IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 8, 2022, accepted May 16, 2022, date of publication May 27, 2022, date of current version June 23, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3178383

On the Performance of Location Management in 5G Network Using RRC Inactive State

LIDIANO A. N. OLIVEIRA[1], MARCELO S. ALENCAR[1], (Senior Member, IEEE), WASLON T. A. LOPES[2], (Senior Member, IEEE), AND FRANCISCO MADEIRO[3]
[1]Department of Electrical Engineering, Federal University of Campina Grande, Campina Grande 58.429-900, Brazil
[2]Department of Electrical Engineering, Federal University of Paraíba, João Pessoa 58051-900, Brazil
[3]Polytechnic School of Pernambuco, University of Pernambuco, Recife 50720-001, Brazil

Corresponding author: Waslon T. A. Lopes (waslon@cear.ufpb.br)

This work was supported in part by the Coordination for the Improvement of Higher Education Personnel (CAPES) under Grant 001, and in part by the National Council for Scientific and Technological Development (CNPq).

ABSTRACT Among the characteristics in fifth generation (5G) networks, a massive number of devices and a network densification stand out. Hence, efficient location management is a key factor in enabling the network to track each user under the coverage area. In order to fulfill the requirements of 5G, a novel location management strategy was introduced by the 3rd Generation Partnership Project (3GPP) based on a new Radio Resource Control (RRC) state. This article presents a new methodology to find out an optimum network configuration that minimizes the signaling costs associated with the location management scheme for 5G networks. In addition to procedures triggered by the core network, the signaling costs are calculated taking into account the paging and update procedures performed in the Radio Access Network (RAN). A genetic algorith'm is applied to optimize the network by reducing signaling costs caused by location management procedures, obtained from a 5G network system-level simulator focusing on mobility events. The proposed approach is compared to the schemes used in previous mobile networks. The results indicate that the new scheme decreases the signaling cost and reduces latency in various network sizes and user profile.

INDEX TERMS Cellular mobile system, location management, 5G networks, paging, location update, RRC states.

I. INTRODUCTION

The 5G network is a recent evolution of mobile communications technology. Unlike the previous generations, which were focused on increasing throughput rate, 5G network is a technological paradigm shift. This new mobile network must support a higher data rate (greater than 10 Gbit/s), low latency (less than 1 ms), high reliability, connectivity and mobility. In addition to the growth in the number of mobile devices, new scenarios have been included for 5G networks, such as massive machine type communication, vehicle-to-device communication and device to device [1].

In order to meet the expected increase in the number of subscribers in a very dense network, location management plays a fundamental role in a 5G network [2]. Tracking the user location requires a substantial effort from the mobile network and an optimized network design is desired.

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

Location management consists of two operations [3]. The first procedure is to update the location, in which the mobile station informs the network its current location. The coverage area is divided into non-overlapping areas called Tracking Areas (TAs). The user location update is performed when the User Equipment (UE) crosses the boundary of that area. The second operation is paging the UE, a feature that allows the network to search for a UE using broadcast messages in the last TA where the user has been registered.

The location management solutions used in predecessor technologies were not designed to support such a large number of devices in a network with dense coverage of gNodeBs (5G base stations), which is required to handle the limited coverage resulting from the use of millimeter waves, as well as to support the requirements of 5G network [4]. In this context, paging and updating the devices' location, procedures that are part of the location management of a mobile network, are more costly than those observed in previous networks because of the massive number of connected devices and the cell density.

In order to improve the systems performance in terms of latency and power consumption, a new state of connectivity in the Radio Resource Control (RRC) was introduced in the specifications of the 5G system, called the Inactive state [5]. This state allows a hierarchical approach to location management. So, parts of the procedures are performed by the Radio Access Network (RAN) elements instead of the Core Network (CN). In addition, a RAN area update (RNAU) procedure was introduced to allow UEs to be findable when changing the RAN-based Notification Area (RNA) [6]. This approach minimizes the signaling cost and latency because the UE does not need to notify the CN while the UE moves inside an RNA.

There is a high computational complexity to find out the location management design (TA,TA List and RNA dimensioning and planning) that minimizes the signaling cost. This design can be considered a combinatorial optimization problem, whose objective is to determine a specific TA association with TAL and cell association with both RNA and TA such that the signaling costs are minimal. However, by utilizing Artificial Intelligence (AI), in particular genetic algorithms (GA), it is possible to achieve an adequate design with reduced location management overhead.

In this work, a comparative analysis of the performance of location management in a 5G network is performed with the existing management strategies and the new scheme proposed by the 3rd Generation Partnership Project (3GPP). The signaling and delay costs in the network are the metrics used in this work. A simulator was implemented to model the user behavior in a mobile network and the network location management procedures, providing traffic and mobility information. These information, generated by the simulation, are used by the GA to design a 5G network with an optimized signaling cost. Furthermore, a comparison of location management schemes used in previous mobile network technologies is made.

This article is organized as follows: Section II summarizes related works. Section III describes the location management scheme in a mobile network. Section IV details the new RRC state and a new location management scheme for 5G network. In Section V the location management cost is calculated. Section VI introduces a system level simulator to generate data to be used as input for a genetic algorithm presented in Section VII. Section VIII presents the results obtained and Section IX contains the conclusions and proposals for future works.

II. RELATED WORK

Location management is one of the most challenging issues in mobile cellular networks [7]. Each new generation proposes an improvement of location management strategies, handling the limitations associated with the characteristics of the actual mobile generation. In LTE (Long Term Evolution) the 3GPP Release 8 introduced a new feature called Tracking Area List (TAL). However, 3GPP does not specify how to find the optimum TAL configuration. So, several studies propose methodologies to reduce the complexity associated with paging and location update events.

A mathematical model was developed, using an embedded Markov chain model, to analyze the signaling cost of a TAL-based scheme [8]. An algorithm for allocating TAL was developed, but the authors consider that a cell is associated with a unique TAL and each TA is composed of one cell [9]. This algorithm can not guarantee that a global optimum will be reached and may only produce local minima. A TAL design using rings of cells was proposed based on movement-based location registration [3]. In this case, when the optimal movement/distance threshold is high, a possible solution may have more TAs than the maximum allowed in a TAL. The effect of TAL design in reducing the signaling overhead was analyzed and it was proved that TAL scheme provides a minimum signaling overhead compared with the TA scheme [10].

Many researches have proposed new methods based on AI techniques in Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and LTE networks, like Tabu Search [11], Particle Swarm Optimization [12] and Genetic Algorithm [13]. These meta-heuristics algorithms area valuable to find out solutions of location management problems.

Several works have been carried out to investigate location management in 5G networks. Researchers have shown that the RRC Inactive state can improve latency, power efficiency and signaling overhead reduction, when compared to the LTE RRC Idle state [14], [15]. However, there is no strategy to find the optimal TA, TAL and RNA associations. A UE assisted dynamic RNA configuration scheme was proposed to effectively reduce the latency and minimize the total number of paging as well as the number of RNA update of inactive UEs [16]. A hybrid paging and a location tracking scheme for UEs in the RRC Inactive state was proposed in [5]. A significant reduction was achieved in signaling load due to the hierarchical location tracking and paging. However, the authors consider all UEs in the same mobility patterns and moving in a straight line trajectory. A pre-optimization step has been proposed, based on k-means to optimize TA and based on GA to optimize TAL [17], and a new strategy was devised to find optimal TALs based on a two-state framework [18]. Both works do not consider the new RRC Inactive state and, therefore, do not use all available features implemented in 5G to optimize the signaling.

III. LOCATION MANAGEMENT

One of the most relevant aspects of mobility in a cellular system is its ability to locate the UE. It is not a trivial task, because it can not be deduced by the network access point, such as in wired networks [19]. Mobile network functionalities related to location management are used to manage the information required to locate a UE.

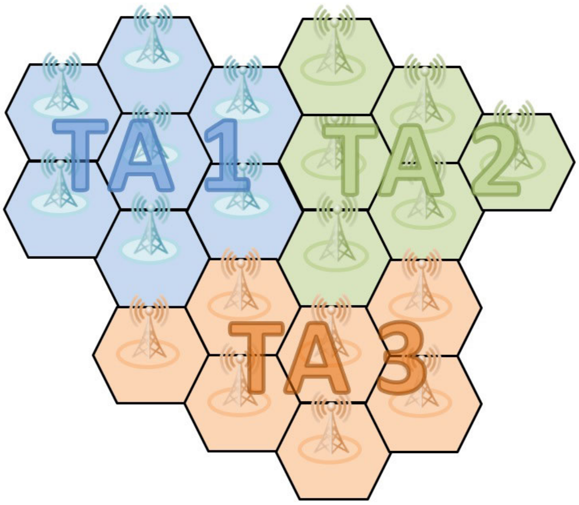

FIGURE 1. Cells in a cellular system with three tracking areas.

