

UAV Position Estimation Using Remote Radio Head With Adaptive Power Control

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Abstract—The adaptive power control of Code Division Multiple Access (CDMA) communications using Remote Radio Head (RRH) between multiple Unmanned Aerial Vehicles (UAVs) with a link-budget based Signal-to-Interference Ratio (SIR) estimate is applied to four inner loop power control algorithms. It is concluded that Base Station (BS) can calculate not only UAV distance using linearity between speed and Consecutive Transmit-Power-Control Ratio (CTR) of Adaptive Step-size Closed Loop Power Control (AS-CLPC), Consecutive TPC Ratio Step-size Closed Loop Power Control (CS-CLPC), Fixed Step-size Power Control (FSPC), but also UAV position with Received Signal Strength Indicator (RSSI) ratio of RRHs.

Keywords—speed estimation, adaptive power control, link-budget, SIR, multi-bit quantizer, RRH

I. INTRODUCTION

THE communication system of an Unmanned Aerial Vehicle (UAV) with multiple UAVs requires a mobile wireless network to share data between UAVs. One communication network protocol that may be used is Code Division Multiple Access (CDMA). CDMA differs from both Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) in that it uses the same frequency for multiple users.

Since all users utilize a single frequency, the near-far effect is generated [1]. To eliminate the near-far effect in CDMA systems, the transmission signal power from every UAV must be the same level at the receiver. This technique of controlling the magnitude of the transmission power according to the distance between the UAV and the Base Station (BS) is officially termed power control. It equalizes the received power and eliminates the near-far effect, though it is subject to such complications as path loss, shadowing, multi-path fading, etc.

This power control technique is differentiated into open loop power control and closed loop power control. The closed loop power control is further divided into inner loop power control and outer loop power control. The inner loop power control is responsible for adjusting the power transmitted to maintain the received Signal-to-Interference Ratio (SIR) at the BS at a level equal to that at the SIR_{target} . The outer loop power control is responsible for setting the SIR_{target} based on the Bit Error Rate (BER) or service requirement.

In general, an aircraft measures its air speed by pitot tube and calculates its ground speed by Global Positioning System/Inertial Navigation System (GPS/INS). In these days,

there is an effort that optic flow measurements from CCD camera have been used to augment GPS/INS to provide more precise velocity information [2]. But, GPS/INS does not provide exact information of speed and position due to timing error when communication link is not robust or when GPS is not available.

The speed can be calculated with SIR estimates when other speed measurements are not available. Conventional SIR estimates [3], [4] consider only the transmission power and the link-gain, but the paper [5] takes into account the link-budget, which has more realistic parameters including distance information and path loss than the link-gain. Using the SIR estimate that reflects the link-budget, speed estimation [6] is introduced based on a Consecutive Transmit-Power-Control Ratio (CTR) because a faster mobile is likely to receive more CTR than a slower one. The proposed speed estimation method is applied to four algorithms, and the results are compared in [5]. The CTR shows linearity with speed, therefore target speed or distance can be calculated from CTR.

This technique which has only one antenna produces target speed, however, it cannot provide target position information. This paper introduces target distance and position estimation using Remote Radio Head (RRH) [7] on the basis of speed estimation of adaptive power control. With BS that installs three RRHs, one of RRHs can calculate target distance with CTR, the other two RRHs measure received signal strength from target and BS calculates the ratio between two. Then, the ratio tells the target position.

This paper is organized as follows: The literature related to this work is surveyed in Section II. The inner loop power control is described in Section III. The concept of the link-budget based SIR estimate is introduced in Section IV, followed by description of simulation environments in Section V. Section VI gives details of the algorithms, the simulation results are analyzed in Section VII shows performance comparison between algorithms. Finally, conclusions are drawn in Section VIII.

II. RELATED WORK

Kim, Lee, and Kim introduced in [8] the Adaptive Step-size Closed Loop Power Control (AS-CLPC) algorithm for a narrowband CDMA system. This algorithm adapts its power control step-size based on the optimal factors determined with the mean fade duration which is inversely proportional to the maximum Doppler frequency. Nourizadeh, Taaghoul, and Tafazolli [9] proposed the Blind Adaptive Closed Loop Power Control (BA-CLPC) in which the power control step-size is adjusted to cope with the user mobility. Taaghoul [10]

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introduced the Speed Adaptive Closed Loop Power Control (SA-CLPC) algorithm in which the power control step-size is selected based on the user speed estimation categorized by speed ranges. Lee and Cho [11] proposed the Mobility Based Adaptive Closed Loop Power Control (M-ACLPC) algorithm in which the power control step-size is adjusted depending on the combination of the cumulative information of the three power control commands and speed estimation.

