skewness parameter of Zipfian distribution
β	Path-loss exponent
P_{tB}	Transmit power of base-station
P_{tf}	Transmit power of femto AP
r_b	Distance between user and base-station
r_f	Distance between user and femto AP
$\mathcal{C}$	Cache size
$\mathcal{H}$	Hit-rate
P_{th}	Threshold signal strength for detection
$\mathcal{L}$	Transition length of the mobile device
$\mathcal{T}$	Transition time for the mobile device
$\mathcal{V}$	Velocity of the mobile device
P_h	Probability of handover
P_{hff}	Probability of femto-femto handover
P_{hfbs}	Probability of handover between femto and same cell BS
P_{hfbd}	Probability of handover between femto and different cell BS

C. Analytical Results

We assume the BSs, femto APs, and users are distributed over a 2-dimensional space $\mathbb{R}^2$ following three independent homogeneous Poisson point processes (PPP's) with intensity λ_1, λ_2, and λ_3, respectively. We can also assume that $\lambda_2 > \lambda_1$, which is reflects the typical deployment rates of the two types of serving nodes.

We now consider a user request for content. There are two possible sources to serve the request, a nearby femto AP which has the content, and the BS. Let us assume the content is available at the femto AP, in that case the source selection depends on the received signal strength (RSS). Therefore, user downloads a content from the femto AP only if its RSS is greater than the RSS from BS. One important aspect of this form of communication is handling the mobility issues. Once the user moves beyond the range of femto AP, multiple handover scenarios are possible. Therefore, at first we determine the possible handover, 1) Femto to Femto, 2) Femto to BS (same cell), and 3) Femto to BS (different cell), and thereafter, determine the probabilities of each handover.

To determine the handover probabilities, first of all we need to determine the probability of accessing a content from a cache. We denote the content universe by K with n number of unique content. Assuming LRU cache eviction policy, probability of obtaining a requested content from a cache can be calculated following the hit-rate analysis by Che *et al.* [20]. Assume the requested content is k_i and the cache of interest is l. We assume that probability of requesting a content follows Zipfian distribution with skewness α, therefore, probability of requesting content k_i is,

$$p_{k_i} = \frac{i^{-\alpha}}{\sum_{i=1}^{n} i^{-\alpha}} \tag{2}$$

Let us assume the incoming request rate at cache l is λ_l, therefore incoming request rate for content i is given by,

$$\lambda_{li} = \lambda_l p_{k_i} \tag{3}$$

Now following hit-rate analysis in [20] we can calculate the probability of obtaining content i at cache l,

$$\mathcal{H}_{li} = 1 - e^{-\lambda_{li}\tau_{li}}, \tag{4}$$

where τ_{li} is the characteristic time of content i at cache l. Characteristic time for a content in a cache indicates the amount of time in future a recently accessed content is likely to remain in that cache. Now τ_{li} can be obtained by solving,

$$\mathcal{C}_l = \sum_{i=1}^{n} 1 - e^{-\lambda_{li}\tau_{li}}, \tag{5}$$

where $\mathcal{C}_l$ is the size of l^{th} cache.

Now we need to consider a association rule for communication when content is available at one or multiple femto AP. User downloads the content from the source with maximum signal strength. Assuming path-loss exponent to be β, received power from BS and femto AP is given by,

$$P_{BS} = \kappa P_{tB} r_b^{-\beta}, \tag{6}$$

$$P_{femto} = \kappa P_{tf} r_f^{-\beta}, \tag{7}$$

where κ is the proportionality constant and it is normalized to be 1 throughout the paper, r_b and r_f denotes the distance of user from BS and femto AP, respectively. Therefore, maximum distance between the user and femto AP for content download from the femto is,

$$r_{max} = \left(\frac{P_{tf}}{P_{tB}}\right)^{1/\beta} r_b \tag{8}$$

So probability of finding m numbers of femto AP within r_{max} distance can be calculated as,

$$\xi_m = e^{-\pi r_{max}^2 \lambda_2} \frac{(\pi r_{max}^2 \lambda_2)^m}{m!} \tag{9}$$

Now assuming homogeneous traffic distribution among femto APs, the probability of downloading content i from a femto AP is given by,

$$P_{succ} = \sum_{m=1}^{\infty} \sum_{n=1}^{m} \xi_m \binom{m}{n} \mathcal{H}_i^n (1 - \mathcal{H}_i)^{m-n} \tag{10}$$

Now that we have the probability of downloading a content from a femto, we concentrate on the handover probabilities.

