LDMOS Transistors Bias Control in Basestation RF Power Amplifiers Using Intersil's LUT-based Sensor Signal Conditioners

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Introduction

LDMOS transistors are used for RF Power Amplification in numerous applications from point-to-multipoint communications to Radar. The most pervasive application is in cell phone basestations. These RF Power Amplifiers (RFPA) provide from 5W to over 200W of output power per channel, and require very good linearity to maximize the data throughput in a given channel. The main consideration to achieve that linearity is the DC biasing of the LDMOS transistor for optimal drain current for a given power output. This bias needs to be held constant over temperature and time. Typically the target accuracy for bias current over temperature is ±5% but ±3% is much more desirable for a high performance design.

A simplified circuit of an LDMOS amplifier bias circuit is shown in Figure 1. The DC Bias on these amplifiers is set by applying a DC voltage to the gate (Vgs) and monitoring the Drain current (Idd). Ideally, this Idd will be constant over temperature, but since the Vgs of LDMOS amplifier devices varies with temperature, some type of temperature compensation is required. One method of setting this DC bias involves using an adjustable reference, DAC, or Digital potentiometer combined with a temperature compensation source, such as a transistor Vbe multiplier. This solution can work well, but getting tight temperature compensation can be problematic since the Vbe junction temperature characteristic for production transistors will vary. Also, the Vgs tempco for LDMOS amplifiers will vary with Idd. The result is that there are variations in Vbe junction characteristics as well as the LDMOS characteristics. For optimal temperature compensation, in-circuit adjustments need to be made for both the temperature compensation as well as the Vgs bias itself.

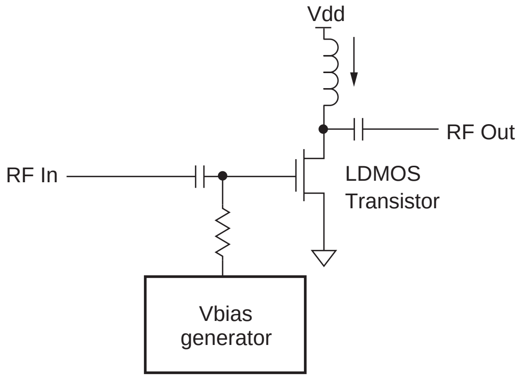


FIGURE 1. RFPA SIMPLIFIED SCHEMATIC

A new way to bias an LDMOS amplifier is presented here, which involves digitally converting temperature information and adjusting the DC bias using Look-Up Table (LUT) memory. The memory is programmed at final test using measured parameters from the amplifier circuit being tested. DC bias performance is optimized over the required temperature range.

The X96011 Sensor Bias Conditioner IC

The X96011 device is one of a family available from Intersil which perform signal conditioning functions using sensor input information. It is particularly suited to this application since it has a temperature sensor, A/D converter, a single LUT and an 8-bit DAC (see Figure 2). The device is programmed with a serial 2-wire interface using the Intersil Windows LabVIEW™ software and Drivers, and the Intersil XDCP ProgramIC board. A similar setup can be used for programming an RFPA in production.

