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Performance analysis of AUL FeLAA and WiFi coexistence in the presence of Rayleigh fading channel and capture effect under unsaturated traffic conditions

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Dear editor,

Recently, the 3rd generation partnership project (3GPP) release 15 has evolved the licensed assisted access (LAA) framework into the autonomous uplink (AUL) future enhanced LAA (FeLAA). The frame of the AUL FeLAA transmits autonomously and needs no scheduling grant. Significantly, how to coexist with WiFi in the unlicensed band is an important issue for the LAA framework. Most of the models on LAA-WiFi coexistence have concentrated on the downlink (DL) performance under the ideal channel conditions [1–3]. However, the ideal channel model and the saturation traffic load model are mostly invalid in the real coexistence scenario. The Rayleigh fading channel and the unsaturation traffic conditions have been adopted to analyze the WiFi alone system, but still not yet applied to the LAA-WiFi coexisting system [4, 5]. To the best of our knowledge, the performance analysis for AUL FeLAA and WiFi coexistence accounting for unsaturation traffic load and Rayleigh fading channel has not been studied.

We propose a model for FeLAA and WiFi coexistence by considering the additional issues such as the unsaturated traffic load, the presence of frame error, the capture effect and the separable interference and noise owing to transmitting over Rayleigh fading environment. To make sure the device can hear the transmission of each other in the coexistence scenario, we have calculated and applied the value of the geometry deployment scope to our simulation according to the path-loss model and the clear channel assessment (CCA) threshold. Though we use system parameters belonging to the listen-before-talk category 4 (LBT Cat 4) and IEEE 802.11ac protocols as reference standards respectively for LAA/FeLAA and WiFi, the proposed theoretical models can also apply to the coexistence of other radio access technologies (RATs) which has similar media access controller (MAC) layer protocols.

Development of the Markov model of LAA LBT Cat 4. This analysis is carried out under the assumptions of the practical network environments which include unsaturation traffic and Rayleigh channel condition. We consider an uplink scenario with fixed number of LAA user equipments (UEs) and WiFi stations (STAs) coexisting in the same 20 MHz channel of 5 GHz unlicensed spectrum, where the UEs perform the LBT Cat 4 as their channel access strategy. Let $n_{\rm l}$ be the number of UEs, $n_{\rm w}$ be the number of STAs, $q_{\rm l}$ represent the probability that at least one transmission in the UE buffer can be transmitted. $p_{\rm eq,l}$ denotes

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the probability of failed transmission, including the capture-failed simultaneous transmission and channel-error induced failure transmission. The probability of the capture-failed collision is $p_{\mathrm{col,l}}$, and the probability of the error transmission is $p_{\mathrm{e,l}}$. We have $p_{\mathrm{eq,l}} = p_{\mathrm{col,l}} + p_{\mathrm{e,l}} - p_{\mathrm{col,l}} \cdot p_{\mathrm{e,l}}$. If τ_{w} is the probability that a STA transmits in a randomly chosed time slot, and τ_{l} is the probability that a UE transmits in a randomly chosed time slot, $p_{\mathrm{idle}} = (1-\tau_{\mathrm{l}})^{n_{\mathrm{l}}}(1-\tau_{\mathrm{w}})^{n_{\mathrm{w}}}$ stands for the probability that the channel is sensed to be idle.

The unsaturated traffic load means that the UE buffer does not always have data to transmit, so we use a_{idle} to represent the idle state caused by the empty UE buffer:

$$a_{\mathrm{idle}} = (1-q_{\mathrm{l}})(1-p_{\mathrm{eq,l}}) \sum_{m=0}^{m_p+K-1} (a_{m,0}+b_{m,0}) + (1-q_{\mathrm{l}})a_{\mathrm{idle}}, \tag{1}$$

a_{idle} reflects the facts that the idle state can be achieved either after a successful transmission or when the buffer of the UE is empty and waiting for the arrival of the frame. The first term of the right hand side of (1) means that the successful transmission empties the buffer with probability $(1-q_{\mathrm{l}})(1-p_{\mathrm{eq,l}})$. Meanwhile, the second term means that the UE is waiting for the idle state with probability $(1-q_{\mathrm{l}})$.

