UAV Trajectory Planning for Data Collection from Time-Constrained IoT Devices

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Short Summary

- The authors jointly optimize the trajectory of a UAV and the radio resource allocation to maximize the number of served IoT devices, in order to guarantee the performance of UAV when collecting data from time-constrained IoT devices.
- The authors propose :
  - a global optimal algorithm based on branch, reduce and bound (BRB) algorithm for relatively small scale scenarios,
  - **a sub-optimal algorithm based on successive convex approximation (SCA) in order to obtain results for larger networks.**
  - an extension of the SCA algorithm to further minimize the UAV flight distance.

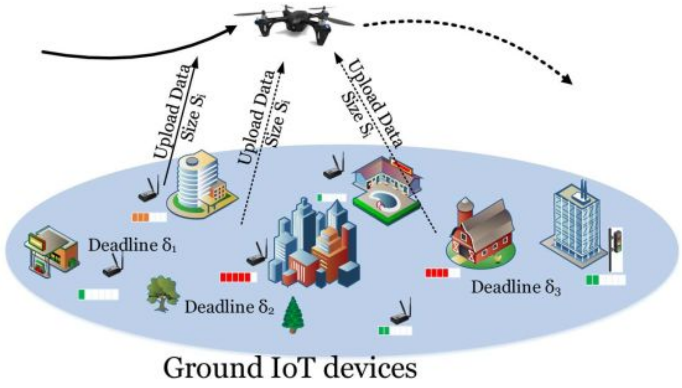


Fig 1: System model: timely data collection in a smart city environment using UAV

Optimization Problem

To optimize the UAV trajectory and allocation of resources to maximize the total number of served IoT devices within a flight mission duration based on a given set of target time constraints.

This original problem is non-convex,

$$(\mathcal{P}_1): \max_{\mathbf{X},\mathbf{Y},\mathbf{B},\mathbf{K}} \sum_{i\in\mathcal{M}} \kappa_i \tag{10a}$$

$$\text{s.t.} \quad \boxed{\begin{aligned} & S_i(b_i^n, x^n, y^n) \geq \kappa_i S_i^{min}, \quad \forall n, i \in \mathcal{M}, && (10b) \\ & \kappa_i \in \{0,1\}, \quad i \in \mathcal{M}, && (10c) \end{aligned}}$$

$$0 \leq b_i^n \leq \kappa_i, \quad \forall n, i \in \mathcal{M}, \tag{10d}$$

$$(2), (6), \tag{10e}$$

$$[x^0 \ y^0] = [x_s \ y_s], \tag{10f}$$

$$[x^N \ y^N] = [x_e \ y_e], \tag{10g}$$

$$(x^{n+1}-x^n)^2+(y^{n+1}-y^n)^2 \leq (v_{max}\delta_t)^2, \ n=1,\ldots,N-1, \tag{2}$$

$$\sum_{i\in\mathcal{M}} b_i^n \leq 1, \quad \forall n. \tag{6}$$

Where,

M : set of M IoT devices

X : $\{x^n, \forall n\}$

x^n : x-axis location of UAV in time slot n

Y : $\{y^n, \forall n\}$

y^n : y-axis location of UAV in time slot n

B : $\{b_i^n, i \in M, \forall n\}$

b_i^n : fraction of spectrum allocated to IoT device i in time slot n, and it is equivalent to a number of resource blocks

K : $\{k_i, i \in M\}$

k_i : binary variable for device i, that is asserted if the UAV can successfully serve device i with a minimum service amount Simin; otherwise, it is set to 0.

