Received September 2, 2019, accepted October 12, 2019, date of publication October 23, 2019, date of current version November 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2949035

User Association With Mode Selection in LWA-Based Multi-RAT HetNet

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This work was supported in part by the Wireless Research Lab (WRL) at Helwan University, Cairo, Egypt, and in part by the National Telecommunication Regulatory Authority (NTRA), Egypt, through the funded Research Project entitled Integrating 3G/4G and Wi-Fi Architectures for Diverse Offloading Capabilities.

ABSTRACT Restrained by the long term evolution (LTE) limited network capacity, WiFi technology is considered as one of the promising solutions to leverage the traffic load and enhance the LTE capacity. Exploiting both the licensed and unlicensed spectrum was the motivated key to standardize the LTE-wireless local area network (WLAN) aggregation (LWA) technology by 3GPP in Release 13. In this paper, we consider the user association problem in LWA-based Multiple Radio Access Technologies (Multi-RAT) Heterogeneous Networks (HetNet) in which three transmission modes are available (LTE, WiFi, and aggregation mode) and the user needs to select not only the wireless node that will associate with it, but also the used transmission mode. For this, a new user association algorithm that considers the joint node and mode selection is proposed in this paper. This association process is formulated as an optimization problem with the aim to maximize total network throughput. To solve this problem, a one-to-many matching game-based association algorithm is designed, where each user is matched to the best transmission mode/node according to well-developed utility function that considers the achieved data rate of each user as well as the proportional fairness among users. Simulation results have shown that our proposed algorithm outperforms comparable association techniques such as WLAN first, LTE first, and LTE-W in terms of system throughput, outage probability and fairness between users.

INDEX TERMS Heterogeneous network, LTE-WLAN aggregation (LWA), multi-RAT, matching game, mode selection, user association.

I. INTRODUCTION

With the improved mobile capabilities and the innovative mobile applications, cellular networks are witnessing a huge growth in mobile data traffic which expected to reach 396 exabytes per month by 2022 [1]. Restrained by the available cellular bandwidth, the mobile network capacity cannot handle such a growth in data traffic. WiFi technology is considered as one of the promising solutions that can be used to leverage the mobile traffic load and support the limited capacity of cellular networks [2].

Multiple Radio Access Technologies (Multi-RAT) Heterogeneous Networks (HetNet) is built upon the coexisting of multiple RATs with the availability of different types of wireless nodes (WNs) [3]. Long-Term Evolution (LTE) and WiFi-based Wireless Local Area Network (WLAN) are considered the most common interworking candidate radio access technologies (RATs) in HetNets. In this context, the 3GPP standardized LTE-WLAN interworking to exploit both the licensed and unlicensed spectrums [4], where the user's data traffic can be transmitted either on LTE or WLAN RAT. In such network architecture that is composed of multiple WNs with different RATs, each user needs to decide which WN/RAT to associate with, and this is known as user association problem.

Most of the research studies modeled the user association problem in multi-RAT HetNet either as a node or RAT selection problem. In the node selection, the strategy is based on selecting the most preferred WN to associate with, and once the node is selected, the RAT is inherently decided according to the operational RAT of the selected node. On the other hand, the RAT selection strategy is based on choosing the

The associate editor coordinating the review of this manuscript and approving it for publication was Ning Zhang.

most preferred RAT first, then selecting one of the nodes that supports this RAT. In this case, the node can be selected either by using the default association criteria of the supported RAT (i.e. the node with the strongest received Signal-to-Interference and Noise Ratio (SINR)/ Received Signal Strength Indicator (RSSI)) or according to specific optimization criterion. In spite of which association strategy will be used, the user will associate with only one WN and the data traffic will be transmitted through single RAT.

To this end, 3GPP standardized LTE-WLAN Aggregation (LWA) in Release 13 [5] to enhance the user's quality of experience (QoE), allowing the user's data to be transmitted on both LTE and WLAN RATs simultaneously. In LWA, the data traffic is aggregated at the radio access network (RAN) level, where the eNB resolves to steer the data traffic either on a switched bearer or split bearer [5]. In the switched bearer, the user's data is completely offloaded to WiFi, but in split bearer, the data is transmitted on both LTE and Wi-Fi links simultaneously. The eNB may decide to steer user's data traffic on LTE only, if the WiFi connection will lead to degradation in the user's QoE. Based on this, the LWA can support three transmission modes: the LTE mode where the user's data is transmitted through LTE radio interface only, the WiFi mode where the user's data is transmitted on WiFi only and finally the LWA aggregation mode where the user's data is split on both LTE and WiFi radio interfaces.

Despite the advantages of LWA, the availability of three transmission modes will complicate the user association problem. In LWA-based Multi-RAT HetNet, the user's association problem cannot further be modeled simply as RAT or node selection problem. Since each LWA supported node has actually two RATs and three transmission modes. For this, the node selection strategy cannot be applied, as if one LWA node is selected, we still need to decide which transmission mode should be used. Also, the traditional RAT selection strategy cannot be applied because of the appearance of a new transmission mode (LWA mode) and the user association problem becomes not simple as to select only LTE or WiFi operating RAT. Therefore, a new user association approach must be formulated for joint node and mode selection in LWA-based multi-RAT HetNet.

A. LITERATURE REVIEW

Many research studies were proposed in the literature to provide solutions for the user association problem in multi-RAT HetNet. These studies cover a wide range of user selection paradigm from centralized to distributive architecture [6]–[12], aiming to achieve different network objectives from load balancing, user fairness achievement to maximization of network throughput. Other user selection paradigms [13]–[16] focused on user's requirements in terms of the user's QoE. However, all of the aforementioned works are limited in representing the user association problem, either as RAT selection problem neglecting the node selection criteria or as node selection problem assuming default RAT selection. Such user association algorithms may offer a sub-optimal solution and will not be efficient to be applied in multi-RAT HetNet supporting LWA deployment with three available transmission modes.

