UAV Speed Estimation With Multi-bit Quantizer in Adaptive Power Control

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***Abstract*—The adaptive power control with multi-bit quantizer of Code Division Multiple Access (CDMA) systems for communications between multiple Unmanned Aerial Vehicles (UAVs) with a link-budget based Signal-to-Interference Ratio (SIR) estimate which has distance information is applied to three inner loop power control algorithms. The speed estimation performance of these algorithms with their consecutive Transmit-Power-Control (TPC) ratios are compared to each other, and it is concluded that the speed can be estimated and shows full linearity with the TPC ratio information of Consecutive TPC Ratio Step-size Closed Loop Power Control (CS-CLPC) and Fixed Step-size Power Control (FSPC).**

***Keywords*-speed estimation; adaptive power control; link-budget; SIR; multi-bit quantizer**

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 signal from each UAV may interfere with other UAVs' receivers [1]. This is referred to as the near-far effect. To eliminate the near-far effect in CDMA systems, the transmission signal power from every UAV must be the same as the signal power 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 Position 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]. In this paper, the speed is calculated with SIR estimates. Conventional SIR estimates [3] consider only the transmission power and the link-gain, but this paper takes into account the link-budget, which has more realistic parameters including distance information than the link-gain. Using the SIR estimate that reflects the link-budget, speed estimation [4] is introduced based on a Consecutive Transmit-Power-Control Ratio (CTR) [5]. The proposed speed estimation method is applied to three algorithms with one, two, and three-bit level quantizers, and the results are compared.

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 speed estimation. The simulation results are analyzed in Section VII. Finally, conclusions are drawn in Section VIII.

II. Related work

Kim, Lee, and Kim introduced in [6] 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, Taaghol, and Tafazolli [7] 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. Taaghol [8] 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 [9] 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.

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Patachaianand and Sandrasegaran [5] 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.

Patachaianand and Sandrasegaran [5] 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 [4] the mapping equation and mapping table which can yield accurate speed estimation using CTR.

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 1500Hz, or Sample Time (T_S) (= 0.667ms) 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][5] are represented in (1) and (3).

$$P_i(t+1) = P_i(t) + \delta_i(t) \cdot TPC_i(t) \tag{1}$$

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 ith UAV at time t.

$$x_i(t) = SIR_{target,i}(t) - SIR_i(t) \tag{2}$$

where $SIR_{target,i}(t)$ (=$SIR_{target}(t)$ here) is the target SIR and $SIR_i(t)$ is the received SIR for the ith UAV at time t.

Non-uniform quantizer [10] used in voice coding is introduced that (m+1)-bit TPC is adopted $TPC_i(t) = \{C_0 C_1 \cdots C_m\}$ where C_0 is the sign bit.

$$TPC_i(t) = sign(x_i(t)) \cdot \lfloor \frac{log((1+\mu|x_i(t)|)/R_P)}{(1+\mu)}(2^m - 1) \rfloor \tag{3}$$

where $\mu = 2^{(m+1)}$-1 and R_P is dynamic range of power adjustment.

Table I
TPC Coefficients

m	d	multilevel	R_P
1	0.5	± 1,2	0.1
2	0.25	± 1,2,3,4	0.3
3	0.125	± 1,2,3,4,5,6,7,8	0.5

IV. Link-budget based SIR

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

$$SIR_i(t) = \frac{P_i(t)G_i(t)}{\sum_{j \neq i} P_j(t)G_{ji}(t) + P_N} \tag{4}$$

where $G_i(t)$ is the link-gain between the ith UAV and the connected BS, and $P_i(t)$ is the transmission power from the ith UAV. $G_{ji}(t)$ is the link-gain between the jth UAV and the BS to which the ith UAV connects. Equation (4), however 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

$$SIR_i(t) = \frac{P_{R,i}(t)}{\sum_{j \neq i} P_{R,ji}(t) + P_N} \tag{5}$$

where $P_{R,i}$ is the received power from the ith UAV. $P_{R,ji}$ is the received power from the jth UAV with the BS to which the ith UAV connects. The received power is affected by factors including the free space loss [11] which has distance information and gaseous path loss [12] varied by humidity. Speed estimation can be possible with distance per T_S and $SIR_i(t)$ is measured with $P_{R,i}$ by distance variation.

