COMPATIBILITY OF FM HYBRID IN-BAND ON-CHANNEL (IBOC) SYSTEM FOR DIGITAL AUDIO BROADCASTING

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ABSTRACT

A robust In-Band On-Channel (IBOC) Digital Audio Broadcast (DAB) System for improved performance over existing FM broadcasting is under development by Westinghouse for USA Digital Radio. Both the analog FM and the DAB signals are transmitted simultaneously in the FM Hybrid IBOC system. Broadcasters can simultaneously transmit both analog and digital signals within the allocated channel mask, allowing full compatibility with existing analog receivers. It is shown here that the solution is tolerant of interference from adjacent channels, or interference from the co-channel analog transmission, even in a multiple station, strong-signal urban market. Although the primary focus of this paper is to discuss the compatibility issues between the existing FM and the DAB signals, the paper also briefly describes spectral occupancy, power ratios, modulation formats, and coding, as well as the introduction of frequency and time diversity.

I. INTRODUCTION AND BACKGROUND

Digital Audio Broadcasting is a medium for providing digital-quality audio, superior to existing analog broadcasting formats. The advantages of digital transmission for audio include better signal quality with less noise and wider dynamic range than with existing FM radio. The goal of FM IBOC DAB is to provide virtual-CD-quality stereo audio along with an ancillary data channel with optional capacity up to 64 kbps, depending upon a particular station's interference environment. The development of new high-quality stereo codec algorithms indicates that virtual-CD stereo quality will soon be practical at rates as low as 96 kbps. IBOC requires no new spectral allocations because each DAB signal is simultaneously transmitted within the same spectral mask of an existing allocation. IBOC DAB is designed, through power level and spectral occupancy, to be transparent to the analog radio listener. IBOC promotes economy of spectrum while enabling broadcasters to supply digital quality audio to their present base of listeners.

An independent technical evaluation conducted by *the Deskin Research Group* in 1996 revealed various weaknesses [1] in the previously proposed FM IBOC systems [5]. These deficiencies included DAB interference to host, first and second adjacent interference, and lack of robustness in multipath fading. These deficiencies were addressed in subsequent development work as reported in [2], and substantially eliminated in the new design which has evolved since the *Deskin* study.

II. BRIEF FM OFDM IBOC SYSTEM DESCRIPTION

A brief description of the IBOC simulation model is presented here. Several modulation techniques were evaluated for the IBOC DAB application, including multicarrier spread spectrum, high-rate single carriers and Orthogonal Frequency Division Multiplexing (OFDM). Tradeoff analyses led to the selection of OFDM. OFDM modulation has been shown to be tolerant of multipath fading when used in conjunction with FEC coding and interleaving. Furthermore, OFDM can be tailored to fit an interference environment that is nonuniform across frequency, while also providing flexibility for additional optional subcarriers.

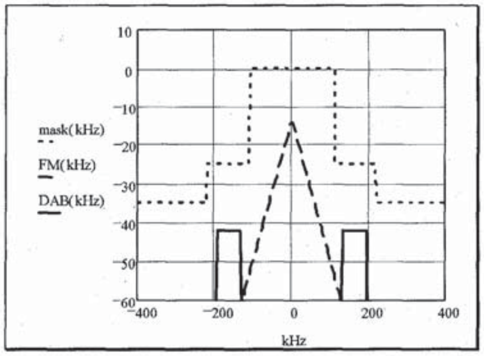

Figure 1. Power spectral densities of FM and DAB signals below FM spectral mask.

The DAB signal is transmitted on OFDM subcarriers located on either side of the analog spectrum. A spectral mask along with the FM and DAB power spectral densities is presented in Figure 1. Note that the FM spectral mask is defined as peak power measured in a 1-kHz bandwidth over any 5-minute interval. The power spectral density for the FM signal was empirically determined by power-averaging the FM spectrum over 5 minutes. Five stations in the Baltimore/Washington area exhibited the triangular power spectral density with a slope between 0.35 and 0.38 dB/kHz. Interestingly the stations measured included diverse signals ranging from "heavy metal" music to talk. The average slope of the 5 stations is 0.36 dB/kHz, which is assumed for the modulated spectral plots.

The total FM power can be found by integrating the triangular power spectral density.

