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• **Supplementary File** •

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

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Appendix A The LBT Cat4 mechanism of FeLAA

Appendix A.1 Adaptive uplink access strategy of FeLAA

Table A1 shows the permitted parameters values, where m_p is the maximum backoff stage, $CW_{t_p,min}$ the minimum contention window size, and $CW_{t_p,max}$ the maximum contention window size.

Table A1 Channel access priority class [1]

Channel access priority class (t_p)	m_p	$CW_{t_p,min}$	$CW_{t_p,max}$	Allowed CW_{t_p} size
1	2	3	7	$\{3,7\}$
2	2	7	15	$\{7,15\}$
3	3	15	1023	{15,31,63,127,255,511,1023}
4	7	15	1023	{15,31,63,127,255,511,1023}

Figure A1 shows the discrete-time Markov chain proposed by this work. This model is based on the LAA specification [2]. The two chains in each Markov chain group represent the ICCA and ECCA procedures with the corresponding backoff stage m_p, respectively. If $K = 1$, which means the device use $CW_{t_p,max}$ for transmission for only one time, the Markov chain will consist of m_p groups sorted according to the CW value in descending order. Otherwise, when $K > 1$, the end of this Markov chain will add $K-1$ groups of which all the CW size are W_{m_p}.

Let p_l be the collision probability of the FeLAA UE. If we adopt the short notation: $P\{s(t) = I_c(m), a(t) = i|s(t) = I_c(m), a(t) = i+1\} = P\{I_c(m), i|I_c(m), i+1\}$, the nonzero one-step transmission probabilities formulas of this Markov chain can be given by Eq. (A1)

$$\begin{cases} P\{I_c(m),i|I_c(m),i+1\}=1-p_l, & i\in[0,N-1]; m\in[0,m_p+K-1],\\ P\{I_c(m),N|I_e(m-1),0\}=p_l, & m\in[0,m_p+K-2],\\ P\{I_e(m),k|I_e(m),k+1\}=1, & k\in[0,W_m-2]; m\in[0,m_p+K-1],\\ P\{I_e(m),k|I_e(m-1),0\}=\frac{p_l(1-(1-p_l)^N)}{W_m}, & k\in[0,W_m-1]; m\in[1,m_p+K-1],\\ P\{I_e(0),k|I_e(m_p+K-1),0\}=\frac{p_l(1-(1-p_l)^N)}{W_1}. & k\in[0,W_1-1]. \end{cases} \tag{A1}$$

These formulas account for the following facts: 1) the ICCA counter decreases by one when the channel is sensed to be idle during the ICCA detection period; 2) the device will perform an ICCA detection when a collision occurs during the transmission after the ECCA period; 3) the countdown counter decreases by one for one idle slot detected during the ECCA backoff procedure; 4) a new CW size will be adopted when the channel is sensed to be busy after an ECCA transmission collision; 5) when the device has used the maximum CW for K times, its next CW is the minimum value, and its backoff value is randomly chosen from the range $[0, W_0-1]$. Let $a_{m,i}$ ($a_{m,i} = lim_{t\to\infty} P\{s(t) = I_c(m), a(t) = i\}, m \in [0, m_p+K-1], i \in [0, N]$) be the stationary distribution of the ICCA part of the chain and $b_{m,k}$ ($b_{m,k} = lim_{t\to\infty} P\{s(t) = I_e(m), b(t) = k\}, m \in [0, m_p+K-1], k \in [0, W_m-1]$) be the stationary distribution of the ECCA backoff period. $a_{m,i}$ and $b_{m,k}$ can be obtained by the following relations.

