Reducing Acquisition Times for Hybrid DS/FH Spread Spectrum Signals

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Abstract - **This paper presents new types of hybrid direct sequence (DS)/frequency hopping (FH) signals exhibiting traceability that can be used to assist in synchronization and acquisition of the signal. A parallelism is made between the traceability of a DS signal, FH signal, and three types of hybrid DS/FH signals: fast hopping, slow hopping and synchronized hopping. The narrow band autoambiguity function (NBAAF) is the mathematical tool used to study the effects of synchronization time and frequency mismatches for each signal.**

I. INTRODUCTION

Various hybridization schemes of frequency hopping and direct sequencing have found application in mobile radio. The combination of spread spectrum signals improve the bandwidth efficiency of the signaling scheme. This paper discusses the incorporation of a signal design technique, traceability, to assist in the synchronization and acquisition process. Three types of hybrid signals, slow hopping, fast hopping, and synchronized hopping, are discussed in terms of introducing traceability to the signal.

Traceability is a quality exhibited by fast frequency hopping signals based on linear congruence codes. This quality greatly reduces the initial acquisition time of the signal. Most spread spectrum signals are constructed assuring that the energy coherently sums to a peak that is detected when the receiver is optimally synchronized in time and frequency. This approach is extremely inefficient during acquisition. Traceability designs in "road signs" in place directing the synchronization process. The "road signs" are formed by signal energy coherently summing to a detectable peak for time and frequency mismatches. In order to use them to assist in the synchronization process, the peaks differ in size and in location relative to the main peak. In Figure 1, an illustration shows the energy peaks used to navigate through the time and frequency adjustments. Each axis represents a synchronization adjustment required to achieve perfect synchronization.

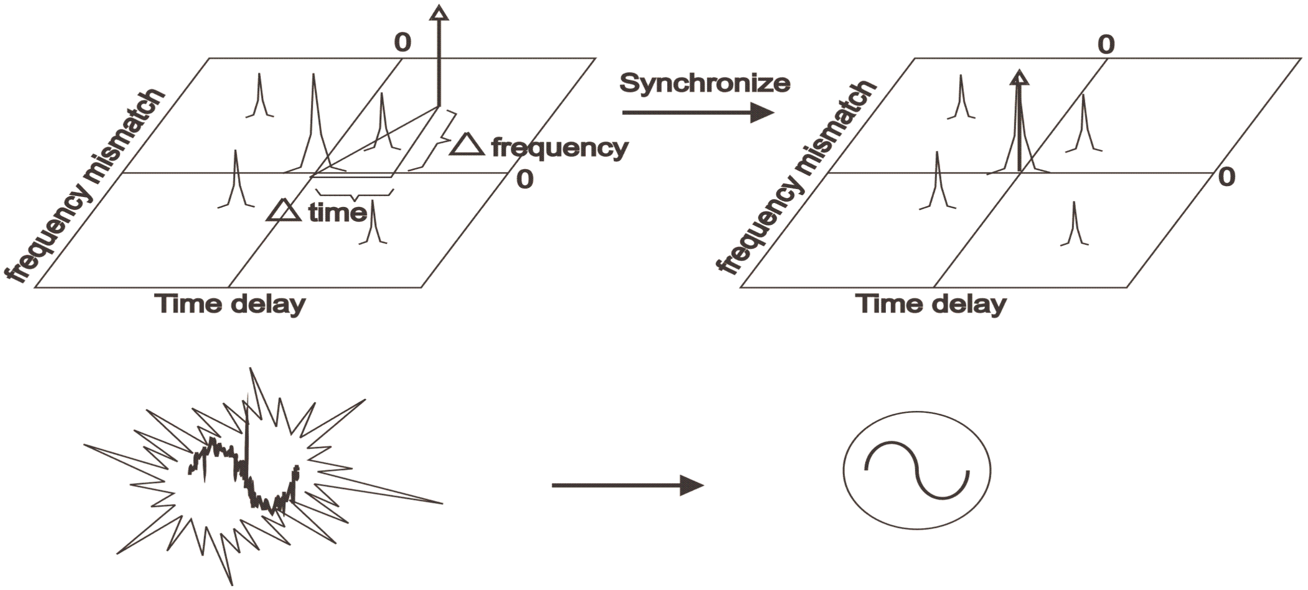

Fig. 1.Illustration of Traceability Used in Assisting Synchronization

By coherently combining frequency hopping (FH) with direct sequence (DS) spread spectrum signals so that traceability is maintained, one significantly reduces the acquisition time for the multi-user communication system. Linear congruence coded FH signals are maximally traceable [4][10] and add the necessary traceability to the narrowband autoambiguity function (NB AAF- see [1][2][3][4]).

