DoubleTalk™ Carrier-in-Carrier® Performance Characterization

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Revision 3 – December 20, 2005

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DoubleTalk Carrier-in-Carrier Performance Characterization

DoubleTalk Carrier-in-Carrier (CnC) is an adaptive cancellation technology that significantly reduces bandwidth occupancy by allowing two carriers to simultaneously occupy the same spectral location, a practice that is disastrous for normal carriers. By comparison, standard carriers must occupy non-overlapping spectral segments with no more than one carrier in the same space.

In a number of ways, CnC carriers behave similar to conventional carriers in satellite links. They are both exposed to adjacent carriers, cross-polarization and rain fade, and exhibit impairments when any of these become too great. In addition, CnC operates in an environment where:

- Carriers intentionally occupy the same spectral slot
- Performance depends upon desired and co-located interfering carrier

Several areas relating to CnC performance are discussed, including:

- Adjacent carrier performance
- Eb/No Degradation as a function of the CnC ratio
- Symbol rate ratio
- Carrier offset
- The effects of rain fade and asymmetric antennas

Nominally, these effects are treated independently so it is possible to add them together to estimate the total degradation. Initially, degradation due to carrier spacing is examined to characterize the adjacent carrier performance. Next, the CnC ratio is evaluated to estimate its impact. The symbol rate ratio of CnC carriers and the allowable carrier offset are discussed followed by some CnC examples.

The rules for CnC operation are summarized below:

- Both earth stations share the same footprint so each sees both carriers
- CnC carriers are operated in pairs
- One outbound with multiple return carriers is not allowed
- Asymmetric data rates are allowed up to a symbol rate ratio of 3
- Minimum symbol rate for CnC is 128 ksps
- The CnC ratio is normally less than 10 dB
- CnC operates with modems not modulators only or demodulators only

Degradation Due To Carrier Spacing

In satellite links, one of the impairments to estimate is the impact of carrier spacing on performance and allocate the degradation to the link budget. Data was taken using the CDM-Qx Modem, operating with Turbo coding, to measure Eb/No degradation with decreasing carrier spacing to characterize performance in the presence of two equally spaced like modulated adjacent carriers. This is done without CnC.

For testing, the modem is initially set up with noise to operate at a nominal or reference Eb/No corresponding to a BER $\approx 10^{-8}$ and with no adjacent carrier present. A like-modulated adjacent carrier is then added and the Eb/No degradation recorded. The test is conducted with a single adjacent carrier as shown in Case A of **Figure 1**, but this is equivalent to two equally spaced adjacent carriers on either side of the desired carrier, each 3 dB less than a single adjacent carrier as shown in Case B.

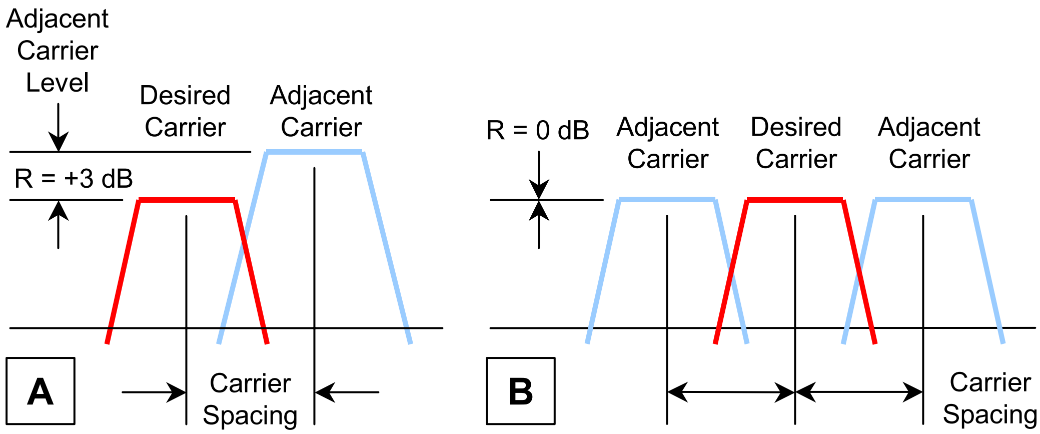

Figure 1. Adjacent Carrier: A) As Tested and B) As Plotted

The results are plotted for two equally spaced adjacent carriers each at -3 dB, 0 dB, +3 dB, and +6 dB relative to the desired carrier to produce a family of operating curves. **Figure 2**, **Figure 3,** and **Figure 4** plot the results for the QPSK, 8-PSK and 16-QAM cases.

