Dynamic Nomadic Node Selection for Performance Enhancement in Composite Fading/Shadowing Environments

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***Abstract*—Next generation mobile and wireless communication systems beyond 2020, aka Fifth Generation (5G) systems, aim at providing ubiquitous user experience with the utmost in quality. One of the promising technologies targeted for 5G systems is the flexible network deployment based on nomadic nodes (NNs). An NN is a low-power movable access node that provides coverage extension and capacity improvement on demand. Yet, NNs require flexible backhaul. One possible cost-efficient realization for flexible backhaul is in-band relaying. In this context, the capacity of the wireless backhaul link between an NN and its serving base station (BS) has a crucial role in the achievable end-to-end performance. The flexible backhaul can be exploited by dynamic NN selection to overcome the limitations of the backhaul link and, thus, to enhance the system performance. To this end, dynamic NN selection is carried out via selecting the serving NN from a set of available candidates considering the signal-to-interference-plus-noise ratio (SINR) on the backhaul link. In this regard, coarse NN selection takes into account only shadowing. Nevertheless, as NNs are stationary or slowly moving during operation, the wireless channels pertaining to NNs are usually subject to simultaneous impairments by both shadowing and multi-path fading, i.e., composite fading/shadowing. In this paper, we present the performance of coarse NN selection in composite fading/shadowing environments with co-channel interference. Further, we evaluate the performance in terms of backhaul link SINR, link rates, and end-to-end rate. Results show that coarse NN selection can yield high performance improvements.**

I. INTRODUCTION

Mobile networks are experiencing the avalanche of data traffic, which is coupled with the billions of wirelessly connected data-intensive devices using diverse multimedia services and applications. Prospective studies suggest that mobile and wireless traffic volume would increase a thousand-fold over the next decade [1]. Furthermore, the users expect the utmost in quality with seamless connectivity to the broadband access. Accordingly, technologies addressing these challenges and fulfilling end-user requirements will lay the foundation of 5G mobile and wireless communications system.

In this context, moving networks emerge as a promising enhancement for 5G system and aim at improving the integration of mobile terminals and nodes into the network while enabling flexible deployment and new services [1]. Within the framework of moving networks, nomadic nodes (NNs) can enable demand-driven service provisioning to increase the network capacity or to extend the cell coverage area, and to reduce network energy consumption [2]. NNs can be mounted on cars within a car-sharing fleet. This also reveals one of the fundamental features of NNs in contrary to fixed access nodes. Namely, an NN is associated with some uncertainty with regards to its availability, i.e., an NN may or may not be available in the target service region. In addition, to attain the aforementioned benefits of NNs, a flexible backhaul needs to be employed, where the capacity of the backhaul link plays a crucial role in the end-to-end user performance.

The flexible backhaul can be realized by inband relaying. In the literature, several studies have elaborated the site planning tools as part of network planning, i.e., *before actual operation*, to improve the performance of fixed inband relays [3], [4], [5]. In those studies, it was shown that via eluding random deployment of fixed relays by selecting a relay site from a set of different possible locations, the backhaul link quality can be clearly improved. In this work, we place the focus on performance enhancement of NNs by means of relaxing the backhaul link limitations. For this purpose, we apply dynamic NN selection *during operation* that considers long-term channel quality which is determined by shadowing, i.e., coarse NN selection. In particular, the serving NN is selected from a set of candidates based on the backhaul link signal-to-interference-plus-noise ratio (SINR). The corresponding performance is evaluated in composite fading/shadowing environments with co-channel interference. Composite fading/shadowing is frequently experienced in scenarios with low or no mobility [6]. Further, given the full-frequency reuse in future cellular networks, co-channel interference is also taken into account. We show the SINR gains on the backhaul link as well as link and end-to-end rate gains by the coarse NN selection (considering only shadowing; slow-scale selection) compared with the optimal NN selection (considering both shadowing and

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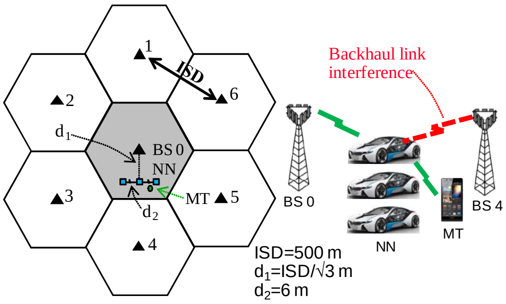

Fig. 1. The network layout and NN location trellis. The distance between two neighboring BSs is the inter-site distance (ISD).

multi-path fading; fast-scale selection). The clear performance improvements justify the use of coarse NN selection.

