Comparison of Adjacent and Co-Channel Interference for Three and Four Channel Assignment Plans in IEEE 802.11b WLAN Networks

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I. BACKGROUND

One of the main issues in deploying a Wireless LAN (WLAN) is providing adequate coverage to the target area with the fewest number of WLAN Access Points (AP). The FCC has provided a limited spectrum of 83 MHz for the ISM frequency band from 2.4 to 2.4835 GHz, of which only 11 IEEE 802.11b standard channels are permitted in 5 MHz offsets in North America due to mandatory guard-bands.

Table 1: IEEE 802.11b channels in North America

CHANNEL #	FREQUENCY (MHZ)
1	2415
2	2420
3	2425
4	2430
5	2435
6	2440
7	2445
8	2450
9	2455
10	2460
11	2465

Although all WLAN equipment is capable of operating at these carrier frequencies, only three (1, 6, and 11) are typically used in practice since they minimize Adjacent Channel Interference (ACI). This makes the assignment of channels difficult because, as we will prove in this paper, fewer available channels substantially increases Co-Channel Interference (CCI). Therefore, an ACI/CCI tradeoff analysis will show whether it is beneficial to use more channels for a given coverage area with fixed AP locations.

Determining AP locations and channel assignment for optimal WLAN coverage is a science that requires an artistic appreciation of color and patterns. Once a site survey determines the location of the APs that provide adequate signal strength throughout the coverage area, the assignment of WLAN channels becomes a map tiling problem. An example of this problem is attempting to color a map of the United States with a limited number of colors without permitting like colored States to touch. This century old problem is proved with the Four Color Theorem[1] which shows that *all* geographic (or AP coverage area) maps can be tiled without like colors touching with only four colors. Four colors are the least number that will work for all maps, and in many cases, three colors will result in like colors in adjacent areas. We can infer from this that as APs with the same channel assignment are spaced further apart, CCI will diminish. The tradeoff for reducing CCI is that ACI increases as channel assignment frequencies move closer together. We will also prove that a four-channel assignment plan induces acceptable ACI while reducing CCI, so higher WLAN data rates are attained throughout the coverage area.

II. CALCULATION OF SIGNAL-TO-INTERFERENCE RATIO (SIR)

ACI is defined as the amount of energy in the side-lobes of the adjacent channel's filtered Sinc function that extend into the 22 MHz bandwidth of the WLAN receiver. The IEEE 802.11b standard specifies the spectral mask of a DSSS WLAN modulated waveform as defined in Table 2.

Table 2: IEEE 802.11b spectral mask requirements

$\|\Delta f\|$ greater than	Attenuation relative to peak of sinc function
11 MHz	-30 dBr
22 MHz	-50 dBr

According to the datasheet for Intersil Inc.'s HFA3783 I/Q Modulator/Demodulator IF chip, the baseband 11 MHz spread spectrum data sequence is low-pass filtered by a 2nd order filter with a 7.7 MHz 3dB bandwidth[2]. It is reasonable to assume that the receiver relies upon a matched filter for optimal reception, so that the transmitted and received waveform is passed through two similar low-pass filters.

The ratio of the total interference from all of the operating APs at the lower and upper adjacent channels and the co-channel to the power from the desired AP at any point is calculated as follows:

$$\text{SIR} = \frac{ACI_{Lower} - ACI_{Lower\_L_p} + ACI_{Higher} - ACI_{Higher\_L_p} + CCI - CCI_{L_p}}{DesiredPwr - Desired_{L_p}}$$

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[1] http://www.math.gatech.edu/~thomas/FC/fourcolor.html

[2] Our simulation shows that a 3rd order Butterworth is capable of meeting the IEEE 802.11b standard's required spectral mask, so it was used instead. It is possible that Intersil used a filter type with a steeper transition band, but still matches the 3rd order Butterworth frequency response.

The descriptions of these variables are listed in Table 3 and the formulas for the contributions of each AP to ACI and CCI are listed in Appendix A.