The following table contains the CDM-Qx configurations tested:

Modulation	Forward Error Correction	Reference Eb/No At BER ≈ 10^{-8}	Symbol Rate	Data Rate	Rolloff (α)
QPSK	3/4 Turbo	3.9 dB	1000 ksps	1500 kbps	20 and 35%
8-PSK	3/4 Turbo	6.3 dB	1000 ksps	2250 kbps	20 and 35%
16-QAM	3/4 Turbo	7.7 dB	1000 ksps	3000 kbps	20 and 35%

The results are plotted for Eb/No degradation versus relative carrier spacing where:

- Eb/No degradation is the difference between the reference Eb/No and the Eb/No read from the modem in the presence of the interfering adjacent carrier
- Relative Carrier Spacing is the distance between the centers of the desired and adjacent carriers divided by the symbol rate

There are two sets of adjacent carrier plots representing operation with 20% and 35% rolloff (α). When α is 20%, the spectrum is narrower than it is for 35%. The effect of this is noticed in the adjacent carrier plots. The 20% plots are displaced slightly to the left of those for 35%. This makes it possible to space carriers slightly closer when the rolloff is 20%. The table below generalizes degradation (≤ 0.5 dB) for all modulation and coding combinations when there are two adjacent carriers:

	Carrier Spacing For 20% Rolloff	Carrier Spacing For 35% Rolloff
Degradation ≤ 0.5 dB	≥ 1.1 x Symbol Rate	≥ 1.2 x Symbol Rate

Some caution is required because carriers with 20% rolloff are more sensitive to impairments and non-linearity in the link.

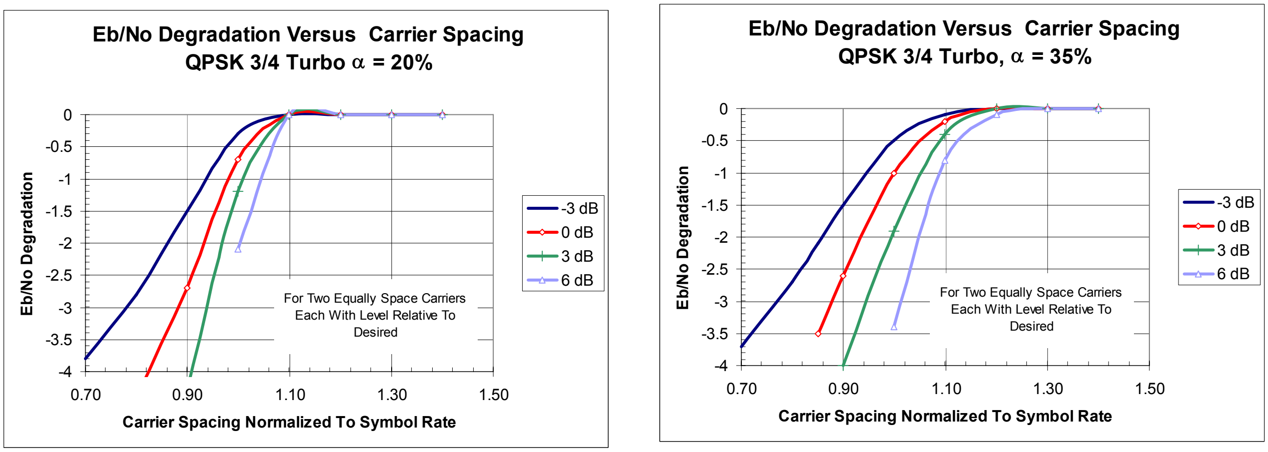

Figure 2. QPSK 3/4 Turbo degradation versus relative carrier spacing (for two adjacent carriers)

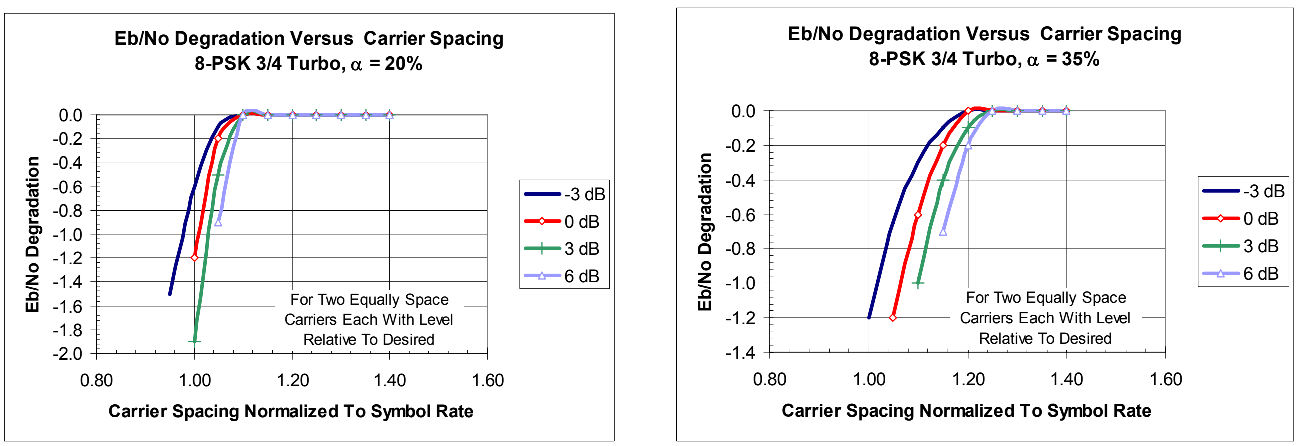

Figure 3. 8-PSK 3/4 Turbo degradation versus relative carrier spacing (for two adjacent carriers)