Patachianand and Sandrasegaran [4] compared performances of the AS-CLPC, BA-CLPC, SA-CLPC, and M-ACLPC in terms of Power Control Error (PCE) under the same simulation environment. In their comparisons, the AS-CLPC showed the best performance when the target speed was lower than 25km/h, while the SA-CLPC was the best when the speed was greater than 25km/h.

Patachianand and Sandrasegaran [4] presented the Consecutive TPC Ratio (CTR) Step-size Closed Loop Power Control (CS-CLPC) algorithm whose power control step-size is determined based on a parameter called CTR. They measured the moving target speed by CTR, then, calculated the PCE as the Root Mean Square (RMS) of the difference between the received SIR and the SIR_{target} . They also suggested in [6] the mapping equation and mapping table which can yield accurate speed estimation using CTR.

Lee [5] presents UAV speed estimation with multi-bit quantizer in Adaptive Power Control. The speed has linearity with CTR when CS-CLPC and FSPC are used. But AS-CLPC is independent of CTR. With this linearity, target moving distance is also calculated.

Unfortunately, research history of target position calculation with RRH is not found.

III. INNER LOOP POWER CONTROL

In CDMA, the process of inner loop power control occurs as follows: In the reverse link direction (from the UAV to the BS), the transmission power information goes to the BS. At the BS, the SIR_{target} and the received SIR are calculated from the transmission power, the link-gain, and the noise power. Based on these factors, the BS sends a Transmit-Power-Control (TPC) command to each UAV at rate of 1500 Hz, or Sample Time (T_S) (=0.667 ms) in the forward link direction (from the BS to the UAV). This power equalization increases the maximum communication number between UAVs and consequently eliminates the near-far effect. These procedures [3], [4] are represented in (1) and (2).

$$P_i(t+1) = P_i(t) + \delta_i(t) \times TPC_i(t) \quad (1)$$

where $P_i(t)$ is the transmission power, $\delta_i(t)$ is the power control step-size, and $TPC_i(t)$ is the TPC command for the i th UAV (UAV $_i$ here) at time t .

$$TPC_i(t) = \text{sign}(SIR_{target,i}(t) - SIR_i(t)) \times \left[\frac{\log((1+\mu|x_i(t)|)/R_P)}{(1+\mu)} (2^m - 1) \right] \quad (2)$$

where $SIR_{target,i}(t)$ (= $SIR_{target}(t)$ here) is the target SIR, $SIR_i(t)$ is the received SIR from the i th UAV at time t , $\mu =$

$2^{(m+1)}-1$ and R_P is dynamic range of power adjustment. Non-uniform quantizer [12] used in voice coding is introduced that $(m+1)$ -bit TPC is adopted $TPC_i(t) = \{C_0 C_1 \dots C_m\}$ where C_0 is the sign bit. Table I illustrates multilevel bit quantizer and sf is a scale factor.

TABLE I
TPC COEFFICIENTS

m	sf	multilevel	R_P
1	0.5	$\pm 1,2$	0.1
2	0.25	$\pm 1,2,3,4$	0.3
3	0.125	$\pm 1,2,3,4,5,6,7,8$	0.5

IV. LINK-BUDGET BASED SIR

The conventional SIR estimate of the i th UAV in CDMA is described as follows :

$$SIR_i(t) = \frac{P_i(t)G_i(t)}{\sum_{j \neq i} P_j(t)G_{ji}(t) + P_N} \quad (3)$$

where $G_i(t)$ is the link-gain between the i th UAV and the connected BS, and $P_i(t)$ is the transmission power from the i th UAV. $G_{ji}(t)$ is the link-gain between the j th UAV and the BS to which the i th UAV connects. However, equation (3) does not have distance information, therefore, $SIR_i(t)$ can not be measured by distance step.

This paper introduces the link-budget based SIR as

$$SIR_i(t) = \frac{P_{R,i}(t)}{\sum_{j \neq i} P_{R,j}(t) + P_N} \quad (4)$$

where $P_{R,i}$ is the received power from the i th UAV. $P_{R,j}$ is the received power from the j th UAV with the BS to which the i th UAV connects. The received power is affected by factors including the free space loss [13] which has distance information and gaseous path loss [14] varied by humidity. The speed is estimated from moving distance per T_S and $SIR_i(t)$ is measured by distance variation.