The power delivered to the receiver [11] is :

$$P_{R,i} = G_{T,i} \cdot P_{T,i} \cdot G_{R,i}/(L_F(D_i) \cdot L_G(D_i)) \tag{6}$$

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 receive antenna gain of the ith 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 which has distance information. D_i is the distance between the ith UAV and the BS in kilometers.

$$L_F(D_i)(dB) = 92.44 + 20log_{10}(F) + 20log_{10}(D_i). \tag{7}$$

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 (8).

$$L_G(D_i) = (\gamma_0 + \gamma_W) \cdot D_i. \tag{8}$$

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P.676-5 of [12] shows equations of γ_0 (attenuation for dry air) and γ_W (attenuation for water vapor). These attenuations are dependent on σ, the water vapor density (g/m^3) specified in Table II from P.836-3 of [12]. The bigger the σ is, the larger the attenuation is.

Table II
WATER VAPOR DENSITY 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 [11] is :

$$P_N = k \cdot T \cdot B \tag{9}$$

where k is the Boltzmann constant (1.38×10^{-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 (5). The frequency, the temperature, the pressure, the water vapor density, and the bandwidth are set to 2.0GHz, 288K, 1013hPa, 20 (Summer in Coast), and 5MHz, respectively. In Figure 1, five UAVs are arranged and D_is are set to 250m, 500m, 750m, 1000m, and 1250m. 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 so that each transmission power shown in Table III is different. Then, UAV1, which is 1250m away from the BS, starts to move outward. It moves at five different speeds and measures the CTR at each speed. SIR_{target} is set to the transmission power of UAV3 on this simulation. This simulation applies one UAV movement and outward/inward direction only.

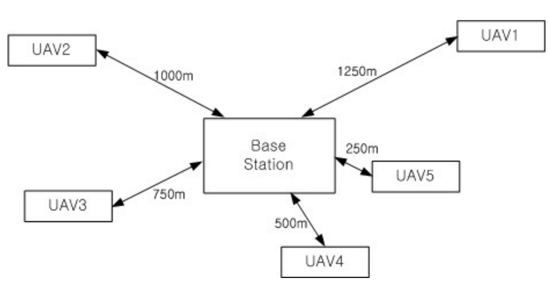

Figure 1. Simulation formation

VI. SPEED ESTIMATION

There are several algorithms addressing inner loop power control, including CTR Step-size Closed Loop Power Control (CS-CLPC) [5], Adaptive Step-size Closed Loop Power Control (AS-CLPC) [6], Fixed Step-size Power Control (FSPC), etc.

Table III
INITIAL CONDITION OF UAV1 TO UAV5

	P_T (dB)	G_T (dB)	G_R (dB)	D_i (m)
UAV1	+8.048	0.0	0.0	1250
UAV2	+4.314	0.0	0.0	1000
UAV3	+0.000	0.0	0.0	750
UAV4	-5.229	0.0	0.0	500
UAV5	-13.979	0.0	0.0	250

This section investigates changes in transmission power for the above three algorithms with the link-budget based SIR. UAV1 moves outward for 42000*0.667ms (the number of the sample = 42000) at the six different speeds listed in Table IV; 100km/h, 200km/h, 300km/h, 400km/h, 500km/h, and 600km/h. As UAV1 moves away, the three inner loop power control algorithms alter the transmission power to compensate for the distance between BS and UAV1. A faster mobile is likely to receive more consecutive TPC command than a slower one. Therefore, average of CTR on certain period can be used to reflect user speed. Equation (10) [5] measures the CTR as follows:

Table IV
UAV1 MOVING DISTANCE FOR 28.0 SEC (=42000*0.667ms).

speed (km/h)	speed (m/s)	moving distance (m)
100	27.7778	777.78
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

$$CTR(t) = \sum_{n=t-m+1}^{t} \frac{d \cdot \mid TPC(n) + TPC(n-1) \mid}{m} \tag{10}$$

where d is a scale factor (see Table I), $m = t$ if $t < w$, and $m = w$ if $t \geq w$. w is the maximum size of the window average.

