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Adaptive network-aware FeLAA LBT strategy for fair uplink FeLAA-WiFi coexistence

Wei WANG[1*], Pingping XU[1], Yuan ZHANG[1] & Hongyun CHU[2]

[1]*National Mobile Communications Research Laboratory, Southeast University, Nanjing* 210096*, China;*
[2]*Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen* 518055*, China*

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Dear editor,

To offload excessive traffic of long-term evolution (LTE), the 3rd generation partnership project (3GPP) has introduced licensed-assisted access (LAA) framework to the 5 GHz unlicensed band. In 2017, the 3GPP technical specifications group radio access network working group 1 (TSG RAN WG1) meeting proposed the autonomous uplink access (AUL) of the further enhanced LAA (FeLAA). AUL FeLAA is no schedule-based, downlink (DL)-independent, and it will work in the small cells of the heterogeneous network (HetNet) in WiFi-dominated 5 GHz band [1]. The previous studies on LAA/FeLAA-WiFi coexistence designed many listen-before-talk (LBT) methods for LAA system [2]. Most of the fairness strategies need the inter-systems coordinations between LAA and WiFi [3–5]. However, the two systems use different subcarrier spacing and different orthogonal frequency division multiplexing (OFDM) symbols duration. Additionally, the energy detection (ED) of LAA clear channel assessment (CCA) check cannot decode the WiFi preamble [6]. Therefore, the inter-system coordinations is hard to be achieved in practice.

We propose a novel adaptive network-aware FeLAA LBT strategy for FeLAA-WiFi coexistence in the unlicensed band. The theoretical analysis of this strategy is based on the two-CCA-period LBT Markov model according to the AUL FeLAA LBT category 4 (Cat4) procedure defined in 3GPP specifications. The proposed strategy adjusts the FeLAA LBT parameters through the evaluated WiFi parameters which are obtained by both the channel sense result and the statistical parameters of FeLAA performance. Different from the existing channel access approaches of fair LAA-WiFi coexistence, our strategy does not need inter-system coordination and inter-system information exchange. These inter-system operations will change the existing specifications and bring extra time delay. Moreover, the proposed method can substantially improve the WiFi performance and conveniently offer fairness under different network size.

*Analysis model of LBT Cat*4. This analysis is carried out under the assumption of ideal channel conditions which exclude hidden node and capture problems. Firstly, we study the single user equipment (UE) behavior with a multi-group Markov model, then we obtain the stationary probability τ_{l} that the UE transmits the data burst in a randomly chosen slot time.

$$\begin{aligned}\tau_{\mathrm{l}} = &\sum_{m=0}^{m_p+K-1} (a_{m,0}+b_{m,0})\\ &=\big\{\{A(1-(Ap_{\mathrm{l}})^{m_p+K})+(1-Ap_{\mathrm{l}}+(Ap_{\mathrm{l}}\\ &\quad-(Ap_{\mathrm{l}})^{m_p+K}))(1-p_{\mathrm{l}})^N\}/\{1-Ap_{\mathrm{l}}\}\big\}\,a_{0,N}\\ &=\{2p_{\mathrm{l}}(1-2Ap_{\mathrm{l}})(A(1-(Ap_{\mathrm{l}})^{m_p+K})+(1-Ap_{\mathrm{l}}\end{aligned}$$

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[*] Corresponding author (email: wwang61140122@seu.edu.cn)

$$+ (Ap_{\rm l} - (Ap_{\rm l})^{m_p+K}))(1-p_{\rm l})^N)\}/\{(1 - 2Ap_{\rm l})(2A + Ap_{\rm l})(1-(Ap_{\rm l})^{m_p+1}) + Ap_{\rm l}(1-(2Ap_{\rm l})^{m_p+1})(1-Ap_{\rm l})W_{\rm l} + \mathbf{1}_{(K-1)>0}Bp_{\rm l}(1-2Ap_{\rm l})\}. \tag{1}$$

