Capacity of Content-Centric Hybrid Wireless Networks

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Abstract. In this paper, we investigate the capacity scaling laws of content-centric hybrid wireless networks, where users aim to retrieve content stored in the network rather than maintain source-destination communication. n nodes that have limited-capacity content store are assumed to be independently and uniformly distributed in the network area. The content store equipped in each node is used to cache contents according to the proposed caching schemes. m base stations are regularly placed and act as relays during the content retrieving process. We consider heterogenous caching access scheme where the cached probability of contents is different and the requested contents follow a Zipf content popularity distribution. We present the closed form capacity formulae for the heterogenous caching access scheme in order sense.

Keywords: Capacity · Wireless hybrid network · Content-centric · Cache

1 Introduction

The number of wireless users is exponentially booming day by day. The scaling behavior of wireless networks fascinates wide interests in both academic and industry communities. In [1], Gupta and Kumar's ground breaking work pioneers the scaling behavior study of wireless networks. By assuming that n nodes are distributed independently and uniformly on a unit area, they show that the per-node throughput capacity in random wireless networks scales as $\Theta(\frac{W}{\sqrt{n \log n}})$, which decreases to zero as the number of nodes goes to infinity. While in this work, nodes can simultaneously serve as sources, destinations, and as relays for other source-destination pairs.

To increase the capacity of wireless networks, researchers study hybrid wireless network which combines base stations and ad hoc mode. Liu et al. [3] first study the scaling behavior of throughput capacity for hybrid wireless networks under two different routing policies. Considering a hybrid wireless network composed of n normal ad hoc nodes and m base stations, they show that under the

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K-nearest cell routing strategy, the per-node capacity scales as $\Theta(\mathrm{W}\sqrt{\frac{1}{n \log n/m^2}})$ when m grows asymptotically slower than $\sqrt{n}$; otherwise, the per-node capacity scales as $\Theta(\frac{Wm}{n})$. Kozat et al. [5] investigate the throughput capacity of hybrid wireless ad hoc networks with the support of infrastructures under different assumptions. By assuming that both the ad hoc nodes and base stations are randomly placed, they show that the per-node throughput capacity is $\Theta(W/\log n)$. Recently, network content is accessed increasingly in different ways in wireless environments. While in wireless applications, caching content objects closest to requesters can significantly decrease the delay of content acquiring, which could improve the throughput capacity potentially. In the academic society, by adopting caching technique, new content-centric networking architectures such as Named Data Networking (NDN) [11] and Content-Centric Networking (CCN) [12] have been developed for efficient content distribution. In [2], Liu et al. study the scaling laws of the throughput capacity of cache enabled content distribution wireless ad hoc networks with Nearest Caching Node scheme, and Transparent Enroute Caching scheme. In [6], they study the per-node throughput capacity of an information-centric network when the data cached in each node has a limited lifetime. In [7], Mahdian et al. study the throughput-delay tradeoffs in content-centric Wireless Networks. The paper [10] presents the problem of great growth demand for video content based on femto-like base stations which can cache the popular content.

In this paper, we characterize the throughput capacity of content-centric hybrid wireless networks. We assume that each node is equipped with cache which can store content objects. Cached content objects closest to requesters can significantly decrease the distance between the sources and destinations, which means that the requesting nodes and its desired contents have minimum number of hops using caching contents in the purely ad hoc mode transmissions. In our network model, we assume that the requested content objects can be accessed successfully in ad hoc mode transmissions in the small distance. Otherwise, if the desired contents have not be cached, or the distance between the sources and destinations is larger than the minimum distance, the request should be carried out by the infrastructure mode. We consider heterogenous caching access scheme where the probability that the jth content cached in a node is q_j and the content popularity distribution is p_j, which means the probability that a typical user request a content is p_j.

The main contributions of our paper are as follows.

