Analyzing Cognitive Network Access Efficiency Under Limited Spectrum Handoff Agility

MohammadJavad NoroozOliaee, Bechir Hamdaoui, Xiuzhen Cheng, Taieb Znati, Mohsen Guizani

***Abstract*—Most existing studies on cognitive radio networks assume that cognitive users can switch to any available channel, regardless of the frequency gap between the target channel and the current channel. However, due to hardware limitations, cognitive users can actually jump only so far from where the operating frequency of their current channel is. This paper studies the performance of cognitive radio networks while considering realistic channel handoff agility, where cognitive users can only switch to their neighboring channels. We use continuous-time Markov process to derive and analyze the forced termination and blocking probabilities of cognitive users. Using these derived probabilities, we then study and analyze the impact of limited spectrum handoff agility on cognitive spectrum access efficiency. We show that accounting for realistic spectrum handoff agility reduces performance of cognitive radio networks in terms of spectrum access capability and efficiency.**

***Index Terms*—Dynamic spectrum access; performance modeling and analysis; spectrum handoff agility.**

I. INTRODUCTION

Cognitive radio access paradigm allows cognitive users (CUs) to exploit unused licensed spectrum on an instant-by-instant basis, so long as it causes no harmful interference to primary users (PUs). For this, CUs must ensure that licensed bands are vacant before using them, and they must vacate them immediately upon the return of any PUs to their licensed bands. Cognitive radio access, also referred to as dynamic or opportunistic spectrum access, has great potential for improving spectrum efficiency and increasing achievable network throughput of wireless communication systems. The research issues and topics that have been addressed in these recent years are numerous, ranging from fundamental networking issues to practical and implementation ones. A few examples of such issues and topics are spectrum access management [1–4], adaptive and learning technique development [5–8] and spectrum prediction models [9–14]. Research efforts have also been given to deriving models and studying behaviors of the cognitive radio access performance [15–18]. Generally, most of these performance studies model cognitive radio access by means of Markov chains, and use these models to derive and analyze network performances. For example, in [19–23], Markov chains are used to model and study the forced termination and blocking probabilities of CUs in a cognitive multichannel access system consisting of primary and cognitive users. However, one common unrealistic assumption made in these existing works that we address in this paper is that CUs, when accessing the multichannel system opportunistically, are allowed to switch/jump to any available channel in the system, regardless of the frequency gap between the target and the current channels [24]. But due to hardware limitations, CUs can actually jump only so far from where the operating frequency of their current channel is, given an acceptable switching delay that users are typically constrained by [25]. Therefore, in this paper, we study the performance of cognitive radio networks, but while considering realistic channel switching (or handoff) agility, where CUs can only switch to channels that are immediate neighbors of their current operating channels.

The rest of the paper is organized as follows. In Section II, we state the system model. In Section III, we model and derive analytically the forced termination and blocking probabilities. Section IV validates the derived results, and analyzes the performance behaviors. Section V investigates the impact of spectrum handoff agility on spectrum access efficiency. Finally, in Section VI, we conclude our work.

II. MULTICHANNEL ACCESS SYSTEM MODEL

We consider a cognitive radio multichannel access system with m primary bands, B_1,...,B_m, where each band is composed of n sub-bands, giving a total of mn sub-bands, termed A_1,...,A_{mn}. Two types of users are present in the system. Primary users (PUs) who have exclusive access rights to B_1 to B_m, and cognitive users (CUs) who are allowed to use the A_1 to A_{mn} sub-bands, but in an opportunistic manner; i.e., so long as they do not cause any harmful interference to PUs. Throughout this work, we assume that CUs are equipped with single-radio devices.

While PUs have strict priority to use the spectrum bands, CUs are allowed to use a sub-band only when the sub-band's associated primary band is vacant; i.e., not being used by any PUs. Here, we ignore the spectrum handoff and spectrum sensing delays, simply because both of them are bounded [25, 26] and hence do not impact the blocking and the forced termination probabilities; i.e., the performances that we study in this work. These delays, however, need to be accounted for when analyzing system throughput and spectrum utilization performances. Therefore, we assume throughout that CUs are

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always aware (with some bounded delay) of the presence of PUs, and that as soon as any PUs reclaim their band, CUs are capable of immediately (or with some bounded delay) vacating the band and switch to another idle sub-band, if any exists. In our model, we assume that, during spectrum handoff [19], CUs can jump to any channel/band situated at no more than k bands away from its current operating band; the set of possible channels to which a CU is able to jump to is referred to as the *target handoff channel set*. Specifically, if a CU is currently using a sub-band belonging to primary band B_i, the CU can only jump to any sub-band from B_{i-k} to B_{i+k} when handoff is initiated.