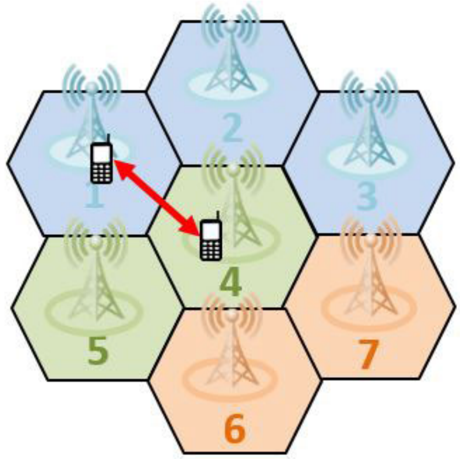

FIGURE 2. Ping-pong effect.

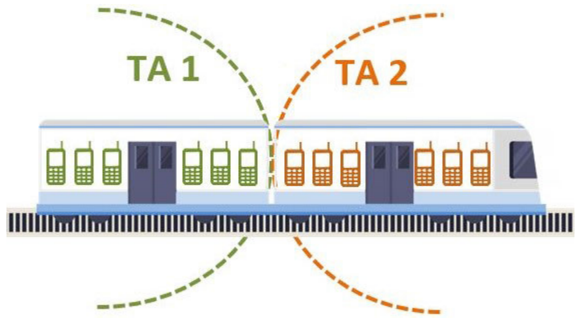

FIGURE 3. Unbalanced load distribution.

When the UE is in idle mode (no connection in progress) and there is a connection to be established between the network and the UE, the CN element sends paging messages to the RAN element to find where the UE currently resides. A large number of UEs can cause an excessive number of paging messages, which increases processor load in CN elements. This increase can cause congestion in the air interface, which drastically reduces the capacity of a network because it limits the call setup procedure.

To minimize these problems, the RAN is partitioned into TAs, which consist of a group of cells in which the UE may move without updating its location. Each time the UE performs a cell reselection procedure to camp on a new cell, the UE compares the Tracking Area Code (TAC) sent by the broadcast channel of the new cell with the TAC stored in its memory [10]. If the TAC is different, it means that the cell belongs to a different TA and then the UE must send a Tracking Area Update (TAU) to the network, keeping the consistency of its location in the CN. Figure 1 shows a typical network design with three TAs.

In addition to the impact on the CN elements, an excessive amount of TAU leads to congestion in Random Access Channel (RACH), which is used for other control operations (network registration, channel request), and this may result in congestion, handover failures and call dropping. The user experience is also affected, with a longer delay in the call establishment and an even larger battery power consumption. With the increasing number of machine to machine devices (M2M) and massive Internet of Things (IoT) devices, the number of RACH attempts must be reduced to avoid degradation in performance (delay, packet loss), especially when many devices attempt to access the network simultaneously. Therefore, an optimal TA design, that reduces overall signaling (both paging and TAU), is desirable.

The conventional use of TA scheme in some specific scenarios has several limitations. When a UE is located on the boundary of TAs and moves back and forth between two or more TAs, excessive signaling may be generated [20]. Figure 2 illustrates this effect, known as *ping-pong effect*, and it always exists when there are two neighboring TAs.

Another scenario that must be mitigated is the massive mobility signaling congestion. When this scenario occurs for a large number of UEs simultaneously, as in the case of many passengers on a train as illustrated in Figure 3, an excessive number of TAUs can cause signaling congestion in the border cells, affecting the quality of service not only for the involved cells but also creating signaling resource congestion in all cells belonging to the TA [21].

The Tracking Area List was introduced in 3GPP release 8 to solve the ping-pong problem, to mitigate the massive number of TAUs and to achieve better load balancing in TAs [22]. When using TAL in a location management scheme, the core element assigns a TA list instead of a single TA for each UE registered. Upon receiving the TA list, the UE stores all TAs in its memory. When the UE moves to a cell in which the new TA is unknown, it initiates the TAU procedure and the network provides a new list of TA to UE. The ping-pong problem can be easily avoided by including both neighboring TAs in a TAL [3].

Figure 4 presents a network with eight cells and two TALs with overlapped TAs. While camping in cell 4, the UE stores

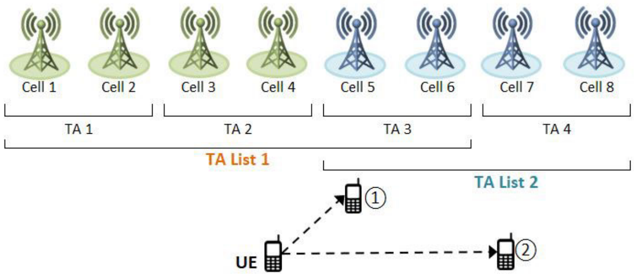

FIGURE 4. Example of a network with eight cells, four TAs and two TALs.

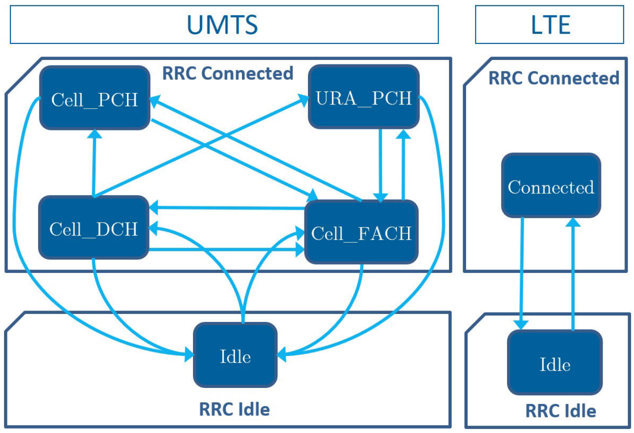

FIGURE 5. RRC states in UMTS and LTE networks.

the list TAL1 = {TA1, TA2, TA3} in its memory. Paging messages are sent to all cells belonging to TAL1 (cells 1 to 6) to find the UE. When moving to point 1, the UE checks whether the TA received from cell 5 is included in the TAL stored in the UE memory. Because TA3 is contained in TAL1, there is no action to be taken by UE. However, if the UE moves to point 2, the UE will not find TA4 in TAL1. Thus, the UE will perform a TAU procedure, informing the network about the registration in cell 7 and receiving the TAL2. It is important to note that users in the same cell coverage may have different lists of TA due to the possibility of overlapping the TA.

IV. RRC STATES ON 5G NETWORKS

The RRC offers a solution to handle system access, energy saving and mobility between the UE and the mobile network. The RRC operation is guided by a state machine that defines resources for each state that the UE is in. There are only two RRC Connection states in LTE networks, the RRC Idle and RRC Connected. There are not common and dedicated transport channels, such as in a UMTS networks, which have five states [23]. This simplification, as shown in Figure 5, improves the performance of using RRC.

The RRC Idle state is used for battery saving, network resource usage minimization and memory consumption for low activity UEs. This state supports Discontinuous Reception (DRX) activities, system information for access, cell reselection and paging information [24]. There is no RRC context established between the UE and the network in this state because the UE is not connected to a cell. Therefore, the exact location (granularity of a cell) of the UE is unknown, but the UE is known at the granularity of TA.

When the UE is in RRC Connected state, it is active and can receive and transmit user and control plane data [6]. Since there is an RRC context established, a minimum delay is required to start the transmission and the reception of data. In this state, the location of the UE is known to the granularity of a cell.

In RRC Idle state, the paging procedure is initiated by the core element by sending paging messages to all cells that are part of the TAL. Upon receiving the paging message, the UE changes to the RRC Connected state [24]. When the UE needs to transfer data, it initiates an RRC connection through signaling messages sent to the CN. The control plane latency is the required transition time from an idle state to an active connection state [25].

Because the UE needs to monitor the control channels frequently, and generate many signaling messages while in the RRC Connected state, it is expected that only when the UE has any data to send or receive it will be in this state. The state transition between RRC Idle and RRC Connected also requires system signaling to setup the context of the UE, introducing a delay in addition to extra messages. To satisfy the challenging latency requirements of 5G, 3GPP introduced a new RRC state, the RRC state machines were redesigned [24].

A. RRC INACTIVE STATE

For more efficient transitions and a reduced paging latency for the RRC Connected state, a new RRC Inactive state has been introduced for 5G networks [24]. It reduces the latency experienced by UEs and decreases the UE power consumption to a level similar to RRC Idle state. In the RRC Inactive state, the CN considers a connection established between the UE and the 5G RAN, maintaining the context of the UE active in the network [5]. The RRC Inactive state can be considered a combination of idle and connected states. The UE in this state is in standby mode, similar to the RRC Idle state.

