DFC: Dynamic UL-DL Frame Configuration Mechanism for Improving Channel Access in eLAA

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***Abstract*—Enhanced Licensed-Assisted-Access (eLAA) and MulteFire are the latest mechanisms that utilize unlicensed bands while keeping the benefits of LTE. Though eLAA/MulteFire helps to solve the Wi-Fi coexistence issue to a significant extent, its performance suffers due to competition from neighboring transmitting nodes in the unlicensed band to access the channel. We take advantage of new frame structure type-3, proposed for eLAA/MulteFire and formulate a Dynamic Uplink-Downlink Frame Configuration (DFC) mechanism to improve the channel access probability which uses an optimization game based on potential game theory. The DFC delivers a minimum of 40% improvement over arbitrary UL-DL frame configuration mechanism.**

***Index Terms*—eLAA, MulteFire, potential game, UL-DL**

I. INTRODUCTION

LTE in unlicensed bands can be achieved using Licensed-Assisted Access (LAA) [1] or MulteFire [2], both of which follow Listen Before Talk (LBT) mechanism similar to IEEE 802.11 (*i.e.,* Wi-Fi). An LAA node uses both licensed and unlicensed spectrum using carrier aggregation feature of LTE Advanced (LTE-A). While LAA (3GPP Rel. 13 [1]) focused on downlink (DL) data transmission, eLAA/MulteFire [1] (3GPP rel. 14 [3]) uses the unlicensed spectrum for both uplink (UL) and DL data transmissions.

In legacy LTE, there is a restriction on TDD frame configuration as it supports only seven fixed UL/DL TDD frame configurations. But, in eLAA, any subframe can be UL or DL because it uses the new frame structure, type-3 [2]. Thus, in eLAA, all UL and DL combinations are feasible. An eLAA node does not have dedicated radio resources for serving its users and instead has to compete with existing devices like Wi-Fi in the unlicensed spectrum. Thus, in eLAA packet drops may happen, especially in UL transmission due to unavailability of the channel because of the transmission from the current neighboring nodes.

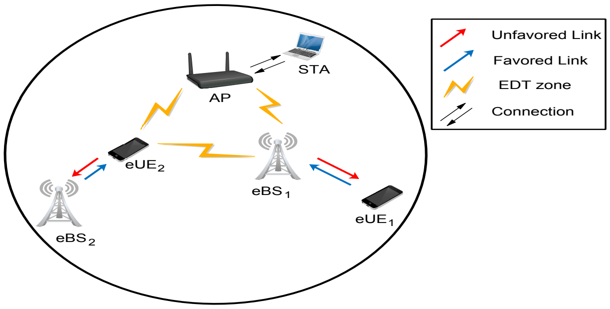

Fig. 1: UL-DL cross interference between eLAA/MulteFire and Wi-Fi.

In literature, the authors of [4] and [5] have proposed adaptive TDD mechanisms and used various possible legacy frame structures to reduce transmission collisions. These mechanisms, however, do not utilize the newly introduced frame structure type-3 which allows any UL and DL subframe configuration, and neither do they consider collisions caused due to the presence of Wi-Fi. In [6], the authors showcased the use of game theory using local altruistic game to reduce collisions in cognitive radios by reducing contention, and we take advantage of this mechanism in eLAA networks along with the new frame structure to improve successful transmissions on the shared channel.

To demonstrate the benefits of intelligent UL-DL configuration, let us consider a scenario of a cluster of eLAA base stations (eBSs), eLAA User Equipments (eUEs), and Wi-Fi nodes (AP/STA), where there is a significant probability of collision as shown in Fig. 1. For a given eBS and its eUE (together denoted by eN), UL and DL are the two distinct configurations of transmission. Thus, either the eBS itself or its eUE can transmit at a time. Due to the changes in the location of the transmitters, the current neighbors of any eN contending for the channel differ in the UL and DL configurations. We observe that if eBS$_1$ and eUE$_2$ wish to transmit at the same time, they have to compete for the channel amongst themselves and AP. Only one of them will be able to transmit at any given time when they are in the Energy Detection Threshold (EDT) zone of each other [1]. Such an unfavored transmission configuration reduces channel access in eLAA networks by half and overall system channel access by two thirds. However, if eUE$_1$ and eBS$_2$ transmit at the same time, they will be able to access the channel simultaneously because they are not in EDT zone of each other and will therefore be in a favored configuration. Thus, the links in a favored (unfavored) configuration are denoted as favored (unfavored) links.