Handover takes place when signal strength of the femto AP drops below a threshold power before the completion of content download. Hence, expression for probability of handover is given by,

$$P_h = P\left(\mathcal{L} > \left(\frac{P_{tf}}{P_{th}}\right)^{1/\beta} \middle| \mathcal{T} < T_c\right), \tag{11}$$

where $\mathcal{L}$ and $\mathcal{T}$ are two random variables, namely, transition length and transition time, are dependent on the mobility model. In this paper we consider the random waypoint (RWP) model in [15], where transition lengths are independent and identically Rayleigh distributed. Mobility of a device can be characterized by the scaling parameter ρ of Rayleigh distribution, where larger ρ implies shorter transition length. We also know that $\mathcal{T} = \mathcal{L}/\mathcal{V}$, where $\mathcal{V}$ can be a positive constant or a positive random variable. Therefore, we can further simplify (11) as,

$$P_h = \frac{P\left(\left(\frac{P_{tf}}{P_{th}}\right)^{1/\beta} < \mathcal{L} < \mathcal{V}T_c\right)}{P(\mathcal{L} < \mathcal{V}T_c)} \tag{12}$$

Now we consider two cases, a) user is moving at a constant velocity, i.e., $\mathcal{V} \equiv \nu$, and b) velocity of user is uniformly distributed on $[v_{\min}, v_{\max}]$.

Theorem 1. *If $\mathcal{V} \equiv \nu$, then handover probability is given by,*

$$P_h = 1 - \frac{1 - \exp\left(-\rho\pi\left(\frac{P_{tf}}{P_{th}}\right)^{2/\beta}\right)}{1 - \exp\left(-\rho\pi\left(\nu T_c\right)^2\right)} \tag{13}$$

Proof. Theorem 1 can be proved by expressing (12) in terms of cdf,

$$P_h = \frac{F_{\mathcal{L}}(\nu T_c) - F_{\mathcal{L}}\left(\left(\frac{P_{tf}}{P_{th}}\right)^{1/\beta}\right)}{F_{\mathcal{L}}(\nu T_c)}, \tag{14}$$

where $F_{\mathcal{L}}(\cdot)$ stands for the cdf of the random variable for transition length. Replacing $F_{\mathcal{L}}(x)$ with $1 - e^{-\rho\pi x^2}$, cdf of the Rayleigh distribution, we obtain theorem 1. □

Theorem 2. *If $\mathcal{V}$ is a uniform random variable distributed between $[v_{\min}, v_{\max}]$, i.e., $\mathcal{V} = Uni(v_{min}, v_{max})$, then handover probability is given by,*

$$P_h = 1 - \frac{T_c(v_{max} - v_{min})\left(1 - \exp\left(-\rho\pi\left(\frac{P_{tf}}{P_{th}}\right)^{2/\beta}\right)\right)}{T_c(v_{max} - v_{min}) + Q(\sqrt{2\rho\pi}v_{max}) - Q(\sqrt{2\rho\pi}v_{min})} \quad (15)$$

Proof. When $\mathcal{V}$ is a random variable, $P(\mathcal{L} < vT_c)$ cannot be expressed as the cdf of $\mathcal{L}$. Hence, in this case we write handover probability as,

$$P_h = \frac{P(\mathcal{L} < vT_c) - F_{\mathcal{L}}\left(\left(\frac{P_{tf}}{P_{th}}\right)^{1/\beta}\right)}{P(\mathcal{L} < vT_c)} \quad (16)$$

Without losing the sense of generality we can assume $\mathcal{L}$ and $\mathcal{V}$ to be independent. Therefore, we can write,

$$P(\mathcal{L} < vT_c) = \frac{1}{T_c}\int_{T_c v_{min}}^{T_c v_{max}}\int_0^v f_{\mathcal{L}}(l) f_{\mathcal{V}}(v) dl dv, \quad (17)$$

where $f_{\mathcal{L}}(\cdot)$ and $f_{\mathcal{V}}$ are the pdf corresponding to the random variable for transition length and and velocity respectively. We already know $\mathcal{L}, \mathcal{V}$ follow Rayleigh and Uniform distribution respectively. Therefore, using corresponding $f_{\mathcal{L}}$ and $f_{\mathcal{V}}$ we obtain the resulting expression for (17),

$$P(\mathcal{L} < vT_c) = 1 + \frac{\mathrm{Q}(\sqrt{2\rho\pi}T_c v_{max}) - \mathrm{Q}(\sqrt{2\rho\pi}T_c v_{min})}{T_c(v_{max} - v_{min})} \quad (18)$$

