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Designing an energy efficient UAV tracking algorithm

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Abstract—In this paper, we present a solution for Unmanned Aerial Vehicle (UAV) energy saving problem while ensuring a continuous tracking of a mobile target. Our tracking algorithm is based on three zones, and according to the target placement in those zones, the UAV will do a specific type of actions. We proposed an additional zone called the authorized zone. In this zone, the UAV keeps a fixed velocity and a fixed altitude, and this contributes to the limitation of the energy consumption while also maintaining a minimal altitude. We also proposed an adapted criterion which considers the velocity, altitude and acceleration changes to evaluate the energy consumption. The idea here is to limit the number of the UAV adjustments to reduce the energy consumption and still keeping the target in its camera field of view.

Keywords: Unmanned Aerial Vehicle (UAV), mobile target, tracking, camera field of view, energy consumption.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are increasingly used in civil applications after being used in military applications. Examples of civil applications are entertainment, environment, agriculture, and disaster management [1].

In this paper, we focus on a challenging issue that is receiving more attention than ever: Mobile target tracking. The challenges of such mission is the transmission of target images in real time, tracking correctly the target, and saving the UAV energy. Visual tracking is applied in many situations, such as search and rescue missions [2], and cars tracking to monitor the vehicular traffic [3].

In the tracking process there is two phases. The first phase of this process is the transient phase, and it is identified by the UAV taking off and starts localizing the mobile target. When the first phase is accomplished, the UAV start doing adjustments to keep the target in its field of view, this second phase is called the steady phase. Several tracking approaches considered both transient and steady phases. In [4], multiple UAVs are collaborating to localize a single target and track it. In the transient phase, the UAV localizes as fast as possible the target. While in the steady phase, the UAV tries to keep the target in its center of view, by updating its position based on the previous one and on the two last target positions errors. In [5], both phases were also considered. In the transient phase, the UAV reaches a desired altitude using a certain strategy. For the steady phase a strategy was developed as well. This

strategy aims to keep the target in the UAV field of view center, so either the UAV aligns its position with the target position or increases its altitude to get a better view of the scene. There are already many contributions done in the transient phase. For instance, minimizing the duration of this phase and minimizing the energy consumption. While for the steady phase the energy efficiency problem was almost not addressed. That is why we consider only the steady phase, we assume that initially the target is in the field of view of the UAV, indeed we do not consider the takeoff and the landing phases. Trying to keep the target exactly in the center of the field of view with no authorized space where the target still can be tracked correctly can cause two limitations: unnecessary adjustments, leading to additional needless energy consumption and limiting the possibility to track multiple targets.

In [6], a fixed wings UAV is tracking a target by doing circular movements. The objective is to generate an optimal path for the UAV when it is tracking a stationary target or when the target velocity is lower than the minimum velocity of the UAV. We do not deal with those two scenarios as we choose to work with a rotary wings UAV with less operational and physical constraints.

In tracking applications, there is also the coverage issue. With a single target this problem is not raised, but with multiple targets same solutions assume a continuous coverage of the tracking area. In [7], multiple UAVs cooperate to track multiple targets. So a strategy was developed to enable each UAV to track a group of target with an optimal pose and to generate conflict-free paths for all UAVs. In [8], several UAVs track several targets. The goal is to save energy while ensuring a continuous coverage. During the tracking only the altitude is adapted and kept as low as possible. However, there is a need to optimize the number of drones while keeping a continuous coverage. Ensuring a continuous coverage is questionable, especially for low targets density, and it raises the problem of UAV placement and replacement.

Ensuring a correct and a stable tacking, i.e., the targets are in the field of view (FoV) of the UAVs cameras, is not the only issue. The issue of UAV energy consumption must be addressed as well. Because this problem is very complex, we start dealing with a single UAV tracking a single mobile target.

The main contribution of this paper is the proposal of a

tracking algorithm for a single UAV and a single mobile target. In this algorithm we define three zones, and according to the position of the target in those zones, the UAV does different types of adjustments and less frequently, allowing to reduce the consumed energy.

The rest of the paper is organized as follows. Section II develops our tracking approach. In section III, we present our tracking algorithm for a single UAV and our approach to compute the dissipated energy. In Section IV, we analyze our simulation results. We conclude in Section V.