III. Modelling and Characterization

We model the channel selection process as a continuous-time Markov process, defined by its states and transition rates. In this section, we define the states and calculate the state transition rates. As stated previously, mn sub-bands are shared by both PUs and CUs. Thus, we define each state as an m-tuple $(i_1, ..., i_m)$ in which i_j, for $j = 1, 2, \ldots, m$, indicates the number of CUs in band j if $i_j > -1$, otherwise i_j is equal to -1, indicating that band j is occupied by a PU. Note that i_j takes on values between -1 and n (i.e., $-1 \leq i_j \leq n$). Thus, the total number of states is $(n+2)^m$ and all these states are valid. We assume that arrivals of CUs and PUs both follow Poisson processes with arrival rates λ_c and λ_p, respectively, and the service times are exponentially distributed with rates μ_c and μ_p, respectively. There are four cases/events under which a state changes, and thus we only have to consider these four cases to compute the transition rate matrix $\mathbf{Q}$. In what follows, let $(i_1, ..., i_m)$ be the current state.

Case 1: First, consider that a CU arrives to the system and selects spectrum band j. The next possible states are then $(i_1, ..., i_j + 1, ..., i_m)$ for all $-1 < i_j < n$. Assuming that the number of these states is α, the transition rate from $(i_1, ..., i_m)$ to $(i_1, ..., i_j + 1, ..., i_m)$ is then λ_c/α. The states whose i_j value is either -1 or n do not change, because the CU will be blocked and denied access to the system in this case. Note that α might be different for different states and it can be calculated via $\alpha = \sum_{l=1,-1<i_l<n}^{m} 1$.

Case 2: Second, consider that a CU leaves spectrum band j. In this case, the next possible states are $(i_1, ..., i_j - 1, ..., i_m)$ for all $i_j > 0$. Thus, the transition rates from $(i_1, ..., i_m)$ to $(i_1, ..., i_j - 1, ..., i_m)$ is $i_j\mu_c$.

Case 3: Third, when a PU leaves band j, the next states are $(i_1, ..., i'_j, ..., i_m)$ where $i'_j = 0$ and $i_j = -1$. Assuming that the number of occupied bands by PUs is β which means that the number of next states is also β, the transition rate from $(i_1, ..., i_m)$ to $(i_1, ..., i'_j, ..., i_m)$ is then μ_p/β, where as stated earlier $i'_j = 0$ and $i_j = -1$. Note that β might be different for different states and it can be calculated via $\beta = \sum_{l=1,i_l=-1}^{m} 1$.

Case 4: Fourth, consider that a PU arrives to spectrum band j. Note that PUs do not select any band upon their arrivals, since they already have their predefined bands to operate on. In this case, the next states are $(i_1, ..., i'_{j-k}, ..., i'_j, ..., i'_{j+k}, ..., i_m)$ where $i'_j = -1$ and $\sum_{l=j-k,l\neq j}^{j+k} (i'_l - i_l) = i_j$ if user is not forced to terminate. User access termination occurs when none of the adjacent bands can accommodate the cognitive user that is required to vacate band j. Thus, the next states are $(i_1, ..., i'_{j-k}, ..., i'_j, ..., i'_{j+k}, ..., i_m)$ where $i'_j = -1$ and ($i'_l = n$ or $i'_l = -1$) for $j - k \leq l \leq j + k$. When the user is forced to terminate, the transition rate is λ_p, and when there is no termination, the transition rate is as follows

$$\gamma_{s'}^{s} = \lambda_p \left(\frac{1}{2k - \sum_{l=j-k,i'_l=-1}^{j+k} 1} \right)^{i_j} \prod_{l=0,l\neq k}^{2k} \binom{i_j}{i'_{j-k+l} - i_{j-k+l}} \tag{1}$$

where $\gamma_{s'}^{s}$ denotes the transition rate from state s to state s', where $s = (i_1, ..., i_m)$ and $s' = (i'_1, ..., i'_m)$. Thus far, we computed the transition rates, and we were able to determine the transition rate matrix $\mathbf{Q}$. One can solve the system of equations

$$\boldsymbol{\pi}.\mathbf{Q} = 0 \;\text{ and }\; \sum_{i=1}^{(n+2)^m} \pi_i = 1 \tag{2}$$

where π_i is the stationary probability of state i and $\boldsymbol{\pi}$ is the stationary probability matrix.

