Very High Speed Ordered Mesh Network of Seismic Sensors for Oil and Gas Exploration

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Abstract

Oil and gas exploration requires channeling the input from thousands of portable sensors located over a large geographical area to a central processing station. High data rates and the requirement to support near-real time processing make this a challenging application for a distributed sensor network. This presentation will describe how specific characteristics of the application can be used to advantage in obtaining a high data rate in a distributed wireless environment.

1. The Application

Oil and gas exploration is carried out by sending a large pulse of mechanical energy into the earth. This energy reflects from geological formations deep in the earth and returns to a sensor array. A typical sensor array consists of several thousand sensors, laid out roughly in the shape of a rectangle. A row consists of 60 to 120 sensors placed 50 to 100 meters apart, while a column consists of 20 to 40 sensors placed 100 to 300 meters apart. Thus an array might cover several square miles. (See Figure 1).

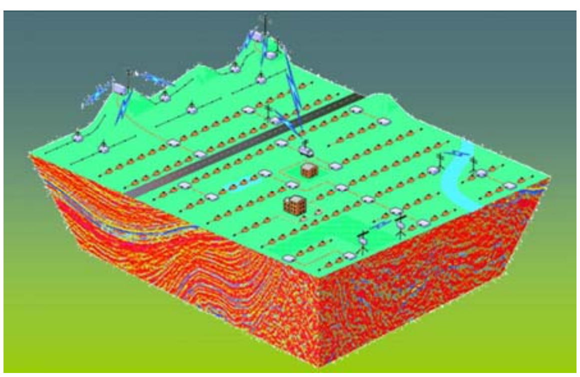

Figure 1. Typical sensor array

Each sensor produces data at the rate of about 12 Kbps and it is important that the data is temporally synchronized with the data from the other sensors. The aggregate data rate from a sensor array can reach tens of Mbps. Sensor data is collected at a central location for processing and display. Ideally, the data is collected in near real time to keep up with the field operations and so that the results of a test can be validated before the sensors are retrieved.

2. The Challenge

Current oil and gas exploration practice makes use of data cables to connect sensors to the central processing facility. This solution is very expensive and labor intensive because it involves laying out many tons of cables. Furthermore, the physical and geographical obstructions within the array (e.g. a highway) can increase the cost and labor of cable set-up and connection. A wireless solution to data collection would be very desirable, but the challenge is to meet the high data rate and the time synchronization requirements.

3. Special Characteristics

We have been able to obtain a solution to the high data rate problem by taking advantage of unique characteristics of the sensor array. First, the basic geometry of the array is known at the outset, because the sensors are placed according to a plan and their physical location is measured very precisely at the time of placement. This is necessary to support proper data processing. Second, sensors are stationary during the entire data collection process. This combined with the generally rectangular layout of the array means that the physical relationship between sensors is known and invariant. Third, because sensors do not move, problems related to rearrangement of the wireless data links do not occur. However, our plan does consider that sensors may drop out and rejoin the network due to failure or temporary, localized interference.

4. The Field Layout

Our wireless data transport approach takes advantage of the inherently rectilinear arrangement of the sensors. Figure 2 shows a schematic idealization of the sensor array. The “long” axis of the array is horizontal in the illustration. Data is transferred from

