Device-to-Device Communications in LTE-Unlicensed Heterogeneous Network

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***Abstract*—In this paper, the authors examine how the envisaged Device-to-Device (D2D) networks can efficiently scale its capacity by utilizing the unlicensed spectrum with appropriately designed LTE-Unlicensed (LTE-U) protocols. The LTE-U Listen Before Talk (LBT) algorithm is adapted for collision avoidance between traditional unlicensed user equipment (UEs), e.g. Wi-Fi UEs, and the LTE-U enabled D2D UEs. By considering different traffic loads, the analysis found that whilst the D2D UEs reduce the unlicensed network capacity, it increases the combined licensed and unlicensed network capacity by 63%.**

***Index Terms*—LTE-Unlicensed spectrum, Heterogeneous Network, Device-to-Device (D2D), Listen-before-talk (LBT).**

I. INTRODUCTION

Recently, the concept of device-to-device (D2D) communications in co-existence with cellular networks has been proposed. D2D communications enable devices to communicate directly with each other without access to a fixed wireless infrastructure. Specifically, D2D communications is a technology for enhancing the cellular network capacity [1] as well as the energy- and spectral-efficiency [2] in order to meet the increasing demands for high data rate access with variable latency requirements. Hence, D2D communications has been identified by the Third Generation Partnership Project (3GPP) as a potential candidate technology[1] to offload delay-tolerant data traffic away from conventional cellular (CC) channels [3].

A. D2D Band Spectrum

The D2D communication can utilize either the inband cellular spectrum or outband spectrum. The outband spectrum can be either unlicensed spectrum or allocated spectrum taken from the licensed band [4]. Outband D2D is advantageous compared with inband D2D because there is no mutual interference between D2D and CC UEs. For example, in [5] the industrial, scientific and medical (ISM) band is selected for D2D communications in LTE. The D2D UEs are grouped based on the different QoS requirements, whereby only one UE per group can use the ISM band for communication. The resulting system throughput was increased.

B. LTE Unlicensed

During the past years, the concept of LTE-U (LTE for Unlicensed Spectrum), which suggests that LTE can operate in the unlicensed spectrum with significant modifications to its transmission protocols. LTE-U must adhere to unlicensed spectrum requirements, i.e., set transmit power limits and collision avoidance [6]. By utilizing the considerable amount of unlicensed spectrum available, low power D2D transmissions can potentially avoid cross-tier interference with CC channels, at the cost of complicating the unlicensed spectrum usage [7]. LTE-U has been included in 3GPP Release 13 standardization along with optional carrier aggregation to improve peak data rates [7].

Wi-Fi is a contention-based system with an appropriate mechanism taken to avoid interference, i.e., Carrier Sense Multiple Access (CSMA). However LTE is a demand-based system, so a critical element of LTE-U is to ensure fairness for Wi-Fi and other unlicensed users. In [8], an example of LTE-U channel access scheme is presented, where the femtocell base station (fBS) senses the unlicensed channel. If it is clear the link will access the unlicensed band, if not the fBS assigns the LTE licensed resource. Another protocol is addressed in [9], which separated time resource to different contention windows for harmonious co-existence of LTE-U and 802.11 protocol. However, in Europe, Japan and India, there exist regulations for unlicensed spectrum that require equipment to periodically check for presence of other occupants in the channel (listen) before transmitting (talk) on a millisecond scale, also known as LBT.

C. Contribution and Organisation

Based on our previous seminal survey paper of D2D with LTE-U [10], in this paper we present the technical details regarding: (1) the waiting probability of D2D UEs with LBT, (2) the resulting expected time delay for the D2D UEs, and (3) the capacity of D2D UEs and Wi-Fi that share the same spectrum. The rest of paper is organized as follows. In section II, the system model is defined, in section III the D2D routing algorithm with LBT connection is presented, in section IV the Wi-Fi and D2D UEs is analyzed with a varying traffic model, and the network-level results are presented in Section V.