Note that only transition rates that are calculated in **Case 4** depend on the value k since spectrum handoff is expected to occur only in this case. In the other three cases, no spectrum handoff occurs, and hence, next states do not depend on the value of k. Thus, in terms of model complexity, we can say that the construction of the transition matrix $\mathbf{Q}$ depends on the value k, because as k increases, the number of possible transitions increases and hence so is the number of non-zero entries of $\mathbf{Q}$. The size of $\mathbf{Q}$ which is $(n+2)^m \times (n+2)^m$ does not, however, depend on k. Therefore, the complexity of solving Eq. (2) may not depend on k if general algorithms are used. But if customized algorithms (those that take advantage of matrix sparsity) are used instead, such a complexity may be reduced depending on the value of k.

Now, the forced termination probability P_f of a cognitive user can be defined as

$$P_f = \frac{\sum_{(s,s')\in T} \pi_s \gamma_{s'}^{s}}{(1 - P_b)\lambda_c} \tag{3}$$

where T is the set that contains all state pairs (s, s') in which a user is forced to terminate when transitions from s to s', and P_b is the blocking probability to be defined later. Formally, T can be defined as $T = \{(s, s') = ((i_1, ..., i_m), (i'_1, ..., i'_m))|N_c(s) > N_c(s') \; and \; N_p(s) < N_p(s')\}$ where $N_c(s)$ and $N_c(s')$ are the numbers of CUs in state s and s', respectively, and $N_p(s)$ and $N_p(s')$ are the numbers of PUs in state s and s', respectively. The number of CUs in state $s = (i_1, ..., i_m)$, $N_c(s)$, can be written as $N_c(s) = \sum_{j=1,i_j\neq-1}^{m} i_j$. Similarly, the number of PUs in state $s = (i_1, ..., i_m)$, $N_p(s)$, can be written as

$N_p(s) = \sum_{j=1, i_j=-1}^{m} 1$. When a new CU arrives to the system and cannot find any empty sub-band, because the bands are occupied by either PUs or any other CUs, the user is denied access to the system. In this case, we say that the CU is blocked, and the blocking probability P_b can then be written as

$$P_b = \sum_{s \in B} \frac{\pi_s \lambda_c}{\sum_{s \in S, s \neq s'} \gamma_{s'}^{s}} \quad (4)$$

where B is the set of all the states in which blocking occurs when a new CU arrives to the system, and is defined as $B = \{s = (i_1, ..., i_m) | \forall j \;\; 1 \leq j \leq m, \;\; -1 < i_j < n\}$.

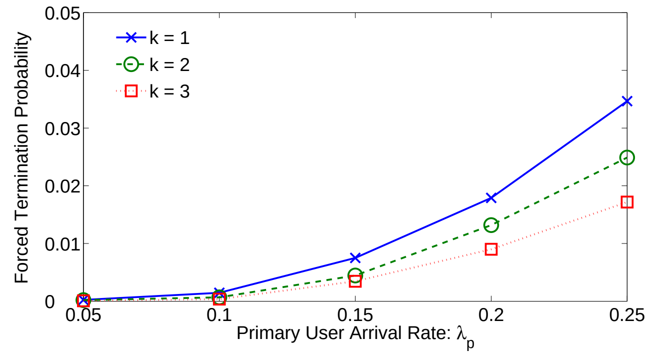
It is worth mentioning that although the focus of this work is on analyzing how the value k affects the forced termination and blocking probabilities and not so much on how one chooses k, one can first set (decide on) acceptable/predefined blocking and forced termination probabilities, and then use Eqs. (3) and (4) to find the value of k that meets such probabilities. Basically, setting upper (lower) bounds on blocking and forced termination probabilities results in a set of values for k that satisfy these upper (lower) bounds.