A. CS-CLPC

Patachaianand and Sandrasegaran [5] introduced the CS-CLPC algorithm, where the step-size is adjusted as shown in (11).

$$\delta(t) = \frac{\alpha}{1 - \beta \cdot min\{CTR(t), CTR_{max}\}} \tag{11}$$

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

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B. AS-CLPC

Kim, Lee, and Kim [6] suggested the AS-CLPC algorithm. This algorithm adapts its step-size based on TPC history. The step-size is given by (12).

$$\delta(t) = \begin{cases} \delta(t) \cdot K, & TPC(t) = TPC(t-1) \\ \delta(t)/L, & Otherwise \end{cases} \quad (12)$$

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.

VII. Simulation results

Six different speeds are measured with CTR, and the relationships are shown in Figure 2 to Figure 7 according to two window sizes and three quantizers. The CS-CLPC and FSPC algorithms show a linear relationship between speed and CTR, in addition they show more linearity and can estimate higher speed as quantizing bits are increased. Therefore, using the CS-CLPC or FSPC, the speed of the vehicle can be measured by mapping the information from CTR. The AS-CLPC algorithm, however, deviates from linearity. In addition, the same results are obtained with different window sizes.

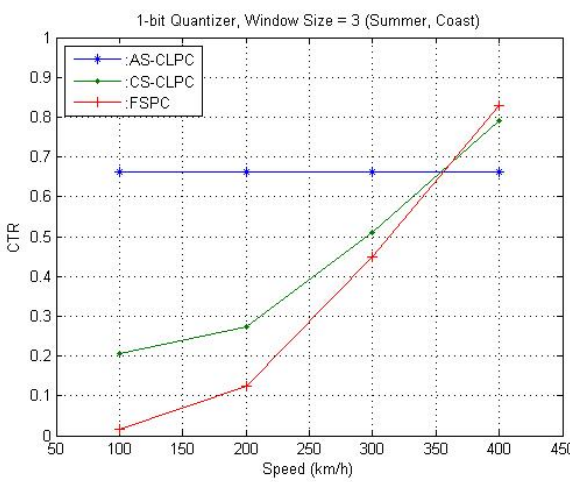

Figure 2. CTR vs. UAV1 speed at 1-bit Quantizer, window size 3 (Summer, Coast)

VIII. Conclusion and Future Work

This paper introduced a speed estimation of three different inner loop power control with consecutive TPC ratios which use the link-budget based SIR in the CDMA communication systems between UAVs. It was concluded that linear relationship exists between speed and Consecutive TPC Ratios, and that UAV speed can be estimated using the Consecutive TPC Ratios of the CS-CLPC and FSPC algorithms.

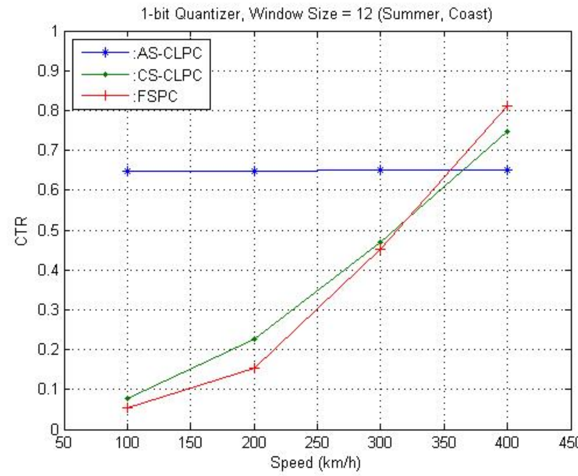

Figure 3. CTR vs. UAV1 speed at 1-bit Quantizer, window size 12 (Summer, Coast)