II. SYSTEM MODEL

The system considered in this paper is an Orthogonal Frequency Division Multiple Access (OFDMA) based 4G LTE multiple-access heterogeneous network. There are 8 Wi-Fi access points (APs) within the coverage of a CC base station,

[1]3GPP TR 36.843: study on LTE device to device proximity services and radio aspects.

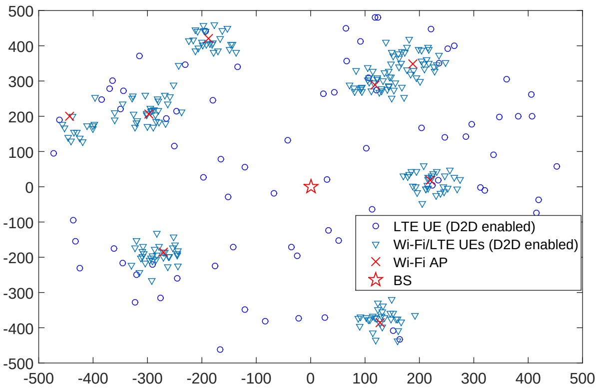

Fig. 1. The UEs distribution in a macro-cell

the D2D UEs communications are using unlicensed band as well. The scenario of D2D communications is a multi-hop relay system, with a greedy path algorithm named shortest-path-routing (SPR) [11].

A. UEs Distribution

The LTE (D2D enabled) UEs' locations are distributed as a Possion Point Process (PPP). The Wi-Fi APs are deployed from another independent PPP $\Phi_{\text{AP}} = \{x_1, x_2, ...\}$ of with density Λ_{AP}. The Wi-Fi (D2D enabled) UEs locations are generated by Poisson cluster processes (PCP), which applies homogeneous independent clustering to an existing Wi-Fi AP process [12]. The Wi-Fi UEs clusters are $\mathfrak{N}_{x_i} = \mathfrak{N} + x_i$ for each $x_i \in \Phi_{\text{AP}}$ and the random point process $\mathfrak{N}$. The whole process of $\Phi_{\text{Wi-Fi}}$ is: $\Phi_{\text{Wi-Fi}} = \bigcup_{x \in \Phi_{\text{AP}}} \mathfrak{N}_x$. A doubly PCP is used for generating the Wi-Fi UEs distribution. The Wi-Fi UEs are uniformly scattered on the ball with the radius r_{AP} centred at each Wi-Fi AP, which is shown in Fig. 1.

For the PCP, the density function of Wi-Fi UEs is [13]:

$$\Lambda_{\text{Wi-Fi}}(x_i) = \frac{N_{\text{Wi-Fi}}}{\frac{\pi^{\frac{d}{2}}}{\Gamma\left(\frac{d}{2}+1\right)} r_{\text{AP}}^d} \mathbf{1}_b\left(0, r_{\text{AP}}\right)(x_i), \tag{1}$$

where $N_{\text{Wi-Fi}}$ is the number of Wi-Fi UEs within r_{AP}, d is the number of dimensions, $\Gamma(\cdot)$ is the Gamma function, and $\mathbf{1}_b\left(0, r_{\text{AP}}\right)(x_i)$ is the indicator function of the condition $x_i \in (0, r_{\text{AP}})$. The Wi-Fi UEs are attached to the closest Wi-Fi AP, with a random variable distance R, which can be derived using the simple fact that the null probability of a 2-D Poisson process in an area.

$$\mathbb{P}\left[R > r\right] = \mathbb{P}\left[\text{no AP closer than } r\right] = e^{-\Lambda_{\text{AP}} \pi r^2}, \tag{2}$$

Therefore, the cumulative distribution function (CDF) is $F_R(r) = 1 - e^{-\Lambda_{\text{AP}} \pi r^2}$ and the probability density function (pdf) can be found as

$$f_R(r) = \frac{\text{d}F_R(r)}{\text{d}r} = 2\Lambda_{\text{AP}} \pi r e^{-\Lambda_{\text{AP}} \pi r^2}. \tag{3}$$

B. Wi-Fi Channel Capacity

The Wi-Fi is a collision avoidance system, there is no same channel interference. The received signal-to-noise-ratio (SNR) for a Wi-Fi UE i is defined as

$$\gamma_i = \frac{H_i P \lambda r_i^{-\alpha}}{\sigma^2}, \tag{4}$$

where H_i is the multipath fading, P is the Wi-Fi AP transmit power, λ is the pathloss constant, r_i is the distance to the AP, σ^2 is the channel noise, and α is the pathloss distance constant.