Table 3: Definition of equation parameters for ACI calculation

Name	Definition
ACI_{Lower}	Contribution of lower adjacent channel to total ACI in client's 22 MHz receive BW
$ACI_{Lower\_L_p}$	Average path loss for APs operating at the lower adjacent channel frequency
ACI_{Higher}	Contribution of higher adjacent channel to total ACI in client's 22 MHz receive BW
$ACI_{Higher\_L_p}$	Average path loss for APs operating at the higher adjacent channel frequency
CCI	Contribution of co-channel CCI, ideal is equivalent to DesiredPwr
CCI_{L_p}	Average path loss for APs operating at the co-channel frequency
$DesiredPwr$	Power received from desired AP in Client's 22 MHz receive BW
$Desired_{L_p}$	Average path loss from the one desired AP to the client

The path loss for co-channel and adjacent channel assigned APs for rectangular and hexagon cells for typical three, four, and 8 cell layout is defined as:

$$\text{Inverse Power Path Loss (dB)} = 10\cdot\log_{10}\left(\frac{4\cdot\pi\cdot f}{c}\right)^2 + 10\cdot N\cdot\log_{10}\left(R\cdot D\cdot\frac{1meter}{3.28\,feet}\right)$$

Where f = carrier frequency in Hz, c = speed of light in m/s, N = propagation exponent, assumed to be 3 for 2.4 MHz frequency range[3], R = cell radius in feet, assumed to be 50 feet for this simulation, and D is the combined relative distance to the other APs as defined in Appendix B.

III. INTERFERENCE CALCULATION FOR A THREE CELL LAYOUT

It is informative to plot the ACI and CCI, if present, for a given physical WLAN cell layout at the point of greatest interference or least Signal-to-Interference Ratio (SIR). SIR is the ratio of useful energy to all interfering power delivered to a single point with the exception of thermal noise. This location depends entirely on the physical layout of the cells,

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[3] See "Understanding Wireless LAN Performance Trade-Offs" by J. Yee and H. Ezfahani in November 2002 issue of Communication System Design magazine.

the cell geometry, and the manner in which frequency channels are assigned. In the case of three adjacent hexagon cells in Figure 1, point ***A*** is the point of *least* SIR. Figure 2 is a plot of the SIR at point A for various channel frequency spacing.

Figure 1: Three hexagonal cell layout where received power from each AP is equal at point A, the point of greatest ACI and least SIR

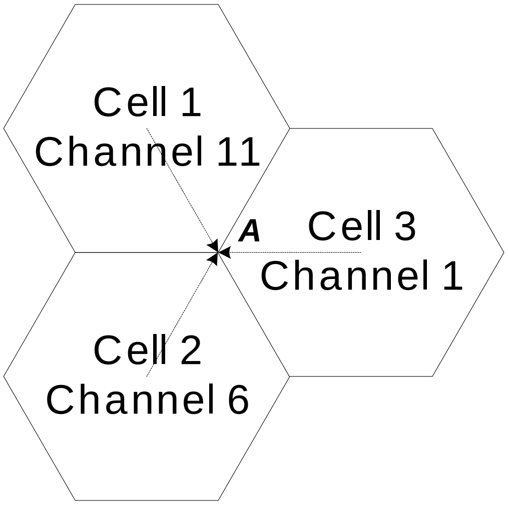
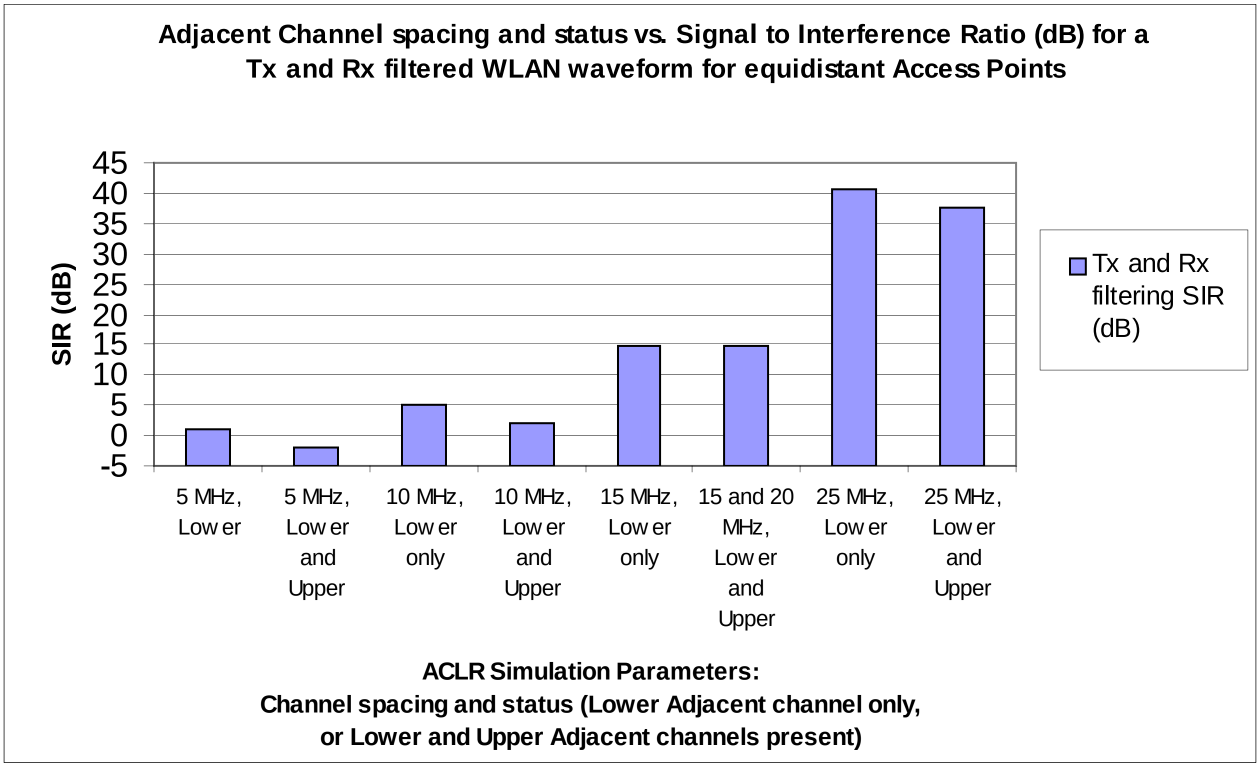