The power delivered to the receiver [13] of BS is :

$$P_{R,i} = G_{T,i} \times P_{T,i} \times G_{R,i} / (L_F(D_i) \times L_G(D_i)) \quad (5)$$

where $G_{T,i}$, $P_{T,i}$, $G_{R,i}$, $L_F(D_i)$, and $L_G(D_i)$ are the transmission antenna gain, the transmission power, the received antenna gain of the i th UAV, the free space loss, and the gaseous path loss, respectively (the component loss is ignored here.). The speed is estimated from moving distance of free space loss.

$$L_F(D_i)(dB) = 92.44 + 20\log_{10}(F) + 20\log_{10}(D_i). \quad (6)$$

D_i is the distance between the i th UAV and the BS in kilometers, F is the frequency in gigahertz, and the specific attenuation due to dry air and water vapor from sea level to an altitude of 5km can be estimated by (7).

$$L_G(D_i) = (\gamma_0 + \gamma_W) \cdot D_i \tag{7}$$

γ_0 in (8) is the attenuation for dry air in dB/km and γ_W in (9) is the attenuation for water vapor in dB/km, both are set at temperature, 288K and pressure, 1013hPa.

$$\gamma_0 = \frac{7.34}{f^2 + 0.36} + \frac{0.3429 \times 2.128 \times 0.03157}{(54 - f)^{-1.2288} + 0.03157} \tag{8}$$

$$\gamma_W = \rho(0.0313 + 0.00173\rho + \frac{3.84 \times g^{22}}{(f - 22.235)^2 + 9.42\xi^2} + \dots + \frac{302.6\xi \times g^{752}}{(f - 752)^2})(f^2 \times 10^{-4}) \tag{9}$$

where, (10) - (13) are supporting (9) and more details are in P.676-5 of [14].

$$g^{22} = 1 + \frac{(f - 22.235)^2}{(f + 22.235)^2} \tag{10}$$

$$g^{557} = 1 + \frac{(f - 557)^2}{(f + 557)^2} \tag{11}$$

$$g^{752} = 1 + \frac{(f - 752)^2}{(f + 752)^2} \tag{12}$$

$$\xi = 0.95 + 0.006\rho \tag{13}$$

Attenuation of water vapor is dependent on σ , the water vapor density (g/m^3) specified in Table II in P.836-3 of [14]. The bigger the σ is, the larger the attenuation is.

TABLE II
WATER VAPOR DENSITY (σ) AT DIFFERENT SEASONS AND REGIONS

	Jan.	April	July	Oct.
Coast (edge of continent)	5	10	20	10
Inland (inside continent)	5	5	10	5
Ocean	20	20	20	20

The noise power [13], P_N is :

$$P_N = k \times T \times B \tag{14}$$

where k is the Boltzmann constant ($1.38 \times 10^{-23} J/K$), T is the temperature in Kelvin, and B is the equivalent bandwidth in hertz.

V. SIMULATION ENVIRONMENTS

This section presents a simulation of the speed estimation using (4). The frequency, the temperature, the pressure, and the bandwidth are set to 2.0GHz, 288K, 1013hPa, and 5MHz, respectively. In Fig. 1, five UAVs are arranged and D_i s are set to 100m, 200m, 300m, 400m, and 500m. The antenna gain of each UAV is set to 0dB, as is the antenna gain of the BS. UAV1 to UAV5 complete their power control by FSPC, therefore each transmission power shown in Table III is different. Then,

UAV1, which is 500m away from the BS, starts to move. CTR is measured at different speed.

BS which has one antenna cannot estimate position of UAV1, only provides speed information. Using three RRH, however, BS can estimate not only the distance, but also position of the target. In Fig. 2, RRH-A sends TPC to UAV1 and estimate distance of UAV1 with calculated CTR. RRH-B and RRH-C cannot send TPC, but can inform Received Signal Strength Indicators (RSSIs) of UAV1 for BS server, then BS server can estimate the position of UAV1 with the ratio of these two RSSIs. If RRH-B and RRH-C have same RSSI, it means UAV1 is in the middle on red line of area2. If RRH-C does not get any radiation from UAV1, it means UAV1 is within area1, vice versa in area3. As UAV1 changes its RF power in every moment by power control, BS server cares the ratio of RSSI only. With this methodology, BS server can track the target distance and position.