The expectation capacity of the any single Wi-Fi UE is [14]:

$$\mathbb{E}\left(C_i\right) = \int_0^{+\infty} \mathbb{P}\left\{B \log_2 \left[1 + \frac{HP\lambda r^{-\alpha}}{\sigma^2}\right] > \zeta\right\} \text{d}\zeta, \tag{5}$$

where B is the Wi-Fi bandwidth. The multipath fading has a pdf of $f_H(h) \sim \exp(\beta)$, where $\beta = 1/P\lambda$. So the capacity yields:

$$\mathbb{E}\left(C_i\right) = \int_0^{+\infty} e^{-\beta r^{-\alpha} \sigma^2 (2^{\frac{\zeta}{B}} - 1)} \text{d}\zeta, \tag{6}$$

By a known spatial distribution of Wi-Fi UEs relative to the APs in Eq. (3), the definition of the mean capacity of the Wi-Fi Channel is given by:

$$\begin{aligned} \overline{C} &= \int_0^{+\infty} \mathbb{E}\left(C_i\right) f_R(r) \text{d}r \\ &= \int_0^1 -e^{\mathcal{A}(y,\alpha)\sigma^2} \frac{B}{\mathcal{A}(y,\alpha)\sigma^2 \ln 2} \Gamma\left(0, \mathcal{A}(y,\alpha)\sigma^2\right) \text{d}y. \end{aligned} \tag{7}$$

Where $\mathcal{A}(y, \alpha)$ is given as:

$$\mathcal{A}(y,\alpha) = \beta \left(\sqrt{\frac{\ln y}{-\Lambda_{\text{AP}} \pi}}\right)^{-\alpha}, \qquad 0 \le y \le 1. \tag{8}$$

The full proof is in Appendix A. Similarly, the capacity for any single hop between two D2D UEs can be found from Eq. (4) and Eq. (5). Due to the fact that this paper's focus is on the coexistence between LTE-U D2D and unlicensed network, the mathematical details of capacity about D2D and CC channels are not derived. In section V, we use simulation results to analyze the performance of the system.

III. The D2D Routing Algorithm with LBT

A. Listen Before Talk (LBT)

Fig. 2 shows the specification for frame based requirement[2]. When the D2D UEs want to transmit, it is required to detect the Wi-Fi energy level for a designed duration-Clear Channel Assessment (CCA) period (typically 20 μs). If the energy level in the channel is below the CCA energy threshold, then the UE transmit for a Channel Occupancy Time (COT) ($1 \sim 10$ ms). If the energy level is over the CCA energy threshold, the D2D UEs will wait for a random period of $N \times 20\mu$s, $N = \{1, 2, 3, ..., 20\}$ before it performs another CCA. After a COT, if the UE needs to continue, it has to repeat the CCA process.

[2] 3GPP Response LS on Clarification of LBT Categories, Release 13, R1-152182, 24 April 2015.

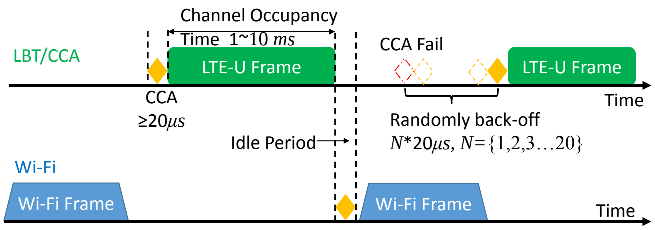

Fig. 2. LBT specification for LET-U

B. Shortest-path-routing (SPR) Routing Algorithm

In SPR, each D2D UE knows its own location and that of the final destination UE. Furthermore, the relay UE can modify the routing path according the periodically signal from the BS, in order to update the SPR path selection in the presence of mobility. The main steps as: (1) Source UE broadcasts a relay request and the request is received by neighbouring UEs in its maximum distance for which reliable data transmission can take place, (2) UE receives feedback of the potential relay UEs and sends the data packet to the relay UE that is the closest to the destination UE, and (3) Repeat the first two steps until the destination UE is reached. At each hop, the Wi-Fi energy level is detected, if over the CCA energy level LBT is activated. Fig. 3 shows a LTE-enabled multi-hop D2D route based on SPR.