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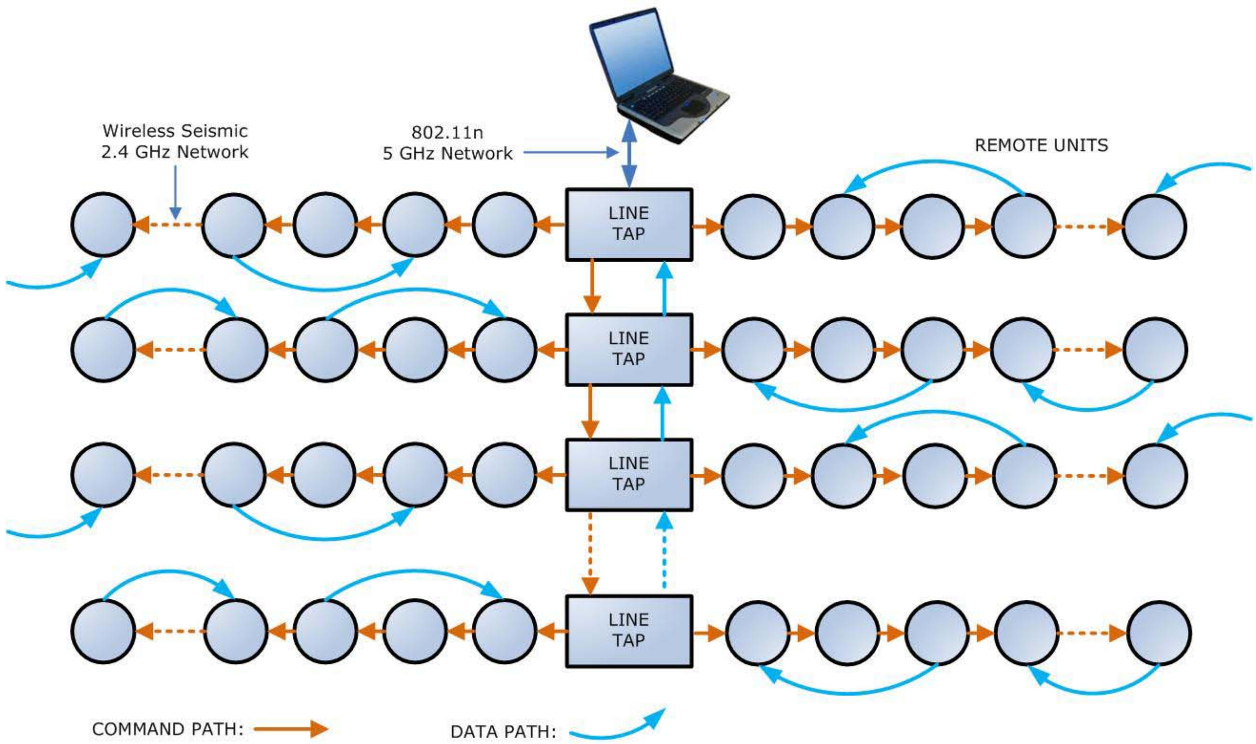

Figure 2. Bucket brigade sensor array.

station to station along the "ribs" using 2.4 GHz modems and a proprietary "Bucket Brigade" protocol. Then, data is stored in the Line Taps and passed along the "backbone" to the Computer System. The Line Taps are part of an 802.11n network implemented using off-the-shelf hardware, operating in the 5 GHz band. We refer to this arrangement as a "rib and backbone" structure.

Not all Remote Units in a Rib need to be placed in a row, but the maximum length of a Rib is limited by the amount of data that needs to arrive in real time at destination. To achieve arrays of hundreds or thousands of units, Ribs need to be connected to each other along a Backbone through the Line Taps. In order to eliminate interference, the Backbone network operates in another band (5 GHz).

5. Data and Command Packets

Communications within the array is by packets. Data packets, containing data collected from sensors are passed horizontally along rows to the central Line Tap nodes. From here the data packets pass "vertically" along the central backbone to the collection station. Commands originating from the collection station proceed down the backbone and radiate out along the ribs to the Remote Units.

A Command Packet encodes the following information: (a) Timing information embedded in the packet structure; (b) A map of all packets and sub-packets that arrived at destination without errors; and (c) Information about the frequency distributions to be used in the next cycle. Other information necessary for the setup and maintenance of the network is carried by dedicated Command Packets that are sent only before the start of the Data Acquisition process.