Figure 2: Plot of Lower and Upper ACI (solely and jointly) for various channel frequency spacing



In order to capture the effect of baseband pulse shaping on ACI, further simulations are conducted for all combinations of transmitter and receiver filtering. The results of the ACI calculations are shown in Table 4.

Table 4: Adjacent Channel Interference (ACI) for various WLAN channel spacing and different combinations of baseband filtering at the Transmitter and Receiver

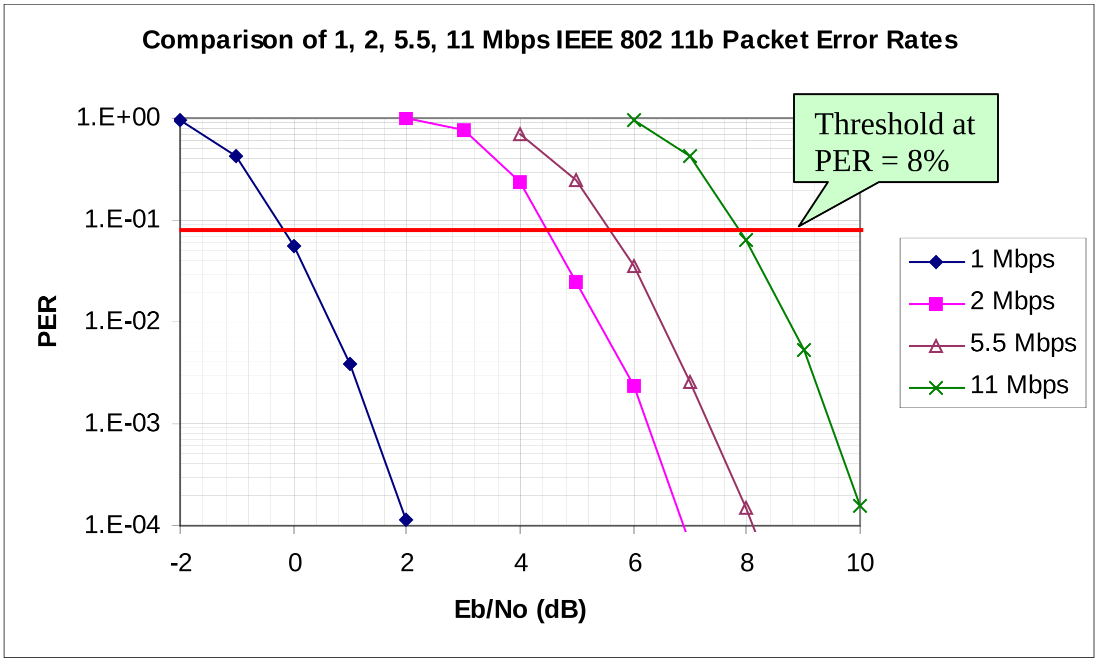
Channel Spacing and Status	Number of channels	Lower Channel Spacing (MHz)	Upper Channel Spacing (MHz)	No Filtering, ACLR %	No Filtering, SIR (dB)	Tx Filtering, ACLR %	Tx Filtering, SIR (dB)	Tx and Rx Filtering, ACLR %	Tx and Rx filtering SIR (dB)
5 MHz, Lower	**11**	5	-	96.4397	0.15744	93.1638	0.30753	78.8863	1.03
5 MHz, Lower and Upper	**11**	5	5	192.0831	-2.8349	185.5583	-2.6848	157.1211	-1.9623
10 MHz, Lower only	**5**	10	-	63.103	1.9995	58.6936	2.3141	31.1989	5.0586
10 MHz, Lower and Upper	**5**	10	10	125.1681	-0.97494	116.4219	-0.66035	61.8846	2.0842
15 MHz, Lower only	**4**	15	-	18.0929	7.4249	12.626	8.9873	3.3025	14.8116
15 and 20 MHz, Lower and Upper	**4**	15	20	21.8067	6.6141	12.7337	8.9504	3.3504	14.749
25 MHz, Lower only	**3**	25	-	3.1997	14.9488	0.02025	35.6824	0.0089584	40.4777
25 MHz, Lower and Upper	**3**	25	25	6.2695	12.0376	0.052952	32.7612	0.017553	37.5565