Since eLAA does not have the restriction of seven fixed UL-DL TDD configurations, for each eN, we can decide whether to transmit data in UL or DL. Hence in this letter, we propose a Dynamic UL-DL Frame Configuration (DFC) selection mechanism. DFC selection mechanism ensures an unselfish configuration decision (UL/DL) in each Configuration Period (T_{cp}) for each eN by considering the sum of the probability of successful transmission of a transmitting eN along with the probabilities of its connectors. The connectors of an eN are the union set of the sets of the current neighbors of the eBS and those of its eUEs. Additionally, T_{cp} is defined as the period for which the UL-DL configuration selected by DFC mechanism

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[1] The term eLAA is used to denote both eLAA and MulteFire in the rest of the paper unless otherwise specified.

remains in effect.

The major contributions of this work are: (i) Using the type-3 frame structure, we have proposed an unselfish, non-cooperative game-theoretic framework to choose between UL and DL transmission in eLAA under Wi-Fi interference with a guaranteed pure Nash Equilibrium (NE) profile which maximizes the average probability of successful transmission, (ii) To achieve this NE, we suggest a system model for a central algorithm and a distributed algorithm along with the proof of its convergence. Further, empirical verification has been provided for the improvement in medium access for both eLAA and Wi-Fi nodes, (iii) To the best of our knowledge, this is the first proposal to make efficient use of the flexible TDD frame structure type-3 in eLAA for improving medium access.

II. SYSTEM MODEL

We consider a system model with a cluster of eBSs and their eUEs along with a few Wi-Fi nodes (APs/STAs) operating on the same unlicensed channel. In any given T_{cp}, each eN can either transmit data in either UL or DL transmission mode. Every eBS randomly selects an eUE for UL transmission to avoid starvation. We assume that in a given T_{cp}, n_u eUEs are receiving and n_d eBSs are transmitting. The eBSs can communicate with each other using the X2-interface and thus identify their currently neighboring eBSs and eUEs. Further, we assume that the eUEs can detect other eUEs using passive sensing [7]. Similar passive sensing enables the eUEs and the eBSs to detect their current Wi-Fi neighbors. In each T_{cp}, DFC updates n_u and n_d to achieve the optimum channel access probability for each eN. This update in UL-DL configuration depends on the metric, *utility*. To analyze DFC theoretically and evaluate its performance, we define the concepts of stationary probability, the probability of successful transmission, and utility of an eBS in this section.

A. Successful Transmission in eLAA

Stationary Probability is the probability that a transmitter attempts to transmit in a randomly chosen period. Since eLAA and Wi-Fi follow LBT and Clear Channel Assessment (CCA), all eUEs, eBSs, and Wi-Fi nodes need to check the medium before transmitting. When transmitter-A is in the EDT zone [1] of another transmitter-B which has already occupied the channel, the transmitter-A has to wait. The impact of any transmitter on the other depends on various factors like traffic generated by the transmitter, the channel conditions, and the deployment strategies. Thus, as given in [8], the stationary probability of each distinct eLAA transmitter and Wi-Fi node is modeled as independent and identically distributed (i.i.d.) since it is dependent on the incoming packet rate and the random back-offs. Note that the stationary uplink (downlink) probability captures the likelihood of uplink (downlink) data being present in the transmitter's buffer. The stationary probability is p_u for an eUE, p_d for an eBS, and p_w for Wi-Fi.