Actual applications, like sensors, social network notification and VoIP applications, which use small data payload size, may have a higher battery consumption and signaling cost when establishing the connection (transition from idle to connected state) [26]. The RRC Inactive state allows the connection to be resumed quickly because the UE context is stored in the RAN network, not involving the CN in its retrieval. In this state, the UE is known by the CN, although the RAN elements must perform extra procedures to locate precisely the UE in RAN. This state avoids the additional signaling and delays involved in switching from an idle to a connected state.

A new pair of states, called CN Idle and CN Connected, related to UE connection with the CN, were also introduced for 5G [24]. The Access and Mobility Management Function

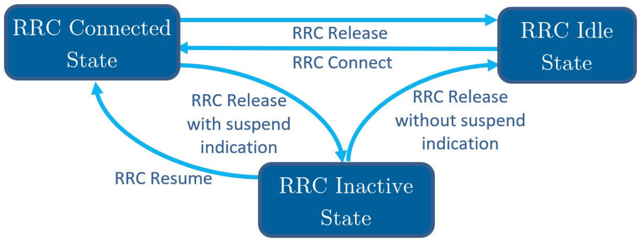

FIGURE 6. RRC state transitions [27].

(AMF), which is a CN function that supports registration and connection management, is not aware of which gNodeB the UE is camping on when the UE is in CN Idle state. To find the UE, the AMF initiates a default paging procedure in the last TA/TAL associated with the user. For a UE in CN Connected state, a context is stored in UE and in the AMF, making the UE in connected state from the CN perspective [6]. Figure 6 shows the state machine transitions for the 5G RRC.

The new RRC Inactive state provides a new approach to devices that require low latency communication and low power consumption simultaneously [26]. The connection is established between the UE and the RAN, but it is suspended (no transaction in progress), reducing the signaling and delay involved in switching from idle to connected.

B. RAN NOTIFICATION AREA

To minimize signaling and power consumption, the UE has to move from connected to inactive state. The last known gNodeB, which served the UE, keeps active the UE context and the connection with the AMF [28]. This gNodeB, called anchor gNodeB, stores the context of the UE when it is in the RRC Inactive state. To keep UE constantly traceable, the RAN is partitioned into smaller areas. These areas consist of groups of gNodeBs connected to each other via the Xn interface and it is called RAN-based Notification Area. An RNA can be associated with a cell, cell list, RNA list and a subset of TA [2].

The UE receives from the network an RNA list that indicates which RNAs a UE can move to without notifying the network, as illustrated in Figure 7. When a UE moves outside the RNA, the UE must perform an RNA update to allow the RAN to update its location. If a gNodeB other than the anchor gNodeB receives this update, it forwards the signaling message to an anchor gNodeB, which returns the RNA list and decides whether to keep the UE in the RRC Inactive state, changes to the RRC Connected or changes RRC Idle state. This RNA update procedure does not require additional signaling with the AMF because the context is already known by the network.

When a data packet is sent to the UE in RRC Inactive state, since the UE is connected from a CN perspective, the AMF forwards the data to the anchor gNodeB. The gNodeB buffers the packet and sends a RAN paging message to all gNodeB belonging to the RNA. When the UE answers the paging in a gNodeB other than the anchor gNodeB, the new gNodeB asks the anchor gNodeB to send both UE context and the buffered data. This retrieve procedure is performed only over Xn interface, not impacting CN elements.

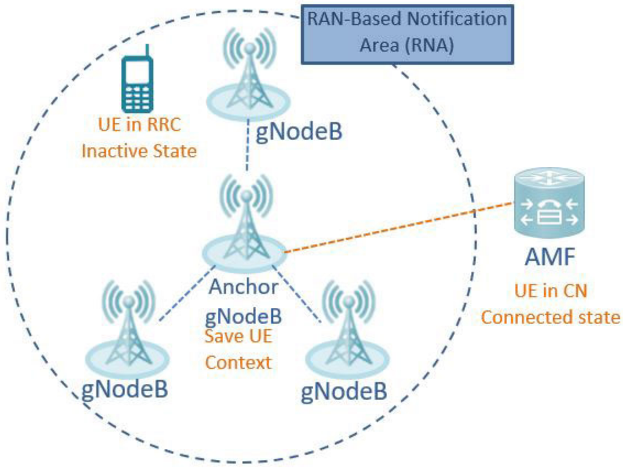

FIGURE 7. RAN-based notification area.

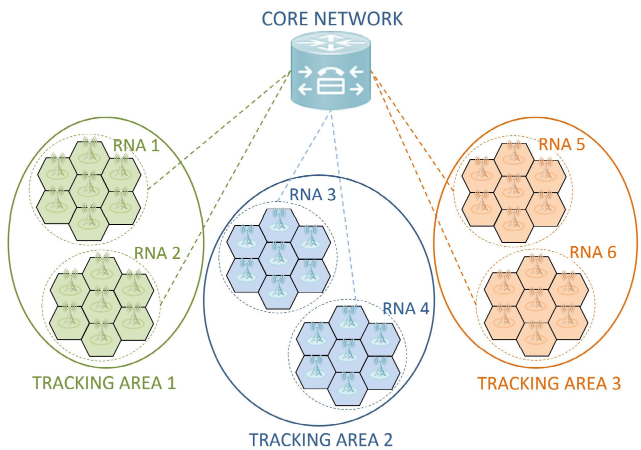

FIGURE 8. RNAs and tracking areas.

Thus, the UE will be tracked by the network depending on its RRC state. When a UE is in RRC Connected state, the UE is sending/receiving packets and, therefore, the CN knows exactly which gNodeb serves the UE. If the UE is in RRC Idle state, the CN only knows the TA that the UE last communicated. Therefore, it is necessary to send paging messages to all gNodeBs belonging to that TA. In case the UE is in RRC Inactive state, the CN knows the gNodeB the UE is in (anchor gNodeB). However, instead of RRC Connected state, the UE may move along the gNodeBs belonging to the same RNA of the anchor gNodeB. Thus, it is necessary to send paging for all gNodeBs belonging to the RNA to find the user. Figure 8 shows an example of a network with various TAs and RNAs.

Table 1 summarizes UE states characteristics related to location management such as UE location information and

TABLE 1. RRC states.

RRC State	UE Location	Location Update	Paging Trigger
Idle	TA Level	TA Update	CN Level
Inactive	RNA Level	RNA Update	RAN Level
Connected	Cell Level	Handover	Not Apply

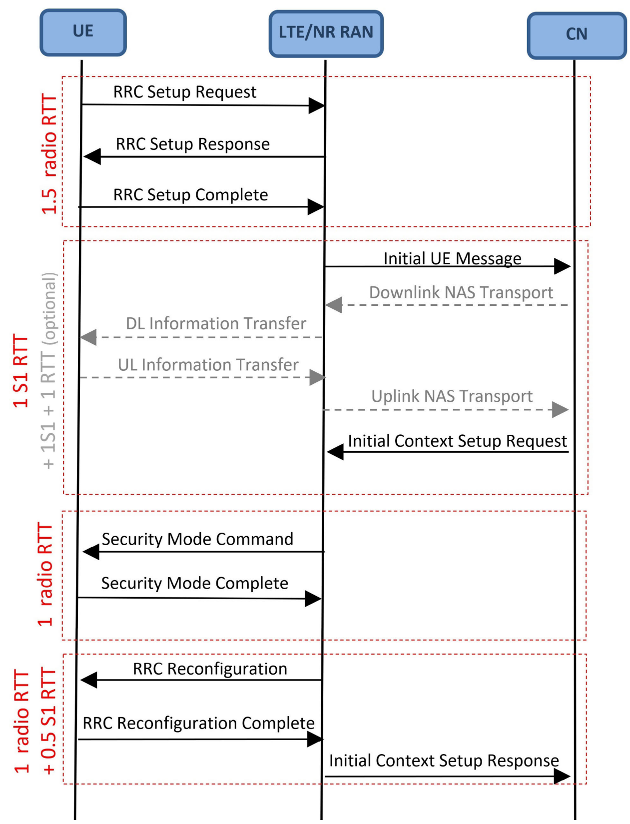

FIGURE 9. Transition from RRC Idle to RRC connected state.

which level location update and paging are triggered by in a 5G network.

C. RRC STATE TRANSITION

A UE must perform an RRC state transition to setup a connection, which is costly in terms of signaling overhead and latency. This transition comprises messages in NG interface, between CN and RAN, and in Uu interface, which is the interface between 5G UE and 5G RAN.