II. SYSTEM MODEL

In this section, we present the UAV type and our tracking approach.

A. UAV type

For simulations, we have the choice between a fixed wings UAV or rotary wings UAV. Authors in [9] [10] [6] used fixed wings UAVs. Authors in [4] [5] used rotary wings UAVs. Rotary wings UAVs are chosen because they land and take off vertically and maintain a null speed. They are suitable when the target is stationary for a period of time, because they can maintain a null speed and still flying. While the fixed wings UAVs require a certain motion planning (circular movements) to persistently track the target because of their operational and physical constraints.

B. Tracking approach

The steps of tracking a mobile object are the detection of the target which means extracting the target from the images backgrounds, target states estimation (velocity and position), and the adjustment of the UAV placement to keep the mobile target in its field of view (FoV).

1) *Target detection*: in a target tracking mission, the first task consists of detecting the presence of the target in the field of view of the UAV camera. This step can be performed by comparing the correlation between the target image and target template to a detection threshold. This issue is beyond the scope of the paper, we assume that the detection of the target is error free.

2) *Target states estimation*: because we got complex and dynamic trajectories with changes of acceleration, we cannot use linear systems to model those trajectories [11]. That is why for the target state estimation step we use an extended Kalman filter (EKF) like in [7] because it is adapted to a nonlinear system.

EKF is a predictor-corrector algorithm. First, the current state is predicted according to the previous state. Then measurements are associated with states, and finally the predictions are corrected using measurements.

The system model equations are:

$$x(k) = f[x(k-1)] + w(k-1) \quad (1)$$

$$z(k) = h[x(k)] + v(k) \quad (2)$$

The equation (1) is the state equation used to predict the state.

The equation (2) is the measurement equation used in our application to extract the position. The time axis is divided into time-slots, and they are called frames. The state vector is denoted $x(k)$ (positions and velocity), $z(k)$ is the measured position vector, $f[x(k)]$ is a function that predicts the state in frame $k+1$ according to the state in frame k , $h[x(k)]$ is a function that associates measurements to the state vectors. The noise processes $w(k)$ and $v(k)$ are Gaussian independent processes with diagonal covariance matrices with variance σ_w^2 and σ_v^2 respectively. These two processes are modeling system and detection errors respectively.

3) *Target tracking*: the innovation in our approach is ensuring not only a correct tracking of the target but also reducing the energy consumption of the UAV. That is why we define three zones: authorized zone, correction zone, and re-detection zone. Fig. 1 introduces the three zones. The center of the three zones is represented by c , r is the radius of the authorized zone, the zone between r and the radius of the camera FoV R is the correction zone, and the re-detection zone is the zone outside the camera FoV. The value of R is computed by using the following expression.

$$R = \frac{(A \times \theta)}{2 \times CST} \quad (3)$$

where A is the altitude of the UAV, θ is the camera angle and CST is a constant equal to 57.3. The bigger the angle, the bigger R , and the higher the altitude, the bigger R .

By defining those three zones the UAV will consume less energy because it will do less frequent adjustments, indeed in each zone the UAV does specific adaptation actions. If the target is in the authorized zone, the UAV does not change its altitude or its velocity. If the target is in the correction zone, the UAV only corrects its velocity and position. In the re-detection zone, i.e., when the target is out of the FoV, the UAV adjusts its velocity, position, and its altitude to get a larger view of the scene to detect the mobile object once again. Also in our approach we maintain a minimal altitude of the UAV before and after the adjustments to reduce the energy consumption.

III. TRACKING ALGORITHM

This section presents our tracking algorithm for a single UAV and a single target and our approach to compute the energy dissipated in UAVs.

A. Tracking algorithm for a single UAV and a single target

Algorithm 1 shows how the UAV reacts considering the target position.