Let $a(t)$ be the decrement process which represents the ICCA counter, and $b(t)$ be the stochastic process which denotes the back-off counter, at an arbitrary time t. $a_{m,n} = \lim_{t\to\infty} P\{s(t) = C_{\mathrm{icca}}(m), a(t) = n\}$, $m \in [0, m_p+K-1]$, $n \in [0,N]$ is the stationary distributions of the ICCA procedure and $b_{m,k} = \lim_{t\to\infty} P\{s(t) = C_{\mathrm{ecca}}(m), b(t) = k\}$, $m \in [0, m_p+K-1]$, $k \in [0, W_m-1]$ is the stationary distributions of the ECCA back-off process. We have the following relations:

$$a_{m,n} = p_{\mathrm{idle}}^{N-n} a_{m,N}, \quad 0 \leqslant n < N, \tag{2}$$

$$\begin{cases} b_{m,k} = \dfrac{W_{\mathrm{l},m}-k}{W_{\mathrm{l},m}} \cdot \left(p_{\mathrm{eq,l}} a_{m,0} + (1-p_{\mathrm{idle}}) \displaystyle\sum_{n=1}^{N} a_{m,n}\right), \\ 0 \leqslant k \leqslant W_{\mathrm{l},m}-1,\ K=1 \text{ or } m \leqslant m_p, \\ b_{m,k} = \dfrac{W_{\mathrm{l},m_p}-k}{W_{\mathrm{l},m_p}} \cdot \left(p_{\mathrm{eq,l}} a_{m,0} + (1-p_{\mathrm{idle}}) \displaystyle\sum_{n=1}^{N} a_{m,n}\right), \\ 0 \leqslant k \leqslant W_{\mathrm{l},m_p}-1,\ K>1 \text{ and } m > m_p. \end{cases} \tag{3}$$

Then one obtains τ_{l} as follows:

$$\begin{aligned} \tau_{\mathrm{l}} = & \sum_{m=0}^{m_p+K-1} (a_{m,0}+b_{m,0}) \\ = & \Big\{2q_{\mathrm{l}}(1-2p_{\mathrm{eq,l}}G)\big(p_{\mathrm{idle}}^N + G\big)\big((1-(p_{\mathrm{eq,l}}G)^{m_p+1}) \\ & + \mathbf{1}_{(K-1)>0}(p_{\mathrm{eq,l}}G)^{m_p}\big((p_{\mathrm{eq,l}}G)-(p_{\mathrm{eq,l}}G)^K\big)\big)\Big\} \\ & /\Big\{A_1(1-2p_{\mathrm{eq,l}}G) + q_{\mathrm{l}}W_{\mathrm{l}}G\big(1-(2p_{\mathrm{eq,l}}G)^{m_p+1}\big) \\ & \cdot (1-p_{\mathrm{eq,l}}G) + \mathbf{1}_{(K-1)>0}A_2(1-2p_{\mathrm{eq,l}}G)\Big\}. \end{aligned} \tag{4}$$

$G = p_{\mathrm{eq,l}} p_{\mathrm{idle}}^N + 1 - p_{\mathrm{idle}}^N$. $A_1 = q_{\mathrm{l}}(2F+G)(1-(p_{\mathrm{eq,l}}G)^{m_p+1}) + 2(1-q_{\mathrm{l}})(1-p_{\mathrm{eq,l}})(p_{\mathrm{idle}}^N + G)(1-(p_{\mathrm{eq,l}}G)^{m_p+1})$, and $A_2 = (q_{\mathrm{l}}(2F+(2^{m_p}W_{\mathrm{l}}+1)G) + 2(1-q_{\mathrm{l}})(1-p_{\mathrm{eq,l}})(p_{\mathrm{idle}}^N+G))(p_{\mathrm{eq,l}}G)^{m_p}((p_{\mathrm{eq,l}}G)-(p_{\mathrm{eq,l}}G)^K)$, and $F = \sum_{n=0}^{N} p_{\mathrm{idle}}^{N-n} = \frac{1-p_{\mathrm{idle}}^{N+1}}{1-p_{\mathrm{idle}}}$.

If $q_{\mathrm{l}} \to 1$, Eq. (4) represents the transmission probability of UE under the saturated traffic load condition. This theoretical analysis contains more details in Appendix A.

