Analyzing Opportunistic Request Routing in Wireless Cache Networks

J. Dinal Herath, Anand Seetharam
Department of Computer Science, SUNY Binghamton, USA
jherath1@binghamton.edu, aseethar@binghamton.edu

***Abstract*—To address the explosive increase in mobile data traffic in recent years, content caching at storage-enabled network nodes has been proposed. Alongside, a variety of forwarding strategies have been developed for wireless networks that exploit the broadcast nature of the wireless medium and the presence of time-varying fading channels to improve user performance. A widely popular forwarding strategy is opportunistic routing that opportunistically selects nodes that overhear packet transmissions to serve as ad hoc relays to forward the packet. In this paper, we investigate the request routing delay of a greedy opportunistic routing strategy for cache-enabled wireless networks considering uncorrelated and temporally correlated Rayleigh fading wireless channels. To this end, we develop Markovian models, leverage the wireless channel characteristics to determine the transition probabilities and then utilize them to obtain the request routing delay. Via numerical evaluation and simulation, we demonstrate the validity and effectiveness of our model in determining the request routing delay. We also investigate the impact of network parameters on performance through our experiments. Our work takes a step forward in providing network operators a tool for analyzing network performance before deploying their networks.**

I. Introduction

To address the explosive growth of mobile wireless traffic in recent years, content caching at storage-enabled in-network nodes has been proposed [6], [10]. By placing content at in-network nodes, requests for content can be served by en route caches in addition to the content custodian (origin server), thus improving user performance. Alongside this increase in data access traffic, recent years have also seen the emergence of various forwarding strategies that exploit the broadcast nature of the wireless medium [1], [8]. In a wireless network, when a node transmits a packet, multiple nodes in its vicinity can receive a copy of the packet and can participate in forwarding the packet toward the destination. One popular forwarding strategy is opportunistic routing. In opportunistic routing, if several nodes receive the same packet, an appropriate relay is selected for the next transmission of that packet.

In this paper, we analyze the request routing delay in cache-enabled wireless networks that forward requests following an opportunistic routing policy. Analyzing the performance of opportunistic routing in wireless cache networks is a relatively unexplored domain. Existing work related to our research can be separated into two categories - *i)* work related to opportunistic routing, *ii)* work related to caching or content placement. Most work in these two categories has primarily focused on developing novel opportunistic routing policies or designing better caching or content placement strategies, while performance analysis of opportunistic routing or caching policies in wireless settings considering realistic channel models has received limited attention.

In this paper, we consider cache-enabled wireless networks (e.g., cache-enabled heterogeneous networks, ad hoc networks, mesh networks, D2D networks) where users send requests for content that is always available at a content custodian, but may also be present at multiple in-network caches. We assume that the network uses a simple greedy opportunistic routing strategy to forward requests for content from users. In greedy opportunistic forwarding, if multiple nodes receive the same copy of the request, the node closest to the custodian forwards the request.

To investigate the performance of opportunistic routing in wireless cache networks, we model the wireless channel as a Rayleigh fading one. In our analysis, we consider *i)* temporally uncorrelated wireless channels where the random fading received for each request transmission by a node is independently and identically distributed, *ii)* temporally correlated wireless channels, where the temporal correlation is modeled as a modified Bessel function of the first kind and zeroth order. Following [14], [15], we model the result (success or failure) of a transmission to depend on the success or failure of the previous transmission.

We design Markovian models to analytically determine the request routing delay for the single flow case (i.e., satisfying requests for content from a single user to the custodian) for both uncorrelated and temporally correlated Rayleigh fading channel models. We derive expressions for the transition probabilities of the Markov chain for both scenarios and leverage them to determine the request routing delay.

We conduct both numerical experiments and simulations to validate the correctness of our models and to draw valuable insight into network performance. Our experiments show that the simulation and numerical results match closely, which demonstrates the effectiveness of our model. As expected, we observe that the request routing delay decreases as the cache capacity at individual nodes increases. Interestingly, we observe that benefit of caching is higher at lower values of packet success probability, primarily because it is easier to reach an in-network cache instead of the custodian in a few transmissions.