In this algorithm, during the simulation time T_{max} if the distance d between the estimated position of the target and the position of the UAV FoV center is lower than r , the UAV will keep its same previous velocity (V_{ux}, V_{uy}). If d is between r and R , the UAV will update its current velocity and position (P_{ux}, P_{uy}) with the estimated values of target velocity (V_{tx}, V_{ty}) and position (P_{tx}, P_{ty}). Finally, if d is higher than R , the UAV will update its current velocity, position, and altitude A . The updated altitude A_n is the altitude allowing the UAV

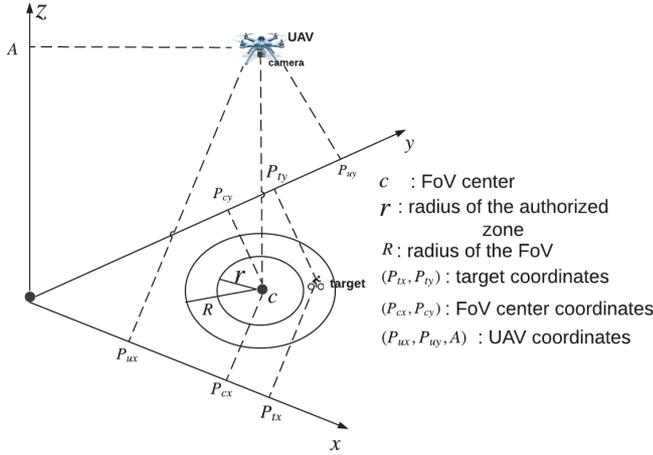


Fig. 1: The adjustment areas

to have the target in its FoV again. ESTIMATION refers to the function that estimates the position and velocity of the target by using EKF.

Algorithm 1: tracking a target using one UAV

Input: $r, R, A, d, (P_{tx}, P_{ty})$ estimated target position, $(P_{real_{tx}}, P_{real_{ty}})$ real target position, $(P_{u_x}, P_{u_y}), (V_{u_x}, V_{u_y}), (V_{tx}, V_{ty})$ estimated target velocity coordinates, T_{max}, A_n UAV adapted altitude, A_{min} minimal UAV altitude, T time between two measurements