S_i^{min} : minimum amount of information (bits/Hz) that need to be uploaded by device i

$[x^0 \ y^0]$: initial position located at $[x_s \ y_s]$

$[x^N \ y^N]$: final position located at $[x_e \ y_e]$

Non-convex constraint 10b

Service amount, the amount of data that one IoT device delivers to the UAV within a given deadline during a data collection mission,

$$S_i(b_i^n, x^n, y^n) = \delta_t \sum_{n=1}^{N} s_i^n, \quad \forall i \in \mathcal{M}, \tag{8}$$

Where,

$$s_i^n = \begin{cases} r_i^n(b_i^n, x^n, y^n), & \text{if } \tau_i \leq n \leq \delta_i \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

instantaneous achievable rate for each IoT device i in time slot n,

$$r_i^n(b_i^n, x^n, y^n) = b_i^n \log_2(1 + \Upsilon_{i,n}), \tag{5}$$

b_i^n : fraction of spectrum allocated to IoT device i in time slot n, and it is equivalent to a number of resource blocks

x^n : x-axis location of UAV in time slot n

y^n : y-axis location of UAV in time slot n

δ_t : length of each time slot

τ_i : data generation time of device i

δ_i : expiry deadline of device i

$\Upsilon_{i,n}$: The signal-to-noise ratio (SNR) of each IoT device i in time slot n

Approximation to Convex Problem

1. Introduce Slack Variable **$G = \{g_i^n \geq 0, \forall n, i \in M\}$** and **$C = \{c_i^n \geq 0, \forall n, i \in M\}$**
2. Relax binary variable in equation (10c), make it continuous between 0 and 1
3. Approximate the log function of SNR with the following inequality,

$$\log_2(1+\Upsilon_{i,n}) \geq -A_i^{r,n}\Big((x_i - x^n)^2 + (y_i - y^n)^2 - (x_i - x^{r,n})^2 - (y_i - y^{r,n})^2\Big) + B_i^{r,n}, \triangleq \zeta_i^{n,r}(x^n, y^n), \quad (12)$$

α : path loss exponent
P : device transmission power
γ_0 : Channel power gain
σ^2 : noise power
$\widehat{h}_i^n$: small scale fading

Where,

$$A_i^{r,n} = \frac{\alpha(P\gamma_0|\widehat{h}_i^n|^2/\sigma^2)\log_2 e}{2\Big((H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2)^{\alpha/2}+(P\gamma_0|\widehat{h}_i^n|^2/\sigma^2)\Big)} \cdot \frac{1}{\Big(H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2\Big)}, \quad \forall n, i \in \mathcal{M}, \quad (13)$$

$$B_i^{r,n} = \log_2\left(1+\frac{P\gamma_0|\widehat{h}_i^n|^2}{\sigma^2\Big(H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2\Big)^{\alpha/2}}\right), \forall n, i \in \mathcal{M}, \quad (14)$$

Reformulated problem

$$\mathcal{P}1_L: \max_{\substack{\mathbf{X},\mathbf{Y},\mathbf{B},\\ \mathbf{K},\mathbf{G},\mathbf{C}}} \sum_{i\in\mathcal{M}} \kappa_i \quad (15a)$$

$$\text{s.t. } \delta_t \sum_{n=\tau_i}^{\delta_i} c_i^n \geq \kappa_i S_i^{min}, \quad i \in \mathcal{M}, \quad (15b)$$

$$\boxed{c_i^n \leq b_i^n g_i^n, \quad i \in \mathcal{M}, n=\tau_i,\ldots,\delta_i,} \quad (15c)$$

$$g_i^n \leq \zeta_i^{n,r}(x^n, y^n), \quad i \in \mathcal{M}, n=\tau_i,\ldots,\delta_i, \quad (15d)$$

$$0 \leq \kappa_i \leq 1, \quad i \in \mathcal{M}, \quad (15e)$$

$$0 \leq b_i^n \leq \kappa_i, \quad \forall n, i \in \mathcal{M}, \quad (15f)$$

$$(x^{n+1}-x^n)^2+(y^{n+1}-y^n)^2 \leq (v_{max}\delta_t)^2, \; n=1,\ldots,N-1, \quad (2)$$

$$\sum_{i\in\mathcal{M}} b_i^n \leq 1, \quad \forall n. \quad (6)$$

$$[x^0 \; y^0] = [x_s \; y_s], \quad (10f)$$

$$[x^N \; y^N] = [x_e \; y_e], \quad (10g)$$

Replace the right side of (15c) by an equivalent Difference of Convex (DC) function,

$$\frac{(b_i^n + g_i^n)^2 - (b_i^n - g_i^n)^2}{4}$$

Linearize the concave term, $\frac{(b_i^n + g_i^n)^2}{4}$ of the constraint at iteration r.