It is demonstrated in this paper that the timing relationship between the frequency hopping and direct sequencing must be maintained for traceability. In the next section, the hybrid DS/FH spread spectrum signals are described. The third section discuss the NB AAF, which is interpreted as a plot of signal energy as a function of synchronization time and frequency mismatch. Traceability of the new signals is evaluated in this section. The paper concludes with the fourth section discussing future work.

II. HYBRID DS/FH SPREAD SPECTRUM SIGNALS

A variety of hybrid DS/FH signals have been presented in recent years ([13][14][15]). Key characteristics of these signals include fast, slow, coherent, and noncoherent frequency hopping relative to the direct sequence signal. This paper focuses on a hybrid DS/FH signal with coherent frequency hopping and a variety of relationships between the FH chip rate and the DS chip rate. The first assumes a hopping rate that is equal and synchronized to the DS chip rate. The second assumes a faster FH chip rate than the DS chip rate. The third and final category assumes FH chip rates that are slower than the DS chip rates.

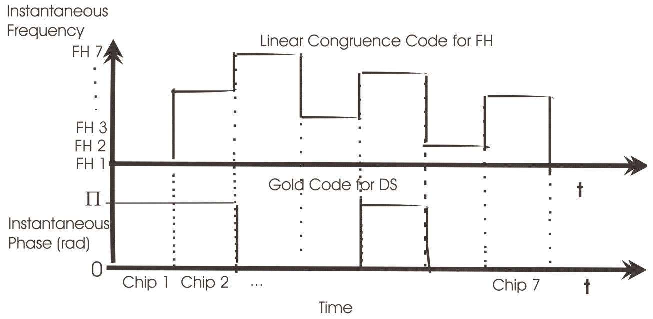

Fig. 2.Illustration of the Synchronized Hybrid DS/FH Waveform

The first form of hybrid DS/FH signal can be derived after considering Figure 2, which illustrates an FH signal and a DS signal with a synchronized chip rate. The FH signal is generated using the linear congruence code and 7 hops. However, the DS signal is based on the gold code sequence. A hybrid FH/DS signal combines the advantages of both types of spreading. Frequency hopping provides more control to avoid interference. Direct sequence spreading takes an averaging approach to reducing interference. An analytical expression for the hybrid signal is

$$s(t) = A_c \sum_{k=0}^{N-1} p\left(t - k\frac{T}{N}\right) \bullet e^{j((\omega_c + \omega_k)t + \theta_k + \theta_i)} \tag{1}$$

where A_c is a normalization constant, ω_c is the carrier frequency of the signal, *T* is the coherent integration time of the signal, *N* is the number of chips coherently integrated, and θ_i is the initial phase. Equation (1) assumes the signal meets the narrowband criteria [1][10]. The gating pulse in (1) is defined as

$$p(t) = \begin{cases} 1, 0 \le t \le \dfrac{T}{N} \\ 0, elsewhere \end{cases} . \tag{2}$$

The DS code controls the instantaneous phase by

$$\theta_k = M_k\frac{\pi}{2} + \frac{\pi}{2} \tag{3}$$

where M_k has a value of -1 or 1 from the Gold code. The frequency hopping controls the instantaneous frequency from

$$\omega_k = y_k\frac{B}{G} \tag{4}$$

where *G* is the total number of frequency hops, *B* is the total bandwidth covered by the frequency hops, and *u(t)* is the unit step function. The placement operator for traceable frequency hopping is based on the linear congruence code or

$$y_k \equiv ak(modG) . \tag{5}$$

For faster hopping signals, the analytic expression is more complex and is expressed by

$$s(t) = \frac{1}{\sqrt{T}} \sum_{j=0}^{N-1} p\left(t - j\left(M\frac{T}{N}\right)\right) \bullet \sum_{k=0}^{M} p\left(\left(t - f(j,k)\left(\frac{T}{N}\right)\right) e^{j(\omega_c + \omega_{f(j,k)} + \theta_j + \theta_i)}\right) \tag{6}$$