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1 for  $i = 1$  to  $T_{max}$  do
2    $(P_{tx}, P_{ty}, V_{tx}, V_{ty}) = \text{ESTIMATION}(P_{real_{tx}}, P_{real_{ty}})$ 
3   if  $d < r$  then
4      $(V_{u_x}(i), V_{u_y}(i)) \leftarrow (V_{u_x}(i-1), V_{u_y}(i-1))$ 
5      $(P_{u_x}(i), P_{u_y}(i)) \leftarrow (P_{u_x}(i-1) + T \times V_{u_x}(i), P_{u_y}(i-1) + T \times V_{u_y}(i))$ 
6   end
7   if  $r \leq d \leq R$  then
8      $(V_{u_x}(i), V_{u_y}(i)) \leftarrow (V_{tx}(i), V_{ty}(i))$ 
9      $(P_{u_x}(i), P_{u_y}(i)) \leftarrow (P_{tx}(i), P_{ty}(i))$ 
10  end
11  if  $d > R$  then
12     $A(i) \leftarrow A_n(i)$ 
13     $(V_{u_x}(i), V_{u_y}(i)) \leftarrow (V_{tx}(i), V_{ty}(i))$ 
14     $(P_{u_x}(i), P_{u_y}(i)) \leftarrow (P_{tx}(i), P_{ty}(i))$ 
15     $A(i) \leftarrow A_{min}$ 
16  end
17 end

```

We assume that the maximal velocity of the target is lower than the maximal velocity of the UAV.

B. Energy consumption

An UAV system can be modeled with several power consumer components [12]. The components are the communication, the motors, the control, the data processing, and the

internal and external load. The communication component involves sending or receiving control commands, data or updating information. The motors component will consume more energy when the UAV increases its altitude, accelerates or decelerates. The control component includes sensors and detectors. In the data processing component, running algorithms such as detection and localization will consume energy. An example of internal load is electrical motors which cause some energy losses due to their operating temperatures. An example of external loads is weather conditions.

For the energy part, we are only interested in the energy consumed due to movements and communication. Because the energy consumption of the other components is the same in all scenarios.

1) *Transmission energy consumption:* first, we compute the dissipated energy when sending compressed images to the base station [13].

$$E = E_o + E_a + M_t \times E_t \quad (4)$$

where E_o is the energy dissipated by the local oscillator which generates the required carrier frequency, E_a is the energy dissipated by the power amplifier which amplifies the signal to produce the required RF transmit power P_t , E_t is the energy dissipated by the transmitter which is responsible of modulation and up-conversion (translating the baseband signal to RF), M_t is the size of the messages to transmit. We assume that the transmission power P_t is always maximal and equal to 20 dbm.

2) *Movement energy consumption:* we compute the movements energy consumption in the three possible phases (cruising, increasing altitude and decreasing altitude) [14] [15] [16]. The energy is computed every second, so T which is the time between two measurements is equal to 1 sec.

a) *Cruising:*

$$E_1 = P_1 \times T + m \times a \times V \times T \quad (5)$$

where E_1 is the energy dissipated in the cruise phase, m is the weight of the UAV, a is the acceleration or deceleration, V is the velocity, P_1 is a constantly consumed energy in the cruise phase equal to 80 Joules.

b) *Increasing altitude:*

$$E_2 = P_2 \times T + m \times g \times h \times T + E_1 \quad (6)$$

where E_2 is the energy dissipated when increasing altitude, g is the gravitational constant, h is the UAV altitude, P_2 is a constantly consumed energy in the changing altitude phase equal to 110 Joules.

c) *Decreasing altitude:*

$$E_3 = m \times g \times h \times T + E_1 \quad (7)$$

where E_3 is the energy dissipated when decreasing altitude

IV. SIMULATION

In this section, we evaluate the performance of the proposed algorithm in terms of correct tracking and reduction of UAV energy consumption.

A. Simulation Parameters

MATLAB is used for simulation purposes. The measurements are done every second. The simulation parameters are presented in table I and table II.