IV. Traffic Model for D2D UEs with LBT

For the analysis of the traffic model, assumptions are made follows: (1) the Wi-Fi UEs can only be attached to one Wi-Fi AP; (2) the probability of different Wi-Fi UEs launching the CCA at the same time is negligible; and (3) only one D2D UE link for any Wi-Fi AP. The waiting time when CCA fails for next CCA is $2 \times 20\mu s$, based on those assumptions the Wi-Fi communication traffic model is conceded as a Markov modulated Poisson process (MMPP). Specifically, in this paper the $M/M/1/K$ queue-size process is chosen [15].

In this model, where the arrival process follows a Poisson process with the parameter τ and service times are assumed to be independent and identically distributed (i.i.d) and exponentially distributed with the parameter μ. The server process are independent of the arrival process. From the Eq. (7), the mean service parameter is defined as:

$$\mu = \frac{\int_0^1 -e^{\mathcal{A}(y,\alpha)N} \frac{B}{\mathcal{A}(y,\alpha)N \ln 2} \Gamma\big(0, \mathcal{A}(y,\alpha)N\big) \mathrm{d}y}{S}, \tag{9}$$

where S is the average data package size. The mean arrival time is $\tau = \frac{N_{\text{Wi-Fi}}}{\sum_{i=0}^{N_{\text{Wi-Fi}}} T_i}$, where $N_{\text{Wi-Fi}}$ is the Wi-Fi UE in any AP and T_i is the Wi-Fi UE data demand duration.

A. D2D UEs Waiting Probability

Define $P_{k(k+1)}(t)$ as the probability that given that the process X is in state k at time t_0, then a time t later, it will be in state $k+1$. This process can be modeled as [16]:

$$P_{k(k+1)}(t) = P\left[X(t_0+t) = (k+1) | X(t_0) = k\right], \tag{10}$$

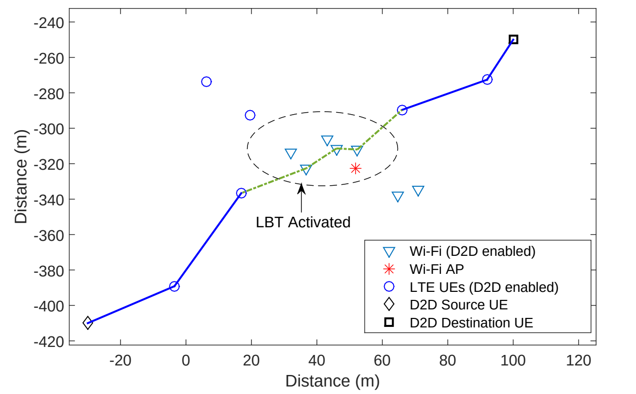

Fig. 3. The Routing Paths for D2D LTE-U with SPR using LBT contention.

The steady-state probabilities are defined as, $\varphi_{k+1} = \lim_{t\to\infty} P_{k(k+1)}(t)$ where φ_{k+1} is the steady-state probability at state $k+1$. The global balance steady-state equations for the $M/M/1/K$ is obtained: $\varphi_k \tau = \varphi_{k+1}\mu$ for $k = 0,1,2,3,...,K-1$ for $K \geq 1$. The normalizing equation is $\sum_{k=0}^{K} \varphi_k = 1$. Therefore, the probability that no UE in the Wi-Fi system is,

$$\varphi_0 = \frac{1}{1 + \sum_{k=1}^{K} \left(\frac{S N_{\text{Wi-Fi}}}{\overline{C} \sum_{i=0}^{N_{\text{Wi-Fi}}} T_i} \right)^k} = \begin{cases} \frac{1-\rho^{K+1}}{1-\rho} & \rho \neq 1 \\ \frac{1}{K+1} & \rho = 1, \end{cases} \tag{11}$$

where $\rho = \frac{S N_{\text{Wi-Fi}}}{\overline{C} \sum_{i=0}^{N_{\text{Wi-Fi}}} T_i}$, and $\overline{C}$ can be found from Eq. (7). The Wi-Fi traffic confliction probability is the probability that at least one Wi-Fi UE is communicating in the system.