IV. Analytic Result Validation and Analysis

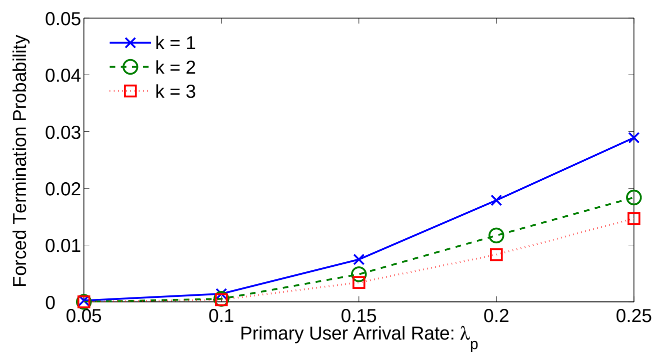
In this section, we validate our derived analytic results via MATLAB simulations, and analyze the performance of cognitive radio spectrum access systems with limited channel handoff by studying the impact of the target handoff channel set size on cognitive users' forced termination and blocking probabilities.

A. Impact of Handoff Agility on Termination Probability

Fig. 1(a) plots the derived forced termination probability of cognitive users as a function of the primary user arrival rate λ_p for three different values of the number of target handoff channels, k. The termination probability is defined as the probability that a cognitive user, already accessing and using a channel whose PU has returned, is forced to cease communication as a result of none of the channels in its target handoff channel set is vacant. First and as expected, observe from the figure that as the primary user arrival rate (i.e., PU load) increases, the probability that cognitive users (already using the system) are forced to leave the system due to not finding an available band in their target handoff channel set increases. Second, for a given primary user arrival rate λ_p, the greater the number of target handoff channels, the lower the forced termination probability. Again, this trend of performance behavior is expected, as having more channels to switch to, increases the chances of cognitive users finding available bands, which explains the decrease in the forced termination probability of cognitive users. Third, the gap between the forced termination probabilities for different numbers of target handoff channel set sizes increases with the primary user arrival rate. To validate the derived analytic results, we use MATLAB to simulate a multichannel access system with primary and cognitive users arriving to the system according to Poisson process with arrival rates λ_p and λ_c, respectively. In these simulations, we compute the actual forced termination probability of cognitive users, measured as the ratio of the number of terminated users to the total number of accepted users. Fig. 1(b) shows the values of forced termination probabilities of the simulated cognitive radio spectrum access network again for three values of k. Observe that the simulated performance behaviors of cognitive systems in terms of the forced termination probability match well those obtained via our analytic results. This validates our derived models.



(a) Analytic results



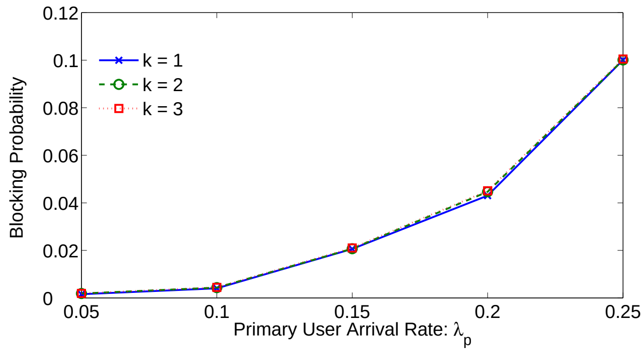
(b) Simulation results

Fig. 1. Forced termination probability as a function of the primary arrival rate λ_p for $k = 1, 2, 3$: $m = 7$ and $n = 2$ ($\mu_p = 0.06$, $\lambda_c = 0.68$, $\mu_c = 0.82$)

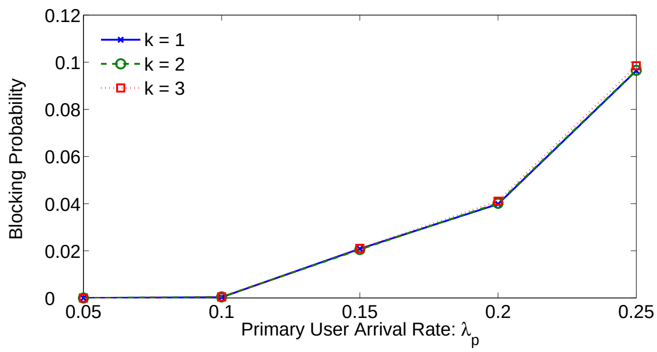
B. Impact of Handoff Agility on Blocking Probability

We now study the impact of channel handoff agility on the blocking probability of cognitive users, defined as the probability that a cognitive user, attempting to access the multichannel system, is denied access to the system due to not finding any available channels. Fig. 2(a) depicts the derived blocking probability of cognitive users as a function of the primary user arrival rate λ_p for three different values of the number of target handoff channels, $k = 1, 2, 3$.