Hence, the constraint (15c) is approximated as

$$-\frac{(b_i^{r,n} + g_i^{r,n})^2}{4} - \frac{(b_i^{r,n} - g_i^{r,n})(b_i^n - b_i^{r,n} + g_i^n - g_i^{r,n})}{2} + \frac{(b_i^n - g_i^n)^2}{4} + c_i^n \leq 0 \quad (16)$$

Algorithm

Algorithm 2 Sub-optimal: Proposed SCA for Solving $\mathcal{P}1_L$ and $\mathcal{P}2_L$

Inputs: The error tolerance ε, the minimum service amount S_i^{min}, and the deadlines δ_i.
Initialization:
Set the initial trajectory $x^{r,n}$ $y^{r,n}$, $\forall n$ the resource allocation $b_i^{r,n}$, $\forall n$, $\forall i$ and iteration number $r = 1$.
while (Obj $(r-1)$ $-$ Obj $(r)) \geq \varepsilon$ **do**
    For *SCA-algorithm problem* $\mathcal{P}1_L$: solve the convex problem (15) to obtain the trajectory $x^{r+1,n}$ $y^{r+1,n}$, $\forall n$ and $b_i^{r+1,n}$, $\forall n$, $\forall i \in \mathcal{M}$.
    For *SCA-distance problem* $\mathcal{P}2_L$*:* solve the convex problem (20) with the updated subset $\mathcal{M}'$ devices to obtain the trajectory $x^{r+1,n}$ $y^{r+1,n}$, $\forall n$ and $b_i^{r+1,n}$, $\forall n$, $\forall i \in \mathcal{M}'$.,
    Update the UAV's trajectory $x^{r,n}$ $y^{r,n}$, $\forall n$,
    Update the resource allocation $b_i^{r,n}$, $\forall i$,
    Update $r = r + 1$.
end while
Output:
For *SCA-algorithm problem* $\mathcal{P}1_L$, the output is the sub-optimal solution for maximizing the number of served IoT devices $\mathcal{M}'$
For *SCA-distance problem* $\mathcal{P}2_L$, the output is the sub-optimal solution for minimizing the flight distance.

Variable Declaration & Objective Function

$$\mathcal{P}1_L: \max_{\substack{\mathbf{X},\mathbf{Y},\mathbf{B},\\ \mathbf{K},\mathbf{G},\mathbf{C}}} \sum_{i\in\mathcal{M}} \kappa_i \tag{15a}$$

```
variable K(M,1);
variable C(M, N);
variable B(M, N)
variable G(M,N)
variable X(N)
variable Y(N)
obj = 0;
for i=1:M
 obj = obj + K(i);
end
maximize(obj)
```

Constraint 15b

$$\delta_t \sum_{n=\tau_i}^{\delta_i} c_i^n \geq \kappa_i S_i^{min}, \quad i \in \mathcal{M}, \tag{15b}$$

```
for i=1:M
  c_sum = 0;
  for n=data_generation(i):deadline(i)
    c_sum = c_sum + C(i,n);
  end
  delta_t*c_sum >= K(i)*S_min;
end
```