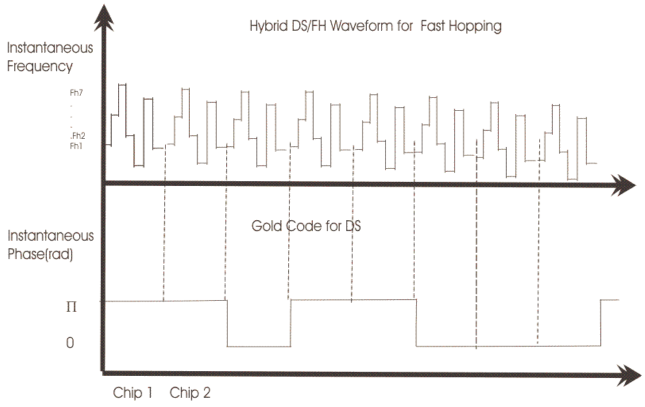

Fig. 3.Illustration of Hybrid DS/FH waveform with Higher FH Chip Rates

where M is the number of frequency hops per DS chip, N is the total number of DS chips coherently integrated, and θ_i is the initial phase of the waveform. Figure 3 illustrates this hybrid DS/FH with a fast FH chip rate. The initial phase is assumed to be 0 radians simplifying the solution. The FH chip rate is a function of both *j* and *k* or

$$f(j,k) = Mj + k\,. \tag{7}$$

The first gating pulse has a longer duration by a factor of *N* than the second gating pulse so that the frequency hops occur more rapidly than the DS chip phase changes. However, the two rates remain synchronized with each other through $f(j,k)$.

The final type of hybrid signal has a higher DS chip rate than the FH chip rate. This is illustrated in figure 4. The analytic expression is similar in complexity to (6) or

$$s(t) = \frac{1}{\sqrt{T}}\sum_{j=0}^{N-1} p\left(t - j\left(M\frac{T}{N}\right)\right) \quad . \tag{8}$$

$$\sum_{k=0}^{M} p\left(t - f(j,k)\left(\frac{T}{N}\right)\right) e^{j((\omega_c + \omega_j)t + \theta_{f(j,k)} + \theta_i)}$$

In this signal, the Gold code changes the phase more rapidly than the frequency hops.

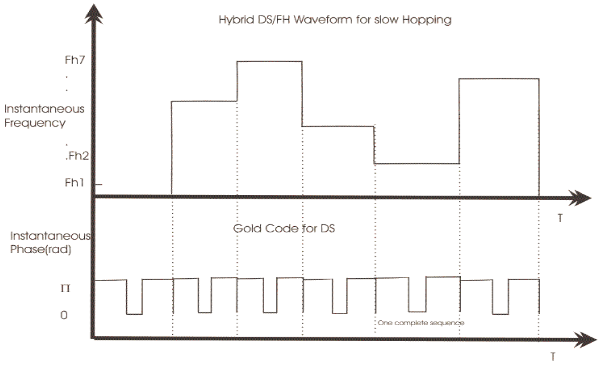

Fig. 4.Illustration of Hybrid DS/FH Waveform with Slow FH Chip Rates

III. TRACEABILITY OF THE HYBRID DS/FH SIGNALS

Traceability can be analytically determined using the narrowband autoambiguity function and determining where the energy coherently integrates to a local, detectable peak. The narrowband autoambiguity function is computed by substituting the analytic expressions from the previous section into

$$\chi(\tau,\omega) = \int_{-\infty}^{\infty} s(t)s^{*}(t-\tau)e^{-j\omega t}dt \tag{9}$$

where τ represents a time mismatch, and ω represents a frequency mismatch between the signal and its replica in the matched filter. These values control the synchronization process in the receiver. More detectable peaks in this 2-dimensional plane indicate greater traceability. These detectable and predictable peaks assist in the system synchronization. A traceability measure is the number of grating lobes exceeding 3 dB in the mainlobe region. For example in figure 7, there are 12 peaks (a traceability measure) to derive synchronization information. In contrast, figure 6 contains a single detectable peak indicative of nontraceable DS signals. This lack of traceability leads to longer synchronization times and false synchronization events. By adding frequency hopping to the DS signal, detectable peaks are created in the NB AAF that add traceability and can be used to reduce the synchronization time.