(1) We investigate the throughput capacity of content-centric hybrid wireless networks under heterogenous caching access scheme and propose the closed form capacity scaling results in order sense, respectively.
(2) We analyze the impact of system parameters such as the number of nodes, the number of base stations, the caching probability of content, as well as the number of content objects on the throughput capacity, which can provide theoretical guidance for content-centric hybrid wireless network design.

The rest of the paper is organized as follows. Section 2 presents the system model. In Sect. 3, we derive the throughput capacity of content-centric hybrid wireless network under heterogeneous caching access scheme. Finally, we conclude the paper in Sect. 4.

2 System Model

2.1 Network Model

We consider a two-tier content-centric hybrid wireless network where n nodes (users) are distributed uniformly and randomly in the low tire, overlaid with infrastructure with m base stations in the high tire on the surface of a torus of unit area. The assumption of torus enables us to avoid edge effects. And for the nodes located on an unit square, the results derived in the paper are applicable as well. We assume each node employs the same transmission range and power. The base stations which are regularly placed in the network divide the area into a hexagonal tessellation. Each hexagon is named a cell which has a base station in its center. And the infrastructure network follows the classic 7-cell reuse model in [8]. These base stations are added as relay nodes instead of data source or data receiver. All the base stations are connected by a wired network. Furthermore, we assume that these base stations have unlimited bandwidth and no power constraints in the wired network.

There is a total number of M distinct content objects in the network. We assume each content object has the same unit size. Each node is assumed to equip with a local cache, which can store copies of content objects. The cache size of each node is C units of content. For the problem of caching contents not to be trivial, it should be $C < M$, so that each node must select which content objects to be cached. In addition, to have large enough memory to store at least one copy of each content object in the network, it has to be $nC \geq M$.

We adopt the Protocol Interference model introduced in [1]. A transmission from node X_i is successfully received by node X_j if the following two conditions are satisfied: (i) The distance between node X_i and node X_j is within the transmission range r, i.e., $|X_i - X_j| \leq r$; (ii) For every other node X_k that is simultaneously transmitting over the same channel, it should be followed, $|X_k - X_j| \geq (1 + \Delta)\,|X_i - X_j|$ for some $\Delta > 0$.

2.2 Routing Strategy and Content Access Scheme

There are two types of transmissions in the system model: ad hoc mode and infrastructure mode. In the ad hoc mode, we use the content-centric access scheme, where a content is requested successfully by the nearest node that has the copies of desired content in its local cache without using any infrastructure. While in the infrastructure mode, the request is first forwarded from the requesting node to the base station, and then to the caching node. For the sake of simplicity but without loss of generality, the two models are as shown Fig. 1.

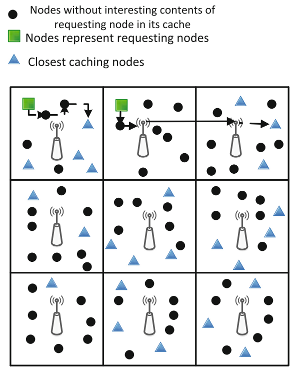

Fig. 1. Illustration of hybrid wireless network architecture.

In this paper, we consider heterogenous caching content access scheme. For the scheme, we assume a random content caching strategy where the jth content object is cached with probability q_j, $0 \leq q_j \leq 1$, $j = 1, \cdots, M$. Then a user requests the jth content object according to the content popularity distribution law p_j, which follows the Zipf laws. In other words, the probability that a user requests a file is p_j. Since we have n nodes, the average number of copies of jth content object is nq_j.

In this paper, we assume channel bandwidth is W bits/second, which is divided into ad hoc mode and infrastructure mode. i.e., the bandwidth is split into W_1 for ad hoc mode, W_2 for the downlink and W_3 for the uplink transmission for the infrastructure mode, respectively. We assume that the uplink bandwidth equals the downlink bandwidth, i.e., $W_2 = W_3$. Hence, $W = W_1 + 2W_2$.

Throughput: The per-node throughput is defined as expected number of bits/second that can be transmitted by each node to its chosen destination. The sum of the per-3node throughput over all the nodes in a network is defined as the aggregate throughput of the network.