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$$P_{total} = \int_{-\infty}^{\infty} P_{peak} \cdot 10^{-0.36 \cdot |f|/10} \cdot df = 24.12747 \bullet P_{peak}$$

Then the peak of the FM power spectral density is located 13.8 dB ($10 \cdot \log(24.12747)$) below the total carrier power reference level (0 dB), as shown in Figure 1. The DAB power level on each side of the FM spectrum is placed 25 dB below the total FM power (this value is adjustable by the broadcaster to accommodate special interference situations). The DAB density in a 1-kHz bandwidth can be calculated. The power spectral density of the DAB signal can be very closely approximated by dividing its total power by its effective Nyquist Bandwidth.

$$PSD_{DAB} = \frac{10^{-25/10}}{81 \cdot 0.796875} = 4.9 \cdot 10^{-5}$$

Then the power spectral density of the DAB signal in dB, as shown in Figure 1, is computed to be -43 dB/kHz ($10 \cdot \log(4.9 \cdot 10^{-5})$).

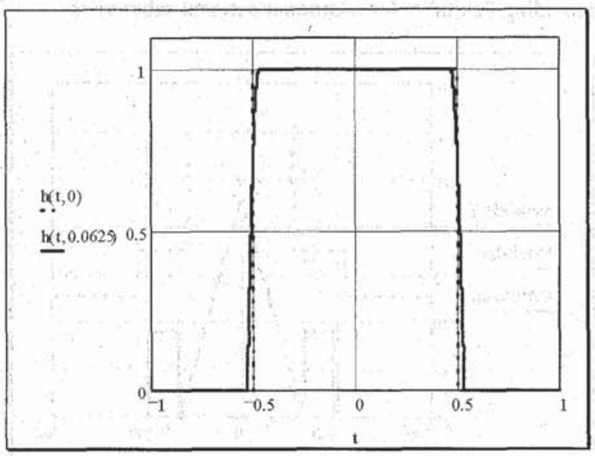

Figure 2. Plot showing rectangular Nyquist pulse (dotted) and the root raised cosine tapered pulse (solid).

The baseline DAB system assumes 95 subcarriers above and 95 below the host FM spectrum. Each DAB subcarrier is QPSK modulated at a symbol rate of approximately 689 Hz. The inphase and quadrature pulse shapes are root-raised-cosine tapered (excess time=7/128) at the edges to suppress the spectral sidelobes. Although this pulse shape reduces the throughput capacity relative to the rectangular pulse by 5.5%, performance in multipath is improved and the resulting spectral sidelobes are reduced, lowering interference. This pulse shape results in orthogonal subcarrier frequency spacing of approximately 727 Hz. A plot of the pulse shape normalized to 1 unit of time is presented in Figure 2. Figure 3 shows plots of one of the two sidebands of the DAB spectra using both the rectangular and root-raised-cosine pulse shapes.

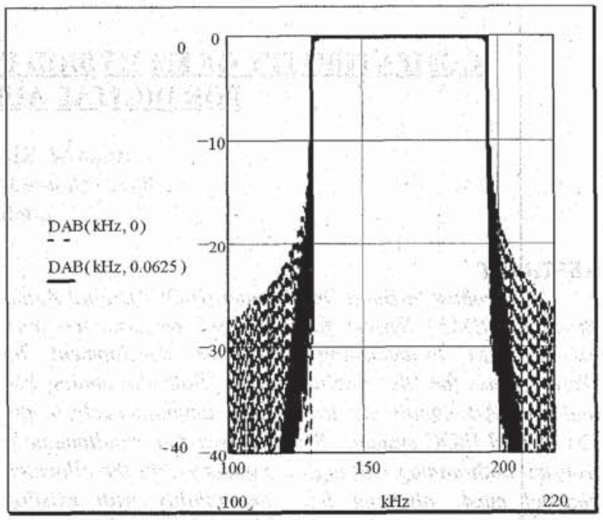

Figure 3. Improved spectral sidelobe suppression of Nyquist root raised cosine tapered pulse (solid) and rectangular Nyquist pulse (dotted).