The signaling flow of an RRC transition from idle to connected state is shown in Figure 9 [24].

Considering a typical transition with no failure cases in radio access network (indicated by gray messages in Figure 9), there are three RRC setup messages, two Security messages and two RRC reconfiguration messages regarding RAN side. With respect to the CN, three messages are used for NG Application Protocol (NGAP). The delay D_I introduced by the Idle-Connected transition, not considering Random

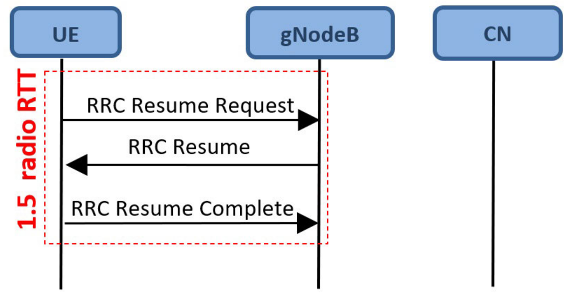

FIGURE 10. Transition from RRC inactive to RRC connected state in anchor gNodeB.

Access request, can be measured in terms of Round Trip Times (RTT) [29] given by

$$D_I = 3.5 \times \mathrm{R}_R + 1.5 \times \mathrm{R}_N, \tag{1}$$

in which R_R is the radio access RTT and R_N is the NG interface RTT.

The transition from the new RRC Inactive state to Connected state is described in Figure 10. When the transition occurs in the anchor gNodeB, the UE context is already available. Thus, no context fetch is required [15]. No NG (interface between RAN and CN in 5G) message is needed because there is a persistent CN/RAN connection. There are just three RRC messages for connection setup. The delay can be estimated as [29]

$$D_I = 1.5 \times \mathrm{R}_R. \tag{2}$$

If the transition occurs in a gNodeB different from the anchor gNodeB, there is a signaling overhead because the new gNodeB needs to fetch UE context from the anchor gNodeB, as shown in Figure 11. In this case, three extra messages in Xn interface and two NGAP messages are necessary. Thus, the estimated D_{I*} when the transition occurs in a new gNodeB is obtained by

$$D_{I*} = 1.5 \times \mathrm{R}_R + 1.5 \times \mathrm{R}_X + 1 \times \mathrm{R}_N, \tag{3}$$

in which R_X is the Xn interface RTT.

When the UE is in RRC Connected state, if there is no data transaction during a period defined by an inactivity timer and there is no pending data traffic in the user plane buffers, then the UE changes its state to RRC Inactive. The network sends an RRC release message with a suspend procedure to the UE to release the connection. Because the NG signaling between AMF and gNodeB remains active, this procedure does not affect the CN elements. Figure 12 shows the messages related to the transition from RRC Connected to RRC Inactive.

Table 2 summarizes the signaling overhead and latency related to these transitions.

V. SIGNALING COST

The location management procedures have a direct impact on the network performance. The performance metrics used to compute the total cost (C_T) related to mobility on a cellular

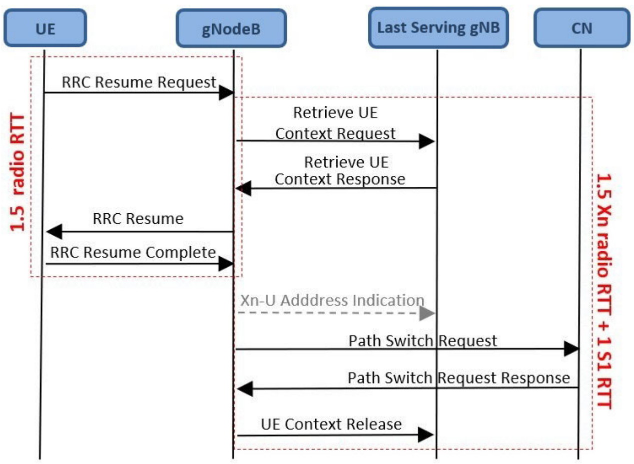

FIGURE 11. Transition from RRC inactive to RRC connected state in a new gNodeB.

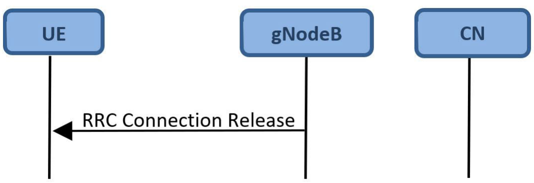

FIGURE 12. Transition from RRC connected to RRC inactive state.

TABLE 2. Signaling cost and latency.

Metric	IDLE→CONNECTED	INACTIVE→CONNECTED
Latency	$3.5\times R_R + 1.5\times R_N$	$1.5\times R_R$ $+(1.5\,R_X + 1\,R_N)$*
Signaling Over-head	7 RRC + 3 NG AP messages	3 RRC messages +(3 Xn + 2 NG messages)*

*When the transition occurs in a new gNodeB.

network are the number of updates performed and the number of paging sent. In [30] the total cost related to mobility is given by

$$C_T = R_1 \times N_L + N_P, \tag{4}$$

in which N_L is the number of updates, N_P is the number of paging messages on the network and R_1 is a constant that represents the ratio between the cost of an update and a paging transaction. The cost of each location update event is higher than that of a paging event due to the complex procedures performed during the update transaction. Usually, $R_1 = 10$ is used [30].

The UE reports its location change by triggering an update message to the gNodeB. The total update cost N_L is the sum of the number of TA updates (N_T) and RNA updates (N_R) that occur depending on the UE RRC state.

To calculate the TAU cost, the variable w_{ij} is defined as the number of users in RRC Idle state who leave cell coverage i and enter a new cell j. The number of TAU for a network with

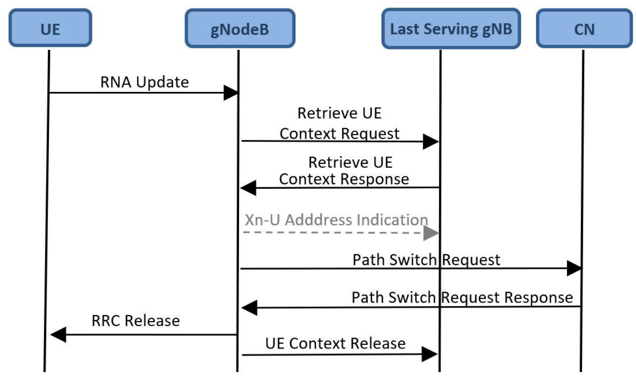

FIGURE 13. RNA update procedure with UE context relocation.

n cells can be calculated by

$$N_T = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\cdot u(i,j), \tag{5}$$

in which $u(i,j)$ is a function that returns 0 if the TA of cell i is the same TA of cell j and returns 1 otherwise.

When a UE is in RRC Inactive state and moves to other RNA, it triggers an RNAU message. Let $z_{i,j}$ be the number of users in RRC Inactive state who move from cell i to cell j. Then, the number of RNAU is

$$N_R = \sum_{i=1}^{n}\sum_{j=1}^{n} z_{ij}\cdot v(i,j), \tag{6}$$

in which $v(i,j)$ is a function that returns 0 if the RNA of cell i is the same RNA of cell j and returns 1 otherwise.

Unlike the RNA update, a TA update message triggered by the UE must reach the CN, making a TAU procedure more costly than an RNAU. According to [24] and illustrated in Figure 13, if a UE moves from the current RNA, it is necessary to perform path switch request in the CN. Hence, for sake of simplicity, everytime RNAU occurs for a UE moving to other RNA it will be computed as a TAU, replacing the RNAU procedure.

For an RNAU procedure, when a UE moves to a cell beloging to the actual RNA, a factor of R_2 is considered to represent the cost ratio between TAU and this RNAU procedure. Thus, the total number of updates N_L is given by

$$N_L = R_2 \cdot N_T + N_R. \tag{7}$$

The radio access network can initiate a paging in 5G when UE is in RRC Inactive or by the CN when UE is in the RRC Idle state. Similar to an update procedure, paging initiated by the RAN consumes fewer resources than that initiated by the CN and has a lower latency [2].

The number of paging b_i initiated by the CN performed in cell i is the sum of the pagings forwarded to this cell plus all pagings forwarded to other cells that belong to the same TA. In the same way, pagings t_i initiated by RAN in cell i are added to the number of pagings from other cells belonging to the same RNA.

The pagings forwarded from CN are costly, in terms of processor load and link usage, than the paging messages sent by RAN. Therefore, a ratio R_3 between CN paging and RNA paging costs are defined. The total number of paging can be calculated using

$$N_P = R_3 \cdot \sum_{i=1}^{n} b_i \cdot m_i + \sum_{i=1}^{n} t_i \cdot g_i, \quad (8)$$

in which m_i is the number of cells in the network that belongs to the same TA of the cell i and g_i is the number of cells that belong to the same RNA of the cell i.