We also observe from the numerical evaluation that the delay of opportunistic routing increases as channel correlation increases. The main reason is that in case of correlated channels, while opportunistic routing requires a node to transmit multiple times over a poor channel to get the request through to downstream relays, it fails to take advantage of good channel conditions. This is in contrast to the uncorrelated case, where nodes get independent fades in different time slots.

The rest of the paper is organized as follows. We begin with a discussion of related work in Section II. We outline the network model and wireless channel model assumptions in Section III. The Markovian model designed for analyzing the request routing delay is then presented in Section IV. We present numerical and simulation results in Section V and conclude the paper with an outlook toward future work in Section VI.

II. Related Work

Our current work builds on our prior work [3], [9]. In [3], we only consider uncorrelated fading channels and compare the performance of opportunistic and cooperative routing strategies in the presence of multiple flows. In [9], we consider correlated fading channels and analyze the performance of greedy opportunistic routing for a simple four node network. In contrast to our previous work, the main difference in this work is that we consider the presence of in-network caches. Presence of in-network caching adds a new dimension to this problem because a request can be satisfied by network nodes in addition to the custodian. Additionally, we consider both uncorrelated and correlated wireless fading channels in this paper and analyze the performance of a single flow in a general network.

We next outline research related to opportunistic routing and caching in wireless networks and contrast it with our work. Most existing work related to design and analysis of opportunistic routing policies consider uncorrelated wireless channel models [4], [11]. Kim *et. al* propose a general framework for accurately capturing link correlation [7] and then leverage link correlation to design an opportunistic routing scheme that improves performance by exploiting the diversity of low correlated links [12].

Analyzing the performance gains of in-network caching for opportunistic forwarding in wireless networks is limited. Most work related to caching in wireless networks focus on heterogeneous cellular networks comprising of a cellular infrastructure and few cache-enabled femtocells [5], [10], [13]. The primary goal in these papers is to find the best content placement strategy to minimize delay subject to some network constraints.

In contrast to prior work, our goal is *not* to propose a new opportunistic routing strategy or to find the optimal content placement in a network, but rather to develop simple models to analyze the performance of wireless cache networks considering uncorrelated and correlated wireless channel models.

III. Assumptions and Problem Statement

In this section, we describe the network model, the wireless channel model and the problem statement.

A. Network Model

We consider a wireless stationary ad-hoc network of N nodes consisting of a single user r_1, a content custodian r_N and $N-2$ cache-enabled nodes in between as shown in Figure 1. $\mathbb{N}$ thus denotes the set of all nodes. We assume that r_1 periodically sends requests for content that is permanently housed at r_N. Without loss of generality, we assume that the network nodes are numbered in terms of the distance from r_N, and that r_1 is located farthest away from r_N. Therefore, $\{r_1, r_2, ...r_{N-1}, r_N\}$ denotes the ordering of the nodes in terms of their distance from r_N, and is known apriori. We denote the distance between any two nodes r_i and r_j by d_{ij}. Figure 1 also shows the possible transmission probabilities (p_{1j} or p'_{1j}) between r_1 and the other network nodes for uncorrelated and correlated wireless channel respectively. We provide expressions for p_{ij} and p'_{ij} in Section III-B.

We consider a content universe of size K. We assume that r_1 does not have any local cache, and all other network nodes except the custodian are provided with a cache of size C ($C < K$). We assume that content popularity varies according to some known distribution (e.g., Zipfian distribution). Let q_i denote popularity of the i^{th} piece of content (i.e., the probability of the user requesting content i).