There are many studies that adopted user association problem while considering LWA technology. In [17], the authors proposed a scenario where all the UEs have the capability to aggregate the traffic. The user's data traffic can be transmitted through WiFi only or split across a Macro cell and WiFi access point (AP), taking into account the UE's effective rate on WiFi AP and UE's spectral efficiency on Macrocell. Moreover, the authors aimed to maximize network proportional fairness through maximizing each user's throughput. However, it enforced all the users to be associated with WiFi AP either through WiFi mode or the aggregated transmission mode, ignoring the third operational mode supported in LWA (LTE only). Preventing the UEs the opportunity to choose between the three available transmissions modes in LWA can lead to degradation in the system throughput and provide a sub-optimal solution. In [18], the authors proposed a centralized user association algorithm, where UE's downlink traffic is served by a flow scheduler to route the UE's traffic through single or multiple RATs based on the achieved throughput on each RAT. For this, an optimal traffic aggregation solution in wireless multi-RAT HetNets representing the three LWA transmission modes was developed in [18]; however, the solution is limited by a maximum one UE's traffic that can be transmitted using aggregation mode.

In [19], an adaptive mode selection mechanism for LWA was proposed, which considered the link quality of each RAT to decide each user's transmission mode. The proposed algorithm aims to utilize the resources of both radio access technologies (LTE and WiFi), taking into consideration cell load in each technology while adapting the control parameters thresholds (SINR/RSSI). However, this adaptive mechanism did not provide an optimum user association solution. In [20], the authors were aiming to find an optimal transmission mode selection strategy while considering the UE's Quality of Service (QoS) requirements. However, the proposed architecture considered only a single user transmission demand. In [21], the authors also adopt the LWA architecture with three transmission modes representing the WiFi AP as a native-mode AP where it transmits WiFi packets to users who choose WiFi only, and LWA mode AP where it transmits WiFi packets simultaneously with LTE packets to users who choose LWA mode. The authors analyzed the native WiFi network throughput only without considering the LTE network throughput and deployed this on small network topology considering only one LTE base station and one WiFi AP.

In [22], LWA architecture was also considered, representing the three available transmission modes (LTE mode, WiFi mode and LWA-based aggregation mode). The authors introduced a mode selection algorithm called LTE-W which utilizes both LTE and WiFi links based on LWA technology. In LTE-W, the authors start the algorithm assuming a number of already associated users either to LTE Macro base station (MBS) or to WiFi AP, in which some users will be selected to re-associate and work in aggregation mode to enhance their achievable downlink data rate. The number of users to be served with aggregation mode is selected to maximize the total utility function which is the sum of LTE and Wifi throughputs while taking into account the intra-cell fairness.

Furthermore, most of aforementioned studies [17]–[22] assumed that all UEs have the capability to aggregate traffic, and this can be impractical, especially with the heterogeneity in users' equipment. Moreover, they neglect the Multi-RAT HetNet architecture features that imply the availability of multiple WNs belonging to the same RAT, who considered more practical, especially in high dense areas. Therefore, this can be led to a sub-optimal solution for the user association problem. In this context, the matching game was proposed in several works as an optimization tool to optimally solve the user association problem. In [23], a one-to-many matching game was proposed to represent the user cell association problem while considering the user's QoS requirements. In [24], a matching game was also presented to optimize device association (DA) and radio resource allocation (RA) in a heterogeneous cloud radio access network. Also, a matching game framework is proposed in [25] to optimize the user association problem while maximizing the uplink throughput in a cognitive Femto cell network architecture. In [26], a controlled matching game theory algorithm was proposed to solve the user association problem for WLANs. However, all these works [23]–[26] applied the matching game theory over single RAT network architecture considering either an LTE or WiFi technology in their proposed system models.

B. CONTRIBUTION

Motivated by the previous observations provided in the literature review, the main contribution in this paper is to introduce a framework for joint user association and mode selection in LWA multi-RAT HetNet. We consider a scenario where UEs who can access both LTE and WiFi RATs have the capability to choose between three transmission modes (LTE mode, WiFi mode, or LWA mode for aggregation) and can associate with different WNs supporting the selected transmission mode. For this, a user association optimization problem is formulated and solved to find the optimal node and mode selection in LWA multi-RAT HetNet while maximizing the overall network throughput. From this, the main contributions of this work can be summarized as follows

- A multi-RAT HetNet architecture that consists of an LTE Macro cell, LTE small cells, WLAN APs and LTE-WLAN integrated small cells is considered. To the best of our knowledge, such architecture has not been studied in the literature.
- A user association algorithm that considers mode selection problem in LWA multi-RAT HetNet is developed and evaluated. To the best of our knowledge, an algorithm that jointly considers the node and mode selection in LWA based multi-RAT HetNet has not been investigated before.

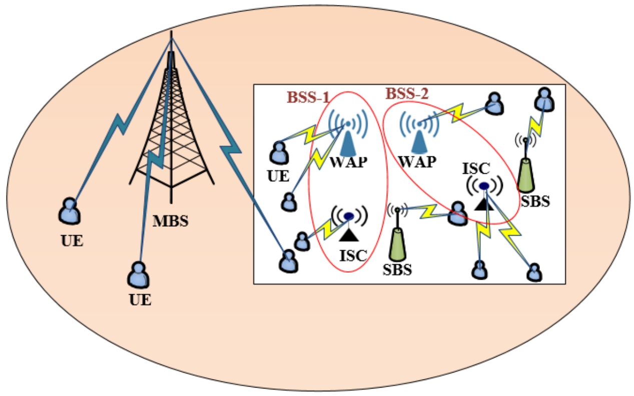

FIGURE 1. System model architecture for LWA Multi-RAT HetNet.

- The proposed association algorithm is designed to take into consideration the heterogeneity of UEs in terms of the supported radio interfaces where not all the users have the capability to aggregate the traffic and each UE may have different radio interfaces.
- One-to-many matching game is adopted to solve the formulated optimization problem for the association process. To the best of our knowledge, a matching game has not been previously applied in an integrated network architecture, which consists of LTE, WLAN, and LTE-WLAN aggregated nodes.
- In the context of the proposed matching game-based user association algorithm, a unified utility function for UE is defined in terms of its achievable data rate while taking into consideration the achievement of fairness among users.
- Efficient models are considered for calculating the user's achieved data rate over WiFi and LTE links which taking into consideration the dissimilarity between LTE and WiFi technologies in terms of their access methods and physical layer specifications.

The rest of the paper is organized as follows: Section III represents a detailed description of the proposed system model, the optimization problem for the association process is formulated in section IV, the proposed matching game-based user association with mode selection algorithm is then presented in section V, followed by the simulation results in section VI, ending by the conclusion in section VII.

