Radio Specifications of Double Conversion Tuner for Cable Modem

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Abstract — *The radio specifications such as noise figure, phase noise, image rejection ratio, CTB, CSO, XMOD, power gain, and AGC range of the tuner for cable modem is analyzed based on DOCSIS and many reported materials. Using the analyzed radio specifications, the specific radio specifications are allocated for up and down converter of the DC tuner architecture and analyzed CTB and CSO requirement in depth. According to the linearity analysis for the DC tuner architecture, it is known that CTB and CSO value of -53dBc, which is commonly accepted by the field engineer, is over-specified. By the more reasonable selection of linearity target, it is possible to design DC tuner with better power efficiency.*

Index Terms — Radio Specifications, Cable Modem, DOCSIS, CTB, CSO

I. INTRODUCTION

Cable Modems are being deployed extensively throughout the world, enabling users to obtain a low cost broadband connectivity to the Internet and other data services. In December 1995, cable industry launched the Data over Cable Service Interface Specification [DOSCIS] project to facilitate the development of interoperable Cable Modem [CM] equipment in pace with Internet Big Bang [1]. Cable Modem Termination System [CMTS] and CM are the front-end system of the service provider and the customer in the broadband cable networks, respectively. In cable networks, the signal flows from CM to CMTS are defined as "up-stream" and the reverse as "down-stream". The pass-band of down-stream is 50MHz ~ 860MHz, up-stream 5MHz ~ 42MHz. In down-stream, NTSC analog television signals in 6MHz channels are assumed to be present on the standard, HRC or IRC frequency plans of EIA Interim Standard IS-6, as well as other narrowband and wideband digital signals. CM and CMTS must coexist with the other services on the cable networks [2].

Traditionally, the radio frequency receiver of one-way broadcasting services such as off-air TV and CATV is called as a tuner.

[1] This work was supported in part by Samsung Electro-Mechanics.

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As one-way broadcasting services over cable networks are advanced to two-way data services, the transmitter becomes required in the traditional tuner. There are two kinds of tuner (receiver) architecture for cable application, which are Single Conversion [SC] tuner and Double Conversion [DC] tuner, respectively. In cable modem service, every service channels, maximum 135 channels, can be the packed with broadband service signals, which generate a severe image channel interference in receiver path considering the relatively low intermediate frequency for demodulation, 36 MHz for European and 44 MHz for American. With SC tuner architecture, the image channel interference can be only solved with impractical highly selective and wide-band tracking band-pass filter. For this reason, the DC tuner architecture is adopted to receive broadband down-stream signal in the many commercial tuners for cable modem, which does not

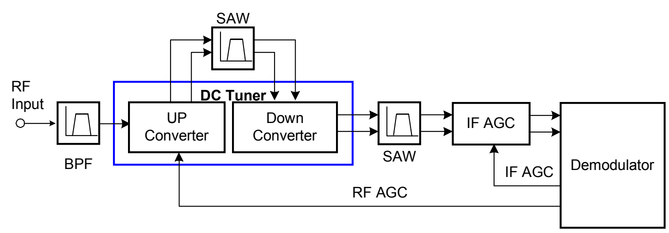

Fig. 1. DC tuner architecture in cable modem

experience the image channel interference [3].

As shown in Fig. 1, DC tuner in cable modem has up and down converter. The highly linear up converter converts up a wanted channel to a fixed first intermediate frequency [1^{st} IF] with many other broadband service channels. The 1^{st} IF tuned SAW rejects the up converted broadband service channels except a wanted channel. And, then, the down converter converts down the wanted channel to 2^{nd} IF. Using this double (up and down) conversion scheme, the image channel interference in the packed broadband service signals can be suppressed. In 2^{nd} IF, the channel selection SAW rejects useless harmonics. IF AGC controls the magnitude of channel signal to demodulate properly. RF AGC is used to prevent the saturation of the up converter by the strong RF broadband down-stream signals.

This paper is analyzed the radio specifications of DC tuner for cable modem based on many reported materials and DOCSIS. In Section II, the general radio specifications for the tuner such as noise figure [NF], image rejection ratio [IRR], phase noise [PN], composite triple beats [CTB], composite second order [CSO], cross modulation [XMOD], power gain and AGC range are analyzed for 256 QAM down stream signal. In Section III, based on the radio specifications of Section II, the radio frequency specifications of up and down

Contributed Paper
Manuscript received May 6, 2003

converter are allocated and summarized in the Table II. Especially, the linearity requirements for up and down converter are analyzed in depth. In Section IV, gives the conclusion of this paper.