The remainder of the paper is organized as follows. Section II briefly presents the channel models. In Section III, the system model including coarse NN selection model and parking lot model is summarized. In Section IV, coarse NN selection is analyzed along with SINR and rate derivations. Performance results and evaluations are provided in Section V. Finally, Section VI concludes the paper.

II. CHANNEL MODELS

Shadowing is usually modeled by a lognormal distribution with standard deviation σ and mean μ; σ defines the severity of shadowing. As the parameters of lognormal distribution are often given in decibels, the mappings $\sigma = \lambda\sigma_{\text{dB}}$ and $\mu = \lambda\mu_{\text{dB}}$ with $\lambda = \ln(10)/10$ can be utilized for the conversion. Besides, the small-scale multipath fading is often characterized by Nakagami distribution with the fading parameter $(0.5 \leq m_{\text{CL}} \leq \infty)$ on a communication link (abbreviated by CL in this notation), Rician or Rayleigh distribution. In case of Nakagami distribution, as m_{CL} increases, the multipath fading effect diminishes. Furthermore, Nakagami distribution yields Rayleigh distribution when $m_{\text{CL}} = 1$ [7].

The channel models pertain to a two-hop half-duplex decode-and-forward inband relaying operation through NNs where end-to-end performance is degraded also by interference on the backhaul link. An exemplified schematic with 3 candidate NNs is depicted in Fig. 1, where a mobile terminal (MT) is connected to a single NN on the access link and is communicating via this NN with a BS. The illustration on the right exemplifies the interference caused by BS 4 on the backhaul link. We model the backhaul and access links by Nakagami-lognormal and Rician-lognormal composite distributions, respectively, which are the two common models in the literature [6], [7]. As these composite distributions do not have closed-form expressions, we utilize mixture gamma (MG) distribution [8] to accurately approximate them. It is assumed that interfering signals on the backhaul link are subject to Rayleigh-lognormal (aka Suzuki) composite fading/shadowing. In the following, the instantaneous signal-to-noise ratio (SNR) and the average SNR are denoted by γ and $\bar{\gamma}$, respectively.

A. MG Distribution

The probability distribution function (PDF) of the SNR is approximated by MG distribution consisting of N gamma components as [4], [8]

$$f_\gamma(x) = \sum_{i=1}^{N} \alpha_i x^{\beta_i - 1} e^{-\zeta_i x}, \quad x \geq 0, \tag{1}$$

where α_i, β_i, and ζ_i are the parameters of the i^{th} gamma component. Further, $\alpha_i = \theta_i / C$ where $C = \sum_{i=1}^{N} \theta_i \Gamma(\beta_i) \zeta_i^{-\beta_i}$ with $\Gamma(\cdot)$ being the gamma function is a normalization factor to ensure that $\int_0^\infty f_\gamma(x)\, dx = 1$. Thus, θ_i is also a parameter of the i^{th} Gamma component. The number of components N determines the accuracy of the approximation and is obtained by matching the first r (herein, $r = 3$) moments of the approximation and the target distribution [8]. Next, the cumulative distribution function (CDF) of the approximation is given as

$$F_\gamma(x) = \sum_{i=1}^{N} \alpha_i \zeta_i^{-\beta_i} \gamma(\beta_i, \zeta_i x), \tag{2}$$

where $\gamma(a,b) \triangleq \int_0^b t^{a-1} e^{-t} dt$ is the lower incomplete gamma function.