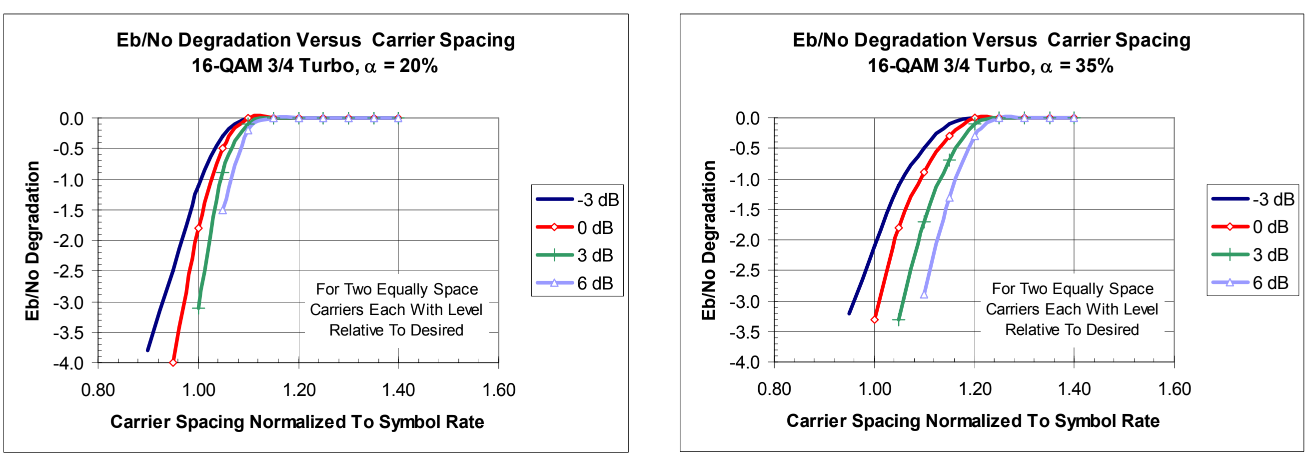

Figure 4. 16-QAM 3/4 Turbo degradation versus relative carrier spacing (for two adjacent carriers)

Other QPSK turbo code rates have similar performance and the QPSK plots above are used to estimate their performance. The degradation plots above are also used for other Turbo 8-PSK and 16-QAM code rates. A good practice for carrier spacing is to operate the links with sufficient spacing so there is no degradation.

Selecting The Adjacent Carrier Curve

The information presented earlier characterizes the case for one or two adjacent carriers relative to the desired carrier. The desired and adjacent carriers may also be CnC carriers occupying the adjacent slots. These cases are summarized by several variants shown in **Figure 5**. Understanding the relationship between these assists in selection of the correct adjacent carrier degradation curve.

Case A in **Figure 5** illustrates the way the adjacent carrier testing is conducted. It shows a single adjacent carrier 3 dB higher than the desired carrier, equivalent to two like-modulated adjacent carriers on either side of the desired carrier, each at the same level as the desired (0 dB higher). Case B shows two adjacent carriers each 3 dB higher than the desired.

Case C illustrates a CnC with a pair of co-located desired carriers (CnC ratio is 0) and a single adjacent slot with pair of CnC carriers whose total composite power is 3 dB higher than the desired pair. The total adjacent power to one of the CnC carriers is 6 dB, or the equivalent of two single adjacent carriers (one on each side of the desired) each 3 dB higher than “one” of the desired CnC carriers. It does not matter whether the adjacent carrier is a pair of CnC carriers or a standard carrier. It is based on the power.