II. RADIO SPECIFICATIONS OF TUNER FOR CABLE MODEM

The up and down-stream signals are coded and modulated following ITU J.83 Annex B which adopts Reed-Solomon and Trellis coding as inner and outer code. The effective coding gain is 5.3dB. The down-stream signals are modulated as 64 or 256 QAM signal. The range of carrier signal level is from –15dBmV to +15dBmV. With 256 QAM, the achievable maximum data rate is 42.884Mbps [1-4]. In DOCSIS, the required SNR and BER requirements for 256 QAM signals are provided as Table I.

TABLE I
SNR AND BER REQUIREMENTS FOR 256 QAM

Carrier to noise	BER after FEC	Carrier Level
≥ 30 dB	$\le 10^{-8}$	-6 dBmV ~ +15 dBmV
≥ 33 dB	$\le 10^{-8}$	-15 dBmV ~ –6 dBmV

A. Noise Figure

In QAM modulation, the relation between channel symbol error probability, P_c, and the average carrier to noise ratio per bit, E_b/N_o, are given as [5]

$$P_c = 2\left(1-1/\sqrt{M}\right)\mathrm{erfc}\left(\sqrt{3kr_b/2(M-1)}\right) \cdot \left[1-1/2\left(1-1/\sqrt{M}\right)\mathrm{erfc}\left(\sqrt{3kr_b/2(M-1)}\right)\right] \quad (1)$$

where, M is the number of states per symbol (for example, $M = 256$ for 256 QAM, $M=2^k$, $k=6$). $r_b = E_b/N_o$.

The relation between carrier to noise ratio, C/N, and E_b/N_o are given as [5]

$$C/N = E_b/N_0 + 10\log(\text{data rate}) - 10\log(\text{band width in Hz}) \quad (2)$$

Using (1) and (2), the C/N ratio for 256QAM is calculated as 34.617dB. If we consider the 5.3dB of effective coding gain [1, 4] after FEC, the C/N ratio at the input of demodulator is equal to 29.317dB. This value is lower than 33dB of carrier to noise ratio in DOCSIS shown in Table I. Maybe, DOCSIS considers additional noise sources in practical applications.

Assuming optimum input conjugate matching and the minimum detectable signal [*MDS*] as –15dBmV of the lowest downstream carrier level, the allowable maximum noise figure, NF_{max}, of DC tuner can be derived using [6]

$$MDS = \text{noise floor} + SNR_{out} = -174\text{dB} + 10\log(\text{band width}) + NF_{max} + SNR_{out} \quad (3)$$

where, SNR_{out} are the C/N ratio at demodulator input.

From (3), the according NF_{max} for 256 QAM signal is equal to 10.21dB.

B. Phase Noise

The phase noise of oscillator adds noise in the wanted channel through the reciprocal mixing between the signals of local oscillator and blocker [6, 7]. The description for the adjacent channel performance in DOCSIS can be applied to derive the required phase noise performance. In DOCSIS, the adjacent channel performance is described as *BER performance must be met with a digital signal at +10dBc in the adjacent channels with an additional 1.0dB allowance of carrier to noise ratio.* This term can be understood that the reciprocal mixing noise, N_{rm}, must not increase the noise floor higher than 1.0dB with MDS + 10dB of blocker. To meet this criterion, N_{rm} must be lower 5.868dB to noise floor level.

The total integrated phase noise, $P_{n,tot}$ can be derived using

$$\begin{aligned} N_{rm} &= PN_{tot} + P_b + 10\log\left(BW_{eff}\right) = PN_{tot} + P_{b,tot} \\ &= \text{noise floor} - 5.868\text{dB} \\ \Rightarrow PN_{tot} &= \text{noise floor} - 5.868\text{dB} - P_{b,tot} \end{aligned} \quad (4)$$

where, P_b is blocker level, BW_{eff} is the bandwidth affected by phase noise.