IV. SIMULATION OF IEEE 802.11b SNR THRESHOLDS

Oberon engineers have conducted baseband simulations on the family of IEEE 802.11b modulation techniques and determined the exact SNR to maintain a given Packet Error Rate (PER). The IEEE 802.11 working group has standardized the minimum acceptable PER for acceptable data throughput as 8% PER for 1024 byte packets, so this is the *threshold PER* of our simulations for all four 802.11b modulation rates. The required SNRs for the four modulation rates are then compared to the SIR at a given point in a cell layout, which allows a WLAN designer to predict what the highest reliable data rate of the WLAN will be at that point.

Figure 3 contains the Packet Error Rate vs. SNR or Eb/N0 plots for each of the data rates available in the IEEE 802.11b standard. A red threshold line is drawn through the 8% PER to highlight that this is the SNR threshold for acceptable data throughput for each of the modulations.

Figure 3: Packet Error Rate for 1, 2, 5.5, and 11 Mbps modulation rates for IEEE 802.11b



It is possible to estimate the threshold of sensitivity from these plots for the various Packet Error Rates. For example, for a given PER of 8%, Table 5 shows the received signal power levels that a WLAN receiver would require in an ideal radio channel where multipath effects are mitigated and *no* co or adjacent channel interference exists.

Table 5: Required SIR spreadsheet calculation to obtain a BER of 10^{-5}

	1 Mbps, 11 chip DSSS BPSK	2 Mbps, 11 chip DSSS QPSK	5.5 Mbps, 8 chip CCK BPSK	11 Mbps, 8 chip CCK QPSK
Simulated Eb/No required for 8% PER (dB)	10.25	10.25	7.50	8
Thermal Noise Floor (dBm)	-100.82	-100.82	-100.82	-100.82
Receiver Noise Figure @ Max Gain (dB)	8	8	8	8
Receiver Noise Floor @ Max Gain (dBm)	-92.82	-92.82	-92.82	-92.82
SNR (dB) required to achieve 8% PER	-0.2	4.4	5.6	7.8
Threshold of Sensitivity for PER of 8% (dBm)	**-93.02**	**-88.42**	**-87.22**	**-85.02**

V. SIR CALCULATION AND MODULATION RATE ANALYSIS FOR MULTIPLE CELL LAYOUTS

The computational approach for calculating SIR is then applied to layouts of four and eight cells for three and four channel assignment plans. Appendix C contains the diagrams of the layouts and the points of maximum interference. It is assumed for the sake of simplicity in comparing the three and four channel frequency assignment plans that there is an absence of receiver-generated thermal noise and the radio channel is ideal. As shown in Table 6, the clear winner in the four-cell layout with hexagonal cells is a four-channel assignment plan. Data rates of 5.5 Mbps are possible even at the point of greatest ACI. The results become less conclusive for the eight cell layouts. The SIR improves about one dB for the four-channel plan, but still does not permit a higher data modulation at a PER of 8%. This may be due to the use of a simple inverse power law for predicting path loss. A more realistic propagation model for indoor wireless can predict a greater path loss over a given distance, which further increases the four-channel plan's CCI immunity. It should be noted that the 8 cell layout does experience slightly better 1 and 2 Mbps reception at the point of greatest ACI.