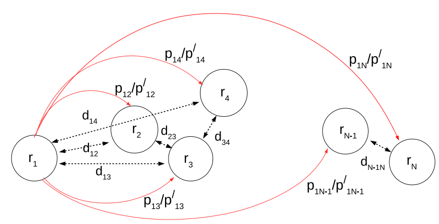


Fig. 1: An N node general network

We assume that the network adopts some content placement strategy (i.e., static caching) that determines the set of content to be placed at the different network caches. The literature is rife with different kinds of content placement strategies [2], [5], [10]. For example, a widely adopted approach is to push popular content closer to the user so as to maximize performance.

We assume that the network adopts an opportunistic routing strategy to forward requests from the user to the custodian. Therefore, there is no notion of a fixed path between the user and the custodian. Due to broadcast nature of the wireless medium, nodes can overhear transmissions and can participate in forwarding the request toward the custodian. We assume that nodes forward requests based on a *greedy opportunistic routing policy*. In this strategy, if multiple nodes have a copy of the request, the node closest to the custodian is always selected to transmit the request. Therefore, the node ordering $\{r_1, r_2, ...r_{N-1}, r_N\}$ also represents the priority for transmitting the request for greedy opportunistic routing. Formally, we denote "$r_i \succ r_j$" to represent that r_i has a higher priority than r_j.

We note that there are several proposals [1], [8] that address implementation details, such as how to select the appropriate relay when multiple nodes overhear the transmission. However, we abstract away these details and focus on analyzing an idealized and simple implementation to appreciate the benefits of opportunistic routing in a cache network.

B. Wireless Channel Model

In order to compare network performance, we consider a realistic Rayleigh fading channel model. We assume that a request transmission between nodes i and j is successful if the Signal to Noise Ratio (SNR) is above a threshold β (where $\beta > 0$). We consider both uncorrelated and temporally correlated wireless channels in our analysis. We assume constant background noise with no interference.

1) Uncorrelated fading Channels: Let us consider a single transmission between nodes r_i and r_j. The signal-to-noise ratio S_{ij} from transmitter r_i to receiver r_j is given by

$$S_{ij} = \frac{\mid x_{ij} \mid^2 \; P\, d_{ij}^{-\alpha}}{N_0} \tag{1}$$

where N_0 is considered to be constant background noise, P the transmission power at r_i, α the path loss exponent and $\mid x_{ij} \mid$ is the Rayleigh fading coefficient. We assume that the parameters of N_0, α, P are constant and known. $\mid x_{ij} \mid^2$ is assumed to be an exponentially distributed random variable with a normalized mean of 1. For uncorrelated channels, we assume $\mid x_{ij} \mid^2$ is independently and identically distributed (i.i.d) in different time slots. Let p_{ij} denote the probability that the request is successfully transmitted from r_i to r_j in a time slot for uncorrelated fading channels. Therefore,

$$p_{ij} = \exp\left(\frac{-\beta\, N_0}{P\, d_{ij}^{-\alpha}}\right) \tag{2}$$

2) Correlated Fading Channels: We also consider the case of temporally correlated wireless channels. This can occur in scenarios where the coherence time for a channel is large, thus causing the channel to be correlated across time slots. Following [14], [15], we model the fading correlation as a modified Bessel function of the first kind and zeroth order. Zorzi *et. al* demonstrate using an information-theoretic approach that for a block error process, a Markovian model is reasonable when fading correlation is taken into account [14], [15]. In other words, the success or failure of a request transmission between a pair of nodes in a particular time slot can be modeled as being dependent on the result of the request transmission in the previous time slot between same pair of nodes. Therefore, the transition matrix would be of the form

$$M = \begin{bmatrix} P[success|success] & P[failure|success] \\ P[success|failure] & P[failure|failure] \end{bmatrix} \tag{3}$$

In this paper, we are primarily interested in the probability, $P[success|failure]$. From [15], the conditional probability of success given failure between nodes r_i and r_j is given by,

$$p'_{ij} = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{\exp(b_{ij}) - 1} \tag{4}$$

In equation 4, $Q(:,:)$ is a Marcum Q function, ρ is a modified Bessel function of the first kind of zeroth order that determines the channel correlation coefficient, $\theta = \sqrt{\frac{2b_{ij}}{1-\rho^2}}$ and $b_{ij} = \frac{\beta N_0}{P d_{ij}^{-\alpha}}$.