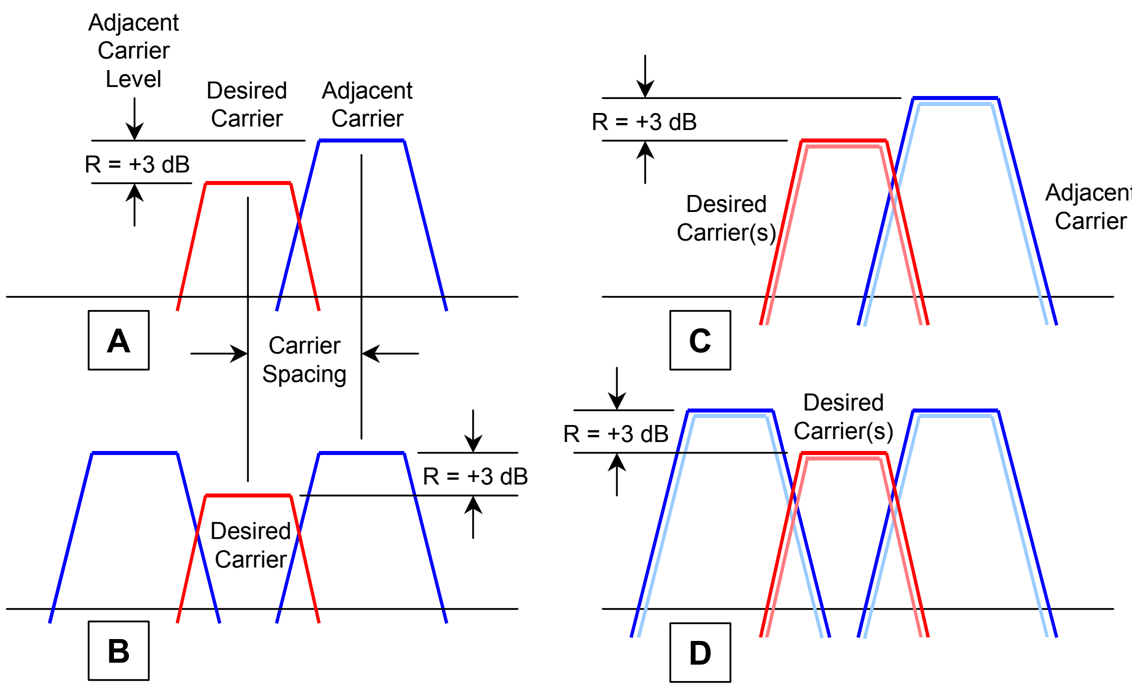

Figure 5. Adjacent Carrier Cases

Case D shows two desired CnC carriers accompanied by a CnC carrier on each side. Again, it does not matter whether the adjacent carriers are CnC or conventional carriers, just the total power. This situation is equivalent to adjacent carriers each 6 dB greater than the one desired CnC carrier. The following table summarizes which adjacent carrier plot to select for this particular example, and which ones to use with a ratio, R, between the composite adjacent and composite desired carriers.

Case (Figure 5)	Desired Carrier	Adjacent Carrier (See Note)	Curve To Use In Figure 2, Figure 3, or Figure 4	Curve To Use For Any Ratio R (dB)
A	1 Carrier	1 Adjacent Carrier	0 dB	R - 3 dB
B	1 Carrier	2 Adjacent Carriers	+3 dB	R + 0 dB
C	1 CnC Carrier	1 Adjacent Carrier	+3 dB	R + 0 dB
D	1 CnC Carrier	2 Adjacent Carriers	+6 dB	R + 3 dB

Note: The adjacent carrier is the composite power for either a conventional carrier or CnC. carrier.

DoubleTalk Carrier-in-Carrier Ratio (CnC Ratio)

The CnC Ratio represents the difference in power between the co-located interfering carrier and the desired carrier in dB.

CnC Ratio = Interferer Power - Desired Carrier

During CnC operation, the interfering carrier is removed by the CDM-Qx using a stored version of the transmitted carrier to adaptively cancel it from the composite received signal. The desired carrier remaining after the cancellation process is delivered to the demodulator and decoder to recover the data.

When the CnC ratio increases, the level of the interferer rises relative to the desired carrier and degradation grows. As the CnC ratio decreases, the desired carrier dominates and degradation becomes negligible. **Figure 6** represents two cases of the CnC Ratio when the interfering and desired carrier are equal, and when the interferer is 6 dB stronger than the desired carrier. This representation is artificial because a real spectral plot displays only the composite power of the combined carriers and is unable to distinguish two carriers, but it is instructive to describe the underlying principle.

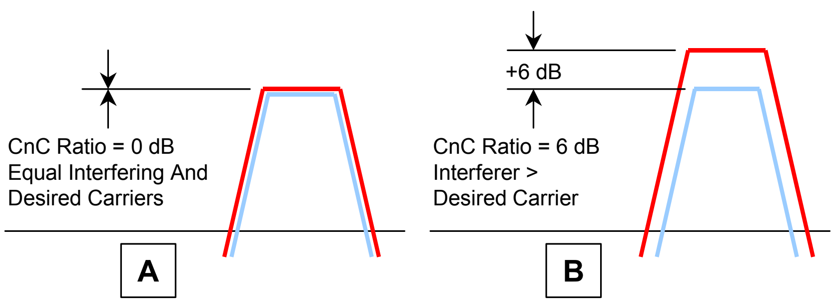

Figure 6. CnC Ratio

The following CDM-Qx configurations were tested for Eb/No degradation as a function of CnC ratio:

Modulation	Forward Error Correction	Reference Eb/No At BER ≈ 10^{-6}	C/N
QPSK	21/44 Turbo	2.6 dB	2.4 dB
QPSK	3/4 Turbo	3.7 dB	5.5 dB
QPSK	7/8 Turbo	4.3 dB	6.7 dB
QPSK	17/18 Turbo	6.5 dB	9.3 dB
8-PSK	2/3 TCM	5.3 dB	7.9 dB
8-PSK	3/4 Turbo	6.1 dB	9.6 dB
8-PSK	7/8 Turbo	7.1 dB	11.3 dB
8-PSK	17/18 Turbo	9.0 dB	13.5 dB
16-QAM	3/4 Turbo	7.2 dB	12.0 dB
16-QAM	7/8 Turbo	8.1 dB	13.5 dB

The Eb/No degradation is the difference between the reference Eb/No with no interfering carrier present and the Eb/No reported by the modem at a given CnC ratio.

Figure 7 plots the impact of CnC ratio on QPSK and 8-PSK constellations, and **Figure 8** shows 16-QAM. In general, the higher the operating C/N of a carrier, the more sensitive it is to degradation. QPSK is the least sensitive to CnC ratio followed by 8-PSK and 16-QAM.

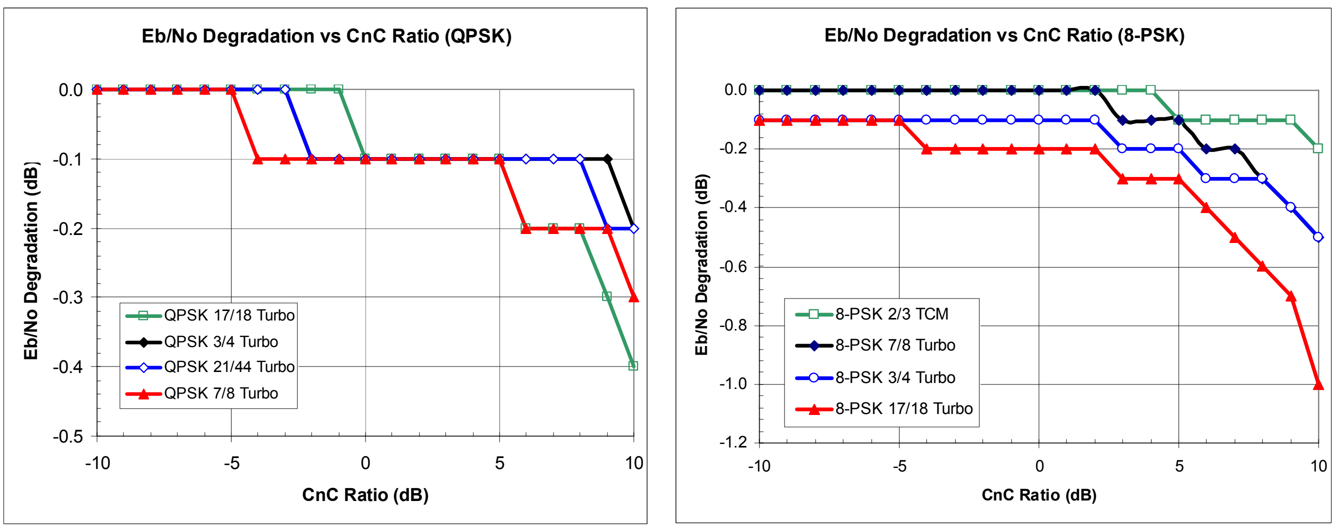

Figure 7. CnC Ratio For QPSK and 8-PSK

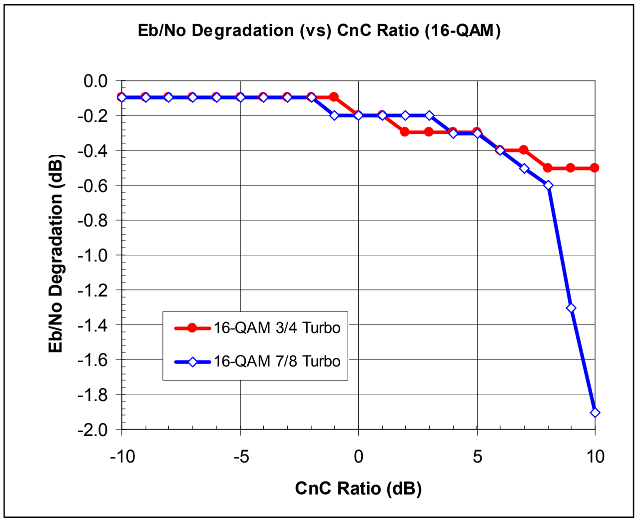

Figure 8. CnC Ratio For 16-QAM

Symbol Rate Ratio

CnC operation is restricted to a maximum symbol rate ratio ≤ 3. This is the ratio of the larger carrier to the smaller one. Within these limits, the performance characterized applies. The limitation on the symbol range still allows a wide range of data rates.