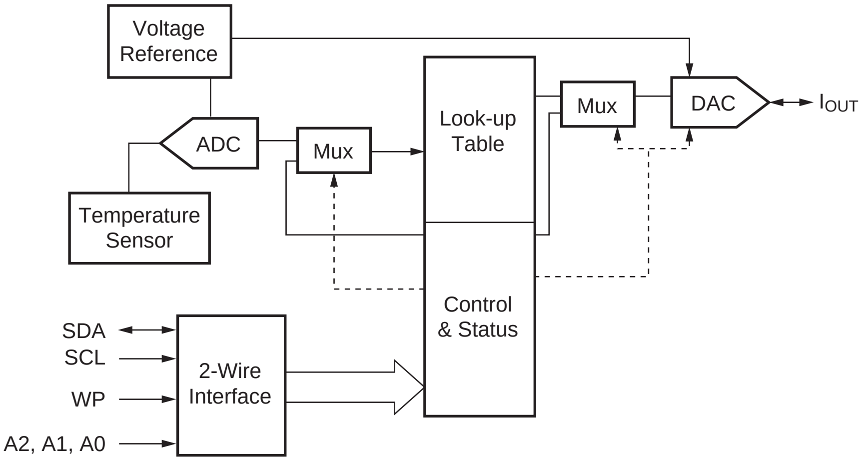


FIGURE 2. X96011 BLOCK DIAGRAM

Other functions available on the device include LUT muxes for directly controlling the LUT address, as well as direct control of the output DAC. The DAC itself has selectable ranges of output current, with 400µA, 800µA and 1.6mA full scale ranges available. Since RFPA's require a bias voltage control, an opamp converts the current to a voltage in this application. Note that the X96011 has an internal temp sensor with an 8-bit A/D converter, of which 6 bits are used for LUT addressing (64 addresses). The resulting 2.2°C/bit resolution is adequate for RFPA applications, but it is possible to improve on this with a different Intersil device, the X96010, plus an external temperature sensor (see section "Design Example: A LUT-based Temperature-Compensated RFPA Module and Measured Results").

Hardware Design using the X96011

Figure 3 shows the circuit used for this application. The LDMOS device is the MRF9080 from Freescale SPS, a 50W device optimized for GSM applications. The RF Portion of the circuit is available by contacting Freescale[1]. The DC bias is applied to the MRF9080 evaluation platform with no RF applied (inputs and outputs terminated with 50Ω). The complete temperature compensated bias control circuit consists of the X96011, an opamp and some discretes, making a small, cost-effective solution.

The MRF9080 device typically requires from 3.25V to 3.80V of bias voltage over a -20 to +100°C temp range for an Idd of 600mA. Although a 50W RFPA will quickly warm up, even at -40°C, the bias voltage should be set at startup for optimum amplifier operation. The full scale output current of the X96011 is programmable with ranges of 400µA, 800µA, and 1.6mA maximum. These ranges are set by internal resistors which have a variation of ±20%. The 800µA range is chosen here to economize on power dissipation yet keep opamp offset currents well below the control range. The X96011 requires a +5V supply so U1 is added to regulate the Vdd supply to +5V. A rail to rail input and output opamp was chosen to assure the voltage ranges of the circuit are met with a +5V supply. The feedback resistor, R1, is chosen according to the following equation:

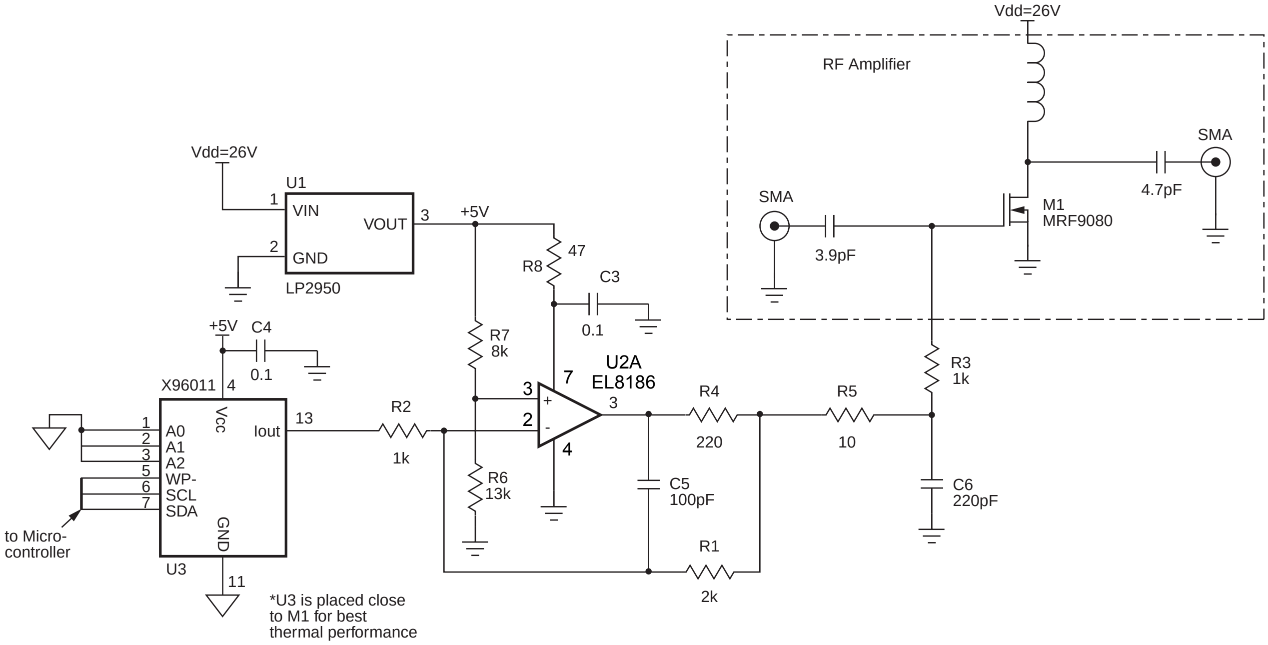
$(V_{gs} – V_a) / R1 = I1$

Va determines the low end of the output range and is fixed here to 3.0V. The maximum Vgs control voltage is needed to determine the range. Since 80% • 800µA = 640µA is the full scale range including device tolerances, R1 minimum is:

$R1 = (4.2–3.0) / (640e\text{-}6)$

$R1 = 1.88K$ minimum

A value of 2.0K was chosen to include some margin. An input resistor, R2, is included to ensure stable opamp operation. The output compliance range of the X96011 is 1.2V when sinking current, so the 1K value chosen here gives a minimum voltage of 2.04V. A lowpass filter is also included in the bias line to block RF energy from entering the bias control circuit. Since the filter presents a capacitive load to the opamp, R4 is included to isolate the load capacitance and insure stability.



*U3 is placed close to M1 for best thermal performance

FIGURE 3. RFPA BIAS CONTROL WITH THE X96011

Lookup Table Construction

There are various methods possible to compute the lookup table values. The accuracy requirement for the amplifier requires that continuous temperature adjustment is made over the range of the amplifier. The X96011 provides a -40 to +100°C temperature measurement range which will work for this application. If higher temperature compensation is needed, an external temperature sensor can be used with one of the other Intersil bias controllers (the X96010 and X96012 provide external sensor inputs). See the hardware example which follows.

The temperature sensor in the X96011 digitizes to 6-bit accuracy, giving a resolution of 2.2°C/bit, or compensation which can change every 2.2°C. In this example, the typical gm of the MRF9080 is about 3.3mhos, and the temperature sensitivity of the Vgs is about -2.8mV/°C. So, between steps of adjustment we can expect the amplifier to drift:

(-2.8mV/°C) • (3.3mA/mV) • (2.2°C/step) = 20mA/step.

The target Idd for the MRF9080 is 600mA, so the error expected due to temperature quantization is about 3.3%. Depending on how well the calibration is done, this can be centered around the target Idd giving an accuracy of ±1.65%, which is within our target.

The other factor in the control of the bias current is the output bias control voltage quantization. There is 8-bit control with the X96011, and using the worst case full range current and the gm of the MRF9080, we get

(3.3) • [(2000Ω) • (800e-6 • 1.2)] / 255 = 24mA/step.

Again, if the calibration is done well, this should result in about ±12mA variation around the target Idd or ±2.0%.

A very simple yet effective way to construct the lookup table is to make measurements at two temperatures that represent the target range for the product, and then interpolate values for the other temperatures with a linear regression. For example, the ADC value (temperature) is recorded for one setting, and then the DAC is adjusted to place the amplifier at a bias point closest to the correct Idd. The amplifier is heated or cooled to the other temperature and allowed to settle, then the second ADC value is recorded while the DAC is set to the best output setting. The table is then constructed using all of the values of ADC outputs (64 entries) and the corresponding DAC values interpolated from the measured values.

Note that since Vgs drift is not perfectly linear with temperature, that the error in this method will increase at the temperature extremes. A more accurate method would include more temperature points and then interpolate between those points.

A LUT-based Temperature-Compensated RFPA Module and Measured Results

X96010 Hardware Design

An amplifier evaluation platform for the Freescale MRF9080 LDMOS amplifier[1] was modified to include biasing by the X96010 device and produced very good results. The modifications included a temperature sensor (LM35) mounted near the LDMOS and remote connections to the X96010 plus op amp on a PC board.

The X96010 device includes inputs to the ADC for external sensors, and for external DAC current range setting resistors (see Figure 4). The temperature sensor circuit has a range starting at 0V at 0°C and increases 10mV/°C. The ADC range of the X96010 is from 0V min to 1.21V, (the internal reference value), so the control range of the X96010 circuit is from 0°C to 121°C. This range is sufficient for the amplifier in most applications since the board/junction temperature will be quite a bit higher than ambient. LUT control also allows for over-temperature control by reducing gate voltage at a specific hot temperature point to prevent thermal failure. The resolution of the LUT DAC control is now 1.92°C/step.