The total cost of signaling for updates and paging messages is given by

$$C_T = R_1 \times R_2 \times \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \cdot u(i,j) + R_1 \times \sum_{i=1}^{n}\sum_{j=1}^{n} z_{ij} \cdot v(i,j)) + R_3 \times \sum_{i=1}^{n} b_i \cdot m_i + \sum_{i=1}^{n} t_i \cdot g_i, \quad (9)$$

VI. 5G NETWORK SIMULATION

A 5G network simulator was implemented in C++ to simulate fundamental aspects of a 5G network regarding location management. The system level simulation is focused on user mobility and traffic characteristics and produces EM and network data, based on user's inputs, instead of generating it randomly with no correlation [30]. The physical layer is abstracted to minimize the computational effort.

Events like cell reselections, RRC state transitions and data traffic are generated by the simulator based on user mobility, user traffic characteristics and network parameters, such as cell coverage area and RRC timers. The location management parameters, such as which cell belongs to RNA and TA, are not taken into account in the simulator.

Figure 14 shows a representation of the input and output of the simulator. The users' mobility and traffic profiles are inputs of the simulator. The simulator generates gNodeBs attributes, such as the number of received packets and the number of users crossing a cell. These metrics are used to evaluate the cost related to location management procedures in a 5G network.

A. USER MOBILITY

The users have an initial uniform distribution and move according to the Random Waypoint Model. This model is similar to the random walk model, in which user moves without direction, destination and velocity constraints, except the fact that the UE may pause when reaching the destination [31]. Each user has a random destination and a random velocity uniformly distributed between v_{min} and v_{max}. After arrival at the destination, the UE pauses for a uniformly distributed period between 0 and t_p. The speed of each UE is updated every time the UE updates its direction.

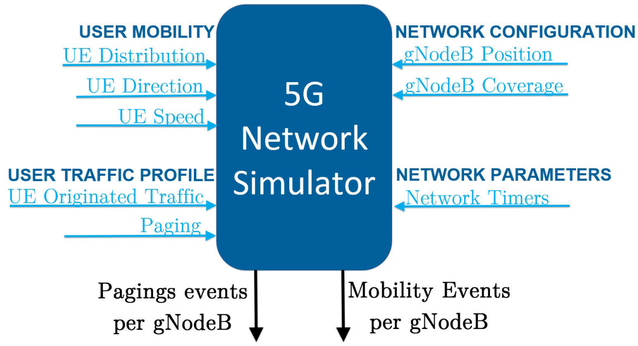

FIGURE 14. Simulator inputs and outputs.

B. USER PROFILE TRAFFIC

The traffic scenarios included in the simulator are Voice over IP (VoIP) and data download [32]. The VoIP periodically generates fixed size packets using codec G.729 (20 bytes for the packet payload at an inter-arrival time of 20 ms) following a Lognormal distribution, with an average duration of 180 seconds. Video streaming is considered for data download, such as YouTube, which recommends videos in 4k resolution and an average coding rate of 50 Mbps with a frame rate of 30 fps. Due to many always-on applications with bursty data transfer, a traffic FTP model 2 based on [33] is also used.

C. NETWORK CONFIGURATION

The gNodeBs are placed in the simulated enviroment according to a homogeneous Poisson Point Process [34] in a square region of 10 km^2. For simplicity, the cell coverage area is obtained from the application of Voronoi tessellation [35]. This method, which uses gNodeB coordinates as generating points for the tessellation, enables the simulation to register the UE in a specific gNodeB. Thus, the coverage area for each cell is delimited without taking into account the propagation phenomena.

D. NETWORK PARAMETERS

When a UE in RRC Idle state transmits or receives data, it must transit to the RRC Connected state. After the transmission occurs, if no activity is detected in uplink and downlink, then the UE initiates an inactive timer, which indicates the time remaining before the UE changes to RRC Inactive state. If the UE remains inactive until an idle timer expires, then the UE changes to RRC Idle state. The Idle and Inactive timers used in this simulation are the same for all users.

E. SIMULATION OUTPUT

The movements and state transitions generated by each user are logged for three hours. Only the last hour is taken into account, ensuring that the network is in steady-state [8]. These steps are replicated ten times and the average values are used. The simulation traces, containing UE RRC state and pair of cells (source and target) involved in reselections,

TABLE 3. Network attributes from the simulator.

Cell	Pagings	Transition 1 $Neigh_1 \leftarrow Cell$	Transition 2 $Neigh_2 \leftarrow Cell$	$\cdots$	Transition v $Neigh_n \leftarrow Cell$
1	$\#pagings_1$	$\#move\_c_1v_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_1v_v$
2	$\#pagings_2$	$\#move\_c_2v_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_2v_v$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
n	$\#pagings_n$	$\#move\_c_nv_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_nv_v$
1	$\#pagings_1$	$\#move\_c_1v_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_1v_v$
2	$\#pagings_2$	$\#move\_c_2v_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_2v_v$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
n	$\#pagings_n$	$\#move\_c_nv_1$	$\#move\_c_1v_2$	$\cdots$	$\#move\_c_nv_v$

are grouped by RRC state, source and target gNodeB. The simulation output example is shown in Table 3, where the simulation attributes are the table fields. Depending on TA, TAL and RNA associations for each cell, different costs will be obtained. The aim is to obtain an optimum cell-to-TA, cell-to-RNA and TA-to-TAL assignments that minimize the signaling cost in a 5G network.

VII. NETWORK OPTIMIZER BASED ON GENETIC ALGORITHM

The optimal design of TAL, TA and RNA is a critical performance factor in designing a mobile network. Therefore, a strategy must be used to find the optimal network configuration that minimizes the location management cost. One possible way to achieve this is to enumerate all possible combinations, transforming the location management optimization into a combinatorial problem. Many algorithms have been proposed to solve the location management problems for older mobile technology. In particular, GSM and UMTS networks have been extensively studied and it is well-known that AI can find optimal or near-optimal solutions to reduce signaling costs [36]. LTE networks introduced the concept of list of TA, but the literature simplifies the usage of TAL, imposing restrictions like considering a TA of the size of a cell [37].

A. GENETIC ALGORITHM OVERVIEW

A GA is an AI technique based on natural selection mechanisms and genetics [38]. According to Darwin's theory of evolution, individuals with inheritable characteristics, which enable them to adapt to their enviroment, will tend to leave more offsprings than their peers. The population has an increased chance of surviving by eliminating weaker individuals over time. Genetic information is passed from generation to generation, allowing the gene to succeed.

The concept of change in heritable characteristics, called evolution, is applied in GA to find a solution to a specific problem using a data structure similar to a chromosome and applying operators that recombine those structures while preserving valuable information [39]. In GA, each candidate solution is an individual in a population and produces, in each generation, a fixed number of new individuals who can be more able to adapt to changing demands. Initially, a random population of individuals is generated. This population is evaluated and, for each individual, the objective function is assigned according to the ability to adapt to a given environment. Then, some individuals are discarded and others are selected to mutate and produce offspring. This process is repeated until a predefined stopping criterion is met. In each iteration, the algorithm creates a new generation that has a population of new individuals. A fitness function is used to rank individuals in the population. The algorithm iteratively creates a new and improved generation and returns the fittest individual, which is the best solution.

TABLE 4. RANAC and TAC association with gNodeB.

TAC			RANAC		
gNodeB 1	$\cdots$	gNodeB n	gNodeB 1	$\cdots$	gNodeB n
TA_1		TA_n	RNA_1		RNA_n

TABLE 5. TA assigned to TAL.

Tracking Area List 1			$\cdots$	Tracking Area List m		
TA 1	$\cdots$	TA *n*	$\cdots$	TA 1	$\cdots$	TA *n*
$TA_{1,1}$	$\cdots$	$TA_{1,n}$	$\cdots$	$TA_{m,1}$	$\cdots$	$TA_{m,n}$

B. CODIFICATION

For a network with n cells, each candidate solution has a set of characteristics (chromosome) represented by a set of genes. Each gene uses an integer based representation to encode TA, RNA and TAL information.

Each gNodeB is associated with TAC and RAN Area Code (RANAC), which are broadcasted in the system information for all UEs. The first n genes are used for TAC, represented by an integer number. The possible values of the TA may vary from 1 (when there is only one TA in network) to n (when each cell has a unique TA). The next n genes are related to the gNodeB association with the RANAC. Table 4 shows this representation.