B. SNR Distribution on the Backhaul Link

The instantaneous SNR on the backhaul link is modeled by a gamma-lognormal distribution (occurs in Nakagami-lognormal channel [6], [8]) . The parameters of i^{th} gamma component are expressed as [8]

$$\begin{aligned} \theta_i &= \left(\frac{m_{\text{BL}}}{\bar{\gamma}}\right)^{m_{\text{BL}}} \frac{w_i e^{-m_{\text{BL}}(\sqrt{2}\sigma t_i + \mu)}}{\sqrt{\pi}\,\Gamma(m_{\text{BL}})}, \\ \beta_i &= m_{\text{BL}}, \quad \zeta_i = \frac{m_{\text{BL}}}{\bar{\gamma}} e^{-(\sqrt{2}\sigma t_i + \mu)}, \end{aligned} \tag{3}$$

where m_{BL} is the fading parameter of Nakagami distribution on the backhaul link (abbreviated by BL in this notation), and t_i and w_i are, respectively, abscissas and weight factors of N^{th} order Hermite integration.

C. SNR Distribution on the Access Link

An NN cell has typically small coverage area due to lower transmit power levels relative to BSs. Thus, we assume that a line-of-sight (LOS) component along with many weak non-LOS (NLOS) scatter components exists on the propagation paths between an NN and an MT on the access link. Further, the LOS component may be partially blocked by surrounding objects, which implies shadowing [6]. Hence, we model the access link by Rician-lognormal distribution. The parameters of the i^{th} gamma component are [4]:

$$\begin{aligned} \theta_i &= \frac{1+K}{\bar{\gamma}} \left(\frac{m_{\text{AL}}}{m_{\text{AL}}+K}\right)^{m_{\text{AL}}} \frac{(m_{\text{AL}})_{i-1}}{(\Gamma(i))^2} \left(\frac{K(1+K)}{\bar{\gamma}(m_{\text{AL}}+K)}\right)^{i-1} \\ \beta_i &= i, \quad \zeta_i = \frac{1+K}{\bar{\gamma}}, \end{aligned} \tag{4}$$

where $0 \leq m_{\text{AL}} \leq \infty$ describes the severity of shadowing on the access link (abbreviated by AL in this notation), and

$K \triangleq \Omega/2b_0$ is the Rician K factor where Ω is the average power of the LOS component and $2b_0$ is the average power of the scatter component.

III. SYSTEM MODEL

A. Coarse NN Selection Model

In the considered scenario, NNs are mounted on vehicles and provide service when the vehicles are parked, i.e., stationary. The height of an NN is assumed to be similar to the one of an MT, i.e., 1.5 m. Hence, more severe fading characteristics are to be observed on the backhaul link similar to those on the link between an MT and the BS.

Within the framework of dynamic NN selection, an NN is chosen from a set of available candidates. Dynamic NN selection takes into account the channel properties at different candidate NNs and considers their links' qualities toward the serving BS in order to enhance the backhaul link quality. In particular, we assume that, at a given time instant, there are M available candidates in cell k out of which we select the best NN in terms of downlink SINR considering shadowing only (coarse NN selection). In the target service region, NN is assumed to be served by a predefined BS solely. Then, the resultant SINR at the selected NN is of the following form

$$\Upsilon^{\text{c}}_{\hat{m},k} = \max\{\Upsilon^{\text{c}}_{m,k} : m = 1, 2, ..., M\}, \tag{5}$$

where $\Upsilon^{\text{c}}_{m,k}$ is the SINR for the m^{th} candidate NN in the k^{th} cell. The SINR at the selected NN $\Upsilon^{\text{c}}_{\hat{m},k}$ can be different than that of the actual SINR $\Upsilon_{\hat{m},k}$, which reflects the actual channel conditions impaired by both shadowing and multi-path fading, i.e., coarse NN selection is carried out based on $\Upsilon^{\text{c}}_{\hat{m},k}$; however, $\Upsilon_{\hat{m},k}$ is the experienced SINR during the operation.