$$\mathbb{P}_c = P\{\text{at least one UE}\} = \begin{cases} 1 - \frac{1-\rho^{K+1}}{1-\rho} & \rho \neq 1 \\ 1 - \frac{1}{K+1} & \rho = 1. \end{cases} \tag{12}$$

B. Average Time Delay for D2D UEs

When the unlicensed channel is occupied the D2D UEs have to wait for a clear channel slot, the time delay for the D2D is:

$$\mathbb{E}(T_D) = \mathbb{E}(T_W) + \mathbb{E}(T_S) \tag{13}$$

where $\mathbb{E}(T_W)$ is the mean waiting time and $\mathbb{E}(T_S)$ is the mean severing time in the Wi-Fi system. The system limit is K so when K UEs are in the system there is no Wi-Fi access for the next UE, therefore, the mean waiting time is [16]:

$$\mathbb{E}(T_W) = \begin{cases} \left[\frac{\rho}{1-\rho} - \frac{(K+1)\rho^{K+1}}{1-\rho^{K+1}}\right] \frac{1}{\tau(1-\rho^K \varphi_0)} & \rho \neq 1 \\ \frac{K}{2\tau(1-\rho^K \varphi_0)} & \rho = 1. \end{cases} \tag{14}$$

And the mean severing time is $1/\mu$, so the $\mathbb{E}(T_D) = \mathbb{E}(T_W) + 1/\mu$, where $\mathbb{E}(T_D)$ can be found in Eq. (14).

V. Results and Analysis

In this section, the simulation results are presented to analyse the performance of LTE-U D2D with LBT protocols. The LTE-U is running at 5 GHz spectrum and Wi-Fi system is IEEE 802.11ac network, the bandwidth is 40 MHz, and

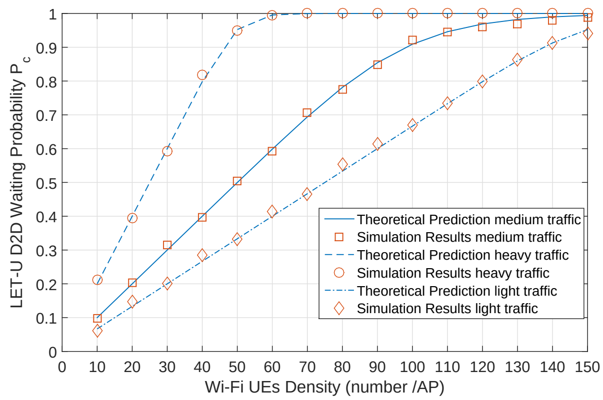

Fig. 4. The theoretical prediction of D2D UE waiting probability under different traffic conditions with the Wi-Fi UEs density compared with simulation

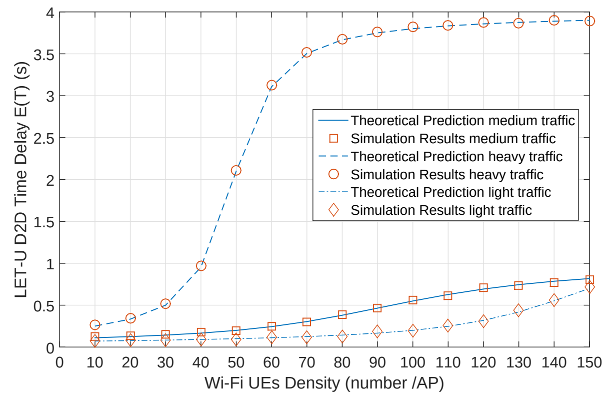

Fig. 5. The theoretical prediction of D2D package delay under different traffic conditions with the Wi-Fi UEs density compared with simulation