Constraint 16

$$-\frac{(b_i^{r,n}+g_i^{r,n})^2}{4}-\frac{(b_i^{r,n}-g_i^{r,n})(b_i^n-b_i^{r,n}+g_i^n-g_i^{r,n})}{2} + \frac{(b_i^n-g_i^n)^2}{4}+c_i^n \leq 0 \quad (16)$$

```
for i=1:M
    for n=data_generation(i):deadline(i)
        -(((B_r(i, n) + G_r(i,n))^2)/4) ...
        - (((B_r(i, n) - G_r(i,n))*(B(i, n) - B_r(i, n) + G(i,n) - G_r(i,n)))/2) ...
        + (((B(i, n) - G(i,n))^2)/4) ...
        + C(i, n) <= 0
    end
end
```

Constraint 15d

$$A_i^{r,n} = \frac{\alpha(P\gamma_0|\widehat{h}_i^n|^2/\sigma^2)\log_2 e}{2\Big((H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2)^{\alpha/2}+(P\gamma_0|\widehat{h}_i^n|^2/\sigma^2)\Big)} \cdot \frac{1}{\Big(H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2\Big)}, \quad \forall n, i \in \mathcal{M}, \quad (13)$$

$$B_i^{r,n} = \log_2\left(1+\frac{P\gamma_0|\widehat{h}_i^n|^2}{\sigma^2\Big(H^2+(x_i-x^{r,n})^2+(y_i-y^{r,n})^2\Big)^{\alpha/2}}\right), \forall n, i \in \mathcal{M}, \quad (14)$$

$$g_i^n \leq \zeta_i^{n,r}(x^n, y^n), \quad i \in \mathcal{M}, n=\tau_i, \ldots, \delta_i, \quad (15d)$$

Where, $\zeta_i^{n,r}(x^n, y^n) \triangleq -A_i^{r,n}\Big((x_i - x^n)^2 + (y_i - y^n)^2 - (x_i - x^{r,n})^2 - (y_i - y^{r,n})^2\Big) + B_i^{r,n}$

```
for i=1:M
    for n=data_generation(i):deadline(i)
          G(i,n) <= -(alpha*((P*ch_power_gain*(abs(h(i,n))^2))/noise_power)*log2(exp(1))) / ...
                    (2*((H^2 + (device_X(i) - X_r(n))^2 + (device_Y(i) - Y_r(n))^2)^(alpha/2)...
                    + ((P*ch_power_gain*(abs(h(i,n))^2))/noise_power))) ...
                    *(1/((H^2 + (device_X(i) - X_r(n))^2 + (device_Y(i) - Y_r(n))^2))) ... % end A ...
                    * ( (device_X(i) - X(n))^2 + (device_Y(i) - Y(n))^2 ...
                    - (device_X(i) - X_r(n))^2 - (device_Y(i) - Y_r(n))^2)...
                    + log2(1 + ((P*ch_power_gain*(abs(h(i,n))^2))/...% start B
                    (noise_power*((H^2 + (device_X(i) - X_r(n))^2 + (device_Y(i) - Y_r(n))^2))^alpha/2)))
    end
end
```

Constraint 15e & 15f

$$0 \leq \kappa_i \leq 1, \quad i \in \mathcal{M}, \tag{15e}$$

$$0 \leq b_i^n \leq \kappa_i, \quad \forall n, i \in \mathcal{M}, \tag{15f}$$

15e

```
for i=1:M
    0<=K(i)<=1;
end
```

15f

```
for n=1:N
    for i=1:M
        0<= B(i,n) <= K(i);
    end
end
```

Constraint 2 & 6

$$(x^{n+1} - x^n)^2 + (y^{n+1} - y^n)^2 \leq (v_{max}\delta_t)^2, \ n = 1, \ldots, N-1, \quad (2)$$

```
for n=1:N-1
    ((X(n+1) - X(n))^2) + ((Y(n+1) - Y(n))^2) <= (v_max*delta_t)^2
end
```