B. Parking Lot Model

In order to take into account the uncertainty for the availability of NNs, we adapt the parking lot model given in [9], which is based on continuous time Markov chain with time variant transition rate [10]. The model can be well defined by the parameters $\{\boldsymbol{O}(t),\ C,\ \Lambda(t),\ \nu(t)\}$. The state of occupation at time t is $\boldsymbol{O}(t) \in \{0,1\}^C$ that takes value of one to indicate that there is a parked vehicle at that parking place and zero for a free parking place. The parking lot has a maximum capacity $C = M_{\max}$ parking places, corresponding to the maximal number of NN candidates in the parking lot. The arrival rate of the system is denoted as $\Lambda(t) \in \mathbb{R}_+$, and the departure rate of each parked vehicle is denoted as $\nu(t) \in \mathbb{R}_+$. According to the definition of Markov chain, the time duration until next vehicle enters or one of the vehicles leaves is exponentially distributed with parameters $\Lambda(t)$ and $\nu(t)$, respectively. Once a vehicle enters the parking lot, it chooses randomly a non-occupied place to park. The system is time variant, since $\Lambda(t)$ and $\nu(t)$ change over time due to varying human activities at different day times. The model suits well with the realistic vehicular movements by choosing proper $\Lambda(t)$ and $\nu(t)$ at different times. Note that the adapted model is equivalent with the $\mathbf{M}/\mathbf{M}/C$ queuing model, where the occupation vector $\boldsymbol{O}(t)$ indicates the occupation state of the servers [10].

C. Multi-cellular Network Model

1) Network Layout and NN Location Trellis: The considered network has a regular hexagonal layout with 7 cells, where we seek a suitable serving NN out of M available candidates in the k^{th} cell. Fig. 1 depicts the network layout and the NN location trellis. The trellis models a practical scenario of a parking lot (line road) where a maximum of $M_{\max} = 25$ parking places are available in a target service region.

2) Path-loss Model: The path loss, including shadowing, is given by

$$L_{m,k} = \alpha d^{\beta}_{m,k} 10^{\zeta_{m,k}/10}/G, \tag{6}$$

where $d_{m,k}$ the distance between m^{th} NN candidate and k^{th} BS, $k = 0, 1, 2, ..., \mathcal{K}$. Further, α and β define the distance dependent path-loss and are, respectively, a propagation constant and the path-loss exponent, G is dimensionless and reflects the impact of antenna gain, which is assumed to be the same for each BS. Besides, $\zeta_{m,k}$ is a zero-mean Gaussian random variable (RV) that models shadowing. RV $\zeta_{m,k}$ can be expressed as a sum of two independent zero-mean Gaussian RVs ξ_m and $\eta_{m,k}$ with standard deviation of σ_{dB} [4] as

$$\zeta_{m,k} = \sqrt{\rho} \cdot \xi_m + \sqrt{1-\rho} \cdot \eta_{m,k}, \tag{7}$$

where ρ is the correlation coefficient related to any pair of BSs. Accordingly, for $k \neq j$, we obtain

$$\text{E}(\zeta_{m,k}\zeta_{m,j}) = \rho\sigma^2_{\text{dB}},\ \text{E}((\zeta_{m,k})^2) = \sigma^2_{\text{dB}},\ \text{E}(\zeta_{m,k}) = 0. \tag{8}$$

As in 3GPP studies, the shadowing correlation coefficient of $\rho = 0.5$ between BSs is applied [11]. In accordance with Gudmundson model [4], the correlation between shadowing samples at different locations in the k^{th} cell is given by

$$\rho(\zeta_{m,k}, \zeta_{n,k}) = e^{-\frac{|d_{m,n}|}{d_{\text{cor}}}\ln 2}, \tag{9}$$

where $\zeta_{m,k}$ and $\zeta_{n,k}$ are the shadowing variables at locations m and n, respectively, $d_{m,n}$ is the distance between the two locations, and $d_{\text{cor}} = 20$ m [5] is the de-correlation distance.