Feasible Throughput: We say that the aggregate throughput, denoted by $T(n)$, is feasible if there is a spatial and temporal scheduling scheme that yields an aggregate network throughput of $T(n)$ bits/sec.

Aggregate Throughput Capacity of A Network: We say that the aggregate network throughput capacity is of order $O(f(n))$ bits/sec if there exists deterministic constant $0 < c_1 < +\infty$ such that

$$\lim_{n\to\infty} \texttt{Prob}(T(n) = c_1\text{f(n) is feasible}) < 1.$$

And is of order $\Omega(f(n))$ bits/sec if there is deterministic constants $0 < c_2 < +\infty$ such that

$$\lim_{n\to\infty} \texttt{Prob}(T(n) = c_2\text{f(n) is feasible}) = 1.$$

3 Heterogenous Content Access Capacity

In this section, we consider heterogenous content access scheme that the random content caching policy where the *jth* content is cached in a node with the probability of q_j. Then, the cooperation policy is the content objects popularity distribution, which means that the probability that a user requests the *jth* content is p_j. The content popularity distribution follows the Zipf law. Hence, $p_j = j^{(-\alpha)}/H_\alpha(M)$, where α is the Zipf's law exponent. And $H_\alpha(M) = \sum_{i=1}^{M} i^{-\alpha}$, it is given by [13].

$$H_\alpha(M) = \begin{cases} \Theta(1), & \alpha > 1; \\ \Theta(logM), & \alpha = 1; \\ \Theta(M^{1-\alpha}), & \alpha < 1. \end{cases}$$

3.1 Ad Hoc Mode Throughput Capacity

For the low tier network component, n nodes are uniformly and independently distributed on a planar torus and a total number of M content objects are requested and cached with different probability. The local cache of each node can store C content units. We first get the achievable lower bound by approaches in [1], shown as follows. $c_i^{\prime}s$ denote deterministic constants independent of n.

Voronoi Tessellation [4]**:** Given a set of n points in a plane, Voronoi tessellation divides the network area into a set of polygonal cells. The border-line of each region is the vertical bisector of the lines joining the points.

Lemma 1 [1]**:** For every $\varepsilon > 0$, a Voronoi tessellation has the property that every Voronoi cell contains a disk of radius ε and is contained in a disk of radius 2ε.

Then for n nodes, we can construct a Voronoi tessellation V_n, which satisfies the following property:

(V1) Every Voronoi cell contains a disk of area $100\frac{\log n}{n}$.
(V2) Every Voronoi cell is contained in a disk of radius $2\rho(n)$. Let $\rho(n) :=$ the radius of a disk of area $100\frac{\log n}{n}$.

Adjacent Voronoi Cells: Two cells are called adjacent neighbor if they share a common point (every cell is a closed set).

We assume that the transmission range of each node is $r(n)$, and we have

$$r(n) = 8\rho(n).$$

The transmission range permits direct communication within a Voronoi cell and between adjacent Voronoi cells.

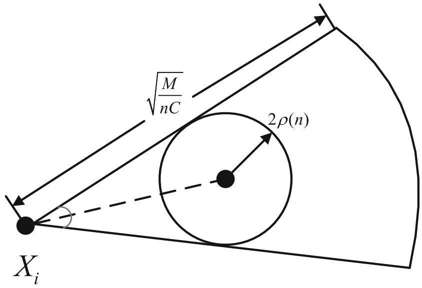

Fig. 2. Illustration for calculate the probability of L_i intersects Voronoi cell V.

Interfering Neighbors: Two Voronoi cells are called interfering neighbors if there is a point in one cell which is within a distance $(2 + \Delta)r(n)$ of some point in the other cell.

Lemma 2 [1]**:** When omnidirectional antennas are used by all nodes in the network, every cell in V_n has no more than c_1 interfering neighbors, and c_1 depends only on Δ and grows no faster than linearly in $(1 + \Delta)^2$.