In this study, the FeLAA system has a fixed number $n_{\rm l}$ of AUL UEs competing for the same unlicensed spectrum. We assume a saturated traffic condition to study the limits of the system performance, which means each UE always has data burst available for transmission. Our model assumes that the collision probability $p_{\rm l}$ is independent of the state $s(t)$ of the UE. The FeLAA UE sets the initial contention window (CW) size $W_{\rm l} = {\rm CW}_{t_p,\min}$ according to the corresponding transmission priority, and the value of the CW will increase until it reaches the maximum ${\rm CW}_{t_p,\max}$. Here, t_p is the channel access priority class and represents that the UE uses different backoff stages m_p and different allowed-CW sizes. If the FeLAA system uses the binary exponential backoff strategy as WiFi system does, there will be $W_m = 2^m W_{\rm l}$ when collisions occur m times, where $m \in (0, m_p)$. And the upper bound is $W_{m_p} = 2^{m_p} W_{\rm l} = {\rm CW}_{t_p,\max}$.

If one UE has consecutive used ${\rm CW}_{t_p} = {\rm CW}_{t_p,\max}$ for K times to generate the value of the ECCA random counter, it will reset ${\rm CW}_{t_p}$ to ${\rm CW}_{t_p,\min}$ in the next LBT access attempt. $\mathbf{1}_X$ is the indicator function of the event X, and its value equals 1 when X is true and zero otherwise. We use $\mathbf{1}_{(K-1)>0} = 1$ to represent the event $K > 1$, which means that the device will use the maximum backoff stage m_p for K times when collisions happen during transmissions. Let N be the number of the time slots of the ICCA period, $a_{0,N}$ be the initial state of the LBT procedure,

$A = 1-(1-p_{\rm l})^{N+1}$ and $B = A(Ap_{\rm l})^{m_p-1}(Ap_{\rm l} - (Ap_{\rm l})^K)(2A + Ap_{\rm l}(1+2^{m_p}W_{\rm l}))$, we can obtain the transmission probability of the UE $\tau_{\rm l}$ as (1).

$\tau_{\rm w}$, the transmission probability of the STA which uses the distributed coordination function (DCF) in WiFi system can be given as (2) in [7].

$$\tau_{\rm w} = \frac{2(1-2p_{\rm w})}{(1-2p_{\rm w})(W_{\rm w}+1) + p_{\rm w}W_{\rm w}(1-(2p_{\rm w})^{m_{\rm w}})}, \tag{2}$$

where $W_{\rm w}$ denotes the minimum CW size in the WiFi system, $m_{\rm w}$ the maximal backoff stage value, and $p_{\rm w}$ the collision probability.

According to [8], for both the LAA and the WiFi systems, we use $\tau_{\rm l}$ and $\tau_{\rm w}$ to calculate the proportions of the airtime of successful transmission in the total duration. We define these successful-airtime ratios as $R_{\rm s,l}$ and $R_{\rm s,w}$, respectively, and use them as the indicators of the system performance. Then we use $F_{\rm R} = \frac{R_{\rm s,l}}{R_{\rm s,w}}$ as the parameter for fairness metric to investigate the performance in the FeLAA-WiFi coexistence scenario. This theoretical analysis contains more details in Appendix A. The simulation result presented in Appendix B shows the validation of the theoretical analysis.

Adaptive network-aware FeLAA LBT strategy. We assume that the number of AUL FeLAA UEs is $n_{\rm l}$ and the number of WiFi STAs is $n_{\rm w}$ in the FeLAA-WiFi coexistence scenario. And we suppose the devices in both systems have saturated traffic load to investigate the limitation of the system performance. Let $C_{\rm l}$ and $C_{\rm w}$ be the number of the time slots of the transmission duration for FeLAA and WiFi, respectively. $F_{\rm R}$, the relationship between the successful airtime ratios, is given as follows:

$$F_{\rm R} = \frac{R_{\rm s,l}}{R_{\rm s,w}} = \frac{n_{\rm l}\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{n_{\rm w}\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}}. \tag{3}$$

In order to balance the successful-airtime allocation of the two systems, we use (3) to adjust the proportion of the channel occupancy. We have the constraint condition

$$|1 - F_{\rm R}| \leqslant \varepsilon, \tag{4}$$

where ε is the boundary condition. By (3) and (4), we obtain

$$\frac{n_{\rm w}}{n_{\rm l}}(1-\varepsilon) \leqslant \frac{\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}} \leqslant \frac{n_{\rm w}}{n_{\rm l}}(1+\varepsilon). \tag{5}$$