For the list of TAs, an association of TAL x TA has to be considered. Let m represent TALs, $n \times m$ genes are added to the chromosome. Each TAL value has n fields, which can be 0 (TA not in the list) or 1 (TA is in the list), as shown in Table 5. The chromosome is considered valid only if all the TAs used by the cells are represented in at least one TAL. Otherwise, the operation that produces this modification is repeated, until a feasible chromosome is obtained. This approach presents better performance than penalizing the invalid results.

Thus, the total size of the chromosome is $2n+n\times m$. Table 6 shows the representation of the chromosome with respect to genes division for TA, RNA and TAL.

TABLE 6. Chromosome representation.

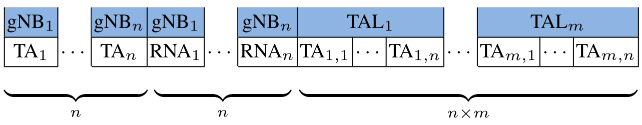

TABLE 7. Parameter settings of genetic algorithm.

Parameter	Specification
Population Size	40
Crossover Type	Multipoint
Crossover Probability of TA	0.9
Crossover Probability of RNA	0.9
Crossover Probability of TAL	0.2
Mutation Probability of TA	3%
Mutation Probability of RNA	3%
Mutation Probability of TAL	1%
Population Recombination	Elitism Selection
Selection Technique	Tournament
Stop Condition (generations)	300

TABLE 8. Location scheme by technology.

Technology	Location Scheme
3G (UMTS)	Tracking Area
4G (LTE)	Tracking Area List
5G (IMT-2020)	Radio Notification Area

Since the quality of the solution depends on the choice of GA parameters, an investigation of the parameters' variation is made to find the ones that better suit the particular problem. For each scenario and set of GA parameters, a number of 100 independent runs are performed. The algorithm stops when no improvement has been produced after 300 iterations.

The parameters used by the GA, obtained by experimentation, are listed in Table 7.

VIII. RESULTS

This section presents the performance of location management procedures in 5G networks using the new RRC Inactive state introduced by 3GPP. All statistical data related to the user traffic, mobility profile and network cell topology were obtained by simulation, as described in Section VI.

A. LOCATION MANAGEMENT SCHEME COMPARISON

Different experiments were conducted with three strategies of location management commonly used in a cellular mobile system. In the first case, the strategy with a TA (typical solution for 2G and 3G mobile generation networks) was adopted, in which a UE is associated with a single TA. In the second case, the location management scheme associates a TAL with a UE (solution introduced on LTE networks). In the last case RNA was introduced in addition to TA and TAL scheme. The UE may change to RRC Inactive state, in which the UE is associated with an RNA. Table 8 shows the location management schemes for mobile phone standards.

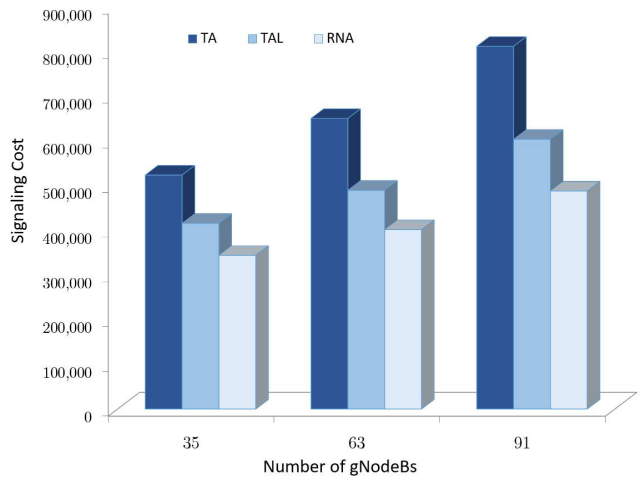

FIGURE 15. Signaling cost for different size networks.

The optimal TA, TAL and RNA design, which results in an optimized network regarding signaling costs, is obtained by the methodology described in Section VI. This work considers $R_1 = 10$ for the ratio between update and paging transactions in RRC Idle state, which is the value used in many studies [30], [40]. Using Table 2, the values for the cost ratio between a TA update and RNA update and between CN and RNA paging were estimated heuristically as $R_2 = 8$ and $R_3 = 6$, respectively. To decrease the complexity of the simulation, it is considered that every gNodeB has the same inactivity timers. When the time expires, the network initiates a procedure to place the UE in the RRC Inactive state by sending RRC suspend request message to gNodeB [29].

Figure 15 shows the signaling cost for a 5G network with 10,000 users and various networks with different numbers of cells. A higher cell density increases the number of users crossing the cells, leading to a higher number of cell reselections. The use of the RNA scheme reduces the signaling cost compared to TA scheme by 36.0% and 16.1% in average compared to TAL scheme.

For networks with 63 cells, the impact of an increase in the number of users is illustrated in Figure 16. The signaling cost increases as the number of users grows. A larger number of users will increase the number of location update events and will also produce more paging messages. The use of the RNA scheme allowed an average decrease of almost 40.0% in the signaling cost, compared to the TA scheme and an improvement of 18.5%, on average, compared to the TAL scheme.

Figure 17 illustrates the signaling cost for three scenarios with average velocity of the UE (3 km/h for pedestrians, 60 km/h for vehicular and 120 km/h for high speed). A network is considered with a fixed number of 63 cells and 10,000 users. An increment in user mobility increases the network signaling cost, because a user in movement is subject to additional location updates. Again, a decrease in signaling cost was found. The RNA scheme has an average decrease

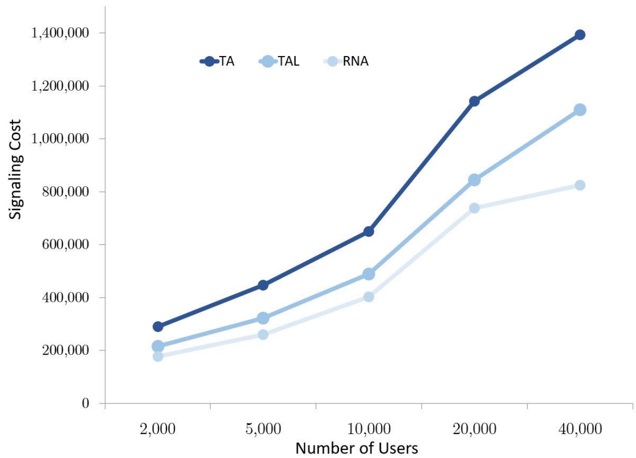

FIGURE 16. Effect of the number of users on the signaling cost.

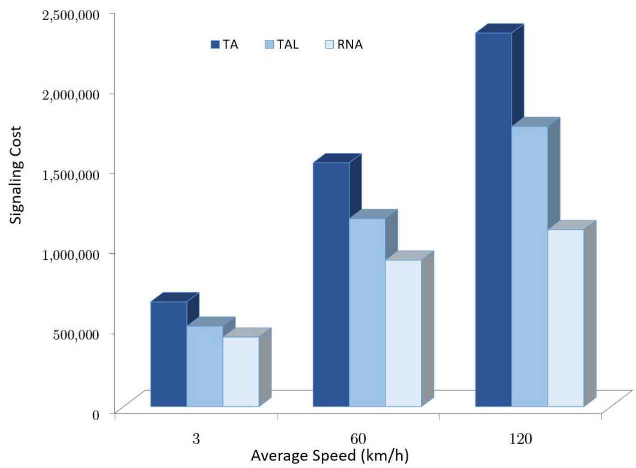

FIGURE 17. Effect of user mobility on signaling cost.

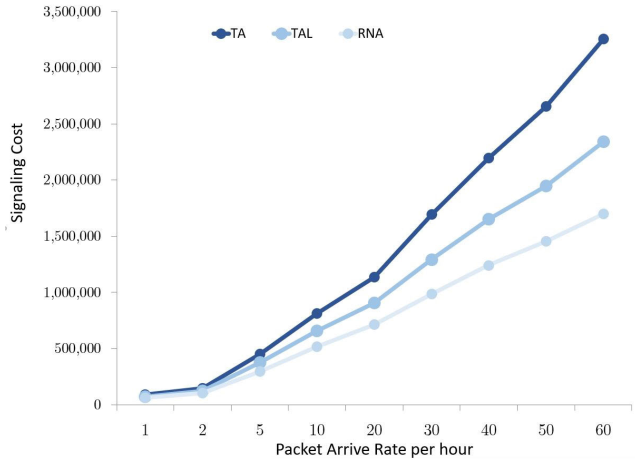

FIGURE 18. Effect of packet arrival rate signaling cost.