II. SYSTEM MODEL

In this paper, a multi-RAT HetNet is considered, where a number of heterogeneous WNs supporting different RATs are deployed. The WNs include an LTE Macro Base Station (MBS), N_{SBS} LTE Small-cell Base Stations (SBSs), N_{WAP} WLAN APs (WAPs) adopting WiFi technology, and N_{ISC} LTE-WLAN Integrated Small Cells (ISCs) which can support both RATs (LTE and WiFi) simultaneously using LWA technology. All the small WNs are deployed in a hotspot area under the coverage area of MBS as shown in Fig. 1.

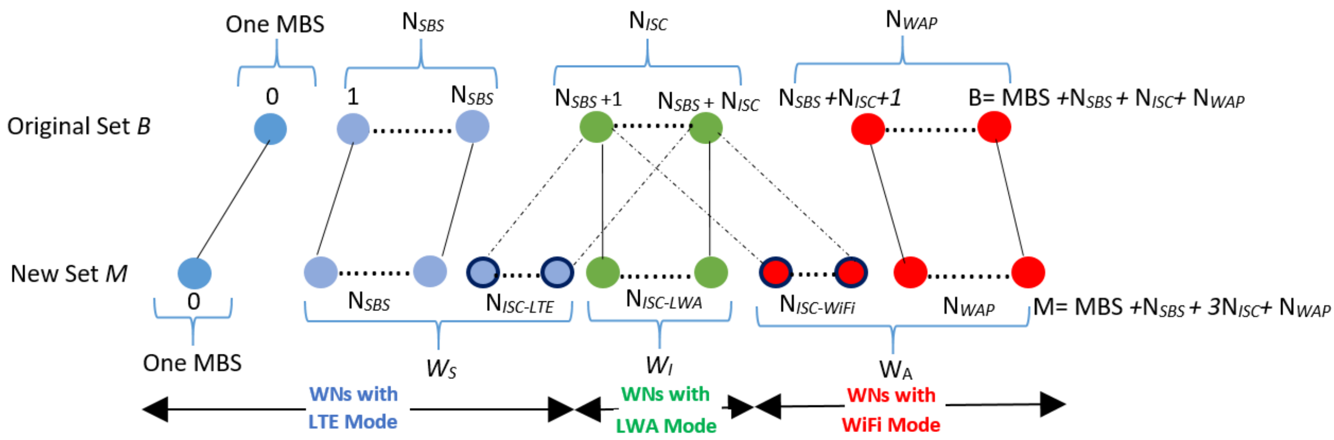

FIGURE 2. **Mapping between the original Set B and the new set *M*.**

A set that represents these different physical WNs is denoted by $\mathcal{B} = \{0, 1, 2, \ldots, B\}$ Here, $b = 0$ represents the MBS, where $b \in \mathcal{B}$ and; the next N_{SBS} WNs represent the LTE SBSs followed by N_{ISC} WNs which represent the ISCs, while the last N_{WAP} WNs represent the WAPs. Therefore, the set $\mathcal{B}$ has a cardinality of $B = 1 + N_{SBS} + N_{ISC} + N_{WAP}$ which represents the physical WNs existing in the network. The WAPs are assumed to operate on a different frequency range from that of LTE MBS and LTE SBSs, while all LTE WNs operate on the same frequency with unity frequency reuse. Furthermore, Orthogonal Frequency Division Multiple Access (OFDMA) with time division duplex mode (TDD) is assumed to be used by all LTE WNs for channel access while all WAPs adopt IEEE 802.11 distributed coordination function (DCF) mechanism that is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for channel access [27]. To be also more practical, the WAPs are assumed to be divided into a number of basic service sets (BSSs) in which the WAPs included in each BSS are operating on different channels while each BSS is competing with other BSSs for the channel forming inter-BSS channel competition.

Moreover, a set of UEs $U = \{1, 2, \ldots, U\}$ with cardinality U that support different radio access capabilities are distributed under the coverage of MBS and inside the Hotspot area. Some of these users are LWA capable which can access the network using LTE RAT only, WLAN RAT only, or aggregate the traffic on both LTE and WLAN using LWA technology. These three access options can be denoted by three transmission modes of operation: M1 (LTE mode), M2 (WiFi mode), and M3 (LWA mode). Users who do not have the capability of LWA, can only access the network using either M1 or M2 mode. Since the ISC WNs support both RATs (LTE and WiFi), it is clear to show that the first mode (M1) can be supported by LTE WNs (MBS and SBSs) as well as ISC nodes, the second mode (M2) can be supported by WAPs and ISC WNs, while the third one (M3) can be supported only by ISC WNs. This implies that the three modes of operation can be supported by any of ISC node and hence any UE associates with an ISC needs to decide which mode of operation will be selected during its association process. Therefore, from the association point of view, each physical ISC node can be represented by three virtual nodes (ISC-LTE, ISC-WiFi, and ISC-LWA) corresponding to its three modes of operation (M1, M2, and M3), respectively, in which the UE associates with one of these virtual nodes when it connects to a physical ISC node.

Based on this and in order to formulate the association with the mode selection problem, a new association set $M = \{0, 1, 2, \ldots, M\}$ is defined to represent the WNs in the network, including the new defined ISC virtual nodes. Here, $m = 0$, where $m \in M$ express the first WN which refers to the MBS, while the rest of the set is divided into three subsets: W_S which includes all WNs that support M1 mode (LTE), W_A which includes all WNs that support M2 mode (WiFi), and W_I which includes all WNs that support M3 mode (LWA).

Therefore, the new set $M = \{MBS\} \cup W_S \cup W_I \cup W_A$ with cardinality $M = 1 + N_{SBS} + 3N_{ISC} + N_{WAP}$. Thus, the mapping between the original set B and the new set M is represented in Fig.2.

For the association purpose, we need to calculate the average SINR/SNR received by any UE from an LTE/WAP WN. For this, the average SINR received by UE i from the LTE MBS can be expressed as

$$SINR_{0,i}^{L} = \frac{P_0 g_{0,i}}{\sum_{k \in W_s} P_k g_{k,i} + \sigma^2}, \quad \forall i \in U \tag{1}$$

where P_0 denotes the transmitted power from MBS while, P_k denotes the average transmitted power from interfering LTE WN $k \in W_s$; $g_{0,i}$ and $g_{k,i}$ represent the average channel gains of the link between MBS and UE i, and between interfering LTE WN $k \in W_s$ and UE i, respectively; and σ^2 denotes the additive noise power. Also, the average SINR received by UE i from LTE WN $m \in W_s$ can be calculated as follows

$$SINR^L_{m,i} = \frac{P_m g_{m,i}}{P_0 g_{0,i} + \sum_{k \in W_s, k \neq m} P_k g_{k,i} + \sigma^2}, \quad \forall i \in U \tag{2}$$

where P_m is the transmitted power from LTE SBS m; $g_{m,i}$ and $g_{k,i}$ represent the average channel gains of the link between SBS m and UE i.