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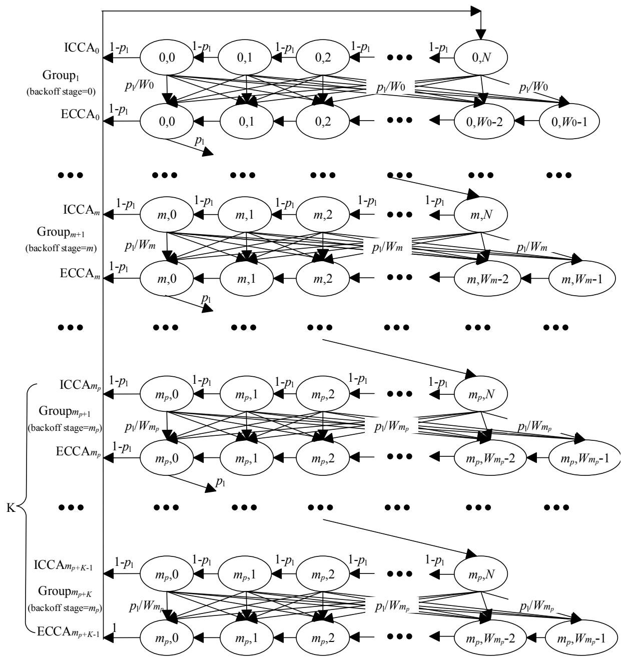

Figure A1 The two-dimensional multi-group Markov Chain model for the FeLAA LBT strategy.

$$a_{m,i} = (1-p_l)^{N-i}a_{m,N},\ 0 \leqslant i < N. \tag{A2}$$

$$\begin{cases} b_{m,k} = \dfrac{W_{1,m}-k}{W_m} \cdot p_l \cdot \sum\limits_{i=0}^{N} a_{m,i}, \quad 0 \leqslant k \leqslant W_m - 1. \quad K=1 \quad or \quad m \leqslant m_p, \\ b_{m,k} = \dfrac{W_{m_p}-k}{W_{m_p}} \cdot p_l \cdot \sum\limits_{i=0}^{N} a_{m,i}, \quad 0 \leqslant k \leqslant W_{m_p} - 1. \quad K>1 \quad and \quad m > m_p. \end{cases} \tag{A3}$$

$a_{0,N}$ is the initial state of the LBT procedure. One can get the relationship between $a_{0,N}$ and $b_{0,0}$, and then get the relationships between $a_{m,N}$ and $b_{m,0}$ in an arbitrary Group$_m$ ($m \in [1, m_p + K - 1]$) in Figure A1. Let $A = 1-(1-p_l)^{N+1}$ as a simplification in the following work, we have $a_{m,N} = p_l^m A^m a_{0,N}$ and $b_{m,0} = p_l^m A^{m+1} a_{0,N}$, which can be proved by mathematical induction as follows. Firstly, it is easy to prove the case $m = 0$.

$$b_{0,0} = p_l \sum_{i=0}^{N} a_{0,i} = (1-(1-p_l)^{N+1})a_{0,N}. \tag{A4}$$

Case 1. $m = 1$.

$$a_{1,N} = p_l b_{0,0} = p_l(1-(1-p_l)^{N+1})a_{0,N}. \tag{A5}$$

$$b_{1,0} = p_l \sum_{n=0}^{N} a_{1,n} = p_l(1-(1-p_l)^{N+1})^2 a_{0,N}. \tag{A6}$$

Case 2. $m > 1$. if

$$a_{m-1,N} = p_l^{m-1}(1-(1-p_l)^{N+1})^{m-1}a_{0,N}. \tag{A7}$$

$$b_{m-1,0} = p_l^{m-1}(1-(1-p_l)^{N+1})^{m}a_{0,N}. \tag{A8}$$

thus

$$a_{m,N} = p_l b_{m-1,0} = p_l^m(1-(1-p_l)^{N+1})^m a_{0,N} = p_l^m A^m a_{0,N}. \tag{A9}$$

$$b_{m,0} = p_l \sum_{n=0}^{N} a_{m,n} = p_l \sum_{n=0}^{N} (1-p_l)^{N-n} a_{m,N} = p_l^m (1-(1-p_l)^{N+1})^{m+1} a_{0,N} = p_l^m A^{m+1} a_{0,N}. \tag{A10}$$

and

$$p_l b_{m_p+K-1,0} = a_{0,N}. \tag{A11}$$

Let $B = A(Ap_l)^{m_p-1}(Ap_l - (Ap_l)^K)(2A + Ap_l(1 + 2^{m_p}W_1))$, and simplify the normalization condition as follows:

$$1 = \sum_{m=0}^{m_p+K-1}(\sum_{i=0}^{N}a_{m,i}+\sum_{k=0}^{W_m-1}b_{m,k}) = \underbrace{\sum_{m=0}^{m_p}(\sum_{i=0}^{N}a_{m,i}+\sum_{k=0}^{W_m-1}b_{m,k})}_{K=1}+\underbrace{\mathbf{1}_{(K-1)>0}\sum_{m=m_p+1}^{m_p+K-1}(\sum_{i=0}^{N}a_{m,i}+\sum_{k=0}^{W_{m_p}-1}b_{m,k})}_{K\geqslant 2}$$
$$= a_{0,N}(\underbrace{\frac{((1-2Ap_{\rm l})(2A+Ap_{\rm l})(1-(Ap_{\rm l})^{m_p+1})+Ap_{\rm l}(1-(2Ap_{\rm l})^{m_p+1})(1-Ap_{\rm l})W_1)}{2p_{\rm l}(1-Ap_{\rm l})(1-2Ap_{\rm l})}}_{K=1}+\underbrace{\frac{\mathbf{1}_{(K-1)>0}B}{2(1-Ap_{\rm l})}}_{K\geqslant 2}). \tag{A12}$$

$\mathbf{1}_X$ is the indicator function of the event X. $\mathbf{1}_X$ equals to 1 when X is true and zero otherwise. We use $\mathbf{1}_{(K-1)>0} = 1$ to represent $K > 1$, which means the maximum backoff stage m_p can be used for K times due to collisions happened during transmissions. The expression of $a_{0,N}$ is finally defined as (A13).

$$a_{0,N} = \frac{2p_{\rm l}(1-Ap_{\rm l})(1-2Ap_{\rm l})}{(1-2Ap_{\rm l})(2A+Ap_{\rm l})(1-(Ap_{\rm l})^{m_p+1})+Ap_{\rm l}(1-(2Ap_{\rm l})^{m_p+1})(1-Ap_{\rm l})W_1+\mathbf{1}_{(K-1)>0}Bp_{\rm l}(1-2Ap_{\rm l})}. \tag{A13}$$

$\tau_{\rm l}$ denotes the stationary probability that a UE transmits the data burst in a generic slot time. This transmission will happen when either the ICCA counter decrease to zero or the ECCA backoff counter is equal to zero. Thus the transmission probability $\tau_{\rm l}$ is got from Eq. (A13).

$$\tau_{\rm l} = \sum_{m=0}^{m_p+K-1}(a_{m,0}+b_{m,0}) = \frac{A(1-(Ap_{\rm l})^{m_p+K})+(1-Ap_{\rm l}+(Ap_{\rm l}-(Ap_{\rm l})^{m_p+K}))(1-p_{\rm l})^N}{1-Ap_{\rm l}}a_{0,N}$$
$$= \frac{2p_{\rm l}(1-2Ap_{\rm l})(A(1-(Ap_{\rm l})^{m_p+K})+(1-Ap_{\rm l}+(Ap_{\rm l}-(Ap_{\rm l})^{m_p+K}))(1-p_{\rm l})^N)}{(1-2Ap_{\rm l})(2A+Ap_{\rm l})(1-(Ap_{\rm l})^{m_p+1})+Ap_{\rm l}(1-(2Ap_{\rm l})^{m_p+1})(1-Ap_{\rm l})W_1+\mathbf{1}_{(K-1)>0}Bp_{\rm l}(1-2Ap_{\rm l})}. \tag{A14}$$

Appendix A.2 The access mechanism of WiFi system

The formula of the transmission probability $\tau_{\rm w}$ is given as Eq. (A15) in the conditions of the saturated traffic conditions, ideal transmission channel, no capture effect, and no hidden terminals [3].

$$\tau_{\rm w} = \frac{2(1-2p_{\rm w})}{(1-2p_{\rm w})(W_{\rm w}+1)+p_{\rm w}W_{\rm w}(1-(2p_{\rm w})^{m_{\rm w}})}. \tag{A15}$$

Appendix A.3 Coexistence analysis

We consider that $n_{\rm l}$ AUL FeLAA UEs and $n_{\rm w}$ WiFi STAs are in the FeLAA-WiFi coexistence scenario. The conditional collision probabilities of the two systems are:

$$p_{\rm l} = 1-(1-\tau_{\rm l})^{n_{\rm l}-1}(1-\tau_{\rm w})^{n_{\rm w}}, \quad p_{\rm w} = 1-(1-\tau_{\rm w})^{n_{\rm w}-1}(1-\tau_{\rm l})^{n_{\rm l}}. \tag{A16}$$