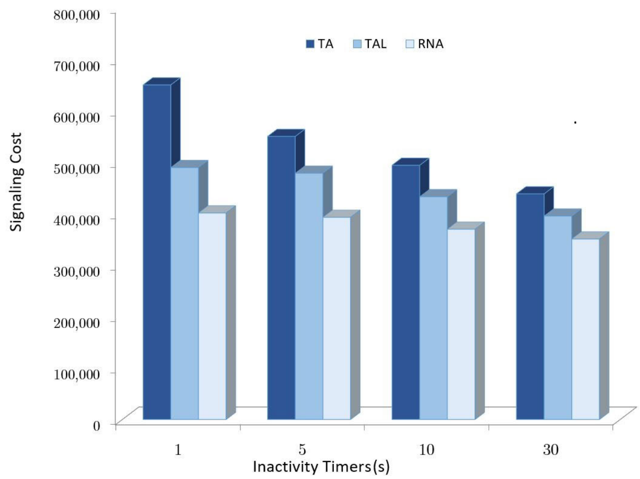

FIGURE 19. Signaling cost for different inactivity timers.

of 42.1% compared to TA scheme and 24.2% compared to TAL scheme.

If smartphone applications, like Facebook and Instagram, begin to transmit small packets more frequently, for example in notifications messages, there will be more transitions to RRC Connected state in addition to more pagings. Figure 18 shows the impact of packet arrival rate per hour on location management cost. RNA schemes decrease the signaling cost in average by 21.6% compared to TAL scheme and by 32.0% compared to TA scheme.

In 5G networks, pagings may be initiated by the CN (as in previous generations of networks) or by the radio access network, depending on RRC state of the UE. The RRC state depends on how long the UE stays in RRC connected state after it transmits/receives the last packet. The inactivity timer is used to manage the transitions between states and it is responsible for a trade-off between signaling cost and latency. For a short inactivity timer value, battery life is extended. However, if a packet arrives and the UE is in RRC Idle state, more signaling and a longer latency are necessary to page the user and wait for its response, causing an extra latency. With a long inactivity time, the UE stays more time in the RRC connected state, decreasing the number of TAUs and RNAUs (replaced by handover procedure) and avoiding paging because the network already knows the UE. Figure 19 shows the signaling cost for a network with 63 cells and 10,000 users with different inactivity timer values. It is noticed that when the inactivity timer increases, the signaling cost difference between the location management schemes decreases because the UE spends more time in RRC connected state.

B. 5G LOCATION MANAGEMENT PERFORMANCE

The new RRC Inactive state, in addition to the RNA scheme, aims to reduce signaling cost while extends UE battery life. The location management procedures are triggered according to RRC state. When a UE is in RRC Idle state, the CN needs to page the UE if a new packet arrives. In case a UE crosses a TA, it must update the CN with its location. Similarly, when a UE is in RRC Inactive state, the RAN is responsible to send pagings and the RNA must be updated when the UE moves to a new cell belonging to another RNA. Figure 20 shows the amount of location management events (pagings and updates) separated by TA and RNA events for a network with 63 cells and 10,000 users. The optimal network configuration, found by the GA, presents more pagings events

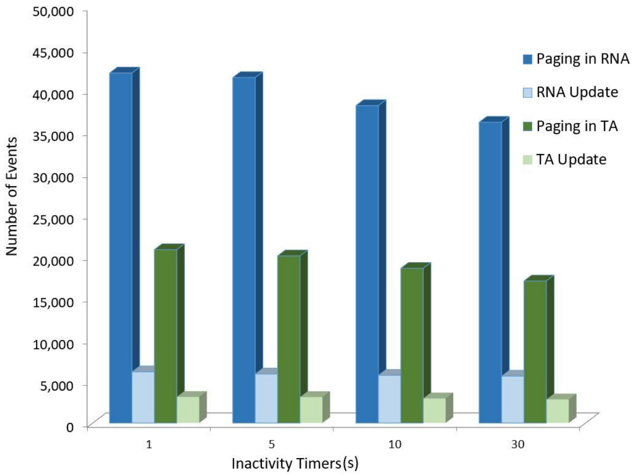

FIGURE 20. Number of LM events per inactivity timer.

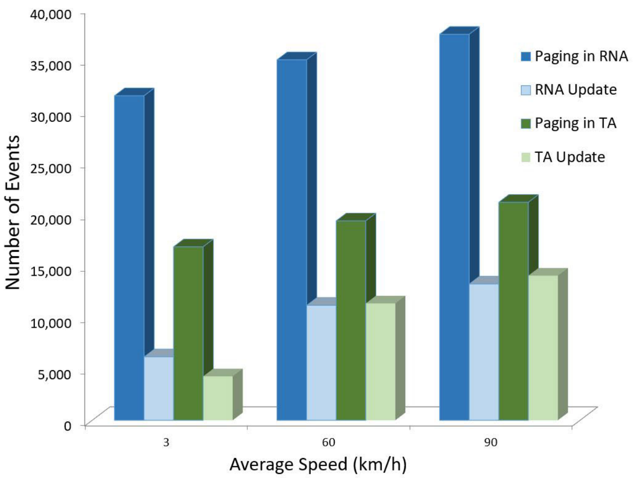

FIGURE 21. Number of LM events per speed.

(both in TA and RNA scenario) than updates. It happens because the algorithm knows that TAUs and RNAUs are more costly than paging and the projected network takes this into account.

Figure 21 shows the location management events for a network with 63 cells and 10,000 users. In this case, the events are calculated based on a network with different UE's average speed. Also in this case, the algorithm provides a network with focus on TAUs and RNAUs.

IX. CONCLUSION

In this work, the new location management scheme introduced in 5G network, RRC Inactive state, was analysed. In order to support the increase in the number of RRC state transitions due to small packets expected in emerging applications for 5G networks, a new RRC Inactive state and a RAN notification area were introduced by 3GPP. The new features of location management in 5G networks were presented as well as the mathematical model of signaling costs in terms of location update and paging messages. To investigate the benefits of this new scheme, a system-level simulation was developed to implement a 5G mobile network and generate typical user data. Then, a new framework using a GA and the simulation data were presented. The objective is to find an optimal network design with respect to signaling costs due to location management procedures.

After conducting simulation experiments, the performance of the new location management scheme was analyzed against the legacy scheme. The schemes used in previous generation networks were not designed to support such a large number of devices in a network with dense cell coverage. Results obtained show that the RRC Inactive state saves more than 30% of signaling cost compared to schemes adopted in other systems. The cost of location management is reduced when the RNA scheme is used, especially in scenarios that use more resources from 5G networks (greater number of users, greater cell density and greater mobility). Isolated events in 5G networks are also presented, indicating that more RAN events than in CN are useful to reduce overall signaling cost. With the new scheme adopted in 5G, it was possible to reduce the cost of the network in all investigated scenarios.

As future work, a multi-objective algorithm can be used to treat other metrics (like latency and speed), in addition to signaling costs of location management events.

REFERENCES

[1] E. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*. New York, NY, USA: Academic, 2018.

[2] A. A. R. Alsaeedy and E. K. P. Chong, "Tracking area update and paging in 5G networks: A survey of problems and solutions," *Mobile Netw. Appl.*, vol. 24, no. 2, pp. 578–595, Apr. 2019.

[3] Y. W. Chung, "Adaptive design of tracking area list in LTE," in *Proc. 8th Int. Conf. Wireless Opt. Commun. Netw.*, May 2011, pp. 1–5.

[4] A. Osseiran, J. F. Monserrat, and P. Marsch, *5G Mobile and Wireless Communications Technology*, 1st ed. New York, NY, USA: Cambridge Univ. Press, 2016.

[5] S. Hailu and M. Saily, "Hybrid paging and location tracking scheme for inactive 5G UEs," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2017, pp. 1–6.

[6] P. Marsch, O. Bulakci, O. Queseth, and M. Boldi, *5G System Design: Architectural and Functional Considerations and Long Term Research*, 1st ed. Hoboken, NJ, USA: Wiley, 2018.

[7] T. Deng, X. Wang, P. Fan, and K. Li, "Modeling and performance analysis of a tracking-area-list-based location management scheme in LTE networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6417–6431, Aug. 2016.

[8] X. Wang, X. Lei, R. Q. Hu, and Y. Qian, "Modeling of tracking area list-based location update scheme in long term evolution," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 2325–2331.

[9] S. M. Razavi, D. Yuan, F. Gunnarsson, and J. Moe, "Exploiting tracking area list for improving signaling overhead in LTE," in *Proc. IEEE Veh. Technol. Conf.*, May 2010, pp. 1–5.

[10] L. O. Widaa and S. M. Sharif, "Effect of tracking area list overlapping in reducing overall signaling overhead in long term evolution system," in *Proc. Int. Conf. Comput., Control, Netw., Electron. Embedded Syst. Eng. (ICCNEEE)*, Sep. 2015, pp. 397–400.