Furthermore, the average SNR received by UE i from WAP $m \in W_A$ can be calculated as follows

$$SNR^W_{m,i} = \frac{P_m g_{m,i}}{\sigma^2}, \quad \forall i \in U \tag{3}$$

where P_m is the transmitted power from WAP m and $g_{m,i}$ represents the average channel gain of the link between WAP m and UE i. It is important to note that the interference between different WAPs is not considered in (3) as the WAPs in each BSS are operating on different channels while the impact of the interference/competition between different BSSs will be considered while modeling the WiFi channel access using ideal CSMA Network (ICN) model as will be shown later in this section.

Since any ISC WN supports both RATs (LTE and WiFi), the average SINR received by UE i over LTE link of the ISC node can be calculated using (2) while the average SNR received over WiFi link of the ISC can be calculated using (3).

Based on the above SINR/SNR calculations for LTE/WiFi links, the data rate that can be achieved by a UE i when associates to WN m will be represented, taking into consideration the different access mechanisms of LTE and WiFi technologies. Since the two technologies have different specifications in many parameters such as the number of sub-carriers, sub-carrier spacing, SINR/SNR ranges, symbol durations, and access mechanisms which all of them have effects on the achievable data rate. Therefore, representing the downlink user's data rate using the Shannon capacity formula without taking into consideration the difference in these parameters will not be applicable.

Based on this, the average downlink data rate that a UE i can achieve when associated with LTE WN $m \in W_s \cup \{MBS\}$, assuming equally allocated resources between the associated users can be represented as follows

$$R^L_{m,i} = \frac{N^L_{sub} N^L_{sym} N^{RB}_m N^{Lbits}_{m,i} N_{slot} C^L_{m,i}}{N_m . T_{sub}}, \quad \forall i \in U \tag{4}$$

where N^L_{sub} represents the number of sub-carriers per one resource block (RB); N^L_{sym} represents the number of symbols per one time slot which can be 6 or 7 according to the OFDM prefix code; N_{slot} is the number of slots per Transmission Time Interval (TTI) which is equal 2; T_{sub} represents the duration of one subframe which is typically equal to 1ms; N^{RB}_m is the total number of RBs for LTE WN m; and N_m represents the total number of users associated to the LTE WN $m \in W_s \cup \{MBS\}$. Furthermore, $N^{Lbits}_{m,i}$ is the number of bits per symbol and $C^L_{m,i}$ is the user's coding rate, where both $N^{Lbits}_{m,i}$ and $C^L_{m,i}$ can be determined from the Channel Quality Indicator (CQI) index, which can be determined from the $SINR^L_{m,i}$ value measured at UE i.

On the other hand, the average downlink achievable data rate of UE i when associated to a WAP $m \in W_A$ can be calculated through the following two steps: first, the normalized throughput of the inter-BSS is calculated based on the Ideal CSMA network (ICN) model [28] in order to take into consideration the inter-BSS channel competition. Then, the impact of channel contention and packet collision on the achieved data rate within a WAP is analyzed using the enhanced 802.11 DCF back-off model [27] considering the Contention Window (CW) resetting scheme with a pre-defined maximum retry limit (μ) which will impact on the channel contention probability τ.

Based on this, we start to compute the normalized throughput of inter-BSS channel competition by modeling the relationship between the co-channel BSSs using network the contention graph G = (V, E). In this graph, V represents the vertices which are the BSSs and E represents the edges which described the carrier sensing relationship of the links between BSSs. The links could be either on an active state or idle state; the links are considered in the active state whenever a certain node (WAP/WiFi UE) within a BSS is transmitting. However, if two links can hear each other, they cannot both be in an active state. In contrast, the link is considered idle when there is no data transmission and all the nodes, including the WAPs and WiFi UEs within a BSS are in backoff state. Thus, Let $S_k = \{0, 1\}$ represents the state of a BSS j, where $S_k = 1$ means that link k is in an active state, while, $S_k = 0$ implies that the link k is in idle (backoff process) state. Therefore, a network with N_{BSS} BSSs feasible state can be represented using $S = S_1 S_2 S_3 \ldots S_{N_{BSS}}$ where, $s \in S$ and S represents the set of all the feasible states of network contention graph. From this, the stationary distribution of the states can be calculated as follows [28]

$$P_s = \frac{\prod_{j:s_j=1 ins} \rho_j}{Z} \quad \forall s \in S \tag{5}$$

$$Z = \sum_{s \in S} \prod_{j:s_j=1 ins} \rho_j \tag{6}$$

where ρ_j represents the access intensity of BSS j and is defined as the ratio between the mean packet transmission time (T_{tr}) and the mean backoff countdown time (T_{cd}) and can be calculated as follows [28]

$$\rho_j = E_j [T_{tr}] / E_j [T_{cd}] \tag{7}$$

in which T_{tr} can be calculated as follows

$$T_{tr} = PD + SIFS + ACK + DIFS \tag{8}$$

where, PD is the Packet duration which consists of Physical layer header, MAC header, and data payload D; $SIFS$ is Short Inter-frame Space; ACK is Acknowledgment short frame, and $DIFS$ is the DCF Inter-frame Space, respectively. While the