C. Problem Statement

Considering the network and wireless channel models described above, we address the following problem in this paper. *For a given content placement at in-network nodes for a cache-enabled wireless network, our goal in this paper is to design simple models to analyze the request routing delay for a greedy opportunistic routing strategy for uncorrelated and correlated wireless channel models.*

IV. Analytical Framework

In this section, we formulate Markovian models for analyzing the request routing delay using greedy opportunistic routing in cached-enabled networks for uncorrelated and correlated fading channels. We consider the single request case, i.e., the user sends a new request only after its previous request has been satisfied. Each request is initiated by the user and is forwarded by in-network nodes until it reaches the custodian or some en route node that has a cached copy of the requested content. As mentioned earlier, we assume that the set of content in a node's cache is determined by a content placement strategy. Let H_f denote the set of nodes that have the copy of content f. Note that H_f thus includes the custodian. We next design the Markovian model and present its transition matrix for uncorrelated and correlated fading channels for the general network considered in Figure 1. However, for the sake of understanding, we explain the model using a simple 4 node network.

A. Uncorrelated Fading

For constructing the Markovian model, we first consider the different states in which a network node could be in for a request in transit. For the uncorrelated fading channel, each node can be in two states - 0 and 1. State 1 denotes the state of a network node if it is going to transmit the request in the next time slot. State 0 captures two scenarios - *i)* the node has not received the request, *ii)* the node has received the request, but is not participating in retransmitting this request as some other higher priority node has also received the same request.

The set of nodes H_f where the content is available being dependent on f, we need to construct a separate Markov chain for each content f. For content f, we denote the state of the network using an n-tuple that captures the active relay for the request in the next time slot. For a four node network, the Markov chain could consist of maximum four states, namely $A_1 = (1, 0, 0, 0)$, $A_2 = (0, 1, 0, 0)$, $A_3 = (0, 0, 1, 0)$, and $A_4 = (0, 0, 0, 1)$. A_4 denotes the state where the request is served which could happen if the request reaches the custodian or some intermediate node that has a cached copy of the content. Additionally, depending on the set of nodes that cache a copy of the content, transitions to and from certain states may not be possible. For example, if we consider that content f is cached at r_3, transitioning to and from state A_3 is not possible because if r_3 receives the request, the network will transition to state A_4 as the request has been satisfied. Therefore, one can remove these states (in this case A_3) from the Markov chain for content f. Recall that we assume that the user transmits a new request after a request has been satisfied. Therefore, when the network transitions to state A_4, (i.e., the request is satisfied), the state transition in the next time step will correspond to the states reachable from the user with the respective probabilities.

Extending the above logic to a network of N nodes, the Markov chain will consist of $N - H_f + 1$ states (A_i, $\forall i = 1$ to $N, r_i \notin H_f - r_N$). Having designed the Markov chain, the next step is to derive its transition matrix. Let P_{ij}^f represent the transition from state A_i to A_j, ($\forall i, j = 1$ to $N, r_i, r_j \notin H_f - r_N$) for content f. Equation 5 shows the transition matrix for the Markov chain described above.

$$P_{ij}^f = \begin{cases} 0 & \text{if } i > j, \forall i < N \\ \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{ik}) \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } i = j, \forall i < N \\ p_{ij} \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{ik}) \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } i < j, \forall j < N \\ 1 - \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } j = N, \forall i < N \\ p_{1j} & \text{if } i = N \end{cases} \tag{5}$$

B. Correlated Fading

For a correlated fading channel, we need to take into account the fact that an unsuccessful transmission of a request by a node in the previous time slot impacts the probability of successful transmission in the next time slot. To model this, we consider that each node can be in three states - 0, 1 and 1^*. State 0 is similar to state 0 for the uncorrelated fading scenario. State 1 denotes that a node is going to transmit a request for the first time in the next time slot, while state 1^* denotes that a node failed to successfully transmit a request to any of the higher priority nodes in the previous time slot and is thus going to transmit it again in the upcoming time slot.