Definition 1: The probability of successful transmission of any transmitter (Eqn. (1)) is the probability that the transmitter can transmit continuously in the transmission opportunity without colliding with the transmissions of another transmitter.

$$P_i(s_i, \mathcal{N}_i) = p_t \prod^{n_u^i}(1 - p_u) \prod^{n_d^i}(1 - p_d) \prod^{n_w^i}(1 - p_w), \tag{1}$$

where $t \in \{u, d, w\}$. The current neighbor of i^{th} transmitter is defined as any active eBS, eUE, or Wi-Fi transmitter which lies in its EDT zone. We denote the set of these transmitters by $\mathcal{N}^i$. s_i denotes the current transmission mode of i^{th} transmitter and it has n_u^i eUE neighbors, n_d^i eBS neighbors and n_w^i WNs.

B. The utility of an eBS

It is challenging to optimize the sum of probabilities of successful transmission of the system with only local information. Thus, we consider a local altruistic game [6], and so while defining an eN,'s utility along with its probability of successful transmission, we also consider the probabilities of successful transmission of its connectors. Here, $\mathcal{C}_i = \mathcal{N}_u^i \cup \mathcal{N}_d^i$ denotes the set of connectors, where $\mathcal{N}_u^i$ is the neighbor set of the i^{th} eUE while $\mathcal{N}_d^i$ is the neighbor set of the corresponding i^{th} eBS.

Definition 2: The utility of i^{th} eN, $U_i(s_i, \mathcal{C}_i)$ (Eqn. (1)), is the summation of probabilities of successful transmission of an eN and all its connectors.

$$U_i(s_i, \mathcal{C}_i) = P_i(s_i, \mathcal{N}^i) + \sum_{j \in \mathcal{C}_i} P_j(s_j, \mathcal{N}^j). \tag{2}$$

III. DFC : GAME OF DYNAMIC UL-DL FRAME CONFIGURATION SELECTION MECHANISM

A. Potential Game Formulation

In this game, we assume that each eN autonomously makes the decisions of its transmission mode based on its connector set and the utility computed after that. Using this utility, we formulate an UL-DL configuration game for optimizing the channel access probability for each eN. We denote each eN as a player with UL and DL modes as its strategies. In each T_{cp}, the eN takes the action of either deviating from its current strategy or continuing with the same one. s_{-i} is the set of strategies of all the other players except the i^{th} player. Further, $\mathcal{N}$ is the set of all the players and S_i is the possible strategy set for the i^{th} player. The utility of the i^{th} player Eqn. (2) is given by $U_i(s_i, s_{-i}) = P_i(s_i, \mathcal{N}^i) + \sum_{j \in \mathcal{C}_i} P_j(s_j, \mathcal{N}^j)$. The proposed dynamic configuration selection game to obtain optimal utility is $\mathcal{G} = (\mathcal{N}, s_i, S_i)$ and it is defined in Eqn. (3).

$$(\mathcal{G}) : \max_{s_i \in S_i} \quad U_i(s_i, s_{-i}) \quad \forall i \in \mathcal{N}, s_i \in S_i. \tag{3}$$

Definition 3: The system utility (Eqn. (4)) is the sum of probabilities of successful transmission of all the players in the game.

$$\Phi(s_i, s_{-i}) = \sum_{i \in \mathcal{N}} P_i(s_i, \mathcal{N}^i). \tag{4}$$

Additionally, we propose to find an optimum solution to the game by finding the pure NE for the game [9].

For a game, $S^* = (s_1^*, s_2^*, ..., s_{|\mathcal{N}|}^*)$ is a pure strategy NE if $U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*)$, where, $\forall i \in \mathcal{N}, \forall s_i \in S_i, s_i^* \neq s_i$. One way to show a game has a pure NE is by proving that it is a potential game [10]. A potential function expresses the incentive of a given player to switch its strategy, and all potential games have been shown to have at least one pure NE. *Theorem 1* establishes that $\mathcal{G}$ is an exact potential game.