According to (1), the value of LAA CW size $W_{\rm l}$ can affect the transmission probability of LAA evolved node B (eNB). Evidently, higher $W_{\rm l}$ will result in lower $\tau_{\rm l}$. We can get $W_{\rm l}$ from the nonlinear equations (1), (2), (5) and the formulas of $p_{\rm l}$ and $p_{\rm w}$ (see Appendix A). These nonlinear equations can hardly get an analytical solution. However, we can get approximate solutions by numerical method.

Obviously, $\tau_{\rm w}$ is the key parameter in the inequality (5), but we cannot get its value directly. We can obtain the formula of $\tau_{\rm w}$:

$$(1-\tau_{\rm w})^{n_{\rm w}} = \frac{R_{\rm s,l}(P_{\rm t,l}C_{\rm l} + (1-P_{\rm t,l})C_{\rm w})}{R_{\rm s,l}(C_{\rm w}-1)(1-P_{\rm t,l}) + C_{\rm l}P_{\rm t,l}P_{\rm s,l}}, \tag{6}$$

where $P_{\rm t,l}$ is the probability of that at least one UE transmits in a time slot, and $P_{\rm s,l}$ the respective successful transmission probabilities of FeLAA system. With simple channel detections, FeLAA devices can obtain the value of $n_{\rm l}$, $n_{\rm w}$, $\overline{C_{\rm l}}$ and $\overline{C_{\rm w}}$ (average $C_{\rm l}$ and $C_{\rm w}$). Then according to (6), we can get an evaluation $\widehat{\tau_{\rm w}}$ of $\tau_{\rm w}$ as follows. Let $T_{\rm d}$ denote a fixed time duration during which the FeLAA use a fixed $W_{\rm l}$ value. FeLAA devices can obtain the statistical averages of $\overline{R_{\mathrm{s,l}}}$ and $\overline{\tau_{\mathrm{l}}}$ from the system transmission records of each T_{d}. $\overline{\tau_{\mathrm{l}}}$ is the statistical average of τ_{l}, and $\overline{R_{\mathrm{s,l}}}$ the statistical average of $R_{\mathrm{s,l}}$. At the end of the T_{d}, FeLAA devices calculate $\widehat{P_{\mathrm{t,l}}}$ and $\widehat{P_{\mathrm{s,l}}}$ according to $\overline{\tau_{\mathrm{l}}}$ and then evaluate $\widehat{\tau_{\mathrm{w}}}$ by (6).

Then FeLAA devices calculate $\frac{\overline{\tau_{\mathrm{l}}}(1-\widehat{\tau_{\mathrm{w}}})\overline{C_{\mathrm{l}}}}{\widehat{\tau_{\mathrm{w}}}(1-\overline{\tau_{\mathrm{l}}})\overline{C_{\mathrm{w}}}}$ as the value of $\frac{\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})C_{\mathrm{l}}}{\tau_{\mathrm{w}}(1-\tau_{\mathrm{l}})C_{\mathrm{w}}}$ and change the values of W_{l} and K via the iterative search shown in Algorithm 1. More details of the theoretical analysis and the result of the simulations can be found in Appendix C.

Algorithm 1 Adaptive network-aware FeLAA LBT strategy (ALS)

Input: Transmission durations C_{l}, C_{w}, transmission probabilities τ_{l}, device numbers n_{l}, n_{w}, the boundary condition value ε, and T_{d}.

Output: The initial CW $W_{\mathrm{l},T_{\mathrm{d}}}$, the maximum CW usage limitation $K_{T_{\mathrm{d}}}$.