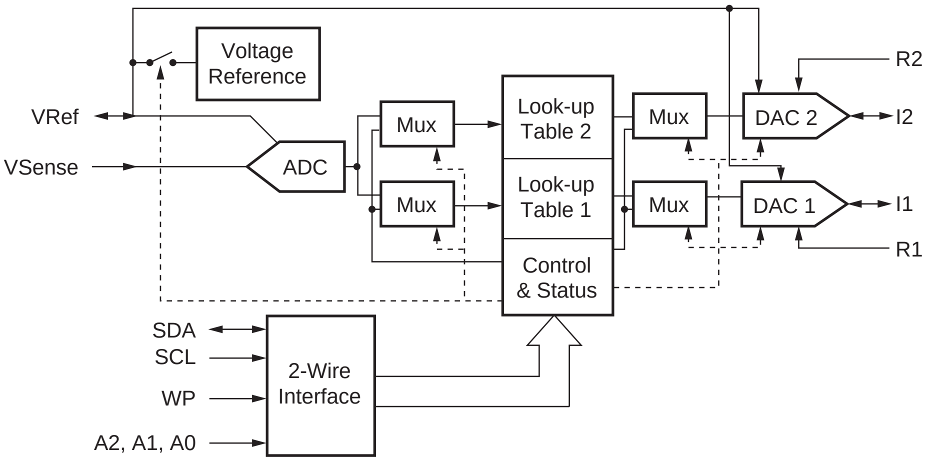


FIGURE 4. X96010 BLOCK DIAGRAM

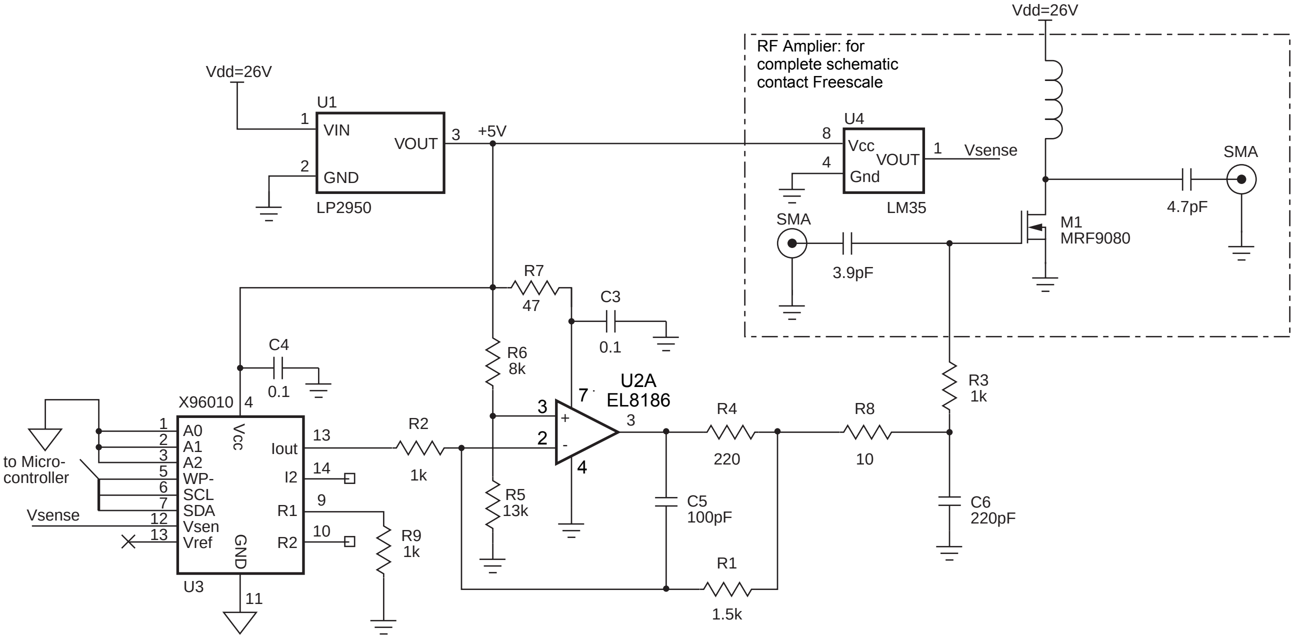


FIGURE 5. RFPA DESIGN USING THE X96010

For better output current accuracy and ease of design, a 1kΩ current setting resistor (connected to pin R1) was used on the X96010, and the gain setting resistor was changed to suit the new output current range. The output current range variation is now limited by the resistor tolerance plus the X96010 reference tolerance, or ±3%. The resulting circuit has a bias range of 3.05V to 4.20V and a DAC resolution of 4.5mV/step. The circuit is shown in Figure 5.