Definition 4: [10], [11]: A game is said to be an exact potential game, if there exists a function, denoted as a potential function $\Phi : S \longrightarrow \mathcal{R}$ (*i.e.,* from the strategy set to the real set), such that for any i^{th} player, a unilateral deviation from

Algorithm 1 DFC : Central Algorithm

```
for Each Possible eLAA Configuration do
    $p_i \leftarrow$ Measure channel access probability (using information from eUEs and eBSs)
    $u_i \leftarrow$ Insert measured value in Eqn. (2)
end for
for Each eBS do
    BestStrategyArray $\leftarrow s_i$ which max $u_i(s_i, s_{-i})$, maximize Eqn. (2)
end for
for Each Possible eLAA Configuration do
    if Strategy of each player in configuration $\in$ BestStrategyArray then
        $NashArray \leftarrow u_i(s_i, s_{-i})$
    end if
end for
Update: $s_i \leftarrow$ max $\sum(NashArray)$, Sleep for $T_{cp}$
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strategy s to s^*, the following property holds: $\Phi(s_i^*, s_{-i}) - \Phi(s_i, s_{-i}) = U_i(s_i^*, s_{-i}) - U_i(s_i, s_{-i})$, where, $U_i(s_i, s_{-i})$ is the utility function of the i^{th} player.

Theorem 1: $\mathcal{G}$ is an exact potential game.

Proof: We propose using the system utility (Eqn. (4)) as the potential function of the game $\mathcal{G}$. For a game to be a potential game, we have to show that a change in strategy of a player causes the utility of that player and the potential function to change by the same amount. Eqn. (5) considers the difference between the utility functions after a strategy change of a single player.

$$\begin{aligned} U_i(s_i^*, s_{-i}) - U_i(s_i, s_{-i}) &= \Big[P_i(s_i^*, \mathcal{N}^i) - P_i(s_i, \mathcal{N}^i)\Big] \\ &+ \Big[\sum_{j \in \mathcal{N}^i} (P_j(s_j, \mathcal{N}^{j^*}) - P_j(s_j, \mathcal{N}^j))\Big]. \end{aligned} \tag{5}$$

Similarly, we calculate the difference between the potential functions after strategy change of a single player in Eqn. (6).

$$\begin{aligned} \Phi(s_i^*, s_{-i}) - \Phi(s_i, s_{-i}) &= \Big[P_i(s_i^*, \mathcal{N}^i) - P_i(s_i, \mathcal{N}^i)\Big] \\ &+ \Big[\sum_{j \in \mathcal{N}^i} (P_j(s_j, \mathcal{N}^{j^*}) - P_j(s_j, \mathcal{N}^j))\Big] \\ &+ \Big[\sum_{j \in \{\mathcal{N} \setminus \mathcal{N}^i\}, j \neq i} (P_j(s_j, \mathcal{N}^{j^*}) - P_j(s_j, \mathcal{N}^j))\Big]. \end{aligned} \tag{6}$$

The change of strategy of the i^{th} player does not affect the players in the set $\{\mathcal{N} \setminus \mathcal{N}^i\} - \{i\}$ implying that $\sum_{j \in \{\mathcal{N} \setminus \mathcal{N}^i\}, j \neq i} (P_j(s_j, \mathcal{N}^{j^*}) - P_j(s_j, \mathcal{N}^j)) = 0$ and thus proving that Eqns. (5) and (6) are equal which proves the theorem. As a consequence of $\mathcal{G}$ being a potential game, we know that the $\mathcal{G}$ has at least one pure NE [10].

B. DFC Mechanism Implementation Methods

We adopt DFC mechanism to facilitate the convergence to NE of the above-proposed game. We propose two methods, central and distributed to implement DFC.

1) Central Approach (Algorithm 1): A central controller is used to compute the utility for each player using DFC by aggregating the information of the current neighbors and the connectors for each eN in a cluster. The computed optimal solution is then sent back to each eN.

2) Distributed Approach (Algorithm 2): In each round a single player decides its strategy independently using the information of its current neighbors and the computed probability of successful transmission of its connectors while the rest of the players maintain the same strategy.

Algorithm 2 DFC : Distributed Algorithm