First, observe that, as expected, the blocking probability of cognitive users increases with the primary user arrival rate. That is, as the rate of primary users increases, the network becomes more and more loaded, resulting in higher blocking probability. Second, observe that unlike the case of forced termination probability, the blocking probability does not depend on the level of spectrum agility; i.e., the value of k.



(a) Analytic results



(b) Simulation results

Fig. 2. Blocking probability as a function of the primary arrival rate λ_p for $k = 1, 2, 3$: $m = 7$ and $n = 2$ ($\mu_p = 0.06$, $\lambda_c = 0.68$, $\mu_c = 0.82$)

This is because any new cognitive user wanting to access the system does so by selecting any available channel, which leads to the same chances of being able to find an available channel, regardless of how agile spectrum handoff is for existing users (users that are already using the system).

Like the case of termination probability studied in the previous section, we now validate our analytic results of blocking probability using MATLAB. We simulate a multichannel system with primary and cognitive users arriving to the system according to Poisson process with arrival rates λ_p and λ_c, respectively. In these simulations, we compute the actual blocking probability of cognitive users, measured as the ratio of the number of blocked users to the total number of arrived users. We show in Fig. 2(b) the blocking probabilities of the simulated cognitive network for three values of channel handoff set size, $k = 1, 2, 3$. Observe that the simulated blocking probability performance behaviors of cognitive systems, shown in Fig. 2(b), match well those obtained via our analytically derived results, shown in Fig. 2(a). This validates the analytic blocking probability performance that we derived in this work.

V. Spectrum Efficiency Evaluation

In this section, we study the impact of spectrum handoff agility on cognitive spectrum access efficiency. We use the blocking and forced termination probabilities derived in the previous sections to evaluate the efficiency of cognitive spectrum access while considering different levels of spectrum handoff agility, k.

We first begin by defining and deriving the cognitive spectrum access efficiency while assuming no limited spectrum handoff agility. This will serve as an upper bound on the maximal achievable spectrum efficiency when considering limited handoff agility. Let us assume that there is no limited spectrum handoff agility, meaning that cognitive users are allowed to switch to any available band without any handoff restriction. Using classic Markovian analysis [27], one can write the probability p_j that j bands (out of m bands) are occupied by PUs as $p_j = \frac{\rho^j}{j! \sum_{i=0}^{m} \rho^i / i!}$ (here only PUs are considered). where $\rho = \lambda_p/\mu$ and $\mu = \mu_p = \mu_c$. It follows that the average number E_p of spectrum bands occupied by PUs can be written as $E_p = \rho - \frac{\rho^{m+1}}{m! \sum_{j=1}^{m} \rho^j / j!}$.

Similarly, the average number E_c of bands occupied by either PUs or CUs can be written as (now both PUs and CUs are considered) $E_c = \rho_c - \frac{\rho_c^{m+1}}{m! \sum_{j=1}^{m} \rho_c^j / j!}$ where $\rho_c = (\lambda_p + \lambda_c)/\mu$.

Note that here both PUs and CUs are treated the same, in that both types are allowed to use the spectrum with equal access rights and opportunities. Again, this simplified cognitive spectrum access is introduced so that it can be used as an upper bound on the maximum achievable spectrum efficiency when considering realistic cognitive network access, where PUs have spectrum access priority over CUs, and when CUs have limited spectrum handoff agility.