IV. ANALYSIS OF COARSE NN SELECTION

A. Derivation of the Backhaul Link SINR

The actual SINR at the m^{th} NN candidate considering composite fading/shadowing is of the following form [4]

$$\Upsilon_{m,k} = \frac{S^2_{m,k} 10^{X_{m,k}/10}}{P_N + \sum\limits_{j \neq k} S^2_{m,j} 10^{X_{m,j}/10}}, \tag{10}$$

where $S^2_{m,k}$ is the power envelope of the Nakagami fading channel on the desired link between the k^{th} BS and m^{th} NN candidate, $S^2_{m,j}$ is the power envelope of the Rayleigh fading channel on the interfering link between the j^{th} BS and m^{th} NN candidate, and P_N denotes the thermal noise. Further, $X_{m,k} \sim \mathcal{N}(\mu_{X_{m,k}}, \sigma^2_{\text{dB}})$ with $X_{m,k} = -\zeta_{m,k} + \mu_{X_{m,k}}$ and $X_{m,j} \sim \mathcal{N}(\mu_{X_{m,j}}, \sigma^2_{\text{dB}})$ with $X_{m,j} = -\zeta_{m,j} + \mu_{X_{m,j}}$ are Gaussian RVs, where means $\mu_{X_{m,k}}$ and $\mu_{X_{m,j}}$ comprise BS transmit power levels, and distance dependent path losses defined in (6). For example, we have $\mu_{X_{m,k}} = 10\log_{10}(P_{\text{Tx},k} G \alpha^{-1} d^{-\beta}_{m,k})$ with $P_{\text{Tx},k}$ being the transmit power of the k^{th} BS.

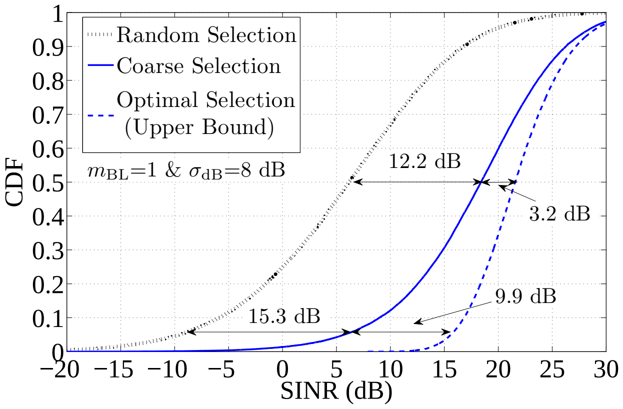

Fig. 2. CDFs of SINR on the backhaul link considering NN selection.

When only shadowing is considered on the backhaul link for coarse NN selection, (10) can be re-written by assigning $S^2_{m,k} = 1$ and $S^2_{m,j} = 1$ to obtain $\Upsilon^{\mathrm{c}}_{m,k}$.

B. Link and End-to-end Rate Derivations

In the k^{th} cell and at the m^{th} NN, backhaul link rate $R_{b;m,k}$ is given in terms of the backhaul link SINR as

$$R_{b;m,k} = \delta_b \cdot A_b \cdot \log_2\left(1 + B_b \cdot \Upsilon_{m,k}\right), \tag{11}$$

where A_b and B_b are, respectively, the bandwidth and SINR efficiency factors, and δ_b is the overhead scaling factor which accounts for, e.g., overhead through reference symbols [4]. In case of performing dynamic NN selection, we obtain the backhaul link rate $R_{b;\hat{m},k}$ by utilizing the backhaul link SINR at the selected NN, i.e., $\Upsilon_{\hat{m},k}$. On the other hand, the access link instantaneous rate R_a is of the form

$$R_a = \delta_a \cdot A_a \cdot \log_2\left(1 + B_a \cdot \gamma_a\right), \tag{12}$$

where γ_a is the instantaneous SNR on the access link.

Due to assumed half-duplex operation[1], transmissions from BS to NN and from NN to MT are scheduled on different time slots. Time resources allocated for the backhaul and access link communications constitute τ_b and τ_a of the total system resources, respectively, where $\tau_b + \tau_a = 1$. Then, the end-to-end rate experienced by a single user served by m^{th} NN in the k^{th} cell is defined as

$$R_{e;m,k} = \min\left(\tau_b \cdot R_{b;m,k}, \tau_a \cdot R_a\right), \tag{13}$$

where rates on the backhaul and access links are scaled by the portion of resources allocated to each. When dynamic NN selection is performed, the end-to-end rate $R_{e;\hat{m},k}$ is formulated similarly considering $R_{b;\hat{m},k}$ instead.