To optimize data rate, each command packet is followed by several data packets. The optimum number of data packets sent between two command packets is automatically determined by the software during the setup. The Command Packets travel from the Line Taps to the end of the Rib. A set of N Data Packets is followed by one Command Packet. The value of N will be determined experimentally, based on the propagation conditions and the size of the array.

The data compression is optimized taking advantage of the time and space correlation of the seismic data. The size of the packets is optimized during setup, based on the propagation conditions. Very good conditions lead to long data packets (fewer retries required), while bad conditions need shorter packets. Each packet contains enough data to fit the optimum size. The data is collected from neighbor stations and contains samples that are close in time.

6. The "Bucket Brigade"

Remote Units acquire data continuously. Data is passed between Remote Units in packets toward the Line Tap nodes. To improve performance the Units along each rib are partitioned into two sets, the even numbered sensors and the odd numbered sensors (See Figure 3). Each of these groups is further divided into pairs. During one phase packets are passed between half the sensors in each group and their nearest even numbered or odd numbered neighbors. In a second phase the roles of transmitter and receiver are reversed. Thus data proceeds toward the Line Tap nodes in a "bucket brigade"-like manner.

bandwidth of the system. We expect to operate with a maximum value of 80. A total of 80 x 15 = 1200 frequency distributions are possible. Each distribution consists of a set of 80 frequency values. All frequency distributions are stored in the memory of each Remote Unit.

A receiving station detects a failure of a transmitting Remote Unit by timing out. A reasonable number of tries is attempted before a station is deemed to have failed. The information is sent to the Line Tap, encoded in a data packet. The Line Tap decides to request more attempts or to reconfigure the network. Reconfiguring the network means selecting another predetermined frequency distribution. The information about next frequency used by each Remote Unit is sent by the Line Tap through the Command Packet. No Remote Unit is aware that another Remote Unit failed. The healing is transparent.

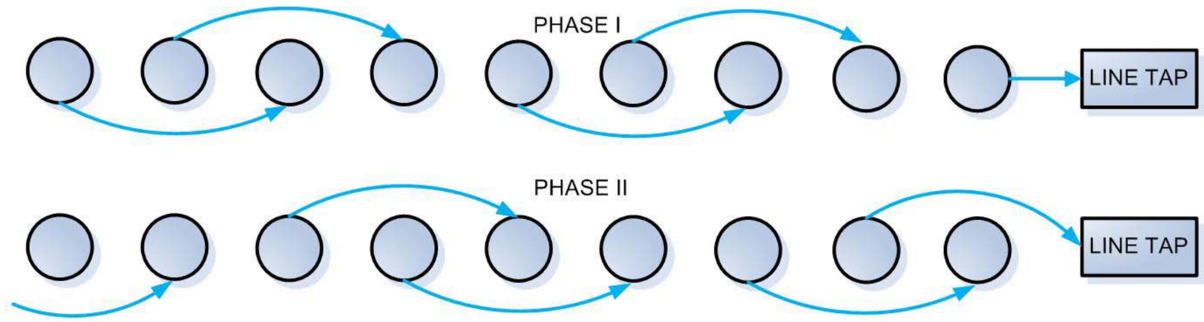

Figure 3. Data flow in bucket brigade.

7. Network Healing

Data is stored in each Unit until the command packet from the Line Tap acknowledges the transfer. When a Remote Unit fails, data is re-routed along the "rib" on a predetermined path. The failed Unit is bypassed by the bucket brigade without any data loss. If the failed Unit is restored, the data is rerouted to the original path. Each node is able to correspond not only with adjacent nodes but also with nodes located 2 to 4 steps away.

A minimum 15 frequency distributions are necessary for normal operation in order to satisfy the FCC permitting requirements for unlicensed radio spectrum. In a rib of N Remote Units, dealing with single failures will result in N possible frequency distributions. The value of N is limited by the

8. Time Synchronization

Transmitters and receivers switch roles based on elapsed time. The process requires very precise clock synchronization between all Remote Units. Additionally, an accurate clock is necessary to time stamp data to within 25 microseconds.