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$W_{\mathrm{l}} \Leftarrow W_{\mathrm{l,min}}$, $K \Leftarrow 1$, evaluate $\widehat{\tau_{\mathrm{w}}}$ as $\tau_{\mathrm{w}}$, and then calculate $\frac{\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})C_{\mathrm{l}}}{\tau_{\mathrm{w}}(1-\tau_{\mathrm{l}})C_{\mathrm{w}}}$;
if $\frac{n_{\mathrm{w}}}{n_{\mathrm{l}}}(1-\varepsilon) \leqslant \frac{\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})C_{\mathrm{l}}}{\tau_{\mathrm{w}}(1-\tau_{\mathrm{l}})C_{\mathrm{w}}} \leqslant \frac{n_{\mathrm{w}}}{n_{\mathrm{l}}}(1+\varepsilon)$. then
    $W_{\mathrm{l},T_{\mathrm{d}}+1} \Leftarrow W_{\mathrm{l},T_{\mathrm{d}}}$, $K_{T_{\mathrm{d}}+1} \Leftarrow K_{T_{\mathrm{d}}}$;
else
    if $t_p = 3$ then
        $\mathrm{CW}_{t_p,\mathrm{max}} = 255$;
    else
        if $t_p = 4$ then
            $\mathrm{CW}_{t_p,\mathrm{max}} = 1023$;
        end if
    end if
    if $\frac{\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})C_{\mathrm{l}}}{\tau_{\mathrm{w}}(1-\tau_{\mathrm{l}})C_{\mathrm{w}}} > \frac{n_{\mathrm{w}}}{n_{\mathrm{l}}}(1+\varepsilon)$ then
        if $2(W_{\mathrm{l},T_{\mathrm{d}}}+1)-1 < \mathrm{CW}_{t_p,\mathrm{max}}$ then
            $W_{\mathrm{l},T_{\mathrm{d}}+1} \Leftarrow 2(W_{\mathrm{l},T_{\mathrm{d}}}+1)-1$;
        else
            $W_{\mathrm{l},T_{\mathrm{d}}+1} \Leftarrow W_{\mathrm{l},T_{\mathrm{d}}}$;
        end if
        if $K_{T_{\mathrm{d}}} < 8$ then
            $K_{T_{\mathrm{d}}+1} \Leftarrow K_{T_{\mathrm{d}}}+1$;
        else
            $K_{T_{\mathrm{d}}+1} \Leftarrow K_{T_{\mathrm{d}}}$;
        end if
    else
        if $\frac{\tau_{\mathrm{l}}(1-\tau_{\mathrm{w}})C_{\mathrm{l}}}{\tau_{\mathrm{w}}(1-\tau_{\mathrm{l}})C_{\mathrm{w}}} < \frac{n_{\mathrm{w}}}{n_{\mathrm{l}}}(1-\varepsilon)$ then
            if $(W_{\mathrm{l},T_{\mathrm{d}}}+1)/2-1 > \mathrm{CW}_{\mathrm{min}}$ then
                $W_{\mathrm{l},T_{\mathrm{d}}+1} \Leftarrow (W_{\mathrm{l},T_{\mathrm{d}}}+1)/2-1$;
            else
                $W_{\mathrm{l},T_{\mathrm{d}}+1} \Leftarrow W_{\mathrm{l},T_{\mathrm{d}}}$;
            end if
            if $K_{T_{\mathrm{d}}} > 1$ then
                $K_{T_{\mathrm{d}}+1} \Leftarrow K_{T_{\mathrm{d}}}-1$;
            else
                $K_{T_{\mathrm{d}}+1} \Leftarrow K_{T_{\mathrm{d}}}$;
            end if
        end if
    end if
end if
return $W_{\mathrm{l},T_{\mathrm{d}}+1}, K_{T_{\mathrm{d}}+1}$.
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Conclusion. We have presented a novel adaptive network-aware FeLAA LBT algorithm for fair uplink FeLAA-WiFi coexistence. The LBT strategy used in this algorithm was built based on the LBT Cat4 access method according to TR 36.889. In contrast to the existing methods, this algorithm needs no inter-system information exchanging. Our method estimated the WiFi performance by both the channel detection result and the statistical parameters of the FeLAA performance. According to the estimation result, the algorithm adjusted the FeLAA LBT parameters dynamically and continuously. By adjusting the delay of the FeLAA channel access, these parameters can determine the competitiveness of UE and thus indirectly influence the performance of WiFi. Our method can improve the WiFi performance, and flexibly allocate the channel occupancy duration to fulfill a variety of fairness requirement.

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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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