Proof: We omit the proof due to space limitation.

Lemma 3 [1]**:** In the Protocol Model, there is a schedule for forwarding packets such that in every $(1 + c_1)$ slots, each cell in the tessellation V_n gets one slot for packet transmission, and all transmissions are successfully received within a distance $r(n)$ from their transmitters.

Lemma 4 [9]**:** Based on the assumptions that there is a total number of nq_j cache copies for each content object. Thus, for any node requesting each content object, the average Euclidean distance from the requesting node to the closest copy of desired content object is $\Theta(\frac{1}{\sqrt{nq_j}})$.

We choose the routes of packets to approximate the straight line connecting the requesting node and its closest interesting content objects. Let L_i denotes the straight segment connecting the requesting node and its closest caching node. Under the heterogenous access content pattern, we bound the probability that a line L_i intersects a given cell V in V_n.

Lemma 5: For segment L_i and Voronoi cell V, under the heterogenous content access pattern,

P(L_i intersects V and L_i uses W_1 transmitting packets successfully) $\leq c_3(\frac{1}{q_j})^{\frac{3}{2}} \frac{\sqrt{\log n}}{n^2}$ (Fig. 2).

Proof: We omit the proof due to space limitation.

Since there is a total number of n lines $\{L(i,j_i)\}_{i=1}^n$, connecting the X_i and Y_i, the expected number of lines passing through a Voronoi cell that uses frequency band W_1 is:

$$\begin{aligned}&E(\text{Number of lines in } \{L(i,j_i)\}_{i=1}^n \text{ intersects } V \text{ and}\\&\text{use } W_1 \text{ transmitting packets successfully})\\&\le \frac{c_2\sum_{j=1}^M p_j}{(q_j)^{\frac{3}{2}}}\frac{\sqrt{\log n}}{n}.\end{aligned}$$

By using the uniform convergence in large numbers law, we have the following two results.

Lemma 6: There is a $\delta(n)' \to 0$ such that
$P(\sup_{V \epsilon V_n}$ (Number of lines L_i intersecting V and L_i uses W_1 transmitting packets successfully)
$\le \frac{c_3\sum_{j=1}^M p_j}{(q_j)^{\frac{3}{2}}}\frac{\sqrt{\log n}}{n}) \ge 1-\delta'(n)$.

Note that a cell is proportional to the number of lines passing through it, which can handle the traffic. Since the frequency band W_1 carries traffic of rate T_a^0(n,m) bits/second of each line L_i, we obtain the following:

Lemma 7: There is a $\delta(n)' \to 0$ such that
$P(\sup_{V\varepsilon V_n}(\text{Traffic needing to be carried by cell } V) \le c_3T_a^0(n,m)(\frac{c_3\sum_{j=1}^M p_j}{(q_j)^{\frac{3}{2}}}\frac{\sqrt{\log n}}{n})$
$\ge 1-\delta'(n)$.

Lemma 7 implies that the rate every cell needs to transmit is less than $c_3T_a^0(n,m)(\frac{c_3\sum_{j=1}^M p_j}{(q_j)^{\frac{3}{2}}}\frac{\sqrt{\log n}}{n})$ with high probability. This rate can be managed by every cell if it is less than the rate available, i.e., if

$$c_3T_a^0(n,m)(\frac{c_3\sum_{j=1}^M p_j}{(q_j)^{\frac{3}{2}}}\frac{\sqrt{\log n}}{n}) \le \frac{W_1}{c_2}. \tag{1}$$

Hence, we derive a lower bound on the per-node throughput capacity contributed by ad hoc mode transmissions, which is shown in the following lemma by changing Eq. (1).