If we assume that the phase noise decreases 20dBc/dec over frequency. The phase noise index, K, can be calculated using [8]

$$\begin{aligned} PN_{tot} &= \int_{f_L}^{f_H} Kf^{-2}df = K(1/f_L - 1/f_H) \\ \Rightarrow K &= PN_{tot} / (1/f_L - 1/f_H) \end{aligned} \quad (5)$$

where, f_L and f_H is low and high end frequency which effectively contribute phase noise

It is known that the offset frequencies that are higher/lower than half of the symbol/packet rate do not contribute the phase noise. In 256 QAM, the symbol and packet rate is 5.36MHz and 14.3kHz, respectively [3]. Using (4) and (5), the total integrated phase noise, PN_{tot}, and phase noise index, K, at *MDS* is given as –45.868dBc and –4.291dB, respectively. These results show that the allowable phase noise of the local oscillator at the offset frequency of 100kHz is equal to –104.291dBc.

C. Image Rejection Ratio

In DOCSIS, the image rejection performance for 256 QAM is described that *the BER performance must be met with an analog or a digital signal at +10dBc in any portion of the RF band other than the adjacent channels*. If we set a guideline as the maximum allowable image noise power, N_{img}, must not increase the noise floor higher than 0.1dB with MDS + 10dB of image signal, this term equals that the image noise power is lower as much as 16.33dB from the noise floor. Using this assumption, we can calculate the required image rejection ratio using

$$\begin{aligned} N_{img} &= P_{img} + IRR = \text{noisefloor} - 16.33\text{dB} \\ \Rightarrow IRR &= \text{noisefloor} - 16.33\text{dB - } P_{img} \end{aligned} \quad (6)$$

where, P_{img} is the power of the image signal

From (6), the *IRR* is given as –59.33dBc for 256 QAM.

D. Linearity – CSO and CTB

In broadband cable system, the semiconductor amplifiers generate composite distortion beats. There are three types of composite distortion, which are CSO, CTB and XMOD, respectively. These composite distortions have numerical relation with well known IIP2 and IIP3 specification.

1) Relation between CSO and IIP2

In multi-carrier system, two different carrier frequencies, ω_1 and ω_2, generates four types of second order distortion beat which are $\omega_1 \pm \omega_2$, $2\omega_1$ and $2\omega_2$, respectively. In general, $2\omega_1$ and $2\omega_2$ terms can be neglected because they are below 6dB to $\omega_1 \pm \omega_2$ in power. In the ANSI/EIA-542 Standard channel plan, the visual carrier has 1.25MHz upward offset from the center frequency of 6MHz channels. The power level of upper composite beat cluster, relative to the sync peak power of the visual carrier, is known as CSO, and is expressed in unit of dBc (meaning decibels relative to the carrier power level, which is always a negative number). Although the lower CSO beats will generally have greater magnitude than the upper beats on lower frequency channels. But it falls at the edge of the video channel and is often ignored since it has a minor effect on video quality compared with the in-band upper cluster. The worst CSO distortion beats are occurred at the band-edge. In this case, the number of distortion CSO beats is equal to $2/N$ with *N* signal carriers. Using the relation of the second order distortion, CSO is given as [5, 9]

$$\begin{aligned} CSO(\text{dBc}) = &-(P_i - P_c) \\ &+ 10\log(\text{Number of CSO Beats}) \end{aligned} \quad (7)$$

where, P_i and P_c is input power level at the second order intercept point and input power level of each carrier, respectively.

2) Relation between CTB and IIP3

In multi-carrier system, three different carrier frequencies, ω_1, ω_2 and ω_3 are generate triple beats of which frequency is composed as $\omega_1 \pm \omega_2 \pm \omega_3$. Triple beats are dominant third order distortions in multi-carrier system because the power of triple beats is 6dB higher than that of well-known third order distortion beats such as $2\omega_1 \pm \omega_2$, $2\omega_2 \pm \omega_3$, etc. The number of CTB beats has the maximum value at the mid band and is equal to $3N^2/8$ with N signal carriers. Since triple beats are the greatest in both number and magnitude, they quickly dominate other third order effects. Thus, CTB, composite triple beat, distortion is defined as the total power level relative to relative to a reference carrier level and represented in dBc. Using the relation of the third order distortion, CTB is given as [5, 9]

$$\begin{aligned} CTB(dBc) = &-2(P_i - P_c) + 6\text{dB} \\ &+ 10\log(\text{Number of CTB Beats}) \end{aligned} \quad (8)$$

where, P_i and P_c is the input power level at the third order intercept point and carrier power level, respectively.