Coexistence performance analysis. The capture effect is not negligible in the uplink system owing to the lower transmission power of UEs. Collision happens if more than one equipment in the same channel transmits simultaneously. However, owing to the capture effect, the concurrent transmission involved in the collisions may success. Therefore, the capture effect can be assumed to be a subset of the collision events [6]. Let $p_{\mathrm{cap,l}}$ be the capture probability of the FeLAA UE, τ_{w} be the probability that the STA transmits in a randomly chosed time slot. $p_{\mathrm{col,l}}$ is given as

$$p_{\mathrm{col,l}} = 1-(1-\tau_{\mathrm{l}})^{n_{\mathrm{l}}-1}(1-\tau_{\mathrm{w}})^{n_{\mathrm{w}}} - p_{\mathrm{cap,l}}, \tag{5}$$

where τ_{w} can be obtained from [7]. First, one can calculate the probability of generating exactly k_{l} interfering UEs and k_{w} interfering STAs out of n_{l} contending UEs and n_{w} contending STAs. For LAA UE, this probability is $(\binom{n_{\mathrm{l}}}{k_{\mathrm{l}}+1}\tau_{\mathrm{l}}^{k_{\mathrm{l}}+1}(1-\tau_{\mathrm{l}})^{n_{\mathrm{l}}-k_{\mathrm{l}}-1}\binom{n_{\mathrm{w}}}{k_{\mathrm{w}}}\tau_{\mathrm{w}}^{k_{\mathrm{w}}}(1-\tau_{\mathrm{w}})^{n_{\mathrm{w}}-k_{\mathrm{w}}})$. And then, the value of $p_{\mathrm{cap,l}}$ can be obtained as follows:

$$\begin{aligned} & p_{\mathrm{cap,l}} \\ & = \mathrm{e}^{-\frac{b}{\mathrm{SNR}_{\mathrm{o,l}}}}(1-\tau_{\mathrm{l}})^{n_{\mathrm{l}}}\Bigg\{(1+b)\left(\left(\frac{1+b(1-\tau_{\mathrm{l}})}{(1+b)(1-\tau_{\mathrm{l}})}\right)^{n_{\mathrm{l}}} \right. \\ & \left. -1\right) \times \left(1-\frac{b\tau_{\mathrm{w}}}{1+b}\right)^{n_{\mathrm{w}}} - \frac{n_{\mathrm{l}}\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})^{n_{\mathrm{w}}}}{1-\tau_{\mathrm{l}}}\Bigg\}. \end{aligned} \tag{6}$$

And $p_{\mathrm{e,l}}$ is given as

$$p_{\mathrm{e,l}} = 1-(1-P_s(E))^{N_{\mathrm{symbol,l}} \times N_{\mathrm{scarrier,l}}}, \tag{7}$$

where $N_{\mathrm{symbol,l}}$ is the number of OFDM symbols in one transmission duration and $N_{\mathrm{scarrier,l}}$ is the number of the OFDM subcarriers in one transmission time duration. $P_s(E)$ is the symbol error rate, and its expression can be obtained from [8]. $P_{\mathrm{t,l}}$ is the probability that at least one UE transmitting in the considered slot when n_{l} UEs and n_{w} STAs contending for the same channel. $P_{\mathrm{t,w}}$ is the probability that at least one STA transmitting in the considered slot when n_l UEs and n_w STAs contending for the same channel.

$$P_{\mathrm{t,l}} = 1-(1-\tau_\mathrm{l})^{n_\mathrm{l}}, \quad P_{\mathrm{t,w}} = 1-(1-\tau_\mathrm{w})^{n_\mathrm{w}}. \tag{8}$$

$P_{\mathrm{s,l}}$ is the conditional probability that only one FeLAA UE transmits on the channel without collisions, given that at least one UE transmits in the determined time slot. And $P_{\mathrm{s,w}}$ is the conditional probability that only one WiFi STA transmits on the channel without collisions, given that at least one STA transmits in the determined time slot.

$$P_{\mathrm{s,l}} = \frac{n_\mathrm{l}\tau_\mathrm{l}(1-\tau_\mathrm{l})^{n_\mathrm{l}-1}(1-\tau_\mathrm{w})^{n_\mathrm{w}}}{P_{\mathrm{t,l}}},$$
$$P_{\mathrm{s,w}} = \frac{n_\mathrm{w}\tau_\mathrm{w}(1-\tau_\mathrm{w})^{n_\mathrm{w}-1}(1-\tau_\mathrm{l})^{n_\mathrm{l}}}{P_{\mathrm{t,w}}}. \tag{9}$$