[11] H. Safa and N. Ahmad, "Tabu search based approach to solve the TAs reconfiguration problem in LTE networks," in *Proc. IEEE 29th Int. Conf. Adv. Inf. Netw. Appl.*, Mar. 2015, pp. 593–599.

[12] L. Wang and G. Si, "Optimal location management in mobile computing with hybrid genetic algorithm and particle swarm optimization (GA-PSO)," in *Proc. 17th IEEE Int. Conf. Electron., Circuits Syst.*, Dec. 2010, pp. 1160–1163.

[13] S. Modarres Razavi, D. Yuan, F. Gunnarsson, and J. Moe, "Performance and cost trade-off in tracking area reconfiguration: A Pareto-optimization approach," *Comput. Netw.*, vol. 56, no. 1, pp. 157–168, Jan. 2012.

[14] A. Khlass, D. Laselva, and R. Jarvela, "On the flexible and performance-enhanced radio resource control for 5G NR networks," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–6.
[15] S. Hailu, M. Saily, and O. Tirkkonen, "RRC state handling for 5G," *IEEE Commun. Mag.*, vol. 57, no. 1, pp. 106–113, Jan. 2019.
[16] X. Huang, C. Cao, X. Fan, and Q. Chen, "User assisted dynamic RAN notification area configuration scheme based on delay sensitivity for 5G inactive UEs," *IEEE Trans. Veh. Technol.*, vol. 69, no. 3, pp. 2671–2683, Mar. 2020.
[17] J. Moysen and M. García-Lozano, "Learning-based tracking area list management in 4G and 5G networks," *IEEE Trans. Mobile Comput.*, vol. 19, no. 8, pp. 1862–1878, Aug. 2020.
[18] M. Bagaa, T. Taleb, and A. Ksentini, "Efficient tracking area management framework for 5G networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 4117–4131, Jun. 2016.
[19] P. S. Bhattacharjee, D. Saha, and A. Mukherjee, "An approach for location area planning in a personal communication services network (PCSN)," *IEEE Trans. Wireless Commun.*, vol. 3, no. 4, pp. 1176–1187, Jul. 2004.
[20] L. Chen, H.-L. Liu, Z. Fan, S. Xie, and E. D. Goodman, "Modeling the tracking area planning problem using an evolutionary multi-objective algorithm," *IEEE Comput. Intell. Mag.*, vol. 12, no. 1, pp. 29–41, Feb. 2017.
[21] S. Modarres Razavi and D. Yuan, "Mitigating mobility signaling congestion in LTE by overlapping tracking area lists," in *Proc. 14th ACM Int. Conf. Modeling, Anal. Simulation Wireless Mobile Syst. (MSWiM)*, 2011, pp. 285–292.
[22] S.-T. Sheu, C.-L. Lin, and J. Chen, "Reducing signaling cost of location management in cellular network using fuzzy logic controller," in *Proc. 11th Int. Conf. Wireless Commun., Netw. Mobile Comput. (WiCOM)*, 2015, pp. 1–8.
[23] J. Puttonen, E. Virtej, I. Keskitalo, and E. Malkamaki, "On LTE performance trade-off between connected and idle states with always-on type applications," in *Proc. IEEE 23rd Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2012, pp. 981–985.
[24] *NR; NR and NG-RAN Overall Description; Stage 2*, document (TS) 38.300, 3GPP, Oct. 2020.
[25] *Study on Scenarios and Requirements for Next Generation Access Technologies*, document TR 38.913, Rel. 16, 3GPP, Jul. 2020.
[26] M. Enescu, *5G New Radio: A Beam-based Air Interface*. Hoboken, NJ, USA: Wiley, 2020.
[27] *NR; Radio Resource Control (RRC); Protocol Specification*, document (TS) 38.331, 3GPP, Mar. 2021. Version 16.4.1.
[28] A. A. R. Alsaeedy and E. K. P. Chong, "Mobility management for 5G IoT devices: Improving power consumption with lightweight signaling overhead," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8237–8247, Oct. 2019.
[29] I. L. Da Silva, G. Mildh, M. Saily, and S. Hailu, "A novel state model for 5G radio access networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, May 2016, pp. 632–637.
[30] J. Taheri and A. Y. Zomaya, "A genetic algorithm for finding optimal location area configurations for mobility management," in *Proc. IEEE Conf. Local Comput. Netw. 30th Anniversary (LCN)l*, 2005, pp. 577–585.
[31] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Commun. Mobile Comput.*, vol. 2, no. 5, pp. 483–502, Sep. 2002.
[32] J. Navarro-Ortiz, P. Romero-Diaz, S. Sendra, P. Ameigeiras, J. J. Ramos-Munoz, and J. M. Lopez-Soler, "A survey on 5G usage scenarios and traffic models," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 905–929, 2020.
[33] *Further Advancements for E-UTRA Physical Layer Aspects*, document TR 36.814, version 9.2.0. Rel. 9, 3GPP, Mar. 2017.
[34] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, "Stochastic geometry and random graphs for the analysis and design of wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 7, pp. 1029–1046, Sep. 2012.
[35] J. N. Portela and M. S. Alencar, "Cellular network as a multiplicatively weighted Voronoi diagram," in *Proc. 3rd IEEE Consum. Commun. Netw. Conf.*, vol. 2, Jan. 2006, pp. 913–917.
[36] S. R. Parija, P. K. Sahu, and S. S. Singh, "Evolutionary algorithm for cost reduction in cellular network," in *Proc. Annual IEEE India Conf. (INDICON)*, Dec. 2014, pp. 1–6.
[37] L. Chen, H.-L. Liu, Z. Fan, S. Xie, and E. D. Goodman, "Modeling the tracking area planning problem using an evolutionary multi-objective algorithm," *IEEE Comput. Intell. Mag.*, vol. 12, no. 1, pp. 29–41, Feb. 2017.
[38] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA, USA: Addison-Wesley, 1989.
[39] M. Mitchell, *An Introduction to Genetic Algorithms*. Cambridge, MA, USA: MIT Press, 1998.
[40] R. Subrata and A. Y. Zomaya, "A comparison of three artificial life techniques for reporting cell planning in mobile computing," *IEEE Trans. Parallel Distrib. Syst.*, vol. 14, no. 2, pp. 142–153, Feb. 2003.

LIDIANO A. N. OLIVEIRA was born in Campina Grande, Paraiba, Brazil. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Federal University of Paraiba, Brazil, in 1998 and 2000, respectively, and the D.Sc. degree in electrical engineering from the Federal University of Campina Grande, Campina Grande, Brazil, in 2021. His research interests include mobile networks, computational intelligence, and network simulation.

MARCELO S. ALENCAR (Senior Member, IEEE) received the bachelor's degree in electrical engineering from the Federal University of Pernambuco (UFPE), Brazil, the master's degree in electrical engineering from the Federal University of Paraiba (UFPB), Brazil, and the Ph.D. degree from the University of Waterloo, Canada. He was at the Federal University of Paraiba (UFPB), the State University of Santa Catarina (UDESC), and the Federal University of Bahia, Brazil. Currently, he has been with the Senai Cimatec, Salvador, Brazil, and Federal University of Campina Grande, Brazil. He is the Founder and the President of the Institute for Advanced Studies in Communications (Iecom). He has published 26 books and over 450 papers. He received the Achievement Awards from the Brazilian Telecommunications Society (SBrT), from the Medicine College of Federal University of Campina Grande (UFCG), and from the College of Engineering of Federal University of Pernambuco (UFPE).

WASLON T. A. LOPES (Senior Member, IEEE) was born in Petrolina, Pernambuco, Brazil. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Federal University of Paraiba, Brazil, in 1998 and 1999, respectively, and the D.Sc. degree in electrical engineering from the Federal University of Campina Grande, Brazil, in 2003. He was at the AREA1 College of Science and Technology, Salvador, Brazil, from August 2003 to December 2009. From November 2018 to October 2019, he was a Visiting Professor at the University of Toronto, Canada. Currently, he is with the Department of Electrical Engineering, Federal University of Paraiba, Brazil. His research interests include robust vector quantization, wireless communication systems, communication theory, and digital signal processing.

FRANCISCO MADEIRO received the D.Sc. degree in electrical engineering from the Federal University of Paraiba, Brazil, in 2001. Since 2006, he has been with the University of Pernambuco (UPE), Brazil, where he is currently an Associate Professor. His main research interests include signal processing, communication systems, and computational intelligence. He was a recipient of the Distinguished Award in Teaching at Polytechnic School of Pernambuco (POLI), UPE, in 2008 and 2013, and the Distinguished Award in Research at POLI, in 2013 and 2018.