3) CSO/CTB and the equivalent IIP2/IIP3

By applying the same guideline used to derive *IRR* specification, the CSO and CTB specification can be obtained. In this case, the maximum allowable power level of composite distortion beats must be below 16.33dB over the noise floor, which is given as [9]

$$\begin{aligned} P_{dis} &= P_c + CSO \text{ or } CTB = \text{noise floor} - 16.33\text{dB} \\ \Rightarrow CSO &\text{ or } CTB = \text{noise floor} - 16.33\text{dB - } P_c \end{aligned} \quad (9)$$

where, P_{dis} and P_c is the power level of composite distortion beats and carrier, respectively.

With MDS, both CSO and CTB specifications are resulted in –49.33dBc for 256 QAM. This result is very close to –53dBc of experience specification of field engineer [5]. Assuming 135 channels in down-stream pass-band, $IIP2_{CSO}$ and $IIP3_{CTB}$ are given as

$$IIP2_{CSO} = P_c + 70.60\text{ dB} \quad (10)$$

$$IIP3_{CTB} = P_c + 46.93\text{ dB} \quad (11)$$

E. Cross Modulation

The third order distortion components such as $3\omega_1$, $3\omega_2$, and $3\omega_3$ cause effective gain variations of fundamental signals. With random phase multi-carrier system, these gain variation works as noise. This effect is known as *XMOD*. Cross modulation is also a kind of third order distortion. The relation with third order intercept point is given as [5, 9]

$$\begin{aligned} XMOD(\text{dBc}) = &-2(P_i - P_c) + 6\text{dB} \\ &+ 10\log(\text{number of carriers}) \end{aligned} \quad (12)$$

where, *XMOD* is the cross modulation below 100% modulation. P_i and P_c are the power level of third order intercept point and down-stream carrier, respectively.

Applying the same guideline for *IRR* specification, the required IIP3 specification is given as

$$IIP3_{XMOD} = P_c + 38.32\text{dB} \quad (13)$$

TABLE II
ALLOCATED RADIO SPECIFICATIONS FOR DC TUNER

Item	Specifications			Overall
	Up Converter	SAW	Down Converter	
Power Gain [dB]	10.0	-4.5	34.5	40.0
Gain Variation [dB]	3.0	0		3.0
NF [dB]	8.0	4.5	4.5	8.5dB
RF AGC Range [dB]	> 20.0	-	-	> 20.0
CTB [dBc]	-50.0	-	-50	-44.0
CSO [dBc]	-44.0	-	-	-44.0
IIP3[1]/IIP3[2] [dBm]	-7.6/12.4	-	-17.5	-9.6/10.4
IIP2[1]/IIP2[2] [dBm]	11.5/31.5	-	-	11.5/31.5
IRR [dBc]	-	-50.0	< -10.0	< -60.0
PN [dBc]		-105 @ 100kHz		-

IIP3[1]/IIP2[1] @ “take-over-point” (-5dBmV); IIP3[2]/IIP2[2] @ maximum input carrier level (+15dBmV)

$IIP3_{XMOD}$ is below 8.61dB than $IIP3_{CTB}$. For this reason, the cross modulation is not a critical in tuner for CM.

F. Power Gain and AGC Range

The overall gain of tuner can be derived from 51~59dBmV of the general input level in the commercial demodulator. Thus, the maximum gain must be around 70dB because the minimum down-stream carrier level is equal to –15dBmV. The required AGC range is obtained from –15dBmV ~ +15dBmV of the input range of down-stream carrier described in DOCSIS. Thus, ACG range must be greater than 30dB.

III. ALLOCATION OF RADIO SPECIFICATIONS FOR UP AND DOWN CONVERTER

Based on the radio specifications of tuner for CM in Section II, the required radio specifications of up and down converter for DC tuner will be allocated in Section III. The allocated radio specifications of up and down converter for DC tuner are summarized in Table II.