TABLE I
SIMULATION AVERAGE CAPACITY

Capacity (Mbits/s)	Co-exist	Non co-exist
Wi-Fi	19.2	23.7
D2D	19.5	21.5
Total	38.7	23.7

LBT back-off duration is 40 μs. The macro-cell radius is 500 m with 8 Wi-Fi APs providing the Wi-Fi access. The Wi-Fi system limit K is 20. The three different Wi-Fi traffic volume is selected to analyse the performance: light traffic with data package size 10 kbits and the Wi-Fi UEs communicating demand parameter is 1/20; for medium traffic data package size is 20 kbits and demand parameter is 1/6 ; and data package size is 30 kbits and demand parameter is 1/4 for heavy traffic.

A. Waiting Probability for D2D UEs with LBT

Fig. 4 shows the D2D UE waiting probability inside a Wi-Fi AP's coverage area. The simulation results match the theoretical prediction well. The waiting probability increases when the Wi-Fi UE density grows. Specifically, the waiting probability is over 90% when more than 100 Wi-Fi are in the same AP's coverage area. From Eq. (12) it can be found that when the number of Wi-Fi UEs increases the traffic ratio ρ also increases, and so the waiting probability is greater.

Our analysis also found that the Wi-Fi traffic volume has a significant effect to the D2D UE waiting probability in Fig. 4. Under heavy traffic loads, the waiting probability increases much more quickly as a function of UE density than the light and medium loads. This is due to the intuitive fact that the large the traffic load, the more time is needed for the contention process in the channel, which in turn incurs a higher waiting probability for D2D UEs demanding LTE-U access.

B. Delay time for the D2D UEs with LBT

When the LBT protocol is utilized, the D2D UEs have to wait for a successful CCA. Fig. 5 shows the correlation between D2D mean delay and Wi-Fi UEs density, and the delay rises with the UEs density from 0.1 s to 0.8 s when the number of Wi-Fi UEs in an AP increases from 10 to 150. This is because higher density means the longer time to be waited for a success CCA, leading to a longer delay.

Generally, the delay is nearly the same for the light and medium traffic load models (only 0.2s difference). However, under the heavy traffic, the delay is 4 times stronger than the light and medium traffic loads.

C. Capacity for D2D and Wi-Fi Network

The network capacity during a time slot T is defined as: $\frac{T_{\text{active}} \times \overline{C}}{T}$, where T_{active} is the active communicating time, in this paper T is 3,000 s. Without the Wi-Fi and LTE-U mutual interference, the capacity of D2D UEs is 23.7 Mbits/s and 21.5 Mbits/s for Wi-Fi UEs shown in Table I (with the Wi-Fi frame is 10ms and COT is 3 ms). Although the Wi-Fi capacity reduces to 19.2 Mbits/s when in coexistence with LTE-U D2D UEs, the D2D UEs get a capacity of 19.5 Mbits/s. The benefit is that the total network capacity (licensed and unlicensed spectrum) increases 63.2% to 38.7 Mbits/s.

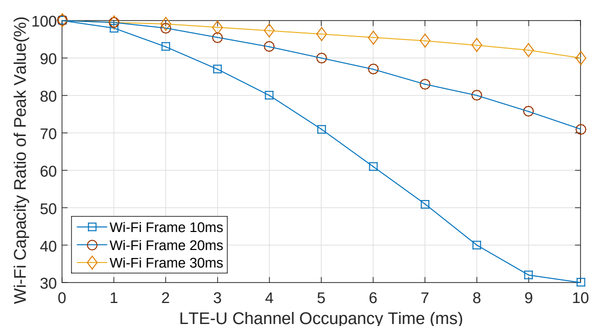

Fig. 6. The Wi-Fi capacity attenuation with different LTE-U COT and Wi-Fi frame size

To analyse the effect of LTE-U D2D on the Wi-Fi capacity, the results in Fig. 6, shows that the Wi-Fi capacity reduces with increased LTE-U COT values. The Wi-Fi capacity reduces to 30% when the LTE-U COT is the same size as the Wi-Fi frame value, 10 ms. As the COT value is reduced, the Wi-Fi capacity is 50% when the COT is 70% of the Wi-Fi frame.