Once again, we consider a simple four node network to understand the different states of the Markov chain. The Markov chain can consist of maximum six states - $A_2 = (0, 1, 0, 0)$, $A_3 = (0, 0, 1, 0)$, $A_4 = (0, 0, 0, 1)$ and $A_1' = (1^*, 0, 0, 0)$, $A_2' = (0, 1^*, 0, 0)$, $A_3' = (0, 0, 1^*, 0)$. Every state in the Markov chain for the uncorrelated fading case except for A_1 and A_4 (i.e., the states that account for the user transmitting the request and the request getting satisfied in the network) has two corresponding states in the Markov chain for the correlated case. This takes into consideration the fact that a node can be in state 1 or 1^* when it serves as an active relay. For example, states A_2 and A_2' denote the cases when r_2 transmits a request for the first time and it retransmits the same request after a failed attempt respectively.

A_4 denotes the state that the request reaches the custodian or is satisfied by an en route cache while $A_1' = (1^*, 0, 0, 0)$ denotes the state that the user transmits the request after a failed attempt. Note that the Markov chain does not need a state $A_1 = (1, 0, 0, 0)$ as it is included in A_4. The state transition from A_4 correspond to the states reachable from the user when it transmits for the first time. Additionally, if the request transmission from the user to all other network nodes is unsuccessful, the Markov chain will transition to state A_1'. Therefore, if a state A_1 is included in the Markov chain, it will be unreachable from all other states and its steady state probability will be zero. Once again, states corresponding to the nodes that have a cached copy of the content (except the custodian) are not part of the Markov chain. For example, if r_3 has a cached copy of content f, then states A_3 and A_3' will not be part of the Markov chain. Extending the above analysis for an N node network, the Markov chain will consist of $2(N - H_f)$ states for content f, (A_i, $\forall i = 2$ to $N, r_i \notin H_f - r_N$; A_i', $\forall i = 1$ to $N - 1, r_i \notin H_f$).

$$P_{ij}^{1f} = \begin{cases} 0 & \text{if } i \geq j, \forall i < N \\ p_{ij} \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{ik}) \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } i < j, \forall j < N \\ 1 - \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } j = N, \forall i < N \\ p_{1j} \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{1k}) \prod\limits_{r_k \in H_f} (1 - p_{1k}) & \text{if } i = N, \forall j < N \\ 1 - \prod\limits_{r_k \in H_f} (1 - p_{1k}) & \text{if } i, j = N \end{cases} \tag{6}$$

$$P_{ij}^{2f} = \begin{cases} 0 & \text{if } i \neq j, \forall i < N \\ 0 & \text{if } i = N, \forall j \neq 1 \\ \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{ik}) \prod\limits_{r_k \in H_f} (1 - p_{ik}) & \text{if } i = j, \forall i < N \\ \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p_{1k}) \prod\limits_{r_k \in H_f} (1 - p_{1k}) & \text{if } i = N, j = 1 \end{cases} \tag{7}$$

$$P_{ij}^{3f} = \begin{cases} 0 & \text{if } i \geq j, \forall i < N \\ p'_{ij} \prod\limits_{\substack{r_k \in N - H_f \\ r_k \succ r_j}} (1 - p'_{ik}) \prod\limits_{r_k \in H_f} (1 - p'_{ik}) & \text{if } i < j, \forall i < N \\ 1 - \prod\limits_{r_k \in H_f} (1 - p'_{ik}) & \text{if } j = n, \forall i < N \end{cases} \tag{8}$$

$$P_{ij}^{4f} = \begin{cases} 0 & \text{if } i \neq j \\ \prod_{\substack{r_k \in N-H_f \\ r_k \succ r_j}} (1-p'_{ik}) \prod_{r_k \in H_f} (1-p'_{ik}) & \text{if } i = j \end{cases} \quad (9)$$