The Remote Units are equipped with a 16 MHz, 10 PPM crystal that drives a programmable oscillator. During each command cycle the listening station decodes from the data carrier the frequency of the transmitting station. The difference between the two clocks is used to adjust the frequency of the

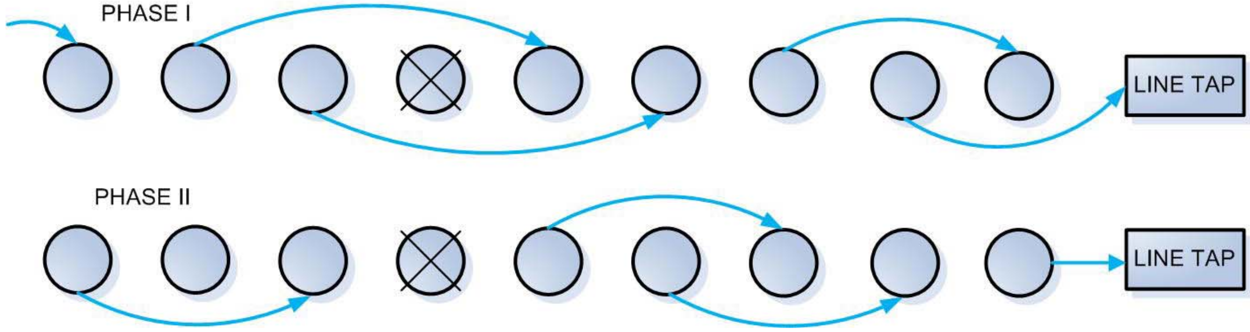

Figure 4. Network healing.

programmable oscillator. With each new packet received, the difference between the two oscillators is reduced further.

9. Interference

In a Wireless Seismic Network, at any given time half of the Remote Units will be transmitting and half will be receiving. Extensive effort has been put in modeling the interference for a field with an infinite number of Remote Units. The key to reducing interference consists in finding a pattern of frequency distributions that offers enough separation between Units in close proximity in order to keep the interference bellow an acceptable level.

Starting from the Path Loss formula, we have computed the total interference for each Unit in an array:

$$\mathrm{RcvdPower(dBm)} = \mathrm{XmitPower(dBm)} - \mathrm{PathLoss(dB)}$$

$$\mathrm{PathLoss(dB)} = 32.45 + 20\times\log(F) + 20\times\log(\mathrm{D})$$

$$\mathrm{D} = \text{Distance in Km.}$$

$$\mathrm{ParasitePower(dBm)} = \mathrm{XmitPower(dBm)} - \mathrm{PathLoss(dB)} - \mathrm{KF(dB)}$$

$$\mathrm{PPn(dBm)} = \mathrm{XP(dBm)} - \mathrm{PL(dB)} - \mathrm{KF(dB)}$$

$$\mathrm{PPn(dBm)} = \mathrm{XP} - (32.45 + 20\times\log(Fn) + 20\times\log(\mathrm{D})) - \mathrm{KF}$$

$$\mathrm{PPn(mW)} = 10^{\frac{\mathrm{PPn(dBm)}}{10}}$$

$$\mathrm{PP(mW)} = \sum_{n=1}^{n} 10^{\frac{\mathrm{XP(dBm)} - (32.45 + 20\times\log(Fn) + 20\times\log(\mathrm{D(n)})) - \mathrm{KF(n)}}{10}}$$

$$KF(n) = 48$$

$$PP(mW) = \sum_{n=1}^{n} 10^{\frac{\mathrm{XP}}{10} - \frac{\mathrm{KF(n)}}{10} - 3.245 - 2\times\log(Fn) - 2\times\log(\mathrm{D(n)})}$$

$$PP(mW) = \sum_{n=1}^{n} (10^{\frac{\mathrm{XP}}{10}} \times 10^{-\frac{\mathrm{KF(n)}}{10}} \times 10^{-3.245} \times 10^{-2\times\log(Fn)} \times 10^{-2\times\log(\mathrm{D(n)})})$$