```
Initialise: $t \leftarrow 0, s_i \leftarrow random$
Repeat
while Not Converged do
    for Each eBS do
        $p_i \leftarrow$ Measure channel access probability (using information from eUEs and eBSs)
        $u_i \leftarrow$ Insert measured value in Eqn. (2)
        $s_i \leftarrow$ max $u_i(s_i, s_{-i})$, maximize Eqn. (2)
    end for
    When we reach an NE state, the state is said to be converged (i.e., no player changes its strategy)
end while
Update: $s_i$, Sleep for $T_{cp}$
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In Algorithm 2, the current player's eBS obtains its DL, UL neighbors and its eUE's DL neighbors using the X2-interface and its Wi-Fi nodes using passive sensing [7]. The eUE gets its UL neighbors and Wi-Fi neighbors using passive sensing and sends this information to its eBS. The eBS computes the UL and DL probability (Eqn. (1)) of successful transmission and retrieves the probabilities of successful transmission of its connector set (assumed to be known apriori) for both the modes. Finally, the eBS calculates both the utilities (Eqn. (2)) and decides upon the maximum value strategy after which it transfers control to the next player.

The central algorithm provides a globally optimal solution but incurs more computational overhead with an increase in the number of players. Further, it requires a central entity which aggravates the delay due to increased communication overhead between eNs and the central entity. On the other hand, the distributed algorithm provides a locally optimal solution, with lower computational and communication overheads. However, the distributed approach has the drawback of increased convergence time along with the sub-optimal solution. Empirically, the distributed algorithm converges reasonably quickly and on an average requires 12.6 iterations.

Definition 5: [11], [12]: A game is said to be a Best Response (BR)-potential game if there exists a function $\Phi : S \longrightarrow \mathcal{R}$, such that for any i^{th} player,

$$\text{argmax}_{s_i \in S_i} U_i(s_i, s_{-i}) = \text{argmax}_{s_i \in S_i} \Phi(s_i, s_{-i}). \tag{7}$$

Theorem 2: Convergence of DFC: Distributed Approach (*i.e,* Algorithm 2) to an NE.

Proof: Note that, as shown in [11], [12] exact potential games are shown to be BR-potential games. As per Theorem 1, our proposed game is an exact potential game, and thus, it is also a BR-potential game.

In our proposed distributed algorithm, a single player changes its strategy to its best response (concerning the other players) while other players keep the same strategy in each round. The rounds continue until NE convergence. This approach is similar to the *asyncBRA (Algorithm 1 in [11])*. Additionally, as shown by the authors in [10], [11], *asyncBRA* does converge to an NE and thus our proposed algorithm too.

The algorithm achieves NE, when all players are satisfied, *i.e.,* no player has any incentive to switch to another strategy. Assuming NE has not been reached, at least one player will change its strategy to the best response strategy which in turn will improve the potential function value (as shown by the property of BR-potential games). By the definition of a BR-potential game, we conclude that no state is reached twice. We

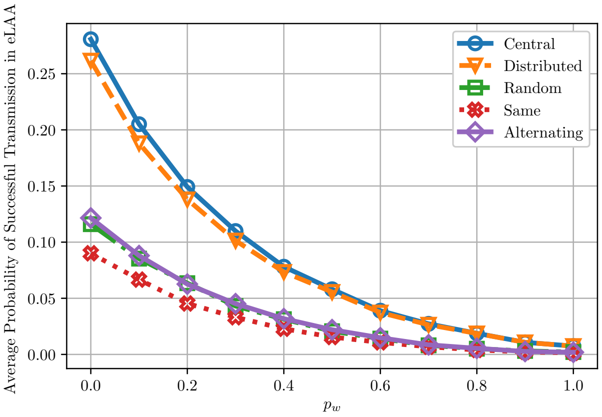

Fig. 2: Average probability of successful transmission in eLAA over p_w.