Finally, replacing (18) in (16) we obtain the expression for handover probability in Theorem 2. □

Theorem 1 and 2 are extremely important as they represent the overall probability of handover. From the overall handover probability we can derive the probability of femto-femto handover,

$$P_{hff} = P_h P_{succ} \quad (19)$$

To determine the probability of a femto to base-station handover, we need to determine the probability of a node remaining in the same cell during the data transfer. However, it cannot be derived similar to (11), rather we need the probability of a node moving within a certain cell, or a certain measurable set $\mathcal{A}$. To derive this probability, conditioning over the random location of an user complicates the mathematical analysis. However, we can assume the user to be placed at the origin of the cell using Slivnyak's theorem. which suggests that conditioning with respect to a certain point does not affect system behavior at other points [19]. It follows from the independence property of Poisson point processes. Even with the user placement on the origin, randomness of Poisson-Voronoi tessellation cell area makes it extremely difficult to derive a closed form solution.

Let us consider that linear contact distribution is given by,

$$H_l(r) = 1 - \exp(-\lambda^{(2)} r), \quad (20)$$

where $H_l(r)$ gives probability of making contact with the cell boundary after traversing r length, and $\lambda^{(2)}$ is the intensity of cells in $\mathbb{R}^2$. We use linear contact distribution to determine if the node remains in the same cell. Leveraging contact distribution we develop an upper-bound for the probability of femto to same cell base station handover. We assume cells to be Poisson polygons to select the $\lambda^{(2)}$, however, it is impossible to determine the exact r at the time of handover, as it depends on the direction switch rate. Therefore, we provide a bound for the probabilities corresponding to femto-BS handover, considering both same and different cell scenarios.

For Poisson polygons, $\lambda^{(2)} = \frac{4\lambda_1}{\pi\sigma}$ [19]. A bound for femto-BS handover probability can be obtained by considering $r = vT_c$, i.e, considering transition in a single direction. Therefore, the bounds for femto-BS handover for same and different cell are given by,

$$P_{hfbs} \geq P_h(1 - P_{succ})(1 - H_l(vT_c)) \quad (21)$$

$$P_{hfbd} \leq P_h(1 - P_{succ})H_l(vT_c) \quad (22)$$

As assumed earlier, there are two possible scenarios of v and each results in a different bound. When v is a random variable, the contact distribution is given by,

$$\begin{aligned} H_l(vT_c) &= \frac{1}{T_c(v_{max} - v_{min})}\int_{v_{min}}^{v_{max}} 1 - \exp\left(-\frac{4\lambda_1}{\pi\sigma}vT_c\right)dv \\ &= \frac{1}{T_c} + \frac{\pi\sigma}{4T_c^2\lambda_1(v_{max} - v_{min})}\left(\exp\left(-\frac{4\lambda_1}{\pi\sigma}v_{max}T_c\right)\right. \\ &\left. - \exp\left(-\frac{4\lambda_1}{\pi\sigma}v_{min}T_c\right)\right) \end{aligned} \quad (23)$$

Similarly for a constant velocity ν, the linear contact distribution is given by,

$$H_l(\nu T_c) = 1 - \exp\left(-\frac{4\lambda_1}{\pi\sigma}\nu T_c\right) \quad (24)$$

Depending on the velocity of the mobile user we replace (23) or (24) in (21) and (22) to obtain the bounds for femto-BS handover.

Once we have the handover probabilities we can determine the expected delay as a function of handover probabilities. Expected delay is given by,

$$\mathbb{E}[d] = \mathbb{E}[d_f] + \mathbb{E}[d_b] + \mathbb{E}[d_h], \quad (25)$$

where $\mathbb{E}[\cdot]$ is the expectation operator, and d_f, d_b, and d_h are download delay from femto AP, BS, and download delay in case of handover, respectively. Understandably, calculation of delay in case of handover requires the information about expected handover time. Therefore, we derive the the expression for expected handover time or the expected time of staying within a femto AP's coverage area. Assuming the femtocell to be circular we can write,

$$\overline{T}_h = \mathbb{E}[T]\int_0^{2\pi}\int_0^{r_{max}} f(r,\theta) r dr d\theta, \quad (26)$$