$$PP(mW) = 10^{\frac{\mathrm{XP}}{10}} \times 10^{-3.245} \times \sum_{n=1}^{n} (10^{-2\times\log(Fn)} \times 10^{-2\times\log(\mathrm{D(n)})} \times 10^{-\frac{\mathrm{KF(n)}}{10}})$$

$$PP(mW) = 10^{\frac{\mathrm{XP}}{10}} \times 10^{-3.245} \times \sum_{n=1}^{n} (\mathrm{Fn}^{-2} \times \mathrm{Dn}^{-2} \times 10^{-\frac{\mathrm{KF(n)}}{10}})$$

$$RP(mW) = 10^{\frac{\mathrm{XP(dBm)}}{10}} \times 10^{-3.245} \times (\mathrm{Fx}^{-2} \times \mathrm{Dx}^{-2})$$

$$\mathrm{S/N} = \text{Signal to Noise Ratio}$$

$$\mathrm{S/N(dB)} = 10\times\log\frac{\mathrm{RP(mW)}}{\mathrm{PP(mW)}}$$

$$\mathrm{S/N(dB)} = 10\times\log\left(\frac{10^{\frac{\mathrm{XP(dBm)}}{10}} \times 10^{-3.245} \times (\mathrm{Fx}^{-2} \times \mathrm{Dx}^{-2})}{10^{\frac{\mathrm{XP}}{10}} \times 10^{-3.245} \times \sum_{n=1}^{n} (\mathrm{Fn}^{-2} \times \mathrm{Dn}^{-2} \times 10^{-\frac{\mathrm{KF(n)}}{10}})}\right)$$

$$\mathrm{S/N(dB)} = 10\times\log\left(\frac{(\mathrm{Fx}^{-2} \times \mathrm{Dx}^{-2})}{\sum_{n=1}^{n} (\mathrm{Fn}^{-2} \times \mathrm{Dn}^{-2} \times 10^{-\frac{\mathrm{KF(n)}}{10}})}\right)$$

$$\mathrm{S/N(dB)} = 10\times\log\frac{\sum_{n=1}^{n} (\mathrm{Fn}\times\mathrm{Dn})^2 \times 10^{\frac{\mathrm{KF(n)}}{10}}}{\mathrm{Fx}\times\mathrm{Dx}}$$

Based on the radio modem specifications, in order to achieve an acceptable Bit Error Rate of 0.1%, a minimum of 18 dB separation is required between each Remote Unit and the total sum of the rest of the field. We tried to find frequency distributions that satisfy this requirement. Using the formula above, we wrote a simulation program that generates pseudo-random distributions and computes the worst case interference for a field of N simultaneous transmitters.

Table 1. is an example of such distribution, for a field of 13 x 6 transmitters overlapped with 13 x 6 receivers (an array of 13 x 12 nodes). The minimum separation achieved is 22.7 dB. The minimum frequency separation between adjacent nodes is 8 MHz. The radio modem has 85 available channels. The total number of frequency distributions in a field of N cells, using 80 channels, is N!/(N-80)! This number is infinite for all practical purposes. We have shown that we can generate a large number of frequency distributions that satisfy the interference criteria.

10. System Performance

Seismic data is generated by each Remote Unit at a rate of 12 kbps. Remote Units are equipped with radio modems operating at 1 Mbps. Each Unit transmits in one phase of the two phases and receives in the other phase, but each Line Tap is equipped with two radio modems and receives data all the time. The maximum possible speed of the data arriving at the line tap is 1 Mbps. The bottleneck of the “rib” is the last Remote Unit before the Line Tap that has to transfer the data from all the Units downstream.

The data rate will be reduced by the following factors:

1. The overhead required to switch between transmission and reception.
2. The time required to send control packets (data acknowledge)
3. Retries caused by loss of packets.