Potential subcarrier locations are identified by their offset from the host FM center frequency. These subcarriers are indexed from zero at the center FM frequency to plus or minus 273 near the edges of the 400 kHz bandwidth. Subcarriers 179 through 273 correspond to 130087 Hz to 198402 Hz from the center. These subcarriers carry about 105 kbps of information which is error protected with a rate 2/5 FEC. This data rate is sufficient for transmission of virtual-CD quality music plus a modest datacasting capacity. Optionally, additional carriers can be added to increase the datacasting capacity. These carriers would be located closer to the host analog FM signal.

The placement of DAB at ± 15 kHz about 114 kHz is avoided in the baseline system in order to reduce the noise introduced into inadequately filtered receivers. However the broadcaster will have the option to utilize this portion of the spectrum to improve robustness of the digital audio signal and/or to provide additional datacasting capacity.

FEC Coding

Forward error correction and interleaving improve the reliability of the transmitted information. In the presence of adjacent channel interference, the outer OFDM subcarriers are most vulnerable to corruption, and the interference on the upper and lower sidebands is independent. The information, coding, and interleaving are specially tailored to deal with this nonuniform interference such that the communication of information is robust. Specifically, this nonuniform interference is the focus here where special coding and error handling results in more robust performance.

The IBOC DAB system will transmit all the digital audio information on each DAB sideband (upper or lower) of the FM carrier. Recall that the baseline system constrains the

DAB signal to within approximately 130 kHz to 199 kHz above and below the FM center frequency, as shown in Figure 1. Each sideband can be detected and decoded independently with an FEC coding gain achieved by a rate-4/5 convolutional code on each sideband. This redundancy permits operation on one sideband while the other is corrupted. However, usually both sides are combined to provide additional signal power and coding gain. Furthermore, special techniques are employed to demodulate and separate strong first adjacent interferers such that a "recovered" DAB sideband can supplement the opposite sideband to improve coding gain and signal power over any one sideband.

The goal here is to transmit the DAB signal on both the upper and lower sidebands such that the sidebands can be independently detected and decoded, each with some FEC coding gain. Additional coding gain, along with some power gain of course, is desired when both sidebands can be combined. The reason for these requirements is that the interference on each sideband is independent of the other; however, the level of interference across the subcarriers on any one sideband is related to the power spectral density of the adjacent interferer. Therefore the grouping of independently detectable and decodable sidebands is appropriate.

In order to effectively achieve coding gain when the pair of sidebands is combined, the code on each sideband should consist of a subset of a larger (lower rate) code. Each subset can be designed through "complementary" puncturing of the lower rate code. Details of the FEC design are presented in [2].

III. INTERFERENCE ANALYSIS

The interference to and from the first adjacent channels placed ± 200 kHz from the host signal can be derived from the relationship of the adjacent signals shown in the plot of Figure 4. FM stations are geographically placed such that the nominal received power of an undesired adjacent channel is at least 6 dB below the desired station's power at the edge of its coverage area. Then the D/U (desired to undesired power ratio in dB) is at least 6 dB. Knowledge of the ratio of each station's DAB signal power to its FM host permits assessment of first adjacent interference to DAB. Similarly the interference of the first adjacent DAB to the host FM signal can be assessed from the relationship.

Figure 5 illustrates the need for DAB spectral sidelobe suppression and bandlimiting due to the second adjacent DAB interference to the host DAB signal. At a station's edge of coverage, a second adjacent's nominal power can be up to 20 dB greater than the host's nominal power.

The effects of the various interference scenarios illustrated here are quantified through analysis and supported through simulation and testing. Analysis of the DAB to first adjacent interference at the edge of coverage showed that the total DAB signal should be set about -22 dB relative to its FM power.

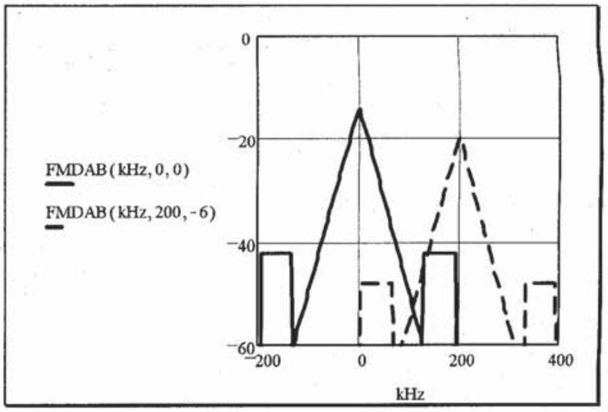

Figure 4. Interference scenario showing first adjacent at -6 dB (worst case edge of coverage).