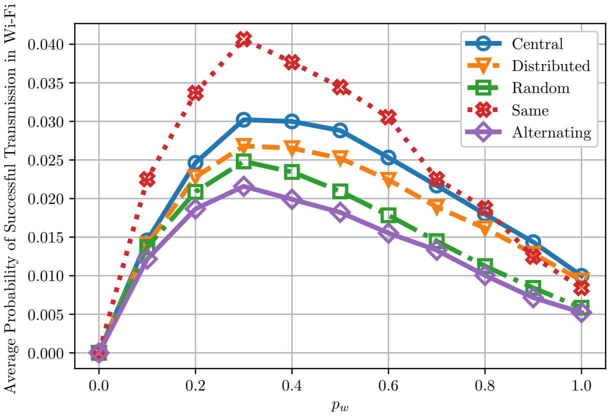

Fig. 3: Average probability of successful transmission in Wi-Fi over p_w.

prove the above statement by considering the two possibilities in the scenario that a state is reached twice. Either, the same state repeats implying that no player has an incentive to change its strategy and thus an NE is reached. The other possibility is that the same state is reached after running through multiple different states. However, the potential function is a strictly increasing function leading to a contradiction. Thus, using the fact that $\mathcal{G}$ is a finite game, the algorithm will necessarily converge to an NE.

TABLE I: Simulation Parameters

Parameter(s)	Value(s)
No. of eBSs, No. of Wi-Fi nodes	6, Random uniform deployment
No. of eUEs (per eBS)	10, Random uniform deployment
Duration of T_{cp}, EDT Range	4 ms, 30m
Simulation time, No. of Seeds	60 sec, 1000
Traffic	Unsaturated Traffic
p_d, p_u, p_w	0.8, 0.2, [0, 1] with 0.1 increments

IV. NUMERICAL RESULTS

To exhibit the merits of DFC, the system is simulated using the parameters shown in Table I. The proposed algorithm is compared with three baseline algorithms. One is the Random Frame Configuration (RFC) which randomly chooses the strategy for each player. Next, the Same Frame Configuration (SFC) which randomly selects either UL or DL as a blanket-strategy for each eN. Finally, the Alternating Frame Configuration (AFC) which randomly allocates UL strategy to half the players and DL to the rest.

Fig. 2 shows the average probability of successful transmissions of each eN against p_w for DFC (central and distributed) and the three baseline algorithms. As expected, the central scheme provides a better success probability in comparison to the distributed. Both the DFC algorithms outperform the baseline algorithms. As the value of p_w increases, the utility value for eLAA decreases owing to an increased collision probability from Wi-Fi for all the algorithms. We notice that RFC and AFC closely align with each other since on an average half the nodes are in UL, and the other half are in DL. SFC, however, slashes the utility (in UL mode), since $p_u = 0.2 (< p_d = 0.8)$.

As a by-product of our proposed algorithm, we studied the effects on Wi-Fi in terms of the average probability of successful transmission (Fig. 3). Central DFC outperforms the distributed as expected. Both the DFC algorithms outperform RFC and AFC. But, SFC performs better due to a lower probability of transmission in all the UL stages giving Wi-Fi the advantage. All the graphs follow an inverted parabolic curve since as p_w increases so does the inter-Wi-Fi collision probability. Additionally, the probability of successful transmission is directly proportional to the throughput and delay inverse since the chances of collision reduce. Delay increases exponentially and the throughput matches the incoming packet rate but finally degrades to zero with increasing p_w.

V. CONCLUSIONS

In this letter, we formulated a local altruistic game based on the dynamic UL-DL frame configuration to obtain the optimal solution for improving channel access probability. Additionally, we proved the existence of a pure NE using potential game theory and analyzed the improvement of channel access probability for the eLAA and Wi-Fi networks. As part of the future work, faster methods like reinforcement learning can be used to implement DFC.

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