Each of these factors reduces performance by 10 to 15%. The combined effect of all three might reduce the effective data rate along each rib by 50%, to 0.5 Mbps.

The data transfer is increased by data compression. Seismic data compresses by about 2/1. The net result is an effective data rate of 1 Mbps to the line tap. Each unit is allocated an equal fraction of this overall data rate, thus a single “rib” may support up to 80 sensors, each providing 12 Kbps per sensor.

Data is passed from Line Taps to the Central Station in a similar fashion. Small packets are stored in the Line Taps and assembled in large packets. The Backbone operates at 5GHz, thus eliminating interference with the ribs. Since each Line Tap acquires data at 1 Mbps, an installation with 20 Line Taps will need an aggregate data rate along the Backbone of minimum 20 Mbps. The 802.11n protocol can achieve peer to peer speeds in excess of 200 Mbps. Thus, a wireless backbone of 20 to 40 Line Taps is feasible.

11. Conclusions

Wireless Seismic has produced an ordered mesh network seismograph that combines ideas from mesh networks and wireless networks but with proprietary implementations of protocol and firmware. In so doing, we have created a system that is capable of satisfying the demanding requirements of the oil industry with regards to weight, power usage, and reliability. It is possible that the same approach might be applicable in related fields that use high data rates required by real time video, such as border security and national defense.

Table 1. Frequency distribution for an array of thirteen by six transmitters and receivers.

Frequency Distribution Calculator

Input Parameters

Starting Frequency:	2400	MHz	Transmission Power:	100	mWatt
Ending Frequency:	2484	MHz	Vertical Node Separation:	20	Meter
Minimum Frequency Separation:	8	MHz	Horizontal Node Separation:	20	Meter

Outpu Starting Freq = 2477, Min Freq Sep = 9, Total Field = 1911.8, Elapsed Minutes = 1.0