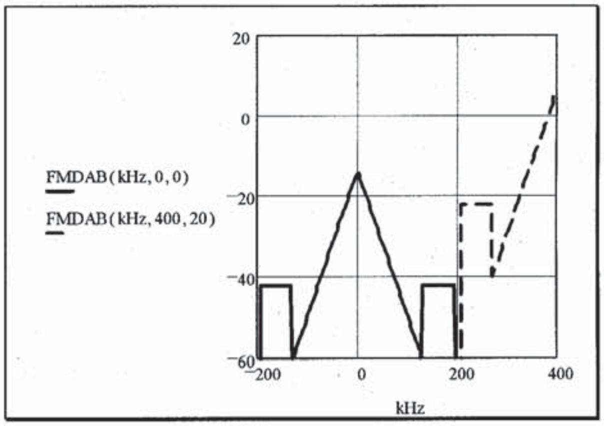

Figure 5. Interference scenario with second adjacent at +20 dB.

The solution to the first adjacent interference problem is to place redundant, although not identical, DAB signals on either side of the carrier. Although the potential capacity is halved with this redundancy, interference problems are substantially reduced and substantial coding gain is achieved after combining both halves. A survey of existing U.S. radio allocations shows that it is very unlikely that both upper and lower adjacent channel interferers are present at their maximum interference levels (-6 dB) at the same geographic location within the host's coverage area. This frequency diversity is especially useful when multipath interference or spectral notches affect one sideband or the other.

A variety of simulations and analyses have characterized performance of the host FM signal in the presence of IBOC DAB. Specifically, main audio channel performance, SCAs, adjacent channels, and stereo subcarrier demodulation were investigated with an IBOC DAB signal appended to the host FM.

Main audio channel performance

Simulations have provided valuable insight into the character of FM post-detection noise in the presence of an IBOC DAB signal. For instance, results indicate that the audio noise level increases with the deviation of the FM signal. In fact, Figure 6 illustrates a significant rise in the post-detection noise power spectral density (PSD) as the FM deviation varies from minimum to maximum in the presence of an IBOC DAB signal placed between 78 kHz and 197 kHz from the FM carrier.

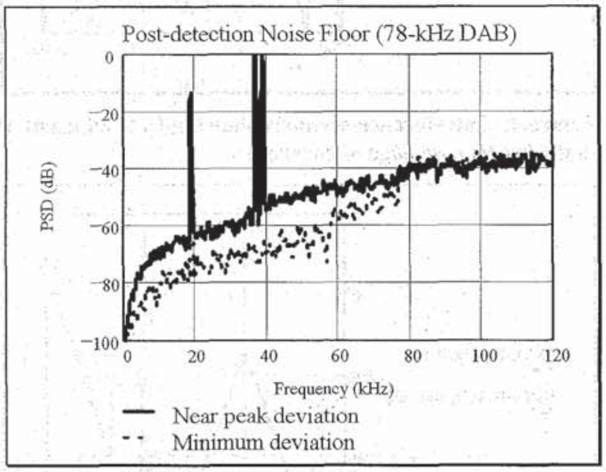

Figure 6. Audio Deviation Effects.

The nonlinear FM detector is responsible for intermodulating overlapping portions of the host FM and DAB spectra. The products are folding back into the post-detection audio band and raising its noise floor. Similar observations and conclusions were independently reached by the Electronic Industries Association (EIA) during their IBOC DAB testing [4].

Although these results are intriguing, they do not predict a degradation in host FM audio quality due to IBOC DAB. Because the DAB-induced post-detection noise floor increases in proportion to the deviation of the FM signal, the effect is self-masking: audio noise will be lowest during quiet passages, and highest only when the audio is loudest. Simulations have demonstrated this phenomenon.