The NB AAF of hybrid DS/FH signals with equal FH and DS chip rates resembles that of the FH signal. It can be expressed as

$$\chi(\tau,\omega) = \frac{1}{T}e^{j\omega_c\tau}\sum_{k=0}^{N-1}\sum_{l=0}^{N-1} e^{j\left(y_l\left(\frac{B}{N}\right)\tau - k\left(\frac{T}{N}\right)\omega\right)} \tag{10}$$

$$\bullet\, e^{j(\theta_k - \theta_l)} e^{j\left(k\left(\frac{BT}{N^2}\right)(y_k - y_l)\right)}$$

$$\bullet\, \chi_p\left(\tau - (k-l)\frac{T}{N}, \omega - (y_k - y_l)\left(\frac{B}{N}\right)\right)$$

The NB AAF for the gating function in (10) is

$$\chi_p(\tau, \omega) = \int_{-\infty}^{\infty} p(t)p(t-\tau)e^{-j\omega t}dt \quad . \tag{11}$$

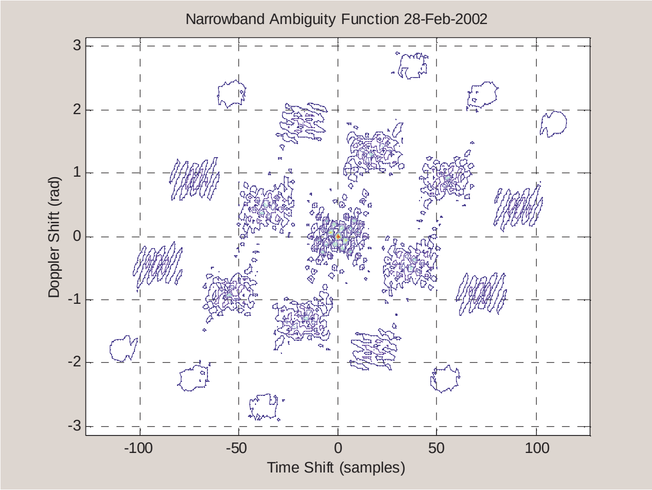

Fig. 5.NBAAF of hybrid DS/FH

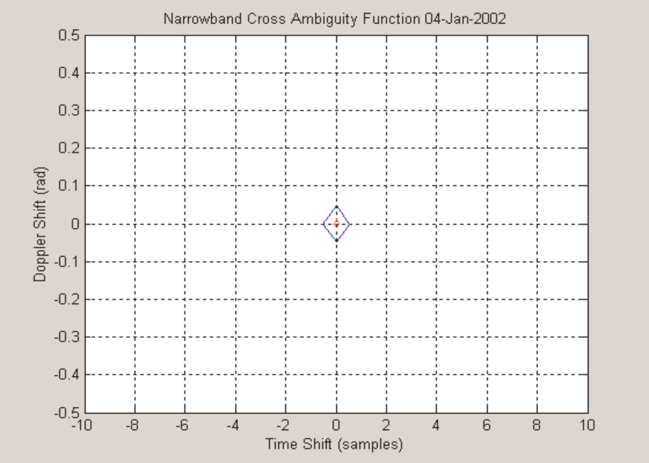

Fig. 6.NBAAF of DSSS signal

Traceability results due to grating lobes forming at certain (τ, ω) locations. This occurs when the argument of the first exponential term in (10) is a multiple of 2π for every combination of *k* and *l* for that (τ, ω). The remaining exponential terms in (10) are already multiples of 2π. The problem of finding the peaks of the grating lobes simplifies down to solving a system of equations from

$$y_l\left(\frac{B}{N}\right)\tau - k\left(\frac{T}{N}\right)\omega = 2\pi\Lambda \tag{12}$$

where Λ is any integer. Figure 8 illustrates the lines described by (12) superimposed on the NB AAF contour plot. One notes that the intersection of the lines do coincide with the centers of the grating lobes. The noise added by the DS signal removes some of the detectable peaks decreasing the overall traceability from 12 to 5.