Table 6: Signal to Interference (SIR) results for various channel plans over three, four, and eight cell layouts

Cell Shape	**# of Channels**	**# of Cells in Layout**	**ACLR (%)**	**SIR (dB)**	**Highest WLAN data modulation rate supported with PER >= 8%**	**1 Mbps PER %**	**2 Mbps PER %**	**5.5 Mbps PER %**	**11 Mbps PER %**
Hexagon	3	3	0.017553	37.5565	**11 Mbps**	0%	0%	0%	0%
Rectangular	3	4	100.0176	-0.00076225	**1 Mbps**	5.2%	100%	100%	100%
Hexagon	3	4	100.0912	-0.0039593	**1 Mbps**	5.4%	100%	100%	100%
Hexagon	3	8	67.7637	1.69	**1 Mbps**	0.04%	100%	100%	100%
Rectangular	4	4	3.3504	14.749	**11 Mbps**	0%	0%	0%	0%
Hexagon	4	4	17.4093	7.5922	**5.5 Mbps**	0%	0%	0.03%	10%
Hexagon	4	8	51.8846	2.8496	**1 Mbps**	0%	75%	100%	100%

Appendix A: Equations for ACI and CCI

$$ACI_{Lower} = \int_{-11MHz}^{+11MHz} \left[\frac{\sin\left(\frac{f + f_{LowerChannelOffset}}{22MHz} \right)}{\frac{f + f_{LowerChannelOffset}}{22MHz}} \right]^2 \left[\frac{1}{1 + \left(\frac{f}{7.7MHz} \right)^{2 \cdot 3}} \right] \left[\frac{1}{1 + \left(\frac{\left(f + f_{LowerChannelOffset} \right)}{7.7MHz} \right)^{2 \cdot 3}} \right] df$$

$$ACI_{Upper} = \int_{-11MHz}^{+11MHz} \left[\frac{\sin\left(\frac{f - f_{UpperChannelOffset}}{22MHz} \right)}{\frac{f - f_{UpperChannelOffset}}{22MHz}} \right]^2 \left[\frac{1}{1 + \left(\frac{f}{7.7MHz} \right)^{2 \cdot 3}} \right] \left[\frac{1}{1 + \left(\frac{\left(f - f_{UpperChannelOffset} \right)}{7.7MHz} \right)^{2 \cdot 3}} \right] df$$

$$CCI = \int_{-11MHz}^{+11MHz} \left[\frac{\sin\left(\frac{f}{22MHz} \right)}{\frac{f}{22MHz}} \right]^2 \left[\frac{1}{1 + \left(\frac{f}{7.7MHz} \right)^{2 \cdot 3}} \right]^2 df$$

$$DesiredPwr = \int_{-11MHz}^{+11MHz} \left[\frac{\sin\left(\frac{f}{22MHz} \right)}{\frac{f}{22MHz}} \right]^2 \left[\frac{1}{1 + \left(\frac{f}{7.7MHz} \right)^{2 \cdot 3}} \right]^2 df$$

Appendix B: Table of relative distances based on cell shape, number of available channels, and number of cells in layout map