$$\sum_{i \in \mathcal{M}} b_i^n \leq 1, \quad \forall n. \quad (6)$$

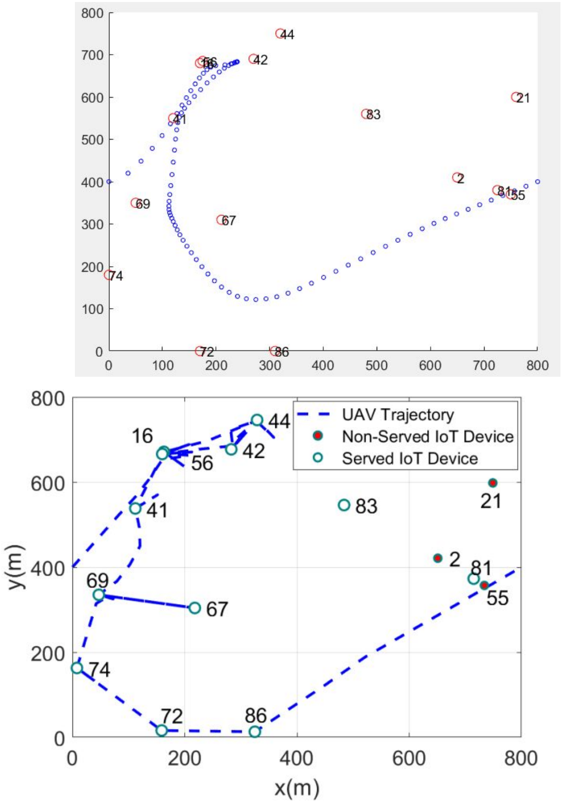
```
for n=1:N
    b_sum = 0;
    for i=1:M
        b_sum = b_sum + B(i, n);
    end
    b_sum <= 1;
end
```

Constraint 10f & 10g

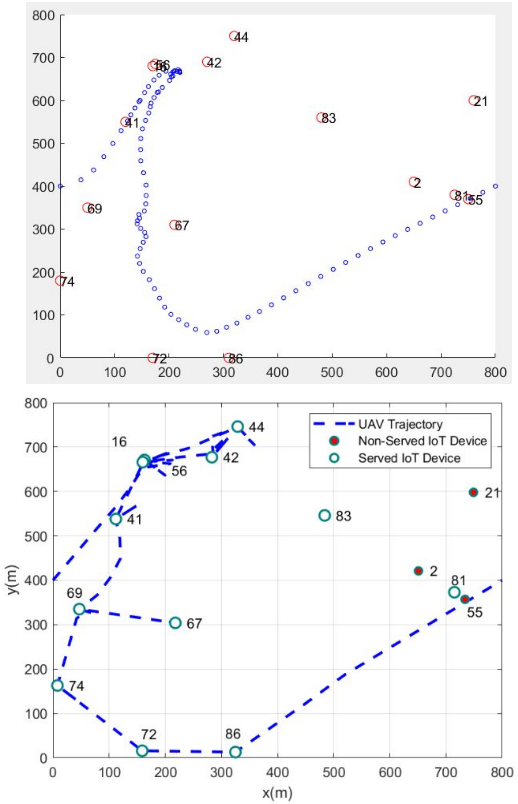
```
% 10f
X(1) == 0
Y(1) == 400

% 10g
X(N) == 800
Y(N) == 400
```

$$[x^0\ y^0] = [x_s\ y_s], \tag{10f}$$
$$[x^N\ y^N] = [x_e\ y_e], \tag{10g}$$

Comparison of Reproduced Figure & Original Figure



(a) Path-loss channel.



(b) Rician channel $K = 3$.

Problem:

Data generation time of each devices is not given in the paper. Here, I assume all devices are generating data from the beginning (time slot 1)

The exact initial trajectory, and also initial B & G are also not given in the paper.

Simulation Parameter

TABLE I

SIMULATION PARAMETERS

Parameter	Value
IoT device transmission power, P	0.1mW
UAV altitude, H	100m
Channel power gain, γ_0	-50 dB
Noise power, σ^2	-110dBm
UAV max speed, v_{max}	50m/s
Pathloss exponent, α	2.7
The error tolerance ε	10^{-3}

Changing delta_t from 1 to 1.5