TABLE I: Simulation parameters for the tracking algorithm

Parameters	Value	Unit
Maximal velocity of the UAV (V_{max})	200	m/s
Minimal velocity of the UAV (V_{min})	0	m/s
Maximal altitude of the UAV (A_{max})	200	m
Minimal altitude of the UAV (A_{min})	60	m
Initial UAV and target positions	(0, 4)	m
Initial UAV and target velocities	(0, 5)	m/s
θ	50	deg
Radius r	R/3	m
σ_w^2	0.5	
σ_v^2	1	
Simulation time	60	sec

TABLE II: Simulation parameters for the energy computation

Parameters	Value	Unit
E_t	18×10^{-3}	J
E_a	$Pt \times 10^{-3}/0.4$	J
E_o	11×10^{-3}	J
m	0.38	kg
g	9.8	m/s^{-2}
V_{max}	5	m/s
V_{min}	0	m/s
A_{max}	200	m
A_{min}	60	m
Initial UAV and target positions	(0, 4)	m
Initial UAV and target velocities	(0, 2.5)	m/s
θ	92	deg
σ_w^2	0.5	
σ_v^2	1	
Simulation time	5	min

For the energy part, we use the parameters of Ar.Drone version 2.0 to get realistic observations. The battery type is Lithium polymer.

B. Simulation Results

1) *Tracking algorithm for a single target and a single UAV:* the movements to study are rectilinear with a constant velocity, rectilinear with variable velocity, nonrectilinear with a constant velocity, and nonrectilinear with variable velocity. We use nonrealistic target movement to observe how the UAV respond. For all scenarios, we assume that the UAV is in the cruising phase, i.e., we do not consider the takeoff and landing phases.

a) *The target moves in a straight line with a fixed velocity:* by testing this scenario we are making sure that there is no estimation and tracking errors.

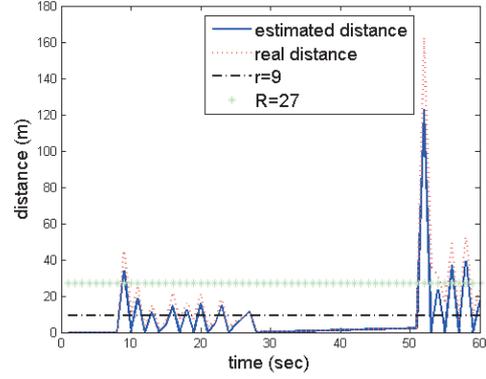


Fig. 2: distance between the target and the UAV FoV center

b) *The target moves in a straight line with a variable velocity:* in Fig. 2 we observe when the different UAVs adaptation occurs. The adaptation of the altitude occurs four times (at the seconds 9, 52, 56 and 58) due to the overrun of R . The adjustment of the speed and position occurs at the seconds 11, 13, 16, 18, 20, 23 and 54 because the estimated values are between r and R . When the estimated values of distance are lower than r , the UAV does not adjust its speed.

c) *The target moves in a nonstraight line with a constant velocity:* this scenario is not realistic because it is not possible to change direction while keeping the same velocity.

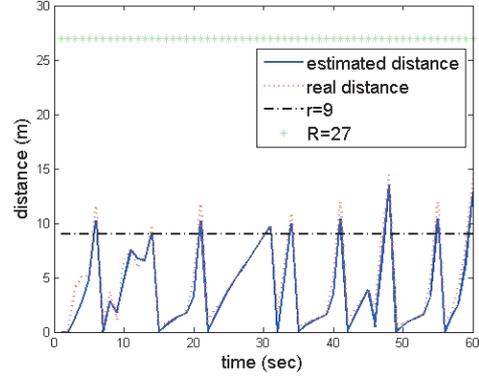


Fig. 3: Distance between the target and the UAV FoV center

When the target only changes its direction, it does not go out from the UAV FoV. In this scenario the estimated distance exceeds r nine times, one second later, this distance becomes equal to zero because of the adjustment done in the corrections zone (Fig. 3).

d) *The target moves in a nonstraight line with a variable velocity:* since this scenario is the combination of the last two ones, we deduce that the error of position estimation is due to velocity changes. For example, from Fig. 4, at the second 19 the actual position is (50m, 50m) while the estimated position is (43.7m, 59.9m). Estimations are different from the real values. Also, the generated values of the UAV does not always

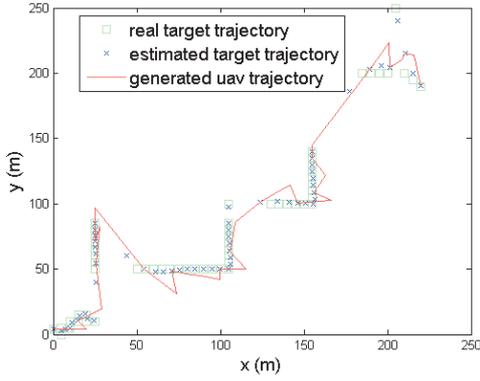


Fig. 4: UAV and target trajectories

coincide with the estimated values of the target because of the adjustments that differ from one area to another.

e) *Extreme cases*: when the velocity of the target exceeds the velocity of the UAV, the UAV reaches its maximal altitude and maximal velocity. So for sure the algorithm continues running.

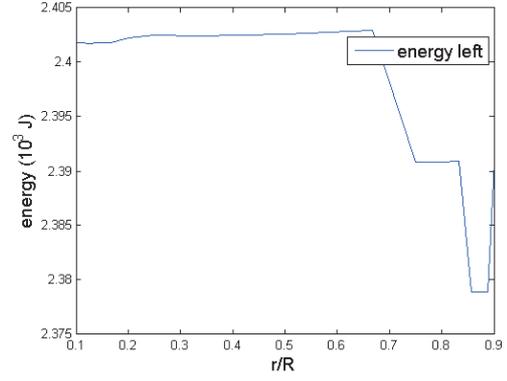
2) *Energy consumption*: in the previous section we validated our tracking algorithm. Now we confirm its effectiveness in minimizing the energy consumed by UAVs motors compared to other algorithms.