Once again, the next step is to derive the transition probabilities of the Markov chain. Recall that for the correlated fading case, equation 4 provides the conditional probability of successful request transmission in the current time slot given an unsuccessful request transmission in the previous time slot between nodes r_i and r_j. For ease of understanding, we split the transition probabilities into four separate pairs to cover the following cases - transitions from *i)* state A_i to state A_j, *ii)* state A_i to state A'_j, *iii)* state A'_i to state A_j and *iv)* state A'_i to state A'_j. Equations 6, 7, 8 and 9 show the transition probabilities for cases *i, ii, iii and iv* for the correlated fading scenario for content f respectively. In general, these equations take care of the fact that transitions cannot take place from A_i to A_j (except when $i < j$) or from A_i to A'_j (unless $i = j$ or $i = N, j = 1$). Additionally, the equations also take care of fact that transitions to state A_N will occur if the request reaches the custodian or any intermediate in-network cache.

C. Delay Calculation

Having designed the Markovian models and derived their transition matrices for the uncorrelated and correlated cases, we leverage them to obtain expressions for the request routing delay. Let Π_i^f and $\Pi_i'^f$ denote the steady state probabilities for states A_i and A'_i for content f respectively. In our model, the expected delay D_f for a request for content f can be calculated as the inverse of the steady state probability of being in state A_N. Therefore, $D_f = \frac{1}{\Pi_N^f}$. Hence, the expected delay D for both uncorrelated and correlated scenarios is given by,

$$D = \sum_{f=1}^{K} q_f \frac{1}{\Pi_N^f} \quad (10)$$

V. Experimental Evaluation

In this section, we present numerical and simulation results for both uncorrelated and temporally correlated wireless fading channels. We observe from our experiments that the numerical and simulation results match closely which demonstrates the validity and effectiveness of our models. We also conduct experiments to study the impact of network parameters on delay.

A. Closeness of Numerical and Simulation Results

For the results presented here, we assume equidistant placement of nodes. Therefore, the probability of successful request transmission between nodes r_i and r_j is $p_{ij} = p^{|j-i|^2}$, where p is the one hop success probability. We assume that content popularity varies according to a Zipfian distribution with skewness parameter a. We assume that content is distributed according to the following strategy. We rank content based on popularity. Half the cache capacity at each node is filled randomly from the top 20% content and the remaining capacity is filled from the bottom 80% content. This ensures that the most popular content is readily available in the network, but also allows in-network caching of less popular content.

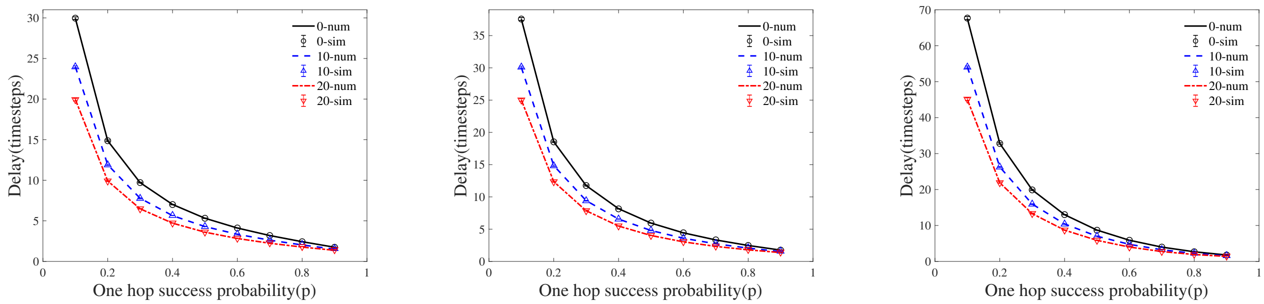
We use the following default parameters in our experiments: number of network nodes including user and custodian $(N) = 4$, cache size at individual nodes $(C) = 10$, the content universe (K) = 100, the skewness parameter (a) = 0.8 and the correlation coefficient (ρ) = 0.9. Each data point in the simulation is obtained over 10 runs of the experiment. For each simulation run, 10000 requests are sent from the user to the custodian and the delay is calculated as the average delay of all requests. Each data point is then calculated as the average of 10 runs and the error bar shown around each data point is twice the standard deviation. We conduct experiments using MATLAB by varying N, C, K, a and ρ where each iterative run is considered as a timestep.