The absolute level of host FM degradation will depend on the particular configuration of DAB. To determine the relationship between DAB location and audio signal-to-noise ratio (SNR), a number of performance tests were run when DAB noise would be most audible – during quiet passages of minimum FM deviation. Simulations were performed in which the receiver audio dynamic range was measured with only a 10%-deviated, 19-kHz-pilot-modulated FM signal and a DAB signal input to an FM stereo receiver located at the transmitter. The total power of the DAB signal was 22 dB below the power of the FM carrier. In the first four tests, the DAB was modulated using orthogonal frequency-division multiplexing (OFDM) with 4750-symbol-per-second quadrature phase-shift keying (QPSK) subcarriers using rectangular pulse shaping. The fifth test employed DAB with four times the number of OFDM carriers -- each occupying one-fourth the bandwidth (1187.5 Hz) -- and root-raised-cosine pulse shaping (to reduce spectral sidelobes that interfere with the host FM). In each test, the spectral occupancy of the DAB signal was changed: the start frequency was varied with respect to the FM center frequency, while the stop frequency was fixed at 197 kHz. Table 1 summarizes the results.

Table 1 - Audio Dynamic Range at Transmitter (peak-to-noise-floor SNR)

DAB start frequency	Audio SNR (dB/15 kHz)
78 kHz	64.7
100 kHz	67.3
124 kHz	68.3
129 kHz	68.8
129 kHz, pulse shaped	77.6

These results indicate that moving the DAB away from the FM carrier, increasing the number of DAB carriers, and pulse shaping the transmitted DAB symbols to reduce spectral sidelobes will significantly improve the performance of the host FM. Modulation and coding characteristics of the DAB signal can be traded for spectral occupancy to meet these goals. Note that the new DAB baseline employs subcarriers spaced at 727, Hz which would improve performance over the carrier spacings reported here.

Audio simulations have verified that an SNR of 77.6 dB during quiet passages should render DAB-induced audio noise imperceptible to the listener. Furthermore, implementation constraints limit the SNR of typical receivers to around 60 dB. The noise engendered by these receivers will mask any degradation caused by DAB. The -22-dB, 129-kHz pulse-shaped DAB configuration is used as the baseline for the balance of this discussion.

SCA performance

SCAs (Subsidiary Communications Authorization) are optional channels multiplexed onto the baseband stereo spectrum from 53 kHz to 100 kHz. The SCA signal, which can be analog or digital, is transmitted by some FM stations for the use of private subscribers who typically pay for program material. Simulations were used to determine the impact of SCAs on IBOC DAB host FM performance, and to determine the impact of DAB on the performance of SCAs. SCAs with 10% deviation at 67 kHz and 92 kHz were simulated because they represent a large percentage of operational subcarriers.

In the current analog FM system, SCAs generally cause negligible interference to the host FM signal. However, when DAB is present, the addition of SCAs could increase the host FM audio noise floor due to the DAB/FM intermodulation effect described above. Figure 7 illustrates stereo subcarrier sensitivity to 92-kHz SCAs when subject to a pulse-shaped (PS) DAB signal starting at 129 kHz. In this case, the 92-kHz SCA reduces the host FM audio SNR from 77.6 to 69.8 dB; however, this noise level is still too low to produce audible effects. Figure 8 shows that SCAs located at 67 kHz have even less impact on audio performance.