A. Power Gain and AGC Range

Considering about 20 dB of power loss and 50 dB of power gain in the commercial 2nd IF channel selection SAW and IF AGC, the maximum gain of DC tuner must be at least 40dB. If we choose the power gain of up converter as 10dB, then, the power gain of the down converter must be 34.5dB for 4.5dB of insertion loss in the commercial 1st IF SAW. In commercial DC tuner product, the gain variation of the up converter over broadband carriers is normally less than 3dB. For the strong broadband down stream input, the RF AGC must decrease the power gain not to saturate up converter. For the weak broadband down stream input, IF AGC must amplify the wanted signal to sufficient level for demodulation. There is a carrier level of which RF or IF AGC will work. This carrier level is called as "take-over-point". Depend on the application, normally digital or analog, the "take-over-point" of tuner is around -5dBmV ~ +5dBmV [3]. In this paper, the "take-over-point" is chosen as -5dBmV.

The power gain of up converter over carrier level is plotted in Fig. 2. As shown in Fig. 2, power gain of up converter decreases linearly proportional to the increase of carrier level above "take-over-point". As shown in Fig. 2, RF AGC must have the gain range of at least 20dB. Considering 30dB of the

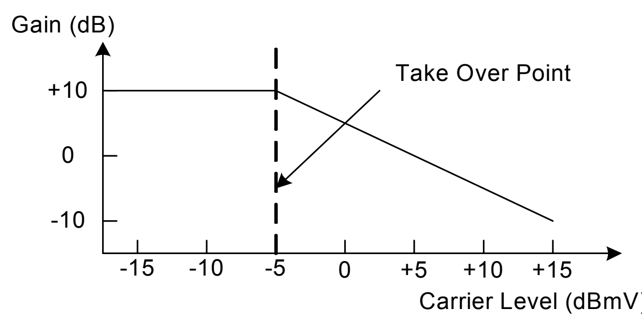

Fig. 2. Power gain of up converter

overall AGC range in Section II, IF AGC must have at least 10dB of gain range.

B. Noise Figure

In section II, NF_{max} is derived as 10.21dB. In this paper, the target NF is chosen as 8.5dB considering assumptions to derive IRR, CTB and CSO in Section II and the unexpected noise in system. NF_{up} and NF_{down} for up and down converter can be allocated as 8.0dB and 4.5dB using friss equation for DC tuner as given in [10]

$$F_{tot} = 1 + (F_{up} - 1) + \frac{L_{SAW} - 1}{G_{up}} + \frac{F_{down} - 1}{G_{up} IL_{SAW}^{-1}} \qquad (14)$$

where, F_{tot}, F_{up}, F_{down}, IL_{SAW}, and G_{up} are the overall noise factors of DC tuner, the noise factor of the up and down converter, the insertion loss of the 1st IF SAW, and the power gain of up converter, respectively.

C. CTB/CSO and IIP3/IIP2

In the cascaded amplifiers with selectivity, the overall IIP3 is given as [11]

$$\frac{1}{IIP3} = \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2 s_1^{3/2}} + \cdots + \frac{G_1 G_2 \cdots G_{n-1}}{IIP3_n (S_1 S_2 \cdots S_{n-1})^{3/2}} \quad (15)$$

where, $IIP3_n$, G_n, and S_n is the input referred third order intercept point, the power gain, and the selectivity of n-th stage. Using (15), the overall linearity of DC tuner, $IIP3_{DCT}$, is given as

$$\frac{1}{IIP3_{DCT}} = \frac{1}{IIP3_{up}} + \frac{G_{up} / IL_{SAW}}{IIP3_{down} S_{SAW}^{3/2}} \quad (16)$$

where, $IIP3_{up}$ and $IIP3_{down}$ are $IIP3$ of up and down converter, respectively. IL_{SAW} and S_{SAW} are the insertion loss and the selectivity of the 1st IF SAW.

As shown in (16), S_{SAW} decrease the affect of $IIP3_{down}$ to $IIP3_{DCT}$ of DC tuner. Simulation shows that $IIP3_{DCT}$ is affected negligibly small by $IIP3_{down}$ when S_{SAW} is higher than 20dBc. In commercial SAW for DC tuner, the bandwidth to provide the 20dB selectivity is roughly 35 MHz [12]. From this fact, after the 1st IF SAW filtering, it is known that the number of in-band carrier and the according composite triple beats driving the down converter are only 5 and 8, respectively. Using above result, the equivalent $IIP3_{down}$ can be calculated for given CTB_{down}.