Lookup Table Generation

To set up the lookup table, the circuit was powered up and tested at two temperatures, 29°C and 75°C. At each temperature, the Idd bias was set to the desired value and the DAC setting recorded. These values were used in a spreadsheet to generate a set of bias values that varied linearly with temperature. Although the Idd bias temperature variation is somewhat nonlinear, the use of the linear control values and two-step calibration is fairly efficient and accurate over a limited temperature range.

The spreadsheet requires a bit of setup beforehand. The ADC output is recorded in 8-bit values which need to be converted to 6-bits for use in the LUT addressing. The DAC values will be calculated linearly to vary with temperature, but need to be rounded off since the increments are non-integer, and then translated to a hex value. Finally, the actual LUT address (DAC output) is offset from zero to start at 90 hex . Once completed, the final spreadsheet has two adjacent columns which contain the LUT address and DAC setting, and these can be copied and pasted into a text document. The text document is easily read by the Intersil X9601x LabVIEW software program which loads the values directly into X96010 EEPROM. See Appendix 1 for the setup table and spreadsheet results (Evaluation boards and software for the X96010 family are available from Intersil, as well as the sample design spreadsheet, see www.intersil.com or call an Intersil sales representative).

Results

The Amplifier platform and control circuit were placed in a temp chamber and tested from 0°C ambient to 90°C. The bias current was monitored (RF power OFF) and the results are shown in Figure 6. Error from Ideal is shown in Figure 7.

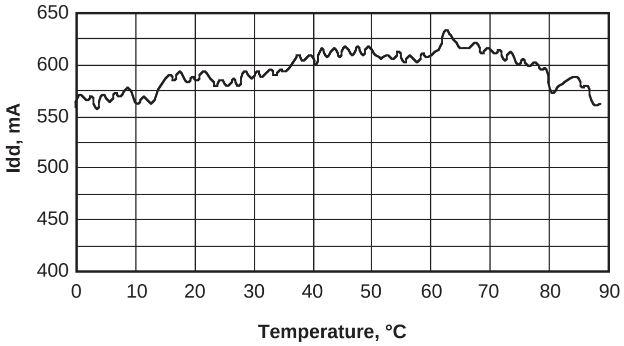


FIGURE 6. MEASURED DRAIN CURRENT vs TEMPERATURE

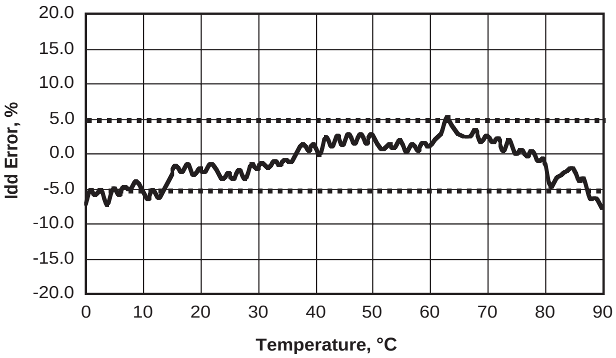


FIGURE 7. DRAIN CURRENT ERROR vs TEMPERATURE

Figure 6 includes ±5% limit indicators, and the amplifier stays within these limits fairly consistently, meeting the design goals. There are some discontinuities in the compensation visible, and those are due to roundoff and quantization error. With a reduced temperature control range, the resolution of the temperature sensor would increase and the resulting drift correction would improve. Note that above and below the measured temperatures the Vgs temp characteristics of the MRF9080 increasingly diverge from a linear relationship, and for greatest accuracy additional characterization points are needed and the LUT modified accordingly.

One thing to note in this design or any that requires temperature compensation is the mechanical properties of the board mounting and the cooling system. In this example, airflow over the LDMOS device and the temperature sensor was limited, which enhanced the resulting compensation. Also, the sensor was surface mounted with conductive grease next to the LDMOS device. In many designs precise control over placement and airflow is not possible, but since calibration takes place *after* the assembly of the unit, these effects can be minimized as long as the final installation is similar to the calibration conditions.