The ratios of the successful airtime, named successful airtime ratio (SAR), can be defined as the ratio of the successful airtime to the total system runtime. Therefore, we can use SAR replace throughput as the performance matric. One can obtain SAR as follows:

$$R_{\mathrm{s,l}} = \frac{(1-p_{\mathrm{e,l}})(P_{\mathrm{t,l}}P_{\mathrm{s,l}}+p_{\mathrm{cap,l}})T_{\mathrm{s,l}}}{T_\mathrm{s}},$$
$$R_{\mathrm{s,w}} = \frac{(1-p_{\mathrm{e,w}})(P_{\mathrm{t,w}}P_{\mathrm{s,w}}+p_{\mathrm{cap,w}})T_{\mathrm{s,w}}}{T_\mathrm{s}}. \tag{10}$$

T_s, the time interval between the starts of the two continuous successful transmissions, can be defined as follows:

$$\begin{aligned}T_\mathrm{s} = {} & (1-P_{\mathrm{t,l}})(1-P_{\mathrm{t,w}})\sigma + P_{\mathrm{t,w}}(1-P_{\mathrm{t,l}})(1-P_{\mathrm{e,w}}) \\ & \cdot (P_{\mathrm{s,w}}+P_{\mathrm{cap,w}}(1-P_{\mathrm{s,w}}))T_{\mathrm{s,w}} + P_{\mathrm{t,l}}(1-P_{\mathrm{t,w}}) \\ & \cdot (1-P_{\mathrm{e,w}})(P_{\mathrm{s,l}}+P_{\mathrm{cap,l}}(1-P_{\mathrm{s,l}}))T_{\mathrm{s,l}} + P_{\mathrm{t,w}} \\ & \cdot (1-P_{\mathrm{t,l}})(P_{\mathrm{e,w}}+(1-P_{\mathrm{e,w}})(1-P_{\mathrm{s,w}}) \\ & \cdot (1-P_{\mathrm{cap,w}}))T_{\mathrm{c,w}} + P_{\mathrm{t,l}}(1-P_{\mathrm{t,w}})(P_{\mathrm{e,l}} \\ & + (1-P_{\mathrm{e,l}})(1-P_{\mathrm{s,l}})(1-P_{\mathrm{cap,l}}))T_{\mathrm{c,l}} + P_{\mathrm{t,w}}P_{\mathrm{t,l}} \\ & \cdot (1-P_{\mathrm{e,w}})P_{\mathrm{cap,w}}(1-P_{\mathrm{cap,l}}(1-P_{\mathrm{e,l}}))T_{\mathrm{s,w}} \\ & + P_{\mathrm{t,w}}P_{\mathrm{t,l}}(1-P_{\mathrm{e,l}})P_{\mathrm{cap,l}}(1-P_{\mathrm{cap,w}}(1-P_{\mathrm{e,w}})) \\ & \cdot T_{\mathrm{s,l}} + P_{\mathrm{t,w}}P_{\mathrm{t,l}}(1-P_{\mathrm{e,w}})(1-P_{\mathrm{e,l}})P_{\mathrm{cap,w}}P_{\mathrm{cap,l}} \\ & \cdot T_{\mathrm{s,w}} + P_{\mathrm{t,w}}P_{\mathrm{t,l}}(1-P_{\mathrm{cap,l}}(1-P_{\mathrm{e,w}})) \\ & \cdot (1-P_{\mathrm{cap,w}}(1-P_{\mathrm{e,l}}))T_{\mathrm{c,l}},\end{aligned} \tag{11}$$

where $T_{\mathrm{s,l}}$ is the successful transmission duration of FeLAA UE and $T_{\mathrm{s,w}}$ is the successful transmission duration of WiFi STA. σ is set to be 9 µs. $T_{\mathrm{c,l}}$ represents that the channel is sensed busy by each device during the failure FeLAA transmitting, and $T_{\mathrm{c,w}}$ represents that the channel is sensed to be busy by each device during the failure WiFi transmitting. This theoretical analysis contains more details in Appendix B. And the simulation result presented in Appendix C shows the validation of the theoretical analysis.

Conclusion. We have presented a Markov chain model to analyze the performance of FeLAA-WiFi coexisting under unsaturated traffic and heterogeneous network environment by accounting for the channel induced errors and the capture effect of Rayleigh fading environment. The model includes a Markov chain of the LAA LBT Cat 4 with the two-CCA process, under the unsaturation traffic conditions. By combining the proposed FeLAA Markov chain with the Markov chain which describes the behavior of WiFi device, the stationary probabilities of the two systems can be calculated to obtain the performance parameters in the unsaturated conditions. Simulation results show that the theoretical model is valid under different network size, channel conditions and traffic load conditions. The proposed theoretical analysis provides insight into the design and the optimization of the FeLAA-LBT parameters in the FeLAA-WiFi coexistence scenario.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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