When working with spectral density plots of CnC carriers, it is necessary to take into account the symbol rate ratio to properly estimate the CnC ratio, although the modem does this automatically. For estimating the link parameters, the CnC ratio is adjusted by 10 Log (Symbol Rate Ratio). If the symbol rate ratio is 2.0 then the narrower carrier has a 3 dB CnC ratio when the CnC carriers have the same spectral density.

CnC Carrier Offset

CnC carriers are normally placed directly on top of each other with the same center frequency for both carriers. Normal operation is obtained when the center frequency of the two carriers is within ± 32 kHz. This is the same as the normal acquisition range of the modem for standard and CnC carriers.

1st CnC Example: Adjacent Carriers, CnC Ratio and Rain Fade

As an example, a pair CnC carriers is flanked by two adjacent CnC pairs with a carrier spacing of 1.3 x Symbol Rate and the power level is the same for all carriers as shown in **Figure 9**. In this scenario, the modulation is 8-PSK 3/4 Turbo with identical data rates.

Referring back to **Figure 3**, the degradation due to adjacent carrier spacing is negligible when spacing is 1.3 x Symbol Rate and 0 db is allocated for adjacent carrier degradation.

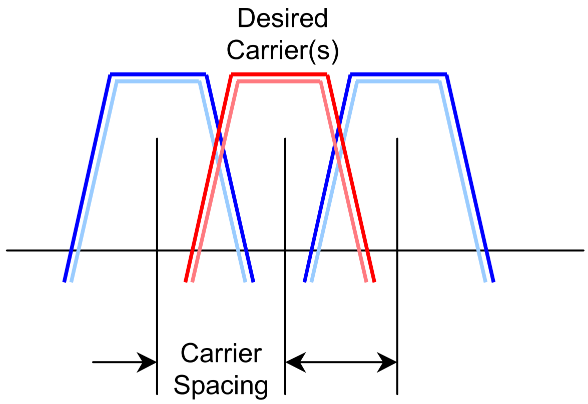

Figure 9. CnC Example

Initially the CnC ratio is 0 dB, and the desired and interfering carriers are operating at the same power level. At one end of the link (Site A), a downlink fade of 4 dB is expected and an uplink fade of 6 dB. The other end of the link (Site B) is allocated 2 dB for downlink and 3 dB for the uplink:

	DL Fade	UL Fade
Site A	4 dB	6 dB
Site B	2 dB	3 dB

When a rain fade occurs at one site, the effect is felt at both sites as outlined in **Figure 10**, which diagrams the worst case fade at Site A. The interfering carrier at Site A is attenuated twice, once due to the uplink and the second time due to the downlink on the return path. The carrier transmitted from Site B sees only the downlink fade when it is received at Site A. The resulting power level changes at each site due to the rain fade and the resulting CnC ratio and Eb/No degradation is summarized in the following table:

Site A			**Site B**		
Parameter	**dB**	**Comment**	**Parameter**	**dB**	**Comment**
Relative Level of Carrier A @ Site A	-10	Due to fade at A	Relative Level of Carrier B @ Site B	0	Due to fade at A
Relative Level of Carrier B @ Site A	-4	Due to fade at A	Relative Level of Carrier A @ Site B	-6	Due to fade at A
CnC Ratio At Site A	-6		CnC Ratio At Site B	+6	
Degradation At Site A	-0.1	Per **Figure 7** 8-PSK	Degradation At Site B	-0.3	Per **Figure 7** 8-PSK

Notice from the table, the CnC change is proportional to the uplink fade. The CnC ratio decreases by the amount of the uplink fade at the near end while the CnC ratio increases by the amount of uplink fade at the distant end. Also, the CnC ratio at opposite ends of the link has the same magnitude but opposite sine.