Then the probability of at least one UE and at least one STA transmits will be represented as follows

$$P_{\rm t,l} = 1-(1-\tau_{\rm l})^{n_{\rm l}}, \quad P_{\rm t,w} = 1-(1-\tau_{\rm w})^{n_{\rm w}}. \tag{A17}$$

Hence, the respective successful transmission probabilities of FeLAA system and WiFi system are as follows

$$P_{\rm s,l} = \frac{n_{\rm l}\tau_{\rm l}(1-\tau_{\rm l})^{n_{\rm l}-1}}{P_{\rm t,l}}, \quad P_{\rm s,w} = \frac{n_{\rm w}\tau_{\rm w}(1-\tau_{\rm w})^{n_{\rm w}-1}}{P_{\rm t,w}}. \tag{A18}$$

We use $R_{\rm s,l}$ and $R_{\rm s,w}$ to represent the successful-airtime ratios of the LAA and the WiFi system, respectively. If $T_{\rm s,l}$ and $T_{\rm s,w}$ stand for the transmission duration of the LAA system and the WiFi system, respectively, the successful-airtime ratios are:

$$R_{\rm s,l} = \frac{P_{\rm t,l}P_{\rm s,l}(1-P_{\rm t,w})T_{\rm s,l}}{T_{\rm s}}, \quad R_{\rm s,w} = \frac{P_{\rm t,w}P_{\rm s,w}(1-P_{\rm t,l})T_{\rm s,w}}{T_{\rm s}}. \tag{A19}$$

Where $T_{\rm s}$ can be obtained by Eq. (A20). σ is the duration of one time-slot. $T_{\rm c,A} = max\{T_{\rm c,l}, T_{\rm c,w}\}$ denote the time duration of the transmission conflicts between LAA and WiFi system.

$$T_{\rm s} = (1-P_{\rm t,l})(1-P_{\rm t,w})\sigma+P_{\rm t,w}P_{\rm s,w}(1-P_{\rm t,l})T_{\rm s,w}+P_{\rm t,l}P_{\rm s,l}(1-P_{\rm t,w})T_{\rm s,l}+P_{\rm t,w}(1-P_{\rm s,w})(1-P_{\rm t,l})T_{\rm c,w}+P_{\rm t,l}(1-P_{\rm s,l})(1-P_{\rm t,w})T_{\rm c,l}+P_{\rm t,w}P_{\rm t,l}T_{\rm c,A}. \tag{A20}$$

Appendix B Validation of the Markov model

The values of the parameters used to obtain the numerical results for both the Markov model and the simulations are summarized in Table B1. Both FeLAA UEs and WiFi STAs are randomly deployed independently in a $90 \times 90m^2$ indoor hall. Our simulation runs for 5×10^7 time slots, i.e., 450 seconds to achieve the convergent result [4].

Figure B1 and Figure B2 show that the analysis model is accurate when the FeLAA transmission priorities are 4 and 3 (i.e., $t_p = 4$ and $t_p = 3$ in Table A1), respectively. Therefore, the analytical Markov model is valid to analyze various LAA-WiFi coexistence scenarios.

Table B1 Parameters used in simulations

Definition	Values
Transmit duration	$WiFi: 4ms, LAA: 4ms$
Transmit power	$WiFi: 20dBm, LAA: 18dBm$
Slot time	$9\mu s$
Energy detection threshold	$WiFi: -62dBm, LAA: -62dBm$
LAA CCA defer and WiFi DIFS	$34\mu s$
WiFi $W_{\rm w}$	32
WiFi $m_{\rm w}$	5
Path loss model indoor hotspot	$16.9log_{10}(d)+32.8+20log_{10}(f_c)$

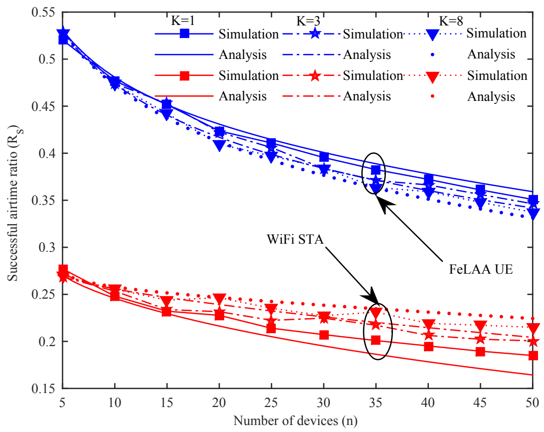

Figure B1 Successful airtime ratio for $t_p = 4$: analysis versus simulation.