Figure 2 shows the variation in delay with the one hop success probability considering i.i.d. fading for the uncorrelated and correlated scenarios for the default set of parameters. In Figure 2, we compare the results obtained via our numerical analysis and the simulations for different cache capacities. We observe from the figure that the numerical and simulation results match closely which demonstrates the validity and effectiveness of our Markovian models. As expected, we observe that the delay decreases as the cache capacity increases. From a caching perspective, we observe that in-network caching has greater benefit for lower values of p. The reason is that for lower values of p, it is harder to reach the custodian in a few transmissions and thus having a cached copy of the content closer to the user helps in satisfying the request earlier.

Similarly, we also observe that the delay decreases as the one hop success probability increases. An interesting observation obtained by comparing Figures 2(a), 2(b) and 2(c) is that as ρ increases, the delay increases for the same values of C and p. This is because as we only model the single request case, greedy opportunistic routing fails to take advantage of good channel, but requires a node to transmit multiple times over a bad channel. This need to transmit multiple times over a bad channel causes higher values of ρ to have a greater impact on delay, in particular for lower values of p ($p < 0.5$).

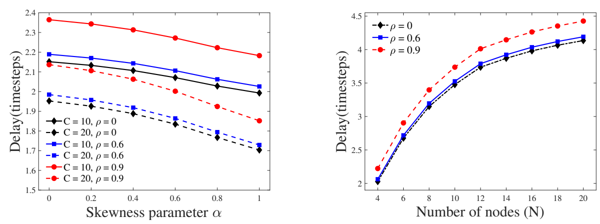
B. Impact of Network Parameters on Delay

We next investigate the impact of varying the network parameters on delay via our numerical evaluation. Figure 3(a) shows the variation in delay as the Zipfian skewness parameter changes. For the uncorrelated and correlated cases, we observe that the delay decreases as a increases, irrespective of the cache capacity. Note that incrementing a increases the skewness of the Zipfian distribution. When $a = 0$, the Zipfian distribution converges to a uniform distribution, while high values of a indicates that some content is considerably more popular in comparison to majority of content. The content placement strategy considered in our evaluation caches popular content with a higher probability. Therefore, for higher values of a, the probability of a request getting satisfied at an in-



(a) Uncorrelated Channel (b) Correlated Channel ($\rho = 0.6$) (c) Correlated Channel ($\rho = 0.9$)

Fig. 2: Delay vs. One Hop Success Probability (p)



(a) Delay vs. Zipfian Skewness Parameter (a) (b) Delay vs. Number of Nodes (N)

Fig. 3: Impact of Network Parameters on Delay

network cache increases, thereby resulting in lower delay. Once again, we observe that the delay increases as ρ increases.

Figure 3(b) shows the variation in delay as the number of network nodes increases. We observe that as the number of nodes increases, the delay increases. This is expected because the average number of transmissions needed to reach the custodian or an en route cache having a copy of the content increases with the number of nodes. We also conduct experiments by increasing size of the content universe. For a fixed ratio of cache size to content universe size, we observe similar delay values, irrespective of content universe.