Lemma 8: For ad hoc mode transmissions, under heterogenous content access scheme, the lower bound of per-node throughput capacity with content-centric is as follows: When $q_j = o(\frac{\log^{\frac{1}{3}} n}{n^{\frac{2}{3}}}(\sum_{j=1}^M p_j)^{\frac{2}{3}})$, there is a deterministic constant $c > 0$ not depending on n, Δ, or W_1, such that $T_a^0(n,m) = \frac{cn(q_j)^{\frac{3}{2}}W_1}{(1+\Delta)^2\sqrt{\log n}\sum_{j=1}^M p_j}$ bits/second is feasible with high probability, i.e., $T_a^0(n,m) = \frac{n(q_j)^{\frac{3}{2}}W_1}{\sqrt{\log n}\sum_{j=1}^M p_j}$.

When $q_j = \Omega(\frac{\log^{\frac{1}{3}} n}{n^{\frac{2}{3}}}(\sum_{j=1}^{M} p_j)^{\frac{2}{3}})$, there is a deterministic constant $c > 0$ not depending on n, Δ, or W_1, such that $T_a^0(n,m) = W_1$ bits/second is feasible with high probability.

Next, we will derive upper bound on the per-node throughput capacity with content-centric under heterogenous content access scheme.

Lemma 9 [1]**:** For protocol model, the number of simultaneous transmissions on any particular channel with content-centric for the entire network is no more than $N_{max} = \frac{4}{c_8 \pi \Delta^2 r^2(n)}$. Hence, $T_a^0(n,m) \le \frac{c_9 W_1}{\Delta^2 (\frac{1}{q_j})^{\frac{3}{2}} \frac{r(n)}{\sqrt{n}} \sum_{j=1}^{M} p_j}$.

It has shown in [9], $r(n) > \sqrt{\frac{\log n}{\pi n}}$ is necessary to guarantee connectivity with high probability, then we obtain $T_a^0(n,m) \le (q_j)^{\frac{3}{2}} \frac{n}{\sqrt{\log n} \sum_{j=1}^{M} p_j}$.

Proof: We omit the proof due to space limitation.

In addition, $T_a^0(n,m) \le W_1$, we have the following lemma.

Lemma 10: For ad hoc mode transmissions, under heterogenous content access pattern, the upper-bound of per-node throughput capacity with content-centric has two cases: When $q_j = o(\frac{\log^{\frac{1}{3}} n}{n^{\frac{2}{3}}}(\sum_{j=1}^{M} p_j)^{\frac{2}{3}})$, an upper bound on per-node throughput capacity is $T_a^0(n,m) = \frac{n (q_j)^{\frac{3}{2}} W_1}{\sqrt{\log n} \sum_{j=1}^{M} p_j}$ bit/second, where $c' < +\infty$, not depending on n, Δ, or W_1. When $q_j = \Omega(\frac{\log^{\frac{1}{3}} n}{n^{\frac{2}{3}}}(\sum_{j=1}^{M} p_j)^{\frac{2}{3}})$, an upper bound on per-node throughput capacity is that $T_a^0(n,m) = W_1$.

Thus, the total traffic in ad hoc mode is $\frac{\pi}{q_j} T_a^0(n,m)$. Combining Lemma 8 and Lemma 10, we have

Theorem 1: Under the heterogenous access pattern, the throughput capacity of the network with content-centric contributed by ad hoc mode transmissions is

$$T_a(m,n) = \begin{cases} \Theta(\frac{n\sqrt{q_j} W_1}{\sqrt{\log n} \sum_{j=1}^{M} p_j}), \\ q_j = o(\log^{\frac{1}{3}} n (\frac{\sum_{j=1}^{M} p_j}{n})^{\frac{2}{3}}); \\ \Theta(\frac{W_1}{q_j}), \\ q_j = \Omega(\log^{\frac{1}{3}} n (\frac{\sum_{j=1}^{M} p_j}{n})^{\frac{2}{3}}). \end{cases}$$

3.2 Infrastructure Mode Throughput Capacity

Since the base stations divide the area into a hexagon tessellation, there exists a 7-cell frequency reuse pattern in the infrastructure mode. We know that the bandwidth of uplink for infrastructure mode transmission is W_2 bits per second. Thus, the throughput capacity per cell is lower bounded by $\frac{1}{7} W_2$ and upper bounded by W_2. We derive the following lemma.