V. PERFORMANCE EVALUATION

Herein, we evaluate the effect of coarse NN selection on the backhaul link quality as well as on the end-to-end performance. We demonstrate the achievable gains relative to the performance bound. The simulations are conducted using MATLAB as the computational environment. In Table I, the system parameters are summarized. The Nakagami fading parameter is set to one (Rayleigh fading) to simulate more severe fading characteristics on the backhaul link, and shadowing standard deviation is set to 8 dB, i.e., $(m_{\mathrm{BL}}; \sigma_{\mathrm{dB}}) = (1; 8)$. Random NN selection is taken as reference. Unless otherwise stated, we set the parking lot model parameters in Section III-B such that a regular day time is simulated (see Table I), where an average number of 22 NN candidates are available.

TABLE I
SYSTEM PARAMETERS

Parameter	**Value**
Carrier Frequency & Bandwidth	2 GHz & 10 MHz (FDD)
(A_b, A_a) & (B_b, B_a) & (δ_b, δ_a)	0.88 & 0.8 & 0.74
Thermal Noise	-174 dBm/Hz
Parking Lot Model Parameters	
Morning Rush Hour (07:00-09:00)	(Λ, ν) = (5, 300) min
Regular Day Time (09:00-17:00)	(Λ, ν) = (15, 300) min
Evening Rush Hour (17:00-19:00)	(Λ, ν) = (300, 5) min
BS Parameters	
Transmit Power	46 dBm
Antenna Gain	14 dBi
Antenna Configuration and Pattern	Tx-1, Omni-directional
NN Parameters	
Antenna Gain	5 dBi
Antenna Configuration and Pattern	Rx-1, Omni-directional
Noise Figure	5 dB
Backhaul Link Path-Loss	
Path-Loss Exponent (β)	3.63
Propagation Constant (α_{dB})	125.2 dB

A. Backhaul Link SINR Distribution

The impact of NN selection on the backhaul link SINR is illustrated by CDF plots in Fig. 2. It is noticed that coarse NN selection provides high SINR gains of about 15 dB and 12 dB at lower and median CDF percentiles, respectively. Moreover, it is observed that the gains via coarse NN selection deviate less from the maximum achievable gains by optimal NN selection particularly at high CDF percentiles. Nevertheless, the observed significant gains through coarse NN selection justify its impact in alleviating the effects of severe fading.

B. Link and End-to-end Rates

Fig. 3 shows the CDFs of link and end-to-end rates with different NN selection schemes. Two cases are considered for the channel conditions on the access link [4]

i) frequent heavy shadowing with average access link SNR of $\overline{\gamma}_a = 10$ dB reflects relatively *moderate channel conditions* as shown in Fig. 3(a), while

ii) infrequent light shadowing with average access link SNR of $\overline{\gamma}_a = 20$ dB corresponds to *good channel conditions* as shown in Fig. 3(b).

The resource allocation parameters are set as $\tau_b = \tau_a = 0.5$. It is seen that coarse NN selection results in clear rate gain on the backhaul link relative to random NN selection. The deviation from the maximum achievable SINR gains translates into deviation in rate gains on the backhaul link,