VI. Conclusion

In this paper, we analyzed the delay of opportunistic request routing in cache-enabled wireless networks. To this end, we designed Markovian models and derived expressions for the transition probabilities considering uncorrelated and temporally correlated wireless fading channels. We then utilized the steady state probabilities of the Markov chain to determine expressions for the request routing delay. Via numerical evaluation and simulation, we demonstrated the validity and effectiveness of our Markovian models in modeling the request routing delay. In future, we plan to extend this work for more realistic scenarios by considering pipelined request streams and interference from multiple competing flows. Additionally, as network size increases, the Markovian model developed in this paper is likely to encounter a state space explosion. Therefore, we plan to develop approximate algorithms to address this issue as part of our future work.

References

[1] S. Biswas and R. Morris. Exor: opportunistic multi-hop routing for wireless networks. *ACM SIGCOMM Computer Communication Review*, 35(4):133–144, 2005.

[2] S. H. Chae and W. Choi. Caching placement in stochastic wireless caching helper networks: Channel selection diversity via caching. *IEEE Transactions on Wireless Communications*, 15(10):6626–6637, 2016.

[3] C.-K. Chau, A. Seetharam, J. Kurose, and D. Towsley. Opportunism vs. cooperation: Comparing forwarding strategies in multihop wireless networks with random fading. In *Communication Systems and Networks (COMSNETS), 2013 Fifth International Conference on*, pages 1–10. IEEE, 2013.

[4] A. Darehshoorzadeh, E. Robson, and A. Boukerche. Toward a comprehensive model for performance analysis of opportunistic routing in wireless mesh networks. *IEEE Transactions on Vehicular Technology*, 65(7):5424–5438, 2016.

[5] M. Dehghan, A. Seetharam, B. Jiang, T. He, T. Salonidis, J. Kurose, D. Towsley, and R. Sitaraman. On the complexity of optimal routing and content caching in heterogeneous networks. In *Computer Communications (INFOCOM), 2015 IEEE Conference on*, pages 936–944. IEEE, 2015.

[6] M. Ji, G. Caire, and A. F. Molisch. Wireless device-to-device caching networks: Basic principles and system performance. *IEEE Journal on Selected Areas in Communications*, 34(1):176–189, 2016.

[7] S. M. Kim, S. Wang, and T. He. Exploiting causes and effects of wireless link correlation for better performance. In *Computer Communications (INFOCOM), 2015 IEEE Conference on*, pages 379–387. IEEE, 2015.

[8] E. Rozner, J. Seshadri, Y. Mehta, and L. Qiu. Soar: Simple opportunistic adaptive routing protocol for wireless mesh networks. *IEEE transactions on Mobile computing*, 8(12):1622–1635, 2009.

[9] A. Seetharam and J. Kurose. An analysis of opportunistic forwarding for correlated wireless channels. In *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2015 IEEE 16th International Symposium on a*, pages 1–3. IEEE, 2015.

[10] K. Shanmugam, N. Golrezaei, A. G. Dimakis, A. F. Molisch, and G. Caire. Femtocaching: Wireless content delivery through distributed caching helpers. *IEEE Transactions on Information Theory*, 59(12):8402–8413, 2013.

[11] W.-Y. Shin, S.-Y. Chung, and Y. H. Lee. Parallel opportunistic routing in wireless networks. *IEEE Transactions on Information Theory*, 59(10):6290–6300, 2013.

[12] S. Wang, A. Basalamah, S. M. Kim, S. Guo, Y. Tobe, and T. He. Link-correlation-aware opportunistic routing in wireless networks. *IEEE Transactions on Wireless Communications*, 14(1):47–56, 2015.

[13] C. Yang, Y. Yao, Z. Chen, and B. Xia. Analysis on cache-enabled wireless heterogeneous networks. *IEEE Transactions on Wireless Communications*, 15(1):131–145, 2016.

[14] M. Zorzi, R. Racd, and L. B. Milstein. A markov model for block errors on fading channels. In *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, volume 3, pages 1074–1078. IEEE, 1996.

[15] M. Zorzi, R. R. Rao, and L. B. Milstein. Arq error control for fading mobile radio channels. *IEEE Transactions on Vehicular Technology*, 46(2):445–455, 1997.