Lemma 11: Under the heterogenous access pattern, the throughput capacity of the network with content-centric contributed by infrastructure mode transmissions is

$$T_b(n,m) = \Theta(mW_2).$$

By Theorem 1 and Lemma 11, we have the following results.

Theorem 2: Under the heterogenous access pattern, the throughput capacity of the network with content-centric is

$$T(n,m) = \begin{cases} \Theta(\frac{n\sqrt{q_j}W_1}{\sqrt{\log n}\sum_{j=1}^{M} p_j}) + \Theta(mW_2), \\ q_j = o(\log^{\frac{1}{3}} n(\frac{\sum_{j=1}^{M} p_j}{n})^{\frac{2}{3}}); \\ \Theta(\frac{W_1}{q_i}) + \Theta(mW_2), \\ q_j = \Omega(\log^{\frac{1}{3}} n(\frac{\sum_{j=1}^{M} p_j}{n})^{\frac{2}{3}}). \end{cases}$$

When $q_j = o(\log^{\frac{1}{3}} n(\frac{\sum_{j=1}^{M} p_j}{n})^{\frac{2}{3}})$. According to Theorem 2, We have $T(n,m) = \Theta(\frac{n\sqrt{q_j}W_1}{\sqrt{\log n}\sum_{j=1}^{M} p_j}) + \Theta(mW_2)$. If $m = \Omega(\frac{n\sqrt{q_j}}{\sqrt{\log n}\sum_{j=1}^{M} p_j})$, we can get higher throughput capacity when $W_1 = 0$, i.e., $W_2 = W/2$, and $T_{max}(n,m) = \Theta(mW)$, and therefore, if $m = \Omega(n)$, $T^0_{max}(n,m) = \Theta(W)$, if $m = o(n)$, $T^0_{max}(n,m) = \Theta(\frac{mW}{n})$. If $m = o(\frac{n\sqrt{q_j}}{\sqrt{\log n}\sum_{j=1}^{M} p_j})$, we can get higher throughput capacity when $W_2 = 0$, i.e., $W_1 = W$, and $T_{max}(n,m) = \Theta(\frac{n\sqrt{q_j}W}{\sqrt{\log n}\sum_{j=1}^{M} p_j})$, and therefore, $T^0_{max}(n,m) = \Theta(\frac{\sqrt{q_j}W}{\sqrt{\log n}\sum_{j=1}^{M} p_j})$ When $n \to \infty$, then $logn \to \infty$, and hence $T^0_{max}(n,m) \to 0$, which implies that the per-node throughput capacity diminishes as n grows. However, we can improve the per-node throughput capacity by increasing the probability of content cached q_j, as shown in Fig. 3.

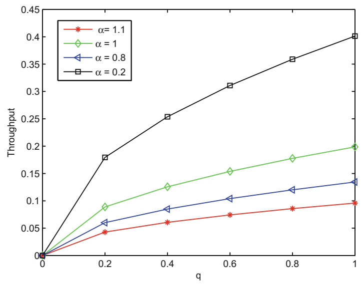

Fig. 3. We show the per-node throughput capacity for various of α vs. caching probability of each content. We assume $M = 500, n = 1000$.

4 Conclusion

In this paper, we studied the through capacity in content-centric hybrid wireless networks under the homogeneous content access scheme and heterogeneous caching scheme, respectively. We shown that under the homogeneous access scheme, the throughput capacity for hybrid wireless networks is a function of the cache size C, the number of contents M, and the number of base stations m. And under the heterogeneous caching scheme, the throughput capacity for hybrid wireless networks greatly depend on the caching probability q_j, the content popularity p_j, and the number of base stations m. We also found that the per-node throughput capacity can scale if the system parameters satisfy certain conditions. As for future work, we plan to investigate the multicast capacity of content-centric hybrid wireless networks.

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