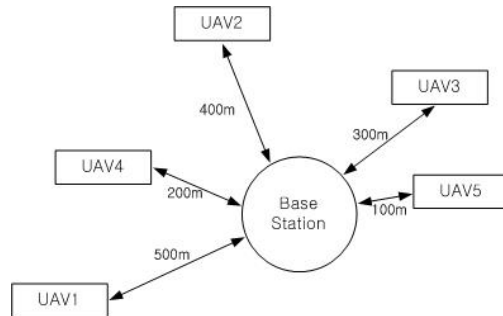


Fig. 1. Simulation formation

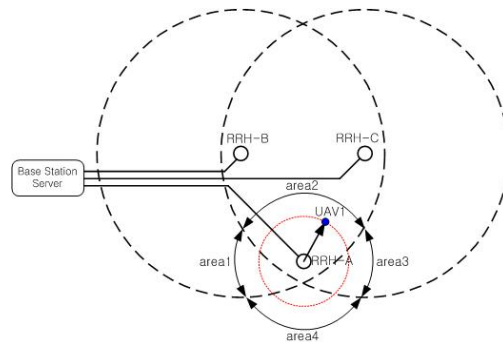


Fig. 2. BS installing Remote Radio Head (dotted line : RF radiation boundary of RRH antenna, red line : UAV1 distance calculated by CTR)

TABLE III
INITIAL CONDITION OF UAV1 TO UAV5

	P_T (dB)	G_T (dB)	G_R (dB)	D_i (m)
UAV1	+3.788	0.0	0.0	500
UAV2	+1.850	0.0	0.0	400
UAV3	-0.650	0.0	0.0	300
UAV4	-4.168	0.0	0.0	200
UAV5	-10.177	0.0	0.0	100

VI. REVIEW OF ALGORITHMS

There are several algorithms addressing inner loop power control, including CTR Step-size Closed Loop Power Control (CS-CLPC) [4], Adaptive Step-size Closed Loop Power Control (AS-CLPC) [8], Fixed Step-size Power Control (FSPC), and Kalman gain Step-size Closed Loop Power Control (KS-CLPC), etc.

This section investigates changes in transmission power for the above four algorithms with the link-budget based SIR. UAV1 moves outward for 42000×0.667 ms (the number of the sample = 42000) at different speeds listed in Table IV.

TABLE IV
UAV1 MOVING DISTANCE FOR 28.0 SEC ($=42000 \times 0.667$ ms).

speed (km/h)	speed (m/s)	moving distance (m)
100	27.7778	0777.78
200	55.5556	1555.56
300	83.3333	2333.33
400	111.1111	3111.11
500	138.8889	3888.89
600	166.6667	4666.67
700	194.4436	5444.42
800	222.2213	6222.19

As UAV1 moves away, the four inner loop power control algorithms alter the transmission power to compensate for the distance between BS and UAV1. Equation (15) [4] measures the CTR as follows:

$$CTR(t) = \sum_{n=t-m+1}^t \frac{sf \times |TPC(n) + TPC(n-1)|}{m} \quad (15)$$

where $m = t$ if $t < w$, and $m = w$ if $t \geq w$. w is the maximum size of the window average.

A. CS-CLPC

Patachianand and Sandrasegaran [4] introduced the CS-CLPC algorithm, where the step-size is adjusted as shown in (16).

$$\delta(t) = \frac{\alpha}{1 - \beta \times \min\{CTR(t), CTR_{max}\}} \quad (16)$$

where α , β , and CTR_{max} are constants.

B. AS-CLPC

Kim, Lee, and Kim [8] suggested the AS-CLPC algorithm. This algorithm adapts its step-size based on TPC history. The step-size is given by (17).

$$\delta(t) = \begin{cases} \delta(t) \times K, & TPC(t) = TPC(t-1) \\ \delta(t)/L, & \text{Otherwise} \end{cases} \quad (17)$$

where K and L are positive real constants with ranges of $1 < K$ and $1 < L < 2$.

C. FSPC

In this simulation, the algorithm uses a fixed step-size.

D. KS-CLPC

The well-known Kalman algorithm [15] for adaptive step-size is used in this simulation.

$$\delta_K(t) = \frac{P_e(t-1)H^T(t)}{H(t)P_e(t-1)H^T(t) + R(t)} \quad (18)$$

$$P_e(t) = (I - \delta_K(t)H(t))P_e(t-1) \quad (19)$$

where $\delta_K(t)$ is a Kalman gain vector, $H(t)$ is the an observation matrix, and $P_e(t)$ is an error covariance matrix at time of t .

VII. SIMULATION RESULTS

Seven different speeds at each conditions are measured with CTR, and the relationships are shown in Fig. 3 to Fig. 4 according to two window sizes. The CS-CLPC, FSPC, and KS-CLPC algorithms show a linear relationship between speed and CTR. Therefore, using the CS-CLPC, FSPC, or KS-CLPC, the speed of the vehicle can be measured by mapping the information from CTR. The AS-CLPC algorithm, however, deviates from linearity. The same results are obtained with different window size.