T_{cd} can be calculated as follows [29]

$$T_{cd} = [(1-\eta)\frac{W}{2} + \ldots + \eta^{\mu'}(1-\eta)\frac{\sum_{i=0}^{\mu'} 2^i W}{2} + \ldots + \eta^{\mu}\frac{\sum_{i=0}^{\mu'} 2^i W + \left(\mu-\mu'\right)2^{\mu'}W}{2}]^* T_s \quad (9)$$

where, W represents the minimum backoff window size; η is the collision probability for a packet being transmitted in a time slot, where, the collision can occur when a WiFi UE/WAP is transmitting within a time slot and happened that any other WiFi UE or WAP is transmitting in the same time slot; μ and μ' are the retry limit and the maximum backoff stage, respectively and T_s is the slot time. Based on the above analysis, the normalized throughput of BSS j can be calculated as follows

$$Th_j = \sum_{s:s_j=1} P_s \quad (10)$$

Secondly, the achievable throughput by UE i when associated to WAP $m \in W_A$ in a specific BSS j can be calculated based on the enhanced 802.11 DCF back-off model [27] to capture the channel contention and packet collision effect taking into consideration the max retry limits μ and the WLAN physical rate as follow

$$Th^w_{m,i} = \frac{\tau(1-\tau)^{N_m}D}{T + \left(\frac{D\tau(1-\tau)^{N_m}}{R^{Phy}_{m,i}}\right)}, \quad \forall i \in U \quad (11)$$

where N_m represents the total number of users associated to the WAP $m \in W_A, \tau$ denotes the channel contention probability considering the CW resetting scheme. Since, a UE use CW to control the backoff window packet transmission, thus, assigning an optimal CW retry limits will impact on the DCF performance. The DCF back-off model in [27] implies that whenever a backoff incident occur, the backoff time is uniformly distributed over interval $[0, w-1]$, where $(w-1)$ is defined as an integer with range determined by physical characteristics CW_{min} and CW_{max}. After each successful transmission, the value of w is set to a maximum value $[w/2, CW_{min}+1]$, while in unsuccessful transmission, w is set to minimum with value $[2w, CW_{max}+1]$, moreover, T can be represented as in [30]

$$T = (1-\tau)^{N_m+1} e + \left(1-(1-\tau)^{N_m+1}\right)(T_{RTS}+T_{DIFS}) + (N_m+1)\tau(1-\tau)^{N_m}(T_{CTS}+T_{ACK}+3T_{SIFS}) \quad (12)$$

where e is the duration of an empty slot time; T_{RTS}, T_{DIFS}, T_{CTS}, T_{ACK} and T_{SIFS} represent the duration of Request to Send (RTS) short frame, DIFS, Clear to Send (CTS) short frame, ACK and SIFS, respectively. $R^{Phy}_{m,i}$ is the physical data rate a UE i can achieve when associated with a WAP $m \in W_A$, and can be calculated as follows

$$R^{Phy}_{m,i} = \frac{N^{Spatial}_{m,i} N^W_{sub} \times N^{Wbits}_{m,i} \times C^W_{m,i}}{T_{symbol}}, \quad \forall i \in U \quad (13)$$

where $N^{Spatial}_{m,i}$ indicates the number of spatial streams; N^W_{sub} indicates the total number of data sub-carriers; T_{symbol} represents the OFDM symbol duration; N^{Wbits}_{im} and $C^W_{m,i}$ are the number of bits per symbol and the coding rate respectively, where both can be determined from CQI index which can be determined from the measured $SNR^W_{m,i}$ value at UE i.

Finally, the average achievable data rate by UE i when associated with a WAP $m \in W_A$ located in BSS j can be calculated by considering the inter-BSS contention as well as the user's contention within the WAP as follows

$$R^w_{m,i} = Th_j.Th^w_{m,i}, \quad \forall i \in U \quad (14)$$

Accordingly, the average achievable downlink data rate $R_{m,i}$ for any user $i \in U$ associated with any WN m can be expressed as follows

$$R_{m,i} = \begin{cases} R^L_{m,i}, & \forall\, m \in W_s \cup \{MBS\} \\ R^W_{m,i}, & \forall\, m \in W_A \\ R^L_{m-N_{ISC},i} + R^W_{m+N_{ISC},i}, & \forall\, m \in W_I \end{cases} \quad (15)$$

III. PROBLEM FORMULATION

In order to formulate the user association problem, an association matrix $X = [x_{i,m}]_{UxM}$ is defined, where $x_{i,m}$ is a binary variable, in which $x_{i,m} = 1$ when a user i associated with WN m and $x_{i,m} = 0$, otherwise.

Based on this, the user association (UA) problem can be formulated as an optimization problem with the objective to maximize the total network throughput as follows

$$\textbf{OPT}-\textbf{UA}: \max_{X} \sum_{m\in\mathcal{M}} \sum_{i\in U} x_{i,m}(R_{m,i}) \quad (16)$$

s.t

$$\sum_{m\in\mathcal{M}} x_{i,m} \le 1, \quad \forall i \in U \quad (17)$$

$$x_{i,m} = \{0, 1\}, \quad \forall i, m \quad (18)$$

$$\sum_{i\in U} x_{i,m} \le N^L_m, \quad \forall m \in W_s \cup \{MBS\} \quad (19)$$

$$\sum_{i\in U} x_{i,m} \le N^W_m, \quad \forall m \in W_A \quad (20)$$

Here, constraint (17) guarantees that each UE i can be associated with at most one WN m; constraint (18) indicates that the association indicator takes only a binary value; constraint (19) and (20) ensure that the number of users associated to a WN m does not exceed the maximum allowed number of users to avoid QoS degradation, where each WN is restricted by a maximum number of UEs that can be associated with, called quota. An LTE quota is defined as the maximum number of users N^L_m that can be associated with LTE WN $m \in W_s \cup \{MBS\}$ and satisfies a required load. This load can be represented by a cell load metric called cell saturation ratio Q^L_m which indicates to at what extent the LTE WN will be able to satisfy the served users by comparing the achievable data rates of associated users to their given reference throughput values and can be represented as follows

$$Q_m^L = \frac{1}{N_m^L} \sum_{i \in U} x_{i,m} \frac{R_i^{ref}}{R_{m,i}^L}.100\%, \quad \forall \in W_s \cup \{MBS\} \quad (21)$$

where R_i^{ref} represents the reference data rate that is defined as the minimum throughput an operator set to maintains user's QoE, $R_{m,i}^L$ is the UE LTE achievable data rate and can be calculated using (4). Similarly, the WiFi quota is defined as the maximum number of users N_m^W that can be associated with WAP $m \in W_A$ and achieves maximum saturation throughput, considering a constant minimum and maximum contention window size ($\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$, respectively). Thus, the quota for any ISC $m \in W_I$ can be defined according to the quota of its two virtual nodes (ISC-LTE and ISC-WiFi) where the quota of ISC node is violated if either the quota of its ISC-LTE or ISC-WiFi virtual nodes is violated.