When the Wi-Fi frame size is 30ms, the Wi-Fi capacity only drops to 10% even when the D2D UEs reach its maximum COT. But the decline is 30% when the Wi-Fi frame size is 20 ms. So, when the Wi-Fi frame size is over 20 ms, the D2D share the same frequency with LBT could archive fair coexistence by only reduces less than 10% of Wi-Fi network capacity.

VI. Conclusion

In this paper, we examine how the Device-to-Device (D2D) network can evolve to be more flexible by employing LTE-Unlicensed protocols and operating in the unlicensed spectrum with due care. It was found that the D2D would take a longer delay when there is a high level of contention in the local unlicensed spectrum. Our results show that whilst D2D UEs reduce the Wi-Fi network capacity by sharing the unlicensed spectrum, it increased the overall network capacity (licensed and unlicensed) by 63%. In this way, D2D with LTE-U can be a friendly neighbour to the existing unsilenced spectrum users.

Appendix A
Wi-Fi Channel Capacity

The definition of the average capacity is given by:

$$\begin{aligned}\overline{C} &= \int_0^{+\infty} \mathbb{E}\left(C_i\right) f_R(r)\mathrm{d}r \\ &= \int_0^{+\infty}\int_0^{+\infty} 2\Lambda_{\mathrm{AP}}\pi r e^{-\beta r^{-\alpha}\sigma^2(2^{\frac{\zeta}{B}}-1)} e^{-\Lambda_{\mathrm{AP}}\pi r^2}\mathrm{d}r\mathrm{d}\zeta \\ &= \int_0^{+\infty}\int_0^{+\infty} -e^{-\beta r^{-\alpha}\sigma^2(2^{\frac{\zeta}{B}}-1)}\mathrm{d}e^{-\Lambda_{\mathrm{AP}}\pi r^2}\mathrm{d}\zeta \\ &\quad \text{let } e^{-\Lambda_{\mathrm{AP}}\pi r^2} = y, \text{ so } r = \sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}} \\ &= \int_0^{+\infty}\int_0^{1} -e^{-\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2(2^{\frac{\zeta}{B}}-1)}\mathrm{d}y\mathrm{d}\zeta \\ &= \int_0^{1} -e^{\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2} \\ &\times \int_0^{+\infty} e^{-\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2 2^{\frac{\zeta}{B}}}\mathrm{d}\zeta\mathrm{d}y,\end{aligned} \tag{15}$$

Which we let $\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2 2^{\frac{\zeta}{B}} = m$, so

$$\begin{aligned}&\int_0^{+\infty} e^{-\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2 2^{\frac{\zeta}{B}}}\mathrm{d}\zeta \\ &= \int_{\left[\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2\right]}^{+\infty} \frac{B\times\frac{1}{m}\times e^{-m}}{\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2\ln 2}\mathrm{d}\zeta \\ &= \frac{B\Gamma\left(0,\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2\right)}{\beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}\sigma^2\ln 2},\end{aligned} \tag{16}$$

where $\Gamma(\cdot)$ is the gamma function.

So the average capacity is shown as:

$$\overline{C} = \int_0^{1} -e^{\mathcal{A}(y,\alpha)\sigma^2}\frac{B}{\mathcal{A}(y,\alpha)\sigma^2\ln 2}\Gamma\Big(0,\mathcal{A}(y,\alpha)\sigma^2\Big)\mathrm{d}y. \tag{17}$$

Where $\mathcal{A}(y,\alpha)$ is given as:

$$\mathcal{A}(y,\alpha) = \beta\left(\sqrt{\frac{\ln y}{-\Lambda_{\mathrm{AP}}\pi}}\right)^{-\alpha}, \qquad 0 \le y \le 1. \tag{18}$$

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