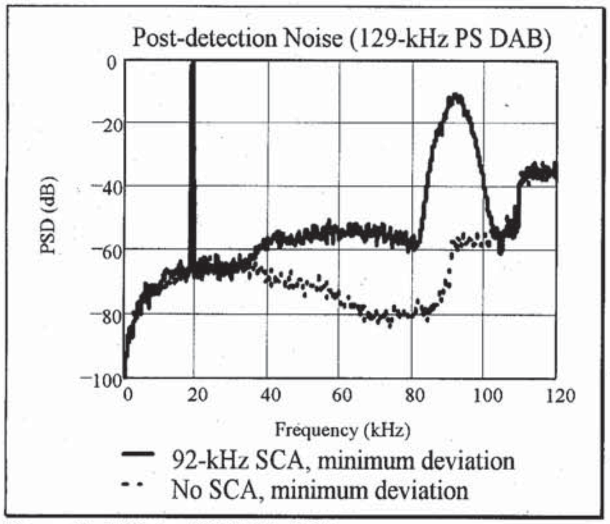

Figure 7. Effects of 92-kHz SCA

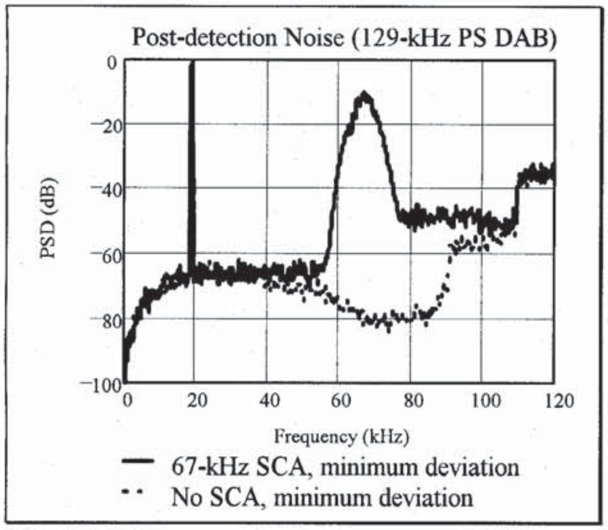

Figure 8. Effects of 67-kHz SCA.

Due to their location at the high end of the baseband spectrum, some SCAs currently operate at low SNRs because the post-detection noise floor increases with the square of the frequency. When DAB is added, the deviation of a wideband host FM signal into its IBOC DAB signal produces intermodulation which increases the post-detection noise floor, particularly in the higher baseband frequencies (since this is nearest the location of the pre-detection DAB). Moreover, the noise masking effect described above does not apply for SCAs, since their audio may be quiet while the main audio channel, at peak deviation, is causing an increase in the SCA noise floor.

Simulations were performed using SCAs with peak-deviated audio signals in the presence of a -22-dB, 129-kHz pulse-shaped DAB signal. Figure 9 indicates that the SNR of a 67-kHz SCA (in a 10-kHz bandwidth) is 25-30 dB at the transmitter when the main audio channel is near maximum deviation.

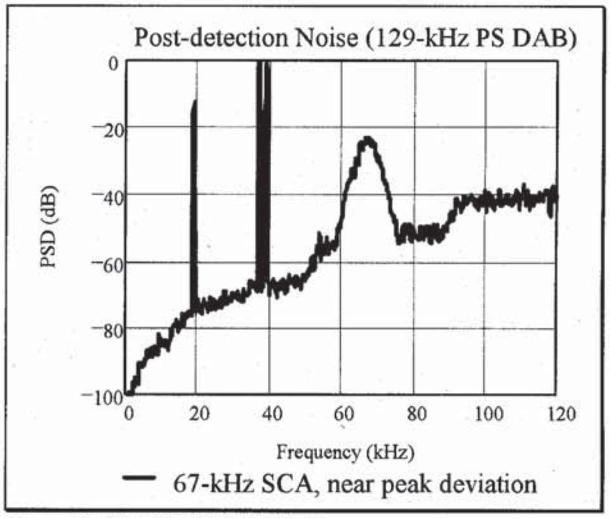

Figure 9. 67-kHz SCA Performance.

For 92-kHz SCAs, the SNR is 20-25 dB, as illustrated in Figure 10.

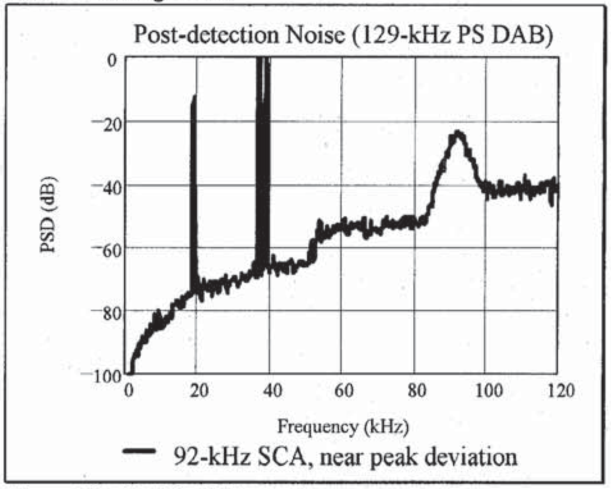

Figure 10. 92-kHz SCA Performance.

Without DAB, typical noise floors are roughly 40 dB. The increase in noise floor should not pose a problem for digital SCAs (e.g., Seiko and Radio Broadcast Data System),

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