Moreover, it can be noticed that the optimization problem in (16) is an NP-hard combinatorial problem due to the binary characteristics of the association indices. For this, we elaborate a framework based on one-to-many matching game to solve the formulated optimization problem.

IV. MATCHING GAME-BASED USER ASSOCIATION ALGORITHM

To solve the expressed user association problem, a two-sided matching game is formulated where each user can be associated with at most one WN, while each WN can be matched to a set of UEs. This can be defined as one-to-many matching game [31], expressed by a tuple $(M, U, \succ_{M,UA} \succ_{U,UA})$. Here, $\succ_{M,UA} = \{\succ_{m,UA}\}_{m \in M}$ and $\succ_{U,UA} = \{\succ_{i,UA}\}_{i \in U}$ denote the sets of preference relations of UEs and WNs, respectively. The matching game for a user association Ω_{UA} can be formulated as two disjoint finite sets of players U and M, a matching Ω_{UA} is defined as a function $\Omega_{UA}: U \to M$, under the following criteria:

1) $\Omega_{UA}(i) \leftrightarrow i \in \Omega_{UA}(m)$;
2) $|\Omega_{UA}(m)| \le N_m^L \; \forall m \in W_s \cup \{MBS\}$; $|\Omega_{\mathrm{UA}}(\mathrm{m})| \le \hat{N}_{\mathrm{m}}^{\mathrm{W}} \; \forall \mathrm{m} \in \mathrm{W_A}$ *and* $|\Omega_{UA}(m)| \min(N_{m-N_{ISC}}^L, N_{m+N_{ISC}}^W) \; \forall m \in W_I$
3) $|\Omega_{UA}(i)| \le 1$.

where, $m = \Omega_{UA}(i)$ defines that a UE i is matched to WN m, accordingly WN m is matched to UE; $(i \in \Omega_{UA}(m))$; $|\Omega_{UA}(m)| \le N_m^L$ and $|\Omega_{UA}(m)| \le N_m^W$ ensure that a maximum of N_m^L and N_m^W of UEs are matched to LTE and WiFi WNs, respectively; and $|\Omega_{UA}(i)| \le 1$ guarantees that each UE is attached to at most one WN. The UEs and WNs utility functions are denoted by $u_i(m)$ and $\upsilon_m(i)$, respectively. The utility function is defined as a function that is used to arrange the most preferred relations to match.

A. USERS UTILITY FUNCTION

In order to solve the optimization problem that implies to maximize the total network throughput, we designed a user's utility function that represents the user's achievable rate with each WN m and implies a proportional fairness. From this, the user's utility function can be represented as a concave function with respect to $R_{m,i}$ that denotes the benefit which user i gets from downlink achievable data rate. Such a utility function increases significantly at the low levels of the achieved downlink rate. Then, its gradient decreases gradually and the utility changes smoothly as the achieved downlink rate increases which can be represented as follows

$$u_i(m) = 1 - e^{-aR_{m,i}} \quad \forall i \in U, \; m \in M \quad (22)$$

where, $a \in R^+$ represents a function of R_i^{ref}. It is important to note that $u_i(m)$ is set to zero if UE i does not support the transmission mode of WN m; hence the radio access capability of heterogeneous UEs is considered during the operation of the matching game-based association algorithm.

B. WIRELESS NODES (WNs) UTILITY FUNCTION

After each user sorts its preference list based on the user's utility function $v_m(i)$, each user sends an association request to the most preferred WN m. Then, a sufficient strategy to accept the UEs requests must be applied where each WN m sort UEs association requests based on a utility function which implies serving the UE i with the highest achievable data rate as follows

$$v_m(i) = R_{m,i} \quad \forall m \in M, \; i \in U \quad (23)$$

The specific details of the proposed matching game-based UA algorithm are described in Algorithm 1. After initialization, Each UE i sorts its preference list $\succ_{i,UA}$ based on the defined user's utility function (22), the UE i sends an association request $ar_{i \to m}^{UA}$ to WN m which has the highest utility in its preference list and set the association request $ar_{i \to m}^{UA} = 1$ or zero otherwise (Lines 1-6). On the other side, each WN m sorts all the received UEs' association requests $ar_{i \to m}^{UA}$ in a preference list $\succ_{m,UA}$ based on the defined WN's utility function (23) (Lines 8-9). Then, each WN m will accept the users' association requests and update its matching list U_m until reaching its quota (Lines 10-13). If the WN m reaches its quota, it rejects the rest of requesting users (Line14) and the UE in the rejected list U_m^{rej} shall remove WN m from their preference list in next UA phase. This process will be repeated until there are no requesting users (Lines 15-16). Furthermore, in case of LWA mode, when a UE i sends an association request to ISC WN $m \in W_I$, the requested WN checks both ISC-LTE and ISC-WiFi quota, if both are satisfied, the requesting UE i will be accepted and the number of users attached to virtual ISC-LTE and virtual ISC-WiFi nodes will be increased by one, else if either the ISC-LTE or ISC-WiFi quota reached the maximum, the user would be rejected and the requested WN $m \in W_I$ will be removed from their preference list.

V. PERFORMANCE EVALUATION

In this section, we present our simulation results to evaluate the proposed matching game-based user association algorithm. We first present our simulation setup and then the simulation results.

Algorithm 1 Matching Game-Based User Association

```
Initialization: M, U, U_m^{ar}, U_m^{rej}, i ∈ U
Utilities Calculations
  each UE i constructs ≻_{i,UA} using (22)
Find Stable Matching:
  While Σ_{∀i,m} ar_{i→m}^{UA} ≠ 0 do:
    For each unassociated UE i:
      Find m = arg max_{m∈≻_i} u_i(m).
      Send a request ar_{i→m}^{UA}(t) = 1 to WN m
    For all WN m:
      Update U_m^{ar} ← {i : ar_{i→m}^{UA} = 1, i ∈ U}.
     Construct ≻_{m,UA} based on (23).
        repeat
          Accept = arg max_{i∈≻_{m,UA}} υ_m(i)
          Update U_m ← U_m ∪ i
        until U_m = N_m^L ∀m ∈ W_s ∪ {MBS}
           or U_m = N_m^W ∀mW_A
    Update U_m^{rej} ← {U_m^{ar} \ U_m}
    Remove WN m ∈≻_i, ∀i ∈ U_m^{rej})
  end while
Results: A stable matching Ω_{UA}
```