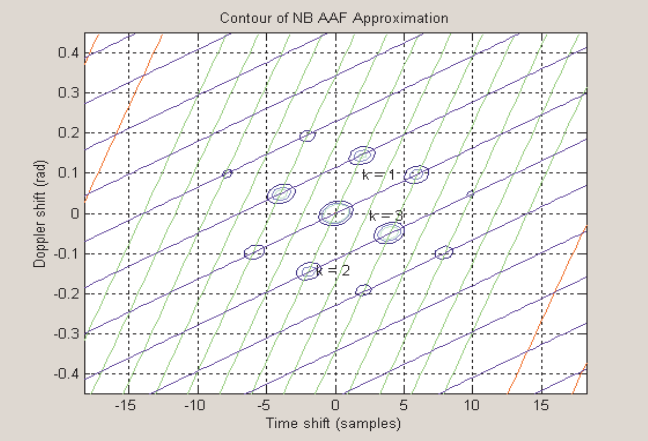

Fig. 7.Mainlobe Region of FH Signal with Contours Exceeding 3 dB

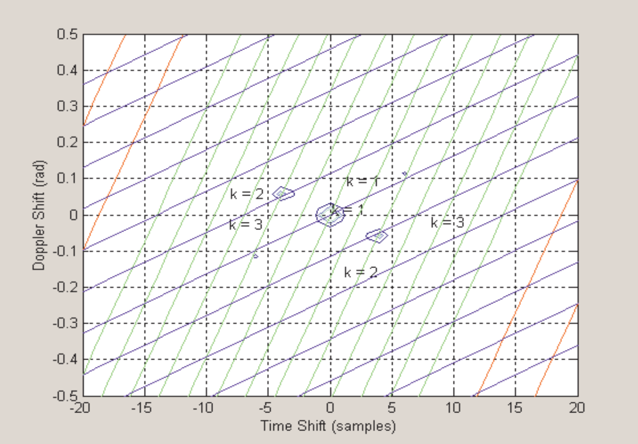

Fig. 8.NB AAF of Hybrid Synchronized FH/DS (contours exceed 3 dB)

The second type of hybrid FH/DS exhibits some traceability but it has been reduced. The NB AAF becomes extremely complex to analyze. It is not presented here because it does not provide much insight. However, lines do emerge similar to those described by (12). The lines shift as their ω intercept shifts by π due to the incorporation of the DS signal. In hybrid DS/FH, the second exponential term may now either be 1 or -1 depending on

$$\theta_k - \theta_l = 0, \pi . \tag{13}$$

The line intercepts are now found from

$$y_{f(l,k)}\left(\frac{B}{N}\right)\tau - f(l,k)\left(\frac{T}{N}\right)\omega + \theta_k - \theta_l = 2\pi\Lambda . \tag{14}$$

Figure 9 and figure 10 contain the resulting grating lobes and the superimposed lines from the FH signal's NB AAF. A different set of grating lobes now emerge and others disappear into the noise. However, the peaks still occur at the line intercepts. Although the traceability is reduced, it still exists.