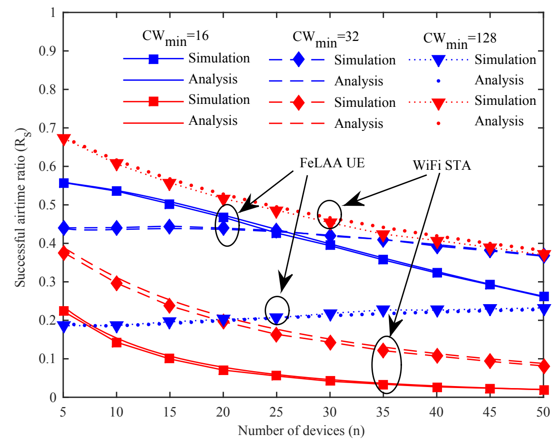

Figure B2 Successful airtime ratio for $t_p = 3$: analysis versus simulation.

Appendix C The proposed strategy

Appendix C.1 Theoretical analysis

Let $T_{\rm s,l} = C_{\rm l}\sigma$ and $T_{\rm s,w} = C_{\rm w}\sigma$, the relationship between the successful airtime ratios is:

$$F_{\rm R} = \frac{R_{\rm s,l}}{R_{\rm s,w}} = \frac{n_{\rm l}\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{n_{\rm w}\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}}. \tag{C1}$$

To achieve the same successful-airtime allocation, we use Eq. (C1) to balance the proportion of the channel occupancy. We have the constraint condition:

$$|1-F_{\rm R}| \leqslant \varepsilon. \tag{C2}$$

Where ε is the boundary condition, and by Eq. (C1) we obtain

$$\frac{n_{\rm w}}{n_{\rm l}}(1-\varepsilon) \leqslant \frac{\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}} \leqslant \frac{n_{\rm w}}{n_{\rm l}}(1+\varepsilon). \tag{C3}$$

By simple channel detections, LAA devices can obtain the value of $n_{\rm l}$, $n_{\rm w}$, and the average WiFi transmission duration ($T_{\rm s,w}$ or $T_{\rm c,w}$). However, (A14), (A15), (A16) and inequality (C3) constitute a system of nonlinear equations with five unknown parameters $\tau_{\rm l}$, $\tau_{\rm w}$, $p_{\rm l}$, $p_{\rm w}$ and $W_{\rm l}$, where, $\tau_{\rm w}$ and $p_{\rm w}$ cannot be detected directly by the LAA eNB. From the formula (A19) we obtain the formula of $\tau_{\rm w}$ as a function of $R_{\rm s,l}$, $T_{\rm s}$, $T_{\rm s,l}$, $P_{\rm t,l}$, and $P_{\rm s,l}$.

$$(1-\tau_{\rm w})^{n_{\rm w}} = 1 - P_{\rm t,w} = \frac{R_{\rm s,l}T_{\rm s}}{T_{\rm s,l}P_{\rm t,l}P_{\rm s,l}}. \tag{C4}$$

Set $T_{\rm s,w} \approx T_{\rm c,w} = C_{\rm w}\sigma$ and $T_{\rm s,l} \approx T_{\rm c,l} = C_{\rm l}\sigma$, and $C_{\rm l} > C_{\rm w}$, then

$$T_{\rm s} = (1-P_{\rm t,l})(1-P_{\rm t,w})\sigma + P_{\rm t,w}(1-P_{\rm t,l})C_{\rm w}\sigma + P_{\rm t,l}(1-P_{\rm t,w})C_{\rm l}\sigma + P_{\rm t,w}P_{\rm t,l}C_{\rm l}\sigma. \tag{C5}$$

One have

$$(1-\tau_{\rm w})^{n_{\rm w}} = \frac{R_{\rm s,l}(P_{\rm t,l}C_{\rm l} + (1-P_{\rm t,l})C_{\rm w})}{R_{\rm s,l}(C_{\rm w}-1)(1-P_{\rm t,l}) + C_{\rm l}P_{\rm t,l}P_{\rm s,l}}. \tag{C6}$$