A. SIMULATION SETUP

In order to evaluate our proposed algorithm, multi-RAT HetNet with LWA is considered. This architecture is represented by one LTE MBS, 2 LTE SBSs, 2WAPs, and 2 ISCs. The small cells have a radius of 50m each and deployed in a hotspot area of 325 × 225m^2 under the coverage of MBS which has a radius of 1000m. A number of UEs are uniformly distributed in the hotspot area. Moreover, the indoor WLAN path loss model is represented as follows [32]

$$P_{Loss}^{W} = 20\log_{10} f_w(MHz) + \eta_w \log_{10} d + P_f\,(n_w) - 28 \tag{24}$$

where f_w represents the WLAN transmission frequency; d is the distance in meters between WAP and UE; η_w is the distance power loss coefficient and assumed to be 30; $P_f\,(n_w)$ denotes the penetration loss factor and is equal to $P_f\,(n_w) = n_w + 13$; n_w is the number of walls and assumed to be 3.

While the indoor Path loss model for LTE Femto SBS is expressed as follows [33]

$$P_{Loss}^{L} = 38.46 + \log_{10} d + 0.7R_{2Dindoor} + 18.3 * n_L^{\,n_L\left(\left(n_L+2\right)/\left(n_L+1\right)-0.46\right)} \tag{25}$$

where d is the distance in meters between the LTE SBS and UE, $0.7R_{2Dindoor}$ is the penetration loss that occurs due to the walls and measured in meters, and n_L is the number of penetrated floors and in case of a single-floor building, the last term is ignored. The rest of the simulation parameters are summarized in Table 1. Noting that the simulations are performed for 500 runs, and the obtained results are averaged.

TABLE 1. Simulation parameters.

LTE Parameters	
Transmit power of LTE MBS	46 dBm
Transmit power of LTE SBS	20 dBm
Path loss between MBS and UE	128.1+37.6 $\log_{10}$d(km)
LTE bandwidth	20 MHz
Channel bandwidth	180 KHz
Transmission Frequency	2GHz
Noise Power	174 dBm/Hz
802.11n WiFi Parameters	
WLAN bandwidth	20MHz
Transmit power of WAP	200 mW
Spatial Streams	4
Minimum Contention Window (W)	32
Maximum Number of backoff stage (μ')	5
Maximum Number of Re-transmission (μ)	7
Transmission Frequency (f_w)	2.4GHz
Slot time	9 µs
DIFS	50 µs
SIFS	10 µs
ACK	160 bits
RTS	208 bits
CTS	160 bits
Data Payload Size (D)	1500 bytes

B. SIMULATION RESULTS

In order to evaluate our algorithm, the performance of our proposed algorithm is compared against three other association schemes. The first scheme is the well-known WLAN First strategy (WF), which states that each user will always associate first with the WiFi RAT whenever the WiFi is available, and if there is more than one WAP available in the network, the user will associate to the WAP with the strongest received SNR. Furthermore, as our proposed architecture considered both LTE and WiFi RATs, we need to compare our proposed scheme against LTE first (LF) strategy to reflect the difference between the two technologies. In the LF strategy, a user will always start to associate first with LTE RAT, and if there is more than LTE WN available, the user will associate to the LTE WN with the strongest received SINR. Furthermore, we compared our proposed algorithm to LTE-W algorithm presented in [22].

Moreover, a modification in WF and LF schemes was also considered to be fairly compared to our proposed algorithm. This modification states that, when a user associates either with WAP/SBS and happened to be the virtual ISC-LTE or virtual ISC-WiFi, hence, the user will associate with the two virtual nodes simultaneously and user receives an aggregated rate from LTE and WiFi RATs.

Fig.3 shows that our proposed algorithm outperforms the LTE-W algorithm in terms of total system throughput. This is because, in LTE-W algorithm, the users start by an initial phase of association based on the available radio access technology, either LTE or WiFi and the user's channel condition without taking into consideration which WN of the available technology would give a better achievable rate and may be less congested. Then, the re-association algorithm takes place for only the users who can work in the aggregation mode to enhance their achievable throughputs. In contrast,

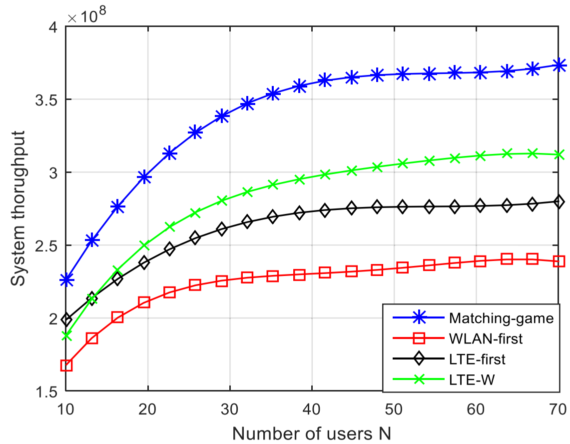

FIGURE 3. System throughput vs. Number of users.

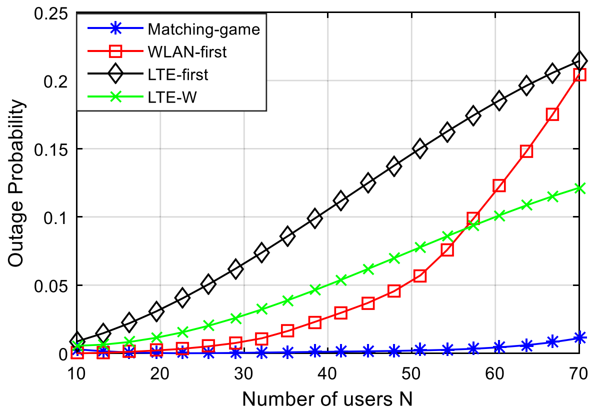

FIGURE 4. Outage probability vs. Number of users.

our proposed matching game-based association algorithm is designed to follow the user's intentions (utility function) to choose the most suitable node with a specific transmission mode (LTE, WiFi or aggregation), that can provide maximum achievable data rate. By means, our proposed algorithm compared to LTE-W algorithm gives the user the opportunity to select the most preferred mode and node that can achieve maximum data rate according to its utility function and hence enhancing the total system throughput. Moreover, regarding the LF and WF performance, the user in these strategies always associates with the preferred RAT first, without taking into consideration that other WNs of other RATs may provide him a better achievable data rate. Consequently, this can lead to a degradation in the system throughput, especially in a dense area where the user may select a preferred RAT which is already congested while the other RAT may be less congested and underutilized.