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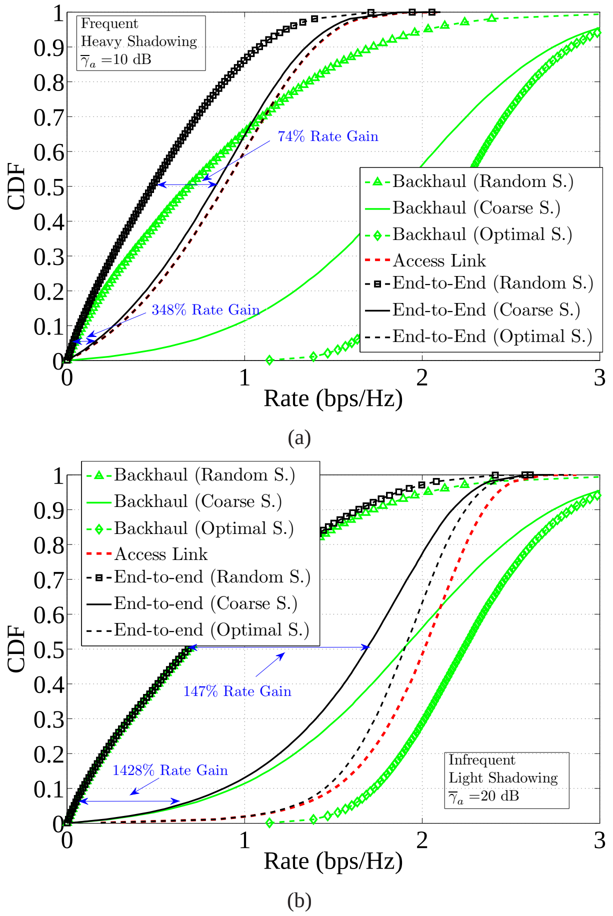
[1] Note that the concepts presented in this work can also be applied for other operation schemes, such as full-duplex operation.



(a)

(b)

Fig. 3. Backhaul link, access link and end-to-end rate CDFs considering NN selection. On the access link, (a) moderate channel conditions and (b) good channel conditions are considered (S. stands for Selection in legends).

as well. Yet, the end-to-end rate depends on the capacities of both the backhaul and access links. In this regard, under moderate access link channel conditions, the end-to-end rate performance is limited mainly by the capacity of the access link; the CDF plots of end-to-end and access link rates overlap. Thus, the end-to-end rate performance of coarse NN selection is similar to that of optimal NN selection. On the other hand, under good access link channel conditions, the end-to-end rate through NN selection is limited by the capacity of the backhaul link. In such a case, the deviation in end-to-end rate performance of coarse NN selection from that of optimal NN selection becomes notable at lower CDF percentiles. Yet, when performing coarse NN selection, a significant gain in end-to-end rate relative to random selection is still observed.

C. Mean End-to-End Rate over Day Time

Fig. 4 depicts mean end-to-end rates of random NN selection and coarse NN selection along with average number of candidate NNs over day time. During the morning rush hour, places for NN candidates are rapidly occupied, while average number of NN candidates stays stable during regular day time, and it decreases during evening rush hour. Mean end-to-end rate for coarse NN selection follows a similar trend, where with larger number of NN candidates achievable rates are also higher. Relative to random NN selection, more than 100% mean end-to-end rate gains are shown most of the day time.

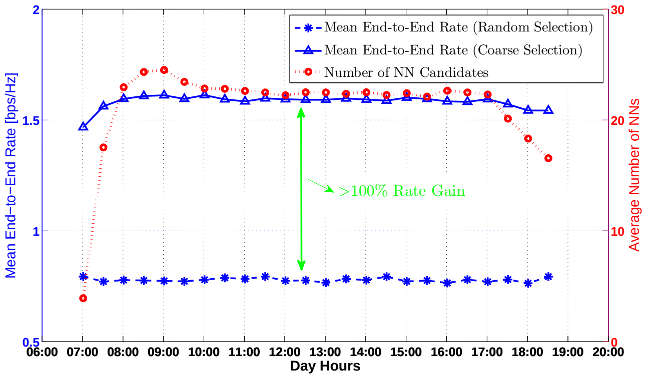


Fig. 4. Mean end-to-end rates and average number of candidate NNs over day time (see Table I for parking lot model parameters).

VI. CONCLUSION

In this work, we investigate coarse NN selection as a practical technique to enhance the wireless backhaul link performance. The NN selection is carried out considering shadowing only, whereas the performance has been analyzed assuming composite fading/shadowing channels.

Results show that performing coarse NN selection provides significant gains on the backhaul link SINR relative to random NN selection, particularly boosting the low SINR regime. Achieved SINR gains on the backhaul link are shown to translate into clear improvements in end-to-end rates. Further, the deviation from the maximum achievable end-to-end rate gains becomes negligible when the access link is the bottleneck.

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