Cell Shape	# of Channels	# of Cells	Equation Name	D (Relative Distance)
Rectangle	3	4	Desired Signal Lp, Co-Channel Lp, Lower Adjacent Channel Lp, Upper Adjacent Channel Lp	$\frac{\sqrt{2}}{2} = 0.7071$
Hexagon	3	3	Desired Signal Lp, Lower Adjacent Channel Lp, Upper Adjacent Channel Lp	1
Hexagon	3	4	Desired Signal Lp, Co-Channel Lp	$\frac{3}{2}$
			Lower Adjacent Channel Lp, Upper Adjacent Channel Lp	$\frac{\sqrt{2}}{2} = 0.7071$
Hexagon	3	8	Desired Signal Lp	1
			Co-Channel Lp	$\frac{1}{\frac{1}{2}+\frac{1}{\sqrt{7}}} = 1.1390$
			Lower Adjacent Channel Lp,	$\frac{1}{\frac{1}{2}+1+\frac{1}{\sqrt{7}}} = 0.5325$
			Upper Adjacent Channel Lp	$\frac{1}{\frac{1}{2}+1} = 0.6667$
Rectangle	4	4	Desired Signal Lp, Lower Adjacent Channel Lp, Upper Adjacent Channel Lp	$\frac{\sqrt{2}}{2} = 0.7071$
Hexagon	4	4	Desired Signal Lp	$\frac{3}{2}$
			Lower Adjacent Channel Lp, Upper Adjacent Channel Lp	$\frac{\sqrt{3}}{2} = 0.8660$
Hexagon	4	8	Desired Signal Lp	1
			Co-Channel Lp	$\frac{1}{\frac{1}{\sqrt{7}}+\frac{1}{\sqrt{7}}} = 1.3229$
			Lower Adjacent Channel Lp,	$\frac{1}{1+\frac{1}{\sqrt{7}}} = 0.7257$
			Upper Adjacent Channel Lp	$\frac{1}{\frac{1}{2}+\frac{1}{2}} = 1$

Append C: Diagrams of four and eight cell layouts for three and four channel assignment plans

Figures 4 and 5: Plot of three and four channel assignment plans

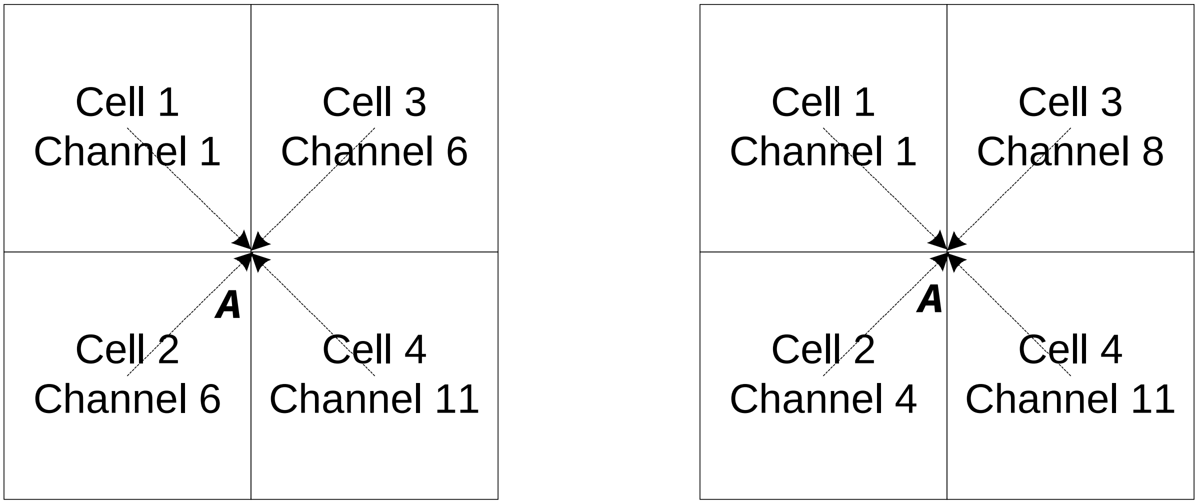


Figure 6: Plot of eight and four cell layouts for three-channel assignment plan (point A is point of least SIR for eight cells, point B is the point of least SIR for four cells)