2477 MHz -46.3 dBm -69.1 dBm 22.7 dB	2400 MHz -46.1 dBm -71.1 dBm 25.0 dB	2409 MHz -46.1 dBm -69.6 dBm 23.5 dB	2418 MHz -46.1 dBm -69.6 dBm 23.4 dB	2427 MHz -46.2 dBm -69.6 dBm 23.4 dB	2436 MHz -46.2 dBm -68.9 dBm 22.7 dB	2445 MHz -46.2 dBm -68.9 dBm 22.7 dB	2454 MHz -46.3 dBm -69.0 dBm 22.7 dB	2463 MHz -46.3 dBm -69.0 dBm 22.7 dB	2472 MHz -46.3 dBm -69.0 dBm 22.7 dB	2481 MHz -46.4 dBm -69.1 dBm 22.7 dB	2405 MHz -46.1 dBm -69.0 dBm 22.9 dB	2414 MHz -46.1 dBm -73.0 dBm 26.9 dB
2423 MHz -46.2 dBm -74.5 dBm 28.4 dB	2432 MHz -46.2 dBm -74.5 dBm 28.3 dB	2441 MHz -46.2 dBm -74.4 dBm 28.2 dB	2450 MHz -46.3 dBm -74.5 dBm 28.2 dB	2459 MHz -46.3 dBm -74.5 dBm 28.2 dB	2468 MHz -46.3 dBm -72.6 dBm 26.2 dB	2478 MHz -46.4 dBm -69.8 dBm 23.4 dB	2402 MHz -46.1 dBm -70.4 dBm 24.4 dB	2411 MHz -46.1 dBm -70.5 dBm 24.4 dB	2420 MHz -46.1 dBm -70.5 dBm 24.4 dB	2429 MHz -46.2 dBm -70.5 dBm 24.4 dB	2438 MHz -46.2 dBm -70.6 dBm 24.4 dB	2447 MHz -46.2 dBm -70.7 dBm 24.4 dB
2456 MHz -46.3 dBm -71.0 dBm 24.7 dB	2465 MHz -46.3 dBm -70.9 dBm 24.6 dB	2474 MHz -46.3 dBm -70.9 dBm 24.6 dB	2483 MHz -46.4 dBm -71.0 dBm 24.6 dB	2407 MHz -46.1 dBm -70.7 dBm 24.6 dB	2416 MHz -46.1 dBm -72.4 dBm 26.2 dB	2425 MHz -46.2 dBm -72.4 dBm 26.2 dB	2434 MHz -46.2 dBm -73.8 dBm 27.6 dB	2443 MHz -46.2 dBm -73.8 dBm 27.6 dB	2452 MHz -46.3 dBm -73.8 dBm 27.6 dB	2461 MHz -46.3 dBm -73.9 dBm 27.6 dB	2470 MHz -46.3 dBm -74.0 dBm 27.6 dB	2479 MHz -46.4 dBm -70.6 dBm 24.2 dB
2403 MHz -46.1 dBm -70.1 dBm 24.0 dB	2412 MHz -46.1 dBm -70.0 dBm 23.9 dB	2421 MHz -46.2 dBm -70.1 dBm 23.9 dB	2430 MHz -46.2 dBm -70.1 dBm 23.9 dB	2439 MHz -46.2 dBm -70.1 dBm 23.9 dB	2448 MHz -46.2 dBm -70.1 dBm 23.9 dB	2457 MHz -46.3 dBm -69.5 dBm 23.2 dB	2466 MHz -46.3 dBm -70.2 dBm 23.9 dB	2475 MHz -46.3 dBm -70.2 dBm 23.9 dB	2484 MHz -46.4 dBm -72.2 dBm 25.9 dB	2408 MHz -46.1 dBm -70.5 dBm 24.4 dB	2417 MHz -46.1 dBm -70.8 dBm 24.7 dB	2426 MHz -46.2 dBm -70.9 dBm 24.7 dB
2435 MHz -46.2 dBm -70.7 dBm 24.5 dB	2444 MHz -46.2 dBm -70.7 dBm 24.4 dB	2453 MHz -46.3 dBm -70.7 dBm 24.4 dB	2462 MHz -46.3 dBm -70.7 dBm 24.4 dB	2471 MHz -46.3 dBm -70.7 dBm 24.4 dB	2480 MHz -46.4 dBm -70.5 dBm 24.2 dB	2404 MHz -46.1 dBm -69.6 dBm 23.5 dB	2413 MHz -46.1 dBm -69.6 dBm 23.5 dB	2422 MHz -46.2 dBm -70.6 dBm 24.4 dB	2431 MHz -46.2 dBm -70.6 dBm 24.4 dB	2440 MHz -46.2 dBm -70.7 dBm 24.4 dB	2449 MHz -46.3 dBm -70.7 dBm 24.4 dB	2458 MHz -46.3 dBm -71.0 dBm 24.7 dB
2467 MHz -46.3 dBm -70.6 dBm 24.3 dB	2476 MHz -46.3 dBm -69.5 dBm 23.1 dB	2401 MHz -46.1 dBm -69.0 dBm 22.9 dB	2410 MHz -46.1 dBm -69.0 dBm 22.9 dB	2419 MHz -46.1 dBm -69.0 dBm 22.9 dB	2428 MHz -46.2 dBm -69.0 dBm 22.9 dB	2437 MHz -46.2 dBm -69.1 dBm 22.8 dB	2446 MHz -46.2 dBm -69.1 dBm 22.8 dB	2455 MHz -46.3 dBm -69.9 dBm 23.6 dB	2464 MHz -46.3 dBm -69.9 dBm 23.6 dB	2473 MHz -46.3 dBm -70.0 dBm 23.6 dB	2482 MHz -46.4 dBm -70.0 dBm 23.6 dB	2406 MHz -46.1 dBm -69.8 dBm 23.7 dB

Reset FreqCalc ShowFreq PowerCalc CalcAll Done