LDMOS amplifiers also have a characteristic Idd drift over time (drain current reduces for a given Vgs), as well as temperature. This can be addressed with lookup table correction with a slightly higher constant bias offset, so that over time the Idd will drift closer to the target bias value, not further away.

References:

1. Freescale Wireless Infrastructure Division
2100 East Elliot Road
Tempe, AZ 85284
(800) 521-6274
http://www.freescale.com/

Appendix 1. Lookup Table Construction

Lookup Table Input Parameters

These parameters were measured after assembly and setup of the bias control and amplifier circuit. Using the serial interface, remote setup and calibration can be done.

CALIBRATION DATA	TEMPERATURE		UNITS
	HIGH	LOW	
Temperature	75	29	°C
ADC =	26	0e	hex
ADC =	38	14	dec
ADC (temp) steps		24	
DAC =	50	60	hex
DAC =	80	102	dec
DAC (Vout) steps		-22	
DAC steps / ADC steps		-0.92	

Lookup Table Spreadsheet Setup and Results

Yellow and Cyan cells indicate calibration points

Shaded columns indicate final LUT entries (to be copied/ pasted to LUT file)

TABLE 1. LOOKUP TABLE SPREADSHEET SETUP AND RESULTS

6-BIT A/D OUT (DECIMAL)	6-BIT A/D OUT (HEX)	LUT ADDRESS W/OFFSET	DAC IOUT SETTING (HEX)	DAC IOUT SETTING (INTEGER)	IOUT SETTING (REAL)
0	0	90	73	115	114.83
1	1	91	72	114	113.92
2	2	92	71	113	113.00
3	3	93	70	112	112.08
4	4	94	6F	111	111.17
5	5	95	6E	110	110.25
6	6	96	6D	109	109.33
7	7	97	6C	108	108.42
8	8	98	6C	108	107.50
9	9	99	6B	107	106.58
10	A	9A	6A	106	105.67
11	B	9B	69	105	104.75
12	C	9C	68	104	103.83
13	D	9D	67	103	102.92
14	E	9E	66	102	102.00
15	F	9F	65	101	101.08
16	10	A0	64	100	100.17
17	11	A1	63	99	99.25
18	12	A2	62	98	98.33
19	13	A3	61	97	97.42
20	14	A4	61	97	96.50
21	15	A5	60	96	95.58
22	16	A6	5F	95	94.67
23	17	A7	5E	94	93.75
24	18	A8	5D	93	92.83
25	19	A9	5C	92	91.92
26	1A	AA	5B	91	91.00
27	1B	AB	5A	90	90.08
28	1C	AC	59	89	89.17
29	1D	AD	58	88	88.25
30	1E	AE	57	87	87.33
31	1F	AF	56	86	86.42
32	20	B0	55	85	85.50
33	21	B1	55	85	84.58
34	22	B2	54	84	83.67
35	23	B3	53	83	82.75
36	24	B4	52	82	81.83
37	25	B5	51	81	80.92

TABLE 1. LOOKUP TABLE SPREADSHEET SETUP AND RESULTS (Continued)

6-BIT A/D OUT (DECIMAL)	6-BIT A/D OUT (HEX)	LUT ADDRESS W/OFFSET	DAC IOUT SETTING (HEX)	DAC IOUT SETTING (INTEGER)	IOUT SETTING (REAL)
38	26	B6	50	80	80.00
39	27	B7	4F	79	79.08
40	28	B8	4E	78	78.17
41	29	B9	4D	77	77.25
42	2A	BA	4C	76	76.33
43	2B	BB	4B	75	75.42
44	2C	BC	4A	74	74.50
45	2D	BD	4A	74	73.58
46	2E	BE	49	73	72.67
47	2F	BF	48	72	71.75
48	30	C0	47	71	70.83
49	31	C1	46	70	69.92
50	32	C2	45	69	69.00
51	33	C3	44	68	68.08
52	34	C4	43	67	67.17
53	35	C5	42	66	66.25
54	36	C6	41	65	65.33
55	37	C7	40	64	64.42
56	38	C8	3F	63	63.50
57	39	C9	3F	63	62.58
58	3A	CA	3E	62	61.67
59	3B	CB	3D	61	60.75
60	3C	CC	3C	60	59.83
61	3D	CD	3B	59	58.92
62	3E	CE	3A	58	58.00
63	3F	CF	39	57	57.08