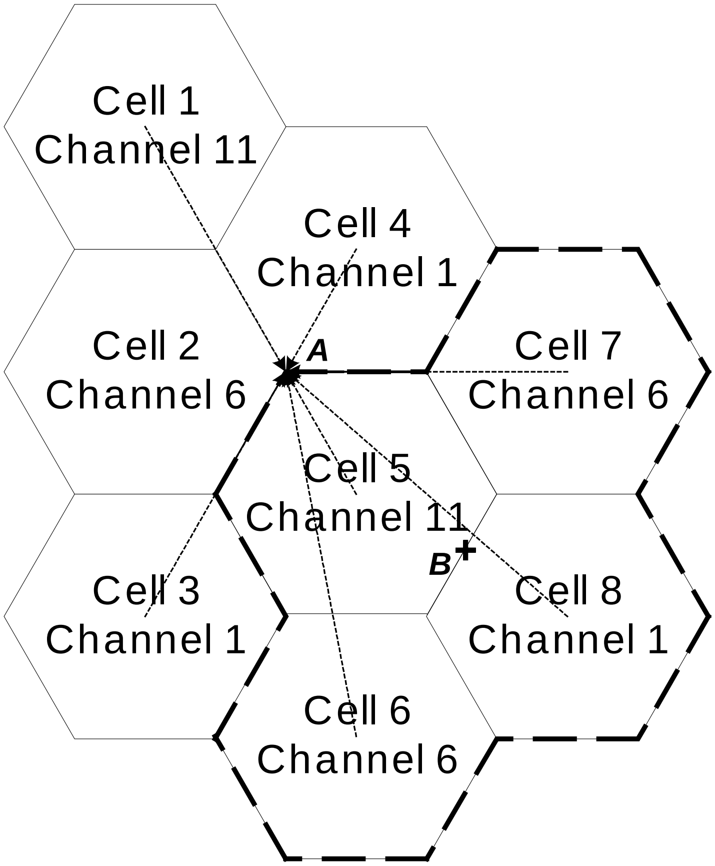
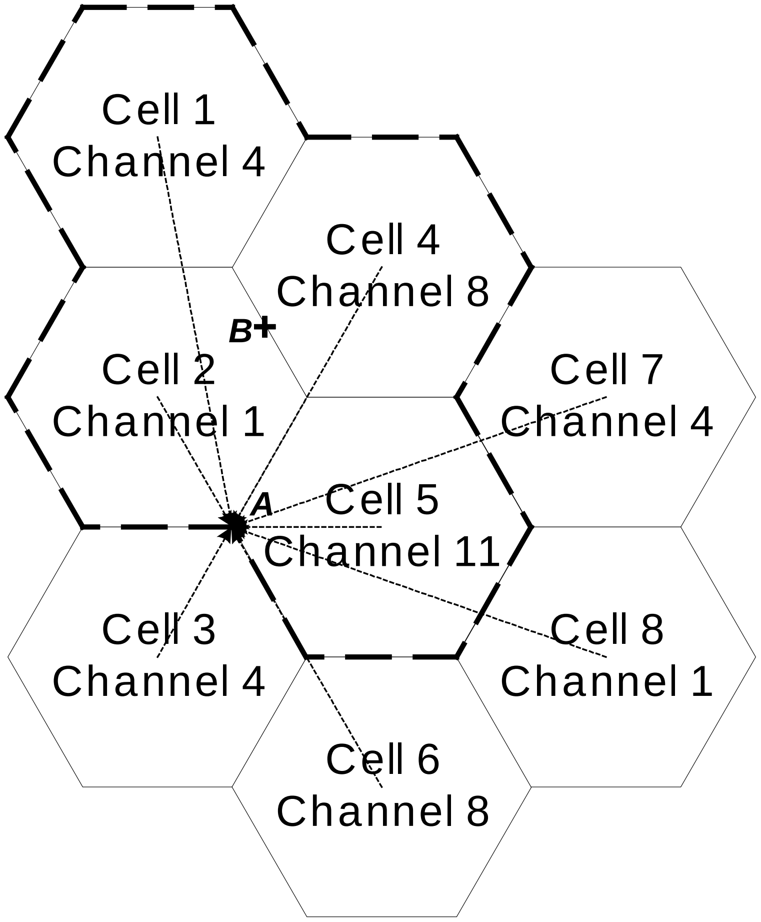
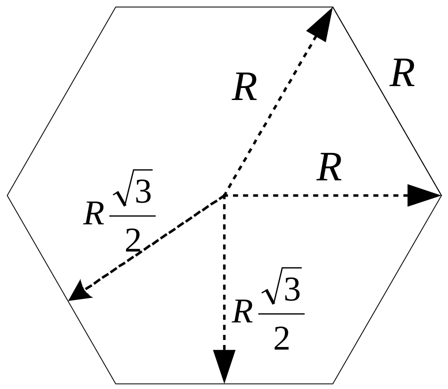


Figure 7: Plot of eight and four cell layouts for four channel assignment plan (point A is point of least SIR for eight cells, point B is the point of least SIR for 4 four cells)