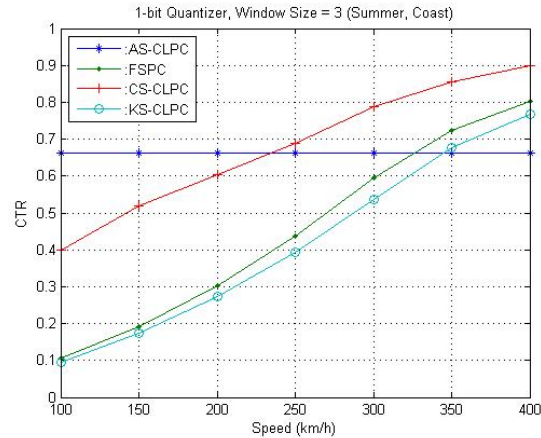


Fig. 3. CTR vs. UAV1 speed at 1-bit Quantizer, window size 3 (Summer, Coast)

For position (1) of table V, RRH-B and RRH-C cannot measure RSSI of UAV1, it means UAV1 is somewhere in area4 in Fig. 5. The ratio of X:loss (X means 'don't care') in position (2) means RRH-C cannot find UAV1, therefore UAV1 is in area1. For the position (3), the ratio 4:6 means the ratio between lineB and lineC is 6:4 in Fig. 5 so that UAV1 is inclined to RRH-C on the red line. This ratio does not reflect exact linearity, but target trajectory can be estimated approximately.

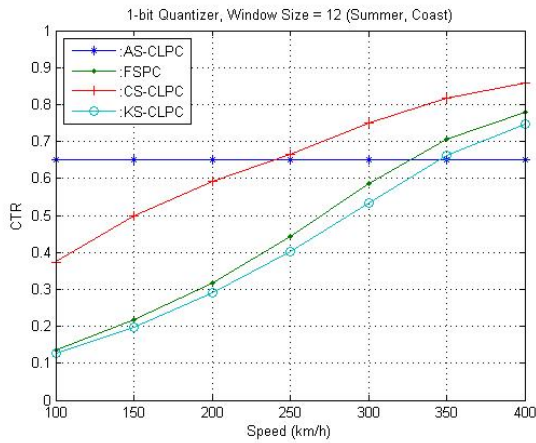


Fig. 4. CTR vs. UAV1 speed at 1-bit Quantizer, window size 12 (Summer, Coast)

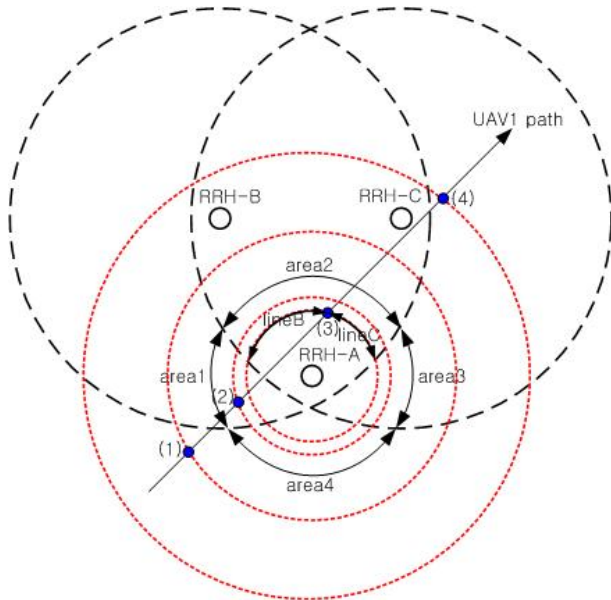


Fig. 5. Distance and Position of UAV1 according to target path

TABLE V
THE RATIO OF RSSI BETWEEN RRH-B AND RRH-C AND UAV1 PATH

Position	CTR of CS-CLPC @ RRH-A	Time (sec)	Moving Distance (m)	RSSI (RRH-B : RRH-C)
(1)	0.6 (=200 km/h)	0	origin (500m from BS)	loss:loss
(2)	0.6 (=200 km/h)	5	277.78	X:loss
(3)	0.6 (=200 km/h)	9	500.00	4:6
(4)	0.6 (=200 km/h)	12	666.67	loss:X

VIII. CONCLUSION

This paper introduced BS server installing three RRHs. One of RRHs provides BS server with target distance, using linearity between speed and CTR. The other two RRHs provide

RSSI ratio between two RRHs for BS server. Then, BS server can calculate target position with distance and ratio.

Future work might be related to distance and ratio error boundary due to timing error.

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