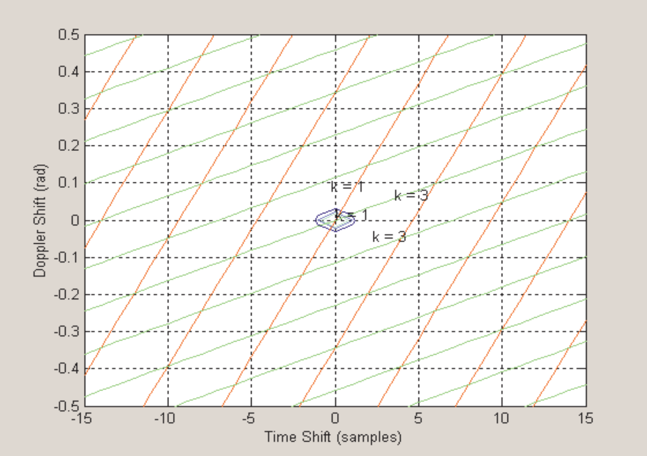

Fig. 9.Hybrid DS/FFH Mainlobe of NB AAF with 3 dB Contours

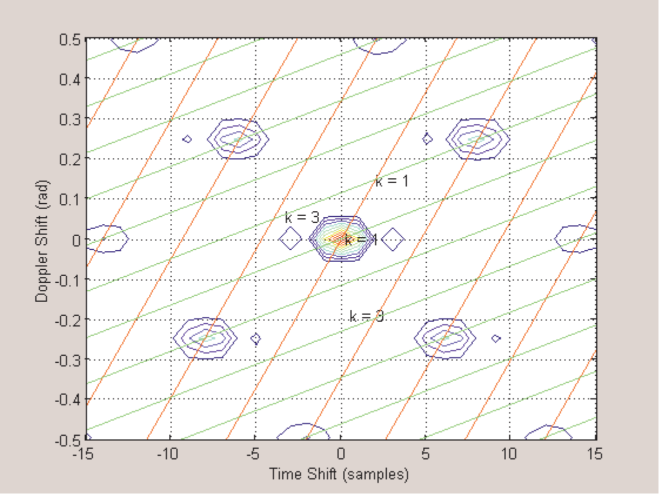

Fig. 10.Hybrid DS/FFH Mainlobe Region of NB AAF

In the final type of hybrid DS/FH signal, the DS chipping rate is faster than the FH chip rate. This is similar to summing coherently the NB AAF of multiple CDMA signals shifted in frequency. The DS signal destroys all traceability in the signal. In other words, (13) now has a phase that rapidly varies spreading all the grating lobes into the noise. This is illustrated in Figure 12.

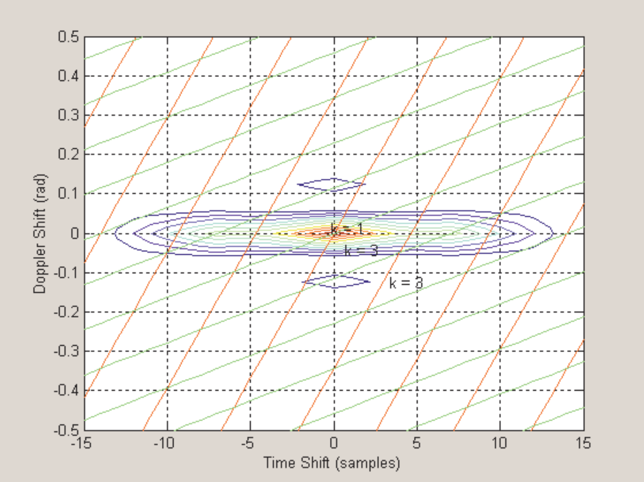

Fig. 11.Hybrid DS/SFH Mainlobe Region of NB AAF with 10 Contours

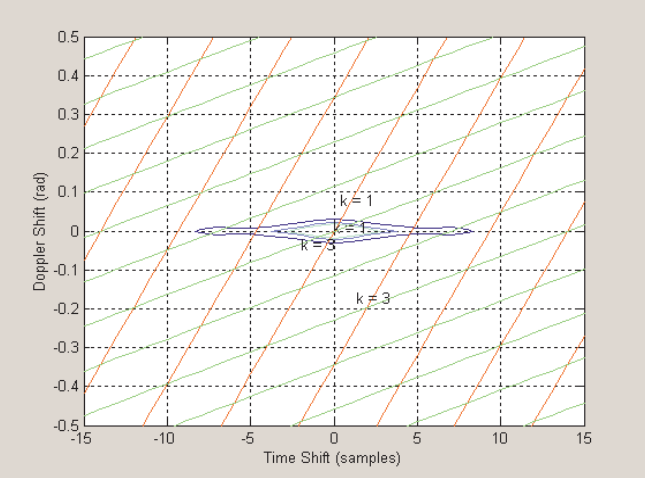

Fig. 12.Hybrid DS/SFH Mainlobe Region of NB AAF with 3 dB Contours

IV. CONCLUSIONS AND FUTURE WORK

The combining of direct sequencing and frequency hopping can be coordinated so that traceability is either enhanced or destroyed. Traceability can be incorporated into a DS signal by adding fast frequency hopping. The FH chip rate must be equal to or an integer multiple of the DS chip rate in order to maintain traceability. If the FH chip rate is faster than the DS chip rate, some traceability will be lost.

Future work will be done analyzing the effects of the traceability degradation on synchronization time and false synchronization events. A variety of synchronization algorithms that take advantage of this traceability pattern will also be designed.

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