Appendix D: Plots of Power Spectral Density for four cell layouts, rectangular cells

Figure 8: PSD for three channel assignment plan, note that the Tx and Rx filtered SIR≅0 dB due to strong CCI, SIR is too low for reliable 1 Mbps data modulation

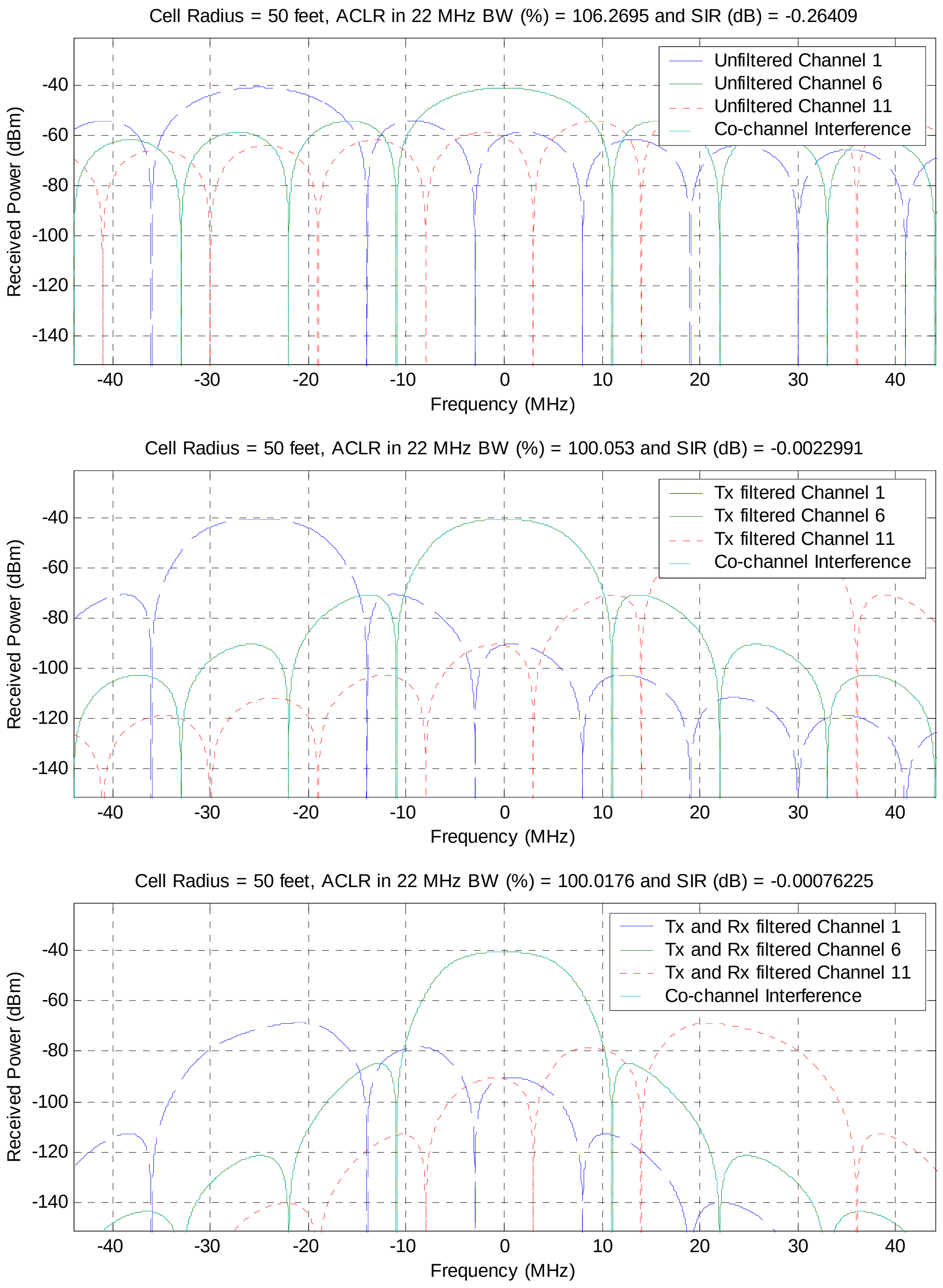


Figure 9: PSD for four-channel assignment plan, note that Tx and Rx filtered SIR permits 11 Mbps data modulation