According to Eq. (A14), the value of LAA CW size $W_{\rm l}$ can affect the transmission probability of LAA eNB. Evidently, higher $W_{\rm l}$ will result in lower $\tau_{\rm l}$. Nevertheless, equations (A14), (A15), (A16) and (C3) constitute a nonlinear system, and

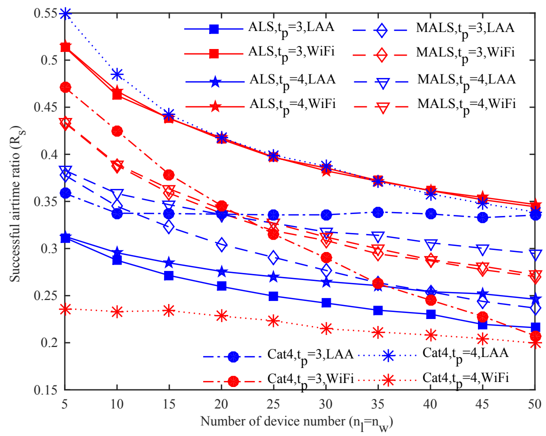

Figure C1 Successful airtime ratio. the ALS/MALS algorithm versus LBT Cat4: $F_{\rm R} = 1$, simulation.

the solution $W_{\rm l}$ must be an integer. This nonlinear system can get approximate solutions by numerical method. As it is shown in inequality (C3), $\tau_{\rm w}$ is the key parameter to adjust the CW size. However, we cannot obtain $\tau_{\rm w}$ directly. According to Eq. (C6), Eq. (A17) and Eq. (A18), we need to know the statistical averages of $\overline{R_{\rm s,l}}$ and $\overline{\tau_{\rm l}}$ to evaluate $\widehat{\tau_{\rm w}}$. Let $T_{\rm d}$ denote a fixed time duration during which the FeLAA use a fixed $W_{\rm l}$ value. $\overline{R_{\rm s,l}}$ and $\overline{\tau_{\rm l}}$ denote the statistical averages of $R_{\rm s,l}$ and $\tau_{\rm l}$, respectively. At the end of the $T_{\rm d}$, FeLAA system calculates $\widehat{P_{\rm t,l}}$ and $\widehat{P_{\rm s,l}}$ according to $\overline{\tau_{\rm l}}$ and then evaluates $\widehat{\tau_{\rm w}}$ by Eq. (C6). Through the evaluated parameters, the FeLAA devices calculate $\frac{\overline{\tau_{\rm l}}(1-\widehat{\tau_{\rm w}})\overline{C_{\rm l}}}{\widehat{\tau_{\rm w}}(1-\overline{\tau_{\rm l}})\overline{C_{\rm w}}}$ to replace $\frac{\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}}$, and update $W_{\rm l}$ and K via the iterative search at the beginning of the next $T_{\rm d}$.

Appendix C.2 Performance analysis of the proposed strategy

Let $T_{\rm d} = 1ms$ in the following works. We use the LBT Cat4 scheme as comparisons and set $CW_{min} = 64$ when $t_p = 3$ and the rest simulation parameters are same as that in Appendix B. Figure C1 shows the performance of FeLAA and WiFi with different channel access priority t_p. Compared with the LBT Cat4 strategies, the proposed algorithm improves the performance of WiFi system while restraining the FeLAA transmission. However, the simulation result of the proposed algorithm (ALS) shows a nearly directly proportional relationship between values of $R_{\rm s,l}$ and $R_{\rm s,w}$ in the both cases of $t_p = 3$ and $t_p = 4$. According to the trend of the curves, we use $x = 0.627$ to multiply the calculated value of $\frac{\tau_{\rm l}(1-\tau_{\rm w})C_{\rm l}}{\tau_{\rm w}(1-\tau_{\rm l})C_{\rm w}}$ in the proposed algorithm, which make $R_{\rm s,l}$ approximately equal to $R_{\rm s,w}$. We call it the modified ALS strategy (MALS). The simulation result in Figure C1 shows that the MALS method can make the curves of $R_{\rm s,l}$ and $R_{\rm s,w}$ closer than that of LBT Cat4.

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