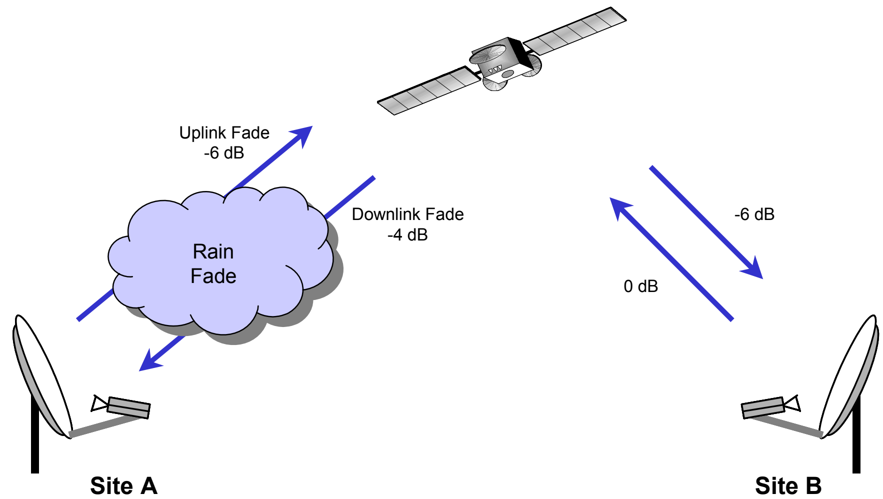

Figure 10. Link With Fading At Site A

As shown, the interfering carrier at Site A is attenuated twice passing through both the uplink and returning on the downlink back to Site A. Since the carrier transmitted and then received at Site A is the interfering carrier this extra attenuation is much less of an issue because it makes the CnC ratio more negative (less degradation). In a practical link the interfering carrier might drop into the noise leaving the demodulator to recover the desired carrier nearly absent the undesired interferer.

At Site B, the desired carrier from Site A is received and attenuated thereby increasing the CnC ratio (more degradation). In links similar to these, the unfaded end of the link has the highest CnC ratio.

In links without rain fade, the CnC ratio is constant and only the asymmetry of link due to satellite footprint, different antenna sizes, different symbol rates, or modulation and code rates alter the ratio.

2nd CnC Example: CnC Ratio With Asymmetric Links

Networks with asymmetric antennas are common with a larger antenna at one site (hub) and smaller ones at the other sites (remotes) and often have asymmetric data rates. In a number of links even a significant rain fade is not a big factor in CnC performance. Some links, particularly C-Band or X-Band, have insignificant rain fades and the key to performance is setting both ends of the link to handle the asymmetry.

In asymmetric links, taking advantage of the available modulation and coding schemes is another tool for building efficient CnC links. In these links the ideal CnC ratio is 0 dB, but keeping the CnC ratio less than 7 dB, under all conditions, establishes links with margin. A link with a negative CnC ratio is also acceptable because the interfering signal is below the desired signal.

An asymmetric C-Band link is shown in **Figure 11**. It has equal symbol rate carriers but the antenna at Site A is 4.5 meters antenna and Site B is 2.4 meters.

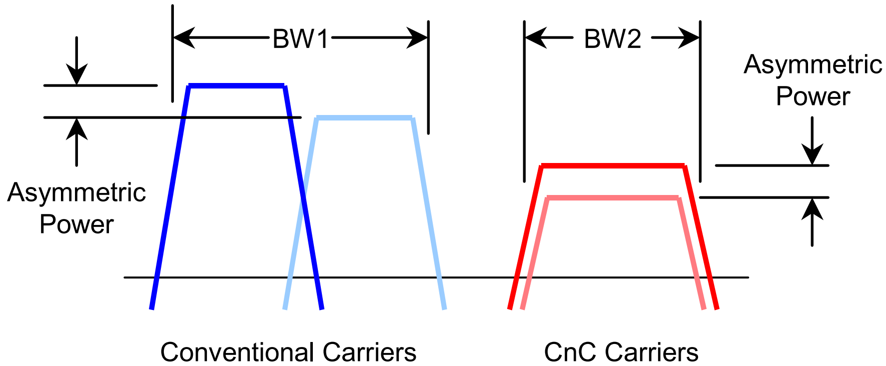

Figure 11. Asymmetric Link with the Same Data Rate but Different Antennas

Conventional side-by-side carriers are transmitted by the link on the left, and CnC carriers are deployed on the right. The conventional carriers are 8-PSK 2/3 TCM, and the CnC carriers are QPSK 3/4 Turbo. Notice that the bandwidth to support the two conventional carriers (BW1) is larger than the bandwidth for CnC (BW2), even though the conventional link uses 8-PSK 2/3 while CnC is QPSK 3/4. The benefit of CnC becomes apparent when it is realized that the bandwidth reduction possible with CnC is also accompanied by a reduction in power compared to the conventional link.