To compute the radius of each zone we vary the r/R proportion from 0.1 to 0.9 and we choose the proportion that gives the best results in term of energy left in the UAV battery and in term of distance between the target and the UAV FoV center. So in Fig. 5, we compute for each r/R the energy left and the average distance between the target and the FoV center for 5min of simulation.

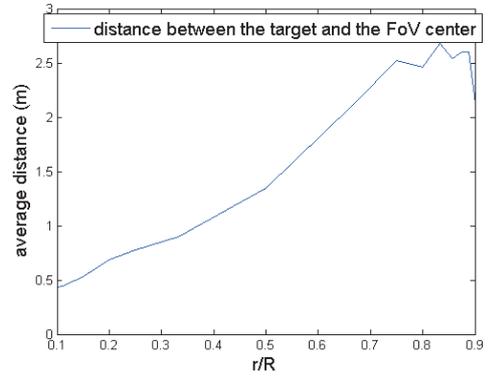
From Fig. 5(a), we conclude that for $r = 2 \times R/3$ the UAV consumes less energy but the distance between the target and the FoV center is greater than for the other proportions (Fig. 5(b)). The $r = R/3$ and $r = R/4$ proportions are the best choices because the energy consumption is almost the same as in $r = 2 \times R/3$ and the average distance is less than one meter.

Also to choose the altitude a compromise must be found between the image quality, the motor energy consumption, and the communication energy consumption. The higher the altitude, the higher the power needed to transmit images. Since we always transmit at the highest power, the altitude will not have an effect on the communication energy consumption. Because sending high images quality is our priority, we fix the altitude before and after adaptation to the minimal possible which is 60m. Also with a lower UAV altitude, the target will be defined with a larger number of pixel, so the probability to detect it will be higher.

In other approaches, there are only two zones: inside and outside the FoV with two alternatives. The first alternative consists of always doing the position and velocity corrections when the target is still inside the FoV. The second consists of



(a) The energy left of the UAV battery



(b) The average distance between the target and the FoV center

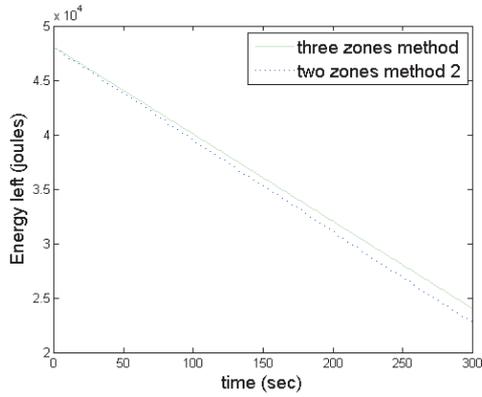
Fig. 5: Impact of r/R on motor energy consumption and on the distance between the target and the FoV center

correcting the UAV placement and velocity only if the target is outside the FoV [5].

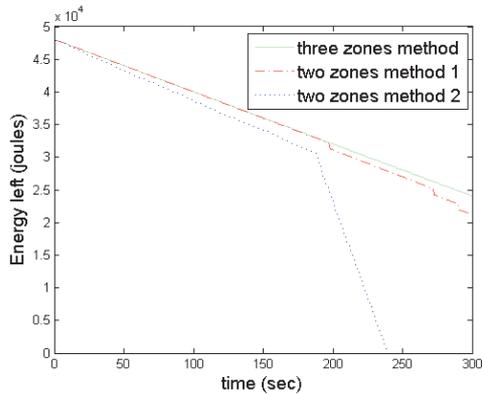
To compute the energy consumption, we run simulations for 5 minutes to get more accurate estimations. Initially, the battery capacity is 47952 J.

In Fig. 6, we compare our method (three zones method) to the method where adjustments are always done (two zones method 1), and to the method where adjustments are done only if the target is out of the UAV FoV (two zones method 2). We observe less energy consumption in our method. We did the simulation when the movement of the target is rectilinear with a variable velocity (Fig. 6(a)), and when it is non rectilinear with a variable velocity (Fig. 6(b)).

For the communication energy part, if the size of the images to transmit is 5Mbit, the battery will be discharged of 0,10 %. This percentage can go up to 1,17 % if the size of images is 100Mbit. For the motor energy consumption, the battery will be discharged around 50 %. So we conclude that the energy consumption due to communication is negligible compared to the one consumed by motors.



(a) The energy left of the UAV battery for a rectilinear movement with a variable velocity



(b) The energy left of the UAV battery for a non rectilinear movement with a variable velocity

Fig. 6: Comparison of the UAV energy dissipation

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a tracking algorithm for a single UAV based on three zones. We computed the energy consumption caused by transmitting images and by vertical and horizontal UAV movements. Finally, simulations showed a successful tracking, a less energy consumption compared to other approaches. Also, simulations showed that the energy consumption due to communication is negligible compared to the energy consumed because of movements.

For future work, we will concentrate on scenarios with multiple targets and multiple UAVs. We will study the communication, the cooperation and the resource sharing between UAVs using the LTE technology.

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