Prior to calculate the CTB performance, we can get the more insight for the linearity requirement of DC tuner by inspecting the distortion beat level and SNR over the corresponding input carrier level shown in Fig. 3.

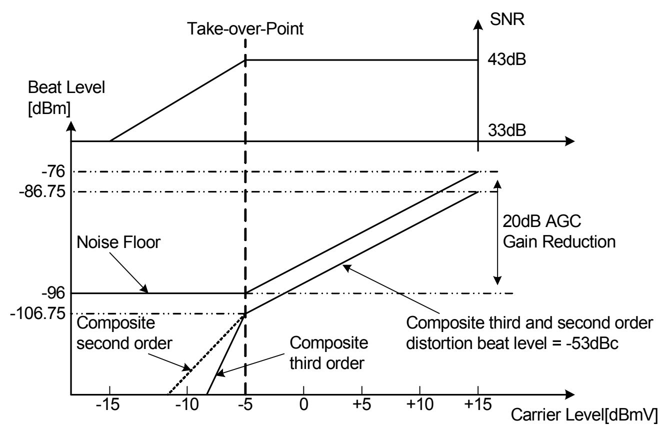

Fig. 3. SNR and distortion beat level over input carrier level

As shown in Fig. 2, the power gain of up converter has the maximum value below "take-over-point" and decreases linearly over the increase of the carrier level above "take-over-point". If there is no distortion noise, DC tuner will have 43dB of constant SNR above "take-over-point" considering –96dBm of noise floor level shown in Fig. 3. As shown in Fig. 3, at "take-over-point", the composite distortion beat level for -53dBc of experience value of CTB and CSO, which is commonly used in field engineer, is 10.75 dB below than that of the noise floor. From this, it is known that SNR degradation by distortion beats is negligible all of the carrier range and the -53dBc of the experience CTB and CSO specification of field engineer [5] is over specified.

Normally, the higher linearity requires the more power consumption in active devices. Thus, to allocate a reasonable linearity specification is very important in developing power efficient commercial products. To allocate the reasonable linearity specification for up and down converter of DC tuner, the relation between the achievable maximum SNR and the composite distortions in DC tuner must be considered first. Assuming the maximum amplitude fluctuation of down stream carriers as 3dB, the composite distortion beat level can fluctuate as much as 7.8dB for the same value of CTB and CSO performance (this assumption is for the simplification of the theory expansion). With 2.2dB of the additional distortion noise margin, the reasonable amplitude of distortion noise can be chosen 10dB lower value than the maximum noise level to satisfy 33dB of SNR requirement in DOCSIS. Thus, -43dBc of CTB and CSO specification may be a reasonable value. The according maximum SNR for –43dBc of CTB and CSO specification is equal to 38dB of maximum SNR as shown in Fig. 4. Fig. 4 is plotted the achievable maximum SNR for given CTB and CSO distortions.

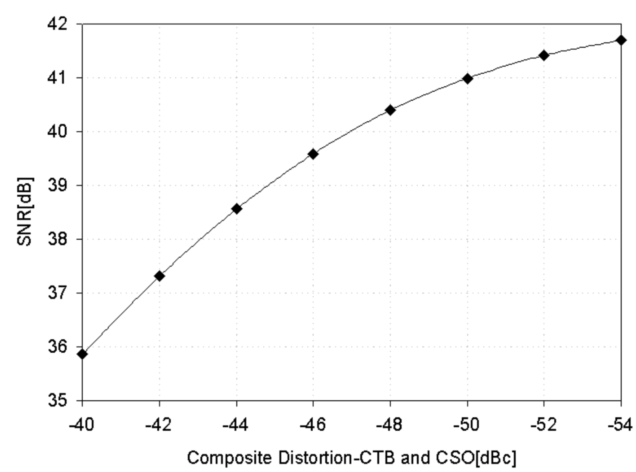

Fig. 4. Maximum SNR over Composite Distortion

The overall CTB of DC tuner is given as [5]

$$CTB = 20 \log \left[10^{\frac{CTB_{up}}{20}} + 10^{\frac{CTB_{down}}{20}} \right] \quad (17)$$

Using (7), (16) and (17), the overall CTB of DC tuner over $CTB_{up}/IIP3_{up}$ and $CTB_{down}/IIP3_{down}$ can be plotted shown in Fig. 5. Using Fig. 4 and 5, we can allocate the CTB and CSO specifications of up and down converter of DC tuner.