We now define the *ideal cognitive spectrum access efficiency*, η, (or cognitive spectrum access efficiency with no limited spectrum handoff agility) as

$$\eta = \frac{E_c - E_p}{m - E_p} \tag{5}$$

In Fig 3, we measure the cognitive spectrum access efficiency with limited handoff agility, normalize it with respect to the ideal spectrum access efficiency (given in Eq. (5)), and show it for various values of primary user arrival rates when $k = 1$, $k = 2$, and $k = 3$. The values of blocking and termination probabilities used in this study are extracted from the results shown in the previous section. First, observe that as the primary user arrival rate increases, the spectrum efficiency of cognitive radio network access with limited channel handoff capability reduces, and this is regardless of the value of the parameter k of handoff agility. Second, note that the efficiency of cognitive spectrum access depends on how agile spectrum handoff is, and the higher the agility, the higher the spectrum efficiency. For example, when $\lambda_p = 0.8$, having a spectrum handoff agility of value $k = 3$ yields a cognitive spectrum efficiency of about 60% of the ideal efficiency (obtained when channel handoff is not limited to k channels), whereas, when handoff is limited to $k = 1$, the efficiency reaches about 18% of the ideal efficiency only. Third, the figure also shows that the difference between achievable spectrum efficiencies under different numbers of target handoff channels increases with the primary user arrival rate. That is, the higher the arrival rate, the

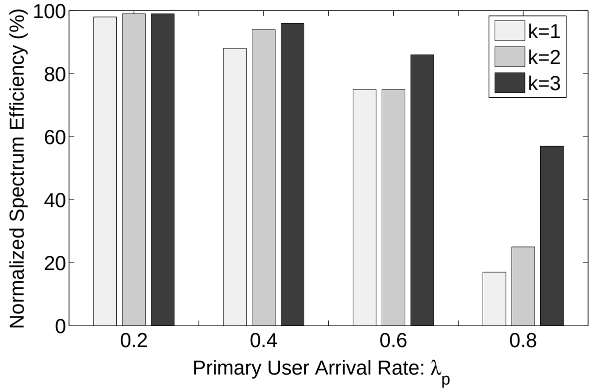


Fig. 3. Spectrum efficiency as a function of the primary arrival rate λ_p for $k = 1, 2, 3$.

higher the gap between the spectrum efficiency under $k = 3$ and that under $k = 1$. Note that $k = 3$ is the case that there is no limited spectrum handoff agility since $m = 7$. To summarize our findings, in this work, we demonstrate the impact of the commonly made assumption of considering that cognitive users can handoff/switch to any available band, regardless of how far the target band is from the current band, on the performance behaviors of cognitive radio spectrum access systems. Our results show the importance of considering realistic spectrum handoff agility (i.e., with restricted/limited target handoff channel set) when assessing the achievable network performances and the spectrum access efficiency of cognitive radio networks. We found (both analytically and numerically) that the achievable cognitive radio performance in terms of system access capability and spectrum access efficiency can be significantly lesser than what is usually claimed in existing works, due to the limited nature of spectrum handoff agility that most works ignore and do not take into account. We therefore conclude that making unrealistic spectrum handoff assumption may lead to very inaccurate and misleading results, and it is then imperative that performance studies of cognitive radio networks do account for the restricted agility of channel switching.

VI. Summary of Findings and Concluding Remarks

This paper models and analyzes the performance behaviors of cognitive radio networks enabled with dynamic multichannel access capability, but while considering realistic channel handoff agility assumptions, where cognitive users can only switch to vacant channels that are immediate neighbors of their current channels. Using Markov chain analysis, we model cognitive access networks with restricted channel handoff agility as a continuous-time Markov process, and analytically derive the forced access termination and blocking probabilities of cognitive users, and evaluate the spectrum access efficiency of cognitive networks. Using MATLAB simulations, we also validate our analytically derived performance results.

Our obtained results demonstrate the impact and importance of considering realistic channel handoff agility in cognitive radio access on the cognitive radio network performances in terms of users' blocking and termination probabilities, as well as cognitive spectrum access efficiency. This work demonstrates the cognitive radio performance implications of the commonly made spectrum-handoff agility assumption of allowing cognitive users to switch to any available band, regardless of how far the target band is from the current band.

Our findings in this work show that the achievable performance of cognitive radio networks in terms of spectrum access capability and efficiency can be significantly lesser than what existing works usually claim, due to the limited nature of spectrum handoff agility that most works do not account for. We conclude that making unrealistic assumption regarding the spectrum handoff agility may lead to very inaccurate and misleading results, and it is then imperative that performance studies of cognitive radio networks do account for the restricted agility of channel switching when modeling and assessing the performance of such networks.

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