where $f(r,\theta)$ is the spatial node density and $\mathbb{E}[T]$ is the expected transition time that depends on the velocity of the mobile node. Lin *et al.* gave the expressions for $\mathbb{E}[T]$ in [15],

$$\begin{aligned}\mathbb{E}[T] &= \frac{1}{2\nu\sqrt{\rho}}, \text{ for constant velocity } \mathcal{V}\equiv\nu \\ &= \frac{\ln v_{max}-\ln v_{min}}{2\sqrt{\rho}(v_{max}-v_{min})}, \text{ for r.v. } \mathcal{V}=\text{Uni}(v_{min},v_{max})\end{aligned} \tag{27}$$

where Uni(a,b) denotes the uniform distribution on $[a,b]$.

Using the spatial distribution given in [15], the expected handover time is given as,

$$\begin{aligned}\overline{T}_h &= \mathbb{E}[T]\int_0^{2\pi}\int_0^{r_{max}}\frac{\sqrt{\rho}}{\pi r}e^{-\rho\pi r^2}rdrd\theta \\ &= \mathbb{E}[T]\left(1-2\text{Q}\left(\sqrt{2\rho\pi}r_{max}\right)\right)\end{aligned} \tag{28}$$

Finally, using (28) expected delay can be expressed as,

$$\begin{aligned}\mathbb{E}[d] &= \frac{M}{S_f}P_{succ}(1-P_h)+\left(\frac{M}{S_b}+d_q\right)(1-P_{succ}) \\ &+\left(\overline{T}_h+\frac{M-S_f\overline{T}_h}{S_b}+d_q+d_h\right)P_{succ}(1-P_{hff}) \\ &+\left(\frac{M}{S_f}+d_h\right)P_{succ}P_{hff}\end{aligned} \tag{29}$$

Third and fourth term of (29) represent the delay in case of femto-BS handover and femto-femto handover, respectively.

IV. Numerical Results

In this section, we study the effect of content caching over mobile wireless environments. Firstly, we assume BSs, femto APs, and mobile users are scattered based on independent homogeneous PPPs with intensities of $\{\lambda_1,\lambda_2,\lambda_3\} = \{\frac{1}{\pi 500^2},\frac{20}{\pi 500^2},\frac{300}{\pi 500^2}\}$. The transmit powers are $\{P_1,P_2\} = \{25,20\}$ dBm, and set the path-loss exponent as $\beta=4$. Other parameters and corresponding values are given in Table II.

TABLE II: Numerical Results Parameter

Parameter	Description	Value
P_{th}	Threshold signal strength for detection	10 dBm
r_b	Average distance to user from BS	100 m
K	Content universe	1000 content
$\mathcal{L}$	Transition length	0.0005
σ	Poisson polygon intensity	0.5×10^{-3}
S_f	Femto AP data rate	10 Mbps
S_b	BS data rate	5 Mbps
d_q	Queuing delay	2 s
d_h	Handover delay	0.5 s

Results are given in Figures 2 and 3, for content size (M) of 50 Mb and 20 Mb, respectively. Each figure comprises of three sets of results, a) handover performance for low velocity, considering both fixed and uniformly distributed velocity scenario; b) handover performance for high velocity with varying content popularity skewness (α), and c) delay performance of network with caches for high and low velocity and the network without caches.

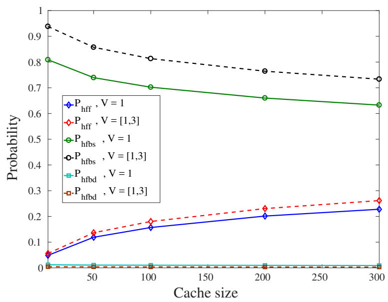
Figures 2(a) and 3(a) illustrates the variation of aforementioned handover probabilities for varying cache sizes between 10-300, and fixed popularity skewness of $\alpha=0.9$. We consider two possible cases for the velocity of mobile user, fixed at 1 m/s and uniformly distributed between 1 and 3 m/s. As expected, greater cache size increases the probability of serving a request from a femto AP, and therefore, the probability of femto-femto handover increases. We also observe that handover probability is less for fixed velocity at 1 m/sand its effect is extremely prominent for smaller content size. For example, in Figure 3(a) we observe that overall handover probability is significantly less in constant velocity case, therefore we can assume that most of the data requests are directly served by the femto APs, which significantly reduces the delay.