In this paper, the maximum SNR is selected as 38.5 dB to allocate the linearity specification from Fig. 4, which corresponds to –44dBc of CSO and CTB performance. At the

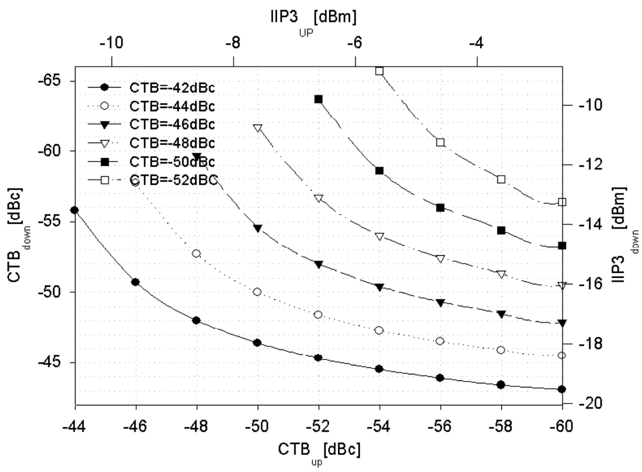

Fig. 5. CTB over CTB_{up}/$IIP3_{up}$ and CTB_{down}/$IIP3_{down}$

curve of "CTB=-44dBc" shown in Fig. 5, the point where both CTB_{up} and CTB_{down} is equal to –50dBc is selected, which are equivalent with –7.6dBm of $IIP3_{up}$ at "take-over-point" and –17.5dBm of $IIP3_{down}$, respectively. Ideally, CTB_{up} will increase linearly proportional to the increase of the input carrier level above the "take-over-point" as RF AGC decrease the power gain. The according maximum $IIP3_{up}$ will be +12.4dBm at +15dBmV of maximum input carrier level, which is 20dB above than that of "take-over-point", -5dBmV.

Since the in-band carrier number driving down converter is only 5, no CSO beats will be generated in down converter. For this reason, CSO specification of down converter in DC tuner has no meaning. Thus, the CSO_{up} is the overall CSO specification for DC tuner. In above paragraph, the CSO performance is selected as -44dBc from Fig. 4, which is equivalent +11.52dBm of $IIP2_{up}$ at "take-over-point", which can be derived using (9). The according maximum $IIP2_{up}$ is +31.52dBm at +15dBmV of the maximum input carrier level.

D. Image Rejection Ratio and Phase Noise

According to Section II, *IRR* for tuner must be lower than -59.33dBc. With commercial 1st IF SAW [12], the image signal can be rejected around -50dB over the wanted signal. This might not be sufficient to meet *IRR* specification. Normally, the commercial DC tuner product adopts IR Mixer in down converter. The required *IRR* specification for IR Mixer is around -10 ~ -15dBc considering around 5dB of margin.

The phase noise performance is allocated as –104.291dBc in Section II. This specification can be applied both oscillators for up and down converter in DC tuner.

IV. CONCLUSIONS

For the data services over the cable networks, DC tuner architecture is widely accepted for the solution of the image channel interference among the packed channels. Based on DOCSIS and many reported materials, the radio specifications such as noise figure, phase noise, image rejection ratio, CTB, CSO, power gain, and AGC range of the tuner for cable modem is analyzed. Even though there are many assumptions to derive radio specifications, it can be accepted as reasonable value considering the commercial tuner specifications. Using the radio specifications of tuner for cable modem in Section II, the specific radio specifications for the up and down converter in DC tuner are allocated, especially analyzed CTB and CSO requirements in depth. According to linearity analysis of DC tuner, it is known that –53dBc of the experience CTB and CSO value, which are commonly used in field engineer, is over-specified. By the more reasonable selection of linearity target, it is possible to design DC tuner with better power efficiency.

ACKNOWLEDGMENT

The authors wish to thank He-Ryung Kim for her corporation, and the staffs of Samsung Electro-mechanics for the support of this project.

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