Fig.4 shows the effect of increasing the number of UEs on the outage probability. The outage probability here is defined as the percentage of unsatisfied users whose downlink achievable rate is below a required reference rate settled by the operator which is set to be 1.5 Mb/S. As shown in Fig.4, our proposed algorithm stays at low outage probability compared to the LTE-W algorithm. Hence, in our proposed, algorithm

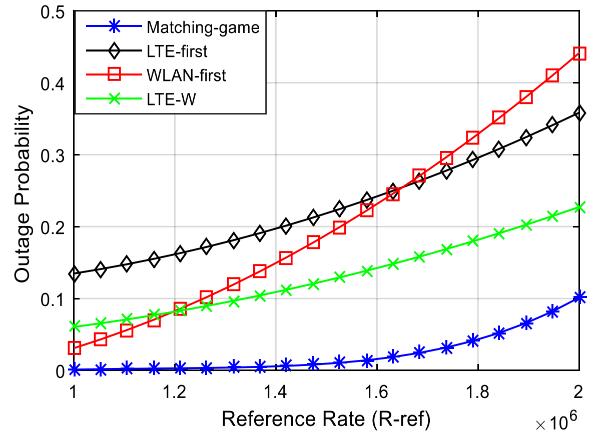

FIGURE 5. Outage probability vs. Reference rate.

we take into consideration the assigned quota for every WN that limits the number of associated users to balance the load between different WNs and help in providing the required reference rate for each user. In contrast, in the LTE-W algorithm, the user associates first with the available WN based on available RAT either LTE or WiFi and the user's channel condition regardless if the user can achieve a better rate with less congested WN. Thus, associating the user with congested WN while other WNs may be less congested can lead to increase in the outage probability, especially with the increase of the number of users. Although, the LTE-W algorithm can achieve high total system throughput, however this cannot guarantee the required reference rate for each user. Furthermore, in LF algorithm the users associate first with LTE SBSs and if some users are not in the coverage of any SBS, they directly associate to the MBS, even if they will achieve low achievable data rate (bad SINR) and with the increase of the number of users, the LF will suffer from degradation of throughput that impact on the outage probability. The WF algorithm also suffers also from high outage probability, especially when the number of users associated with WAP increases, as the contention increase which may lead to degradation in the achievable data rate that as a result affects the outage probability.

The effect of changing the value of the required reference rate R_i^{ref} on the outage probability for the four comparable algorithms is also shown in Fig.5 by setting the number of users equal to N=70. It can be noticed that, when the reference rate increases up to 2Mbps, the proposed matching game-based algorithm outperforms the other comparable algorithms and still able to satisfy the users' rate requirements with maximum outage probability of approximately 0.1. This can be subjected to the load balancing provided by the proposed matching game-based algorithm due to the assigned quota to each WN that limits the number of users attached to each WN and hence support in achieving the required rate by each user.

In Fig.6, we illustrate the Jain's fairness index that evaluates the fairness among different users and can be calculated

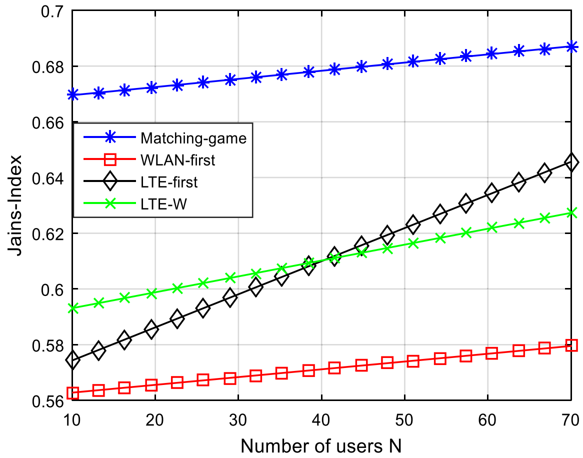

FIGURE 6. Jain's index vs. Number of users.

as follows [34]

$$J = \left[\sum_{i=1}^{U} x_i^2\right]^2 \Big/ U.\left[\sum_{i=1}^{U} x_i^2\right] \qquad (26)$$

where, U represents the number of users in the network while x_i represents the measurement metric which in this case is the user's achievable data rate after the association process which can be calculated as $x_i = \sum_{m\in M} x_{i,m}R_{m,i}, \forall i \in U$. As the value of J gets larger, it indicates better fairness among users [34]. As seen from Fig.6, our proposed algorithm is achieving the fairness among all the users relative to the LTE-W algorithm. Since, in LTE-W, the enhancement in the re-association algorithm, it depends mainly on the users and WNs who have the capability to associate. By means, after the initial association stage, the users who re-associated to be served by the aggregation mode are the only users who can enhance their achievable data rate and can receive data rate form LTE and WiFi RATs simultaneously. While other users who associated with a WN that don't have the capability to aggregate may suffer from congestion and achieve a low data rate. Based on this, the variation among the users' achievable data rate may increase which as a result leads to a degradation in the fairness among users. In LF and WF algorithms, with small number of users in the system, the inequality among the users' downlink data rate is high (system less congested) and with the increase of number of users in the system, the fairness among the users can be reached and become almost constant as the variation among the users' downlink throughput decreased (system more congested). Although of this, the LF's and WF's Jain's index is still low compared to our proposed algorithm, as shown in Fig.6.

VI. CONCLUSION

In this paper, we proposed a framework to jointly optimize the user association and mode selection in LWA multi-RAT HetNet. A number of LTE SBSs, WAPs and ISCs have been deployed to serve a number of UEs in a hotspot area under the coverage of LTE MBS. The user association problem has been formulated as an optimization problem to maximize the network throughput through maximizing the sum throughput across all the associated users while considering the fairness among the users and WNs load. To solve this problem, a one-to-many matching game is formulated by modeling the UEs and WNs behavior through two defined utility functions aiming to validate the main optimization problem. The simulation results show that our proposed algorithm has better performance compared to LTE-W, WLAN first and LTE first algorithms in terms of system throughput, outage probability and Jain's fairness index. For future work, we will study the complexity for applying a larger network with ultra-dense small cells development.

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