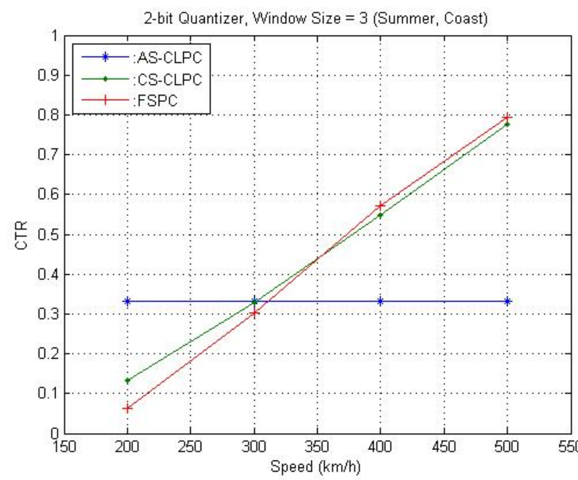

Figure 4. CTR vs. UAV1 speed at 2-bit Quantizer, window size 3 (Summer, Coast)

Future work might be applying this concept to urban fading environments, applying with GPS/INS for more precise speed estimation, or finding the linearity on closed loop power control with Kalman gain step-size.

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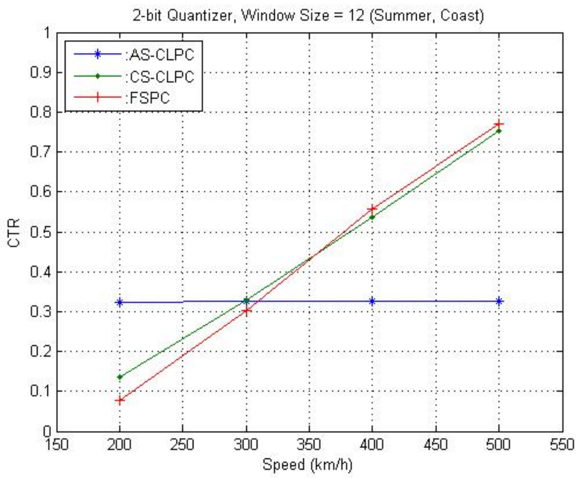

Figure 5. CTR vs. UAV1 speed at 2-bit Quantizer, window size 12 (Summer, Coast)

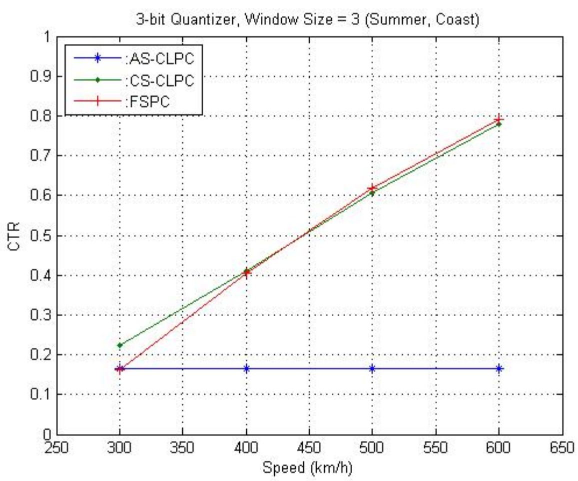

Figure 6. CTR vs. UAV1 speed at 3-bit Quantizer, window size 3 (Summer, Coast)

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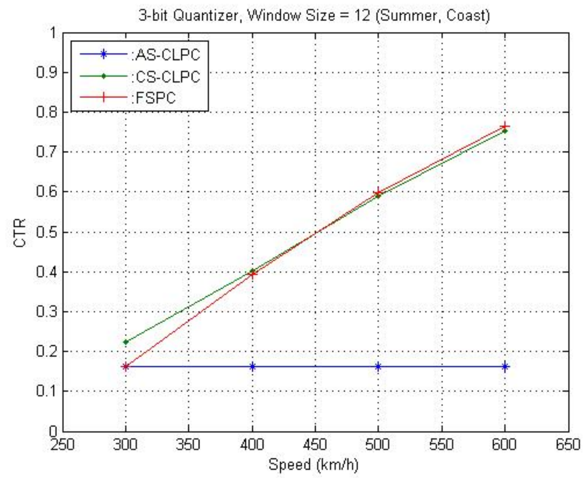

Figure 7. CTR vs. UAV1 speed at 3-bit Quantizer, window size 12 (Summer, Coast)

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