From Figures 2(b) and 3(b), where velocity is considered to be fixed at 10 m/s, cache size is varied between 10-300, and several popularity skewness values $(0.6, 0.9, 1.1)$ are considered. We observe that greater value popularity skewness results in higher femto-femto handover, which is logical as greater value of popularity skewness suggests that fewer number of content are repeatedly requested and therefore, it is highly probable that these popular content are cached at the femto AP and correspondingly significant amount of request is served by the femto AP. Another important point is that femto to different cell BS handover probability is greater for greater data size, as it requires more time to complete the data transfer and by that time mobile might reach another cell.

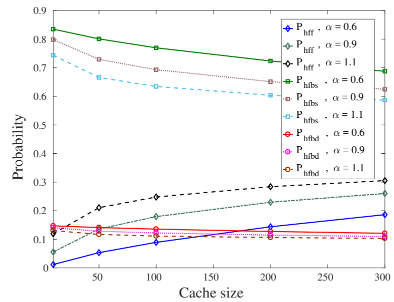
Now from Figure 2(a) we observe that probability of femto-femto handover is similar for both high (10 m/s) and low velocity (1 m/s) with content skewness $\alpha=0.9$. Intuitively it seems that the delay performance should be similar in both cases as well. However, in Figure 2(c) we observe that popularity skewness and cache size does not have significant effect on delay for high velocity mobile users, whereas, things are completely different for low velocity. Primary reason behind this observation is much smaller value of expected handover time. In case of high velocity, expected handover time reduces by a large extent and therefore, the effect of downloading a content from the femto AP gets nullified. Similar explanation can applied to describe the results in Figure 3(c). It is also evident from Figures 2(c) and 3(c) that incorporating cache storage improves delay performance, however, the improvement is nominal for a high velocity scenario. Overall results suggest that content caching is not so useful for mobile devices with high velocity, but for human mobility scenarios.

V. Conclusion

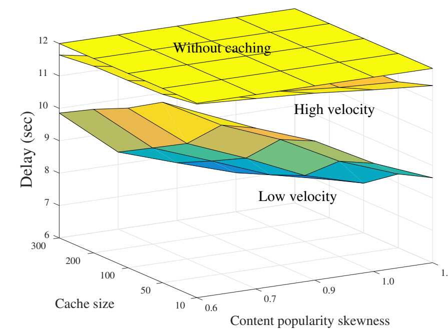
Wireless content-caching, where popular multimedia content is stored at local access points, is an important emerging concept. As the performance of it in wireless channels has previously been investigated without considering user mobility, in this paper we have analyzed the effect of mobility. By using stochastic geometry and the random waypoint model, we derived the handover probabilities and the expected delay. The



(a) Handover for varying velocity

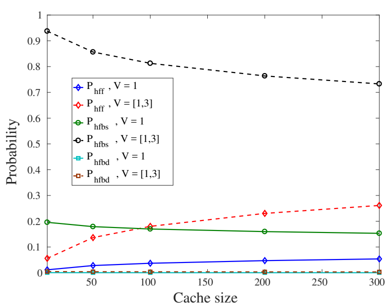


(b) Handover for varying popularity skewness

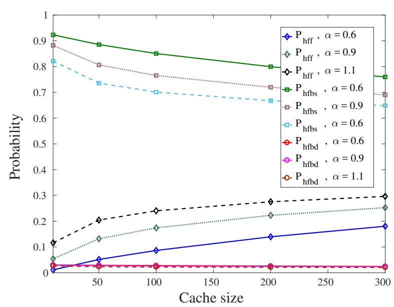


(c) Delay for varying velocity

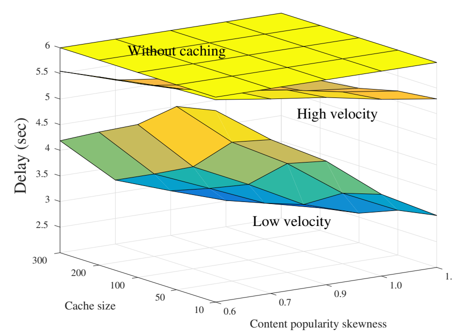
Fig. 2: Performance study for content size = 50 Mb



(a) Handover for varying velocity



(b) Handover for varying popularity skewness



(c) Delay for varying velocity

Fig. 3: Performance study for content size = 20 Mb

numerical results explored the effect of several caching related parameters on expected delay and handover probabilities.

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