The link parameters and results are summarized in the table:

Parameters	Site A	Site B
Satellite EIRP (dBW)	37	37
Satellite BOo (dB)	6	6
Satellite BOi (dB)	10	10
Satellite SFD (dbW/m^2)	-78	-78
Satellite G/T (dB/K)	0	0
E/S Antenna (meters)	4.5	2.4
Data Rate (kbps)	192	192
Carrier Spacing Factor	1.3	1.3
Conventional Link	8PSK 2/3 TCM	8PSK 2/3 TCM
Occupied BW1 for 2 Carriers (kHz)	274.6	274.6
% of Transponder Power	0.55	0.16
CnC Link	QPSK 3/4 Turbo	QPSK 3/4 Turbo
Occupied BW2 for 2 Carriers (kHz)	166.4	166.4
% of Transponder Power	0.37	0.11
CnC Ratio (dB)	+5.3	-5.3
Expected Eb/No Degradation (dB)	-0.1	0.0

The link asymmetry has increased the CnC ratio at Site A to +5.3 dB. Yet this results in a degradation of only 0.1 dB. This is a C-Band link so no additional change in signal level is expected due to rain fade. The CnC ratio at Site B is -5.3 dB so no degradation is expected.

What is done if the CnC ratio is 10 dB or more? In a C-Band link it is possible to tolerate the additional impairment, but then the modem is operating with less margin. One possibility to reduce the CnC ratio is to increase the amount of power transmitted from the remote site with the smaller antenna. This is feasible in some instances where there are higher power satellite transponders. If the installation is a new one, a larger, though more expensive, antenna is possible at the remote site. This simultaneously decreases the CnC ratio at the hub while increasing it at the remote site.

Another alternative is to reduce the modulation order and/or error correction code rate on the receive side of the remote site. This decreases the power transmitted by the hub and reduces its CnC ratio. The hub's CnC ratio will decrease further if it is possible to increase the modulation order or code rate at the hub. In the above example changing from QPSK 3/4 to QPSK 1/2 helps reduce the power but requires additional 1.5 times more bandwidth. The 1.2 dB Eb/No difference between rate 3/4 and 1/2 reduces the CnC ratio at the hub.

3rd CnC Example: Asymmetric Link With Rain Fade

A reasonable question to ask about the previous example is the impact rain fade has on the link. This example combines parts of the previous two examples using the same symbol rates and asymmetric antennas and adds in fade at Site A, with the larger antenna and examines the CnC ratio at both sites. The impact on both sites is also estimated due to a fade at Site B. Just as in the earlier example, the larger fade (6 dB up and 4 dB down) occurs at Site A (hub), and the smaller fade (3 dB up and 2 dB down) is allocated to Site B (remote).

Treating the fades in this way is convenient as a first order approximation, but other factors influence performance such as noise increase and G/T degradation at the receive site.

From the previous examples there are some characteristics worth summarizing:

At the same symbol rate with the same modulation and code rate:

- The CnC ratio is highest at the site with the larger antenna (Site A)
- The CnC ratio for the site with the smaller antenna (Site B) is the same magnitude but opposite sign: CnC (Site B) = -CnC(Site A)

For rain fade:

- The CnC ratio changes by the same amount as the uplink fade
- Uplink fades at the near end decrease the CnC ratio
- Uplink fades at the far end increase the CnC ratio

The tables below summarize the Eb/No degradation at Site A when a fade is introduced first at Site A and then at Site B. Next, the degradation at Site B is evaluated when a fade appears at Site B and then at Site A. For this asymmetric case, the estimated CnC degradation is 0.1 dB despite the significant fade.

Eb/No Degradation For Asymmetric 4.5-Meter Antenna At A and 2.4 Meter Antenna At B

Eb/No Degradation At Site A		
Parameter	**Due To Fade At A (dB)**	**Due To Fade At B (dB)**
CnC Ratio @ Site A	+5.3	+5.3
Uplink Fade @ Site A	6	-
Uplink Fade @ Site B	-	3
Faded CnC @ Site A	-0.7	+8.3
Eb/No Degradation (dB) @ Site A Per **Figure 7** QPSK	0.0	-0.1

Eb/No Degradation At Site B		
Parameter	**Due To Fade At B (dB)**	**Due To Fade At A (dB)**
CnC Ratio @ Site B	-5.3	-5.3
Uplink Fade @ Site B	3	-
Uplink Fade @ Site A	-	6
Faded CnC @ Site B	-8.3	+0.7
Eb/No Degradation (dB) @ Site B Per **Figure 7** QPSK	0.0	-0.1

Conclusion

There are several conclusions for operation with CnC:

- Operate adjacent carriers with sufficient spacing so there is no degradation
- Adjust the modulation and code rate to alter the CnC ratio
- Change the modulation and code rate to scale the symbol rate
- Maximum CnC ratio is 7 dB with plenty of margin
- Maximum CnC ratio is 10 dB with some degradation
- Eb/No degradation is relatively tolerant to fades
- QPSK is least sensitive to adjacent carrier and CnC ratio followed by 8-PSK then 16-QAM

Carrier-in-Carrier is based on Applied Signal Technology's DoubleTalk™, which uses "Adaptive Cancellation," a patented technology that allows full duplex satellite links to transmit concurrently in the same segment of transponder bandwidth.

