Volume 07 Issue 02 Published, May 21, 2003 ISSN 1535-864X

Intel® Technology Journal

Intel® Centrino™ Mobile Technology

Antenna Selection in Multicarrier Communication Systems

Antenna Selection in Multicarrier Communication Systems

Yuval Finkelstein, Wireless Networking Group, Haifa, Intel Corporation

Index words: communication, wireless, OFDM, fading channels

ABSTRACT

Imagine a packet of data transmitted by radio frequency through the air. This packet appears at two separate antenna ports of a radio receiver. Even though the same data appear at both antennas, a different path in space is associated with each antenna. Any path in space results in signal power reduction and usually in a power redistribution in the allocated frequency band. Both effects enhance the error rate and reduce the reliability of the decoded data. The receiver usually supports the wireless link only through a single antenna due to cost considerations. This paper focuses on the particular case where the signal at one antenna is strong, but does not efficiently utilize the available frequency band, and at the other antenna the signal is weak, but uniformly distributed over the band. The paper provides a general algorithm for selecting the optimal antenna and explains both quantitatively and qualitatively which antenna should be selected.

INTRODUCTION

Multipath fading is a major limitation to high-rate data transmission in wireless communication systems. Fading is a result of destructive interference between replicas of the signal arriving through different paths. Another aspect of the same effect is an intersymbol interference. This occurs when the replicas merge again at the antenna and successive data symbols are mixed together, forming a mismatched symbol.

Multicarrier communication methods overcome intersymbol interference by subdividing the allocated bandwidth into a few frequency sub-bands. At each carrier (sub-band), the data is transmitted using long symbol durations compared to the time delay between replicas. Thus, the impact of intersymbol interference is reduced. Transmitting the data simultaneously through all carriers results in an overall high rate of data transmission. However, destructive interference still distorts the data. Those carriers that are subjected to destructive interference have a low Signal-to-Noise Ratio (SNR).

Low SNR at defective carriers is partly overcome by applying spatial diversity (antenna diversity). Receiving the data simultaneously through multiple antennas increases the detection reliability. However, full antenna diversity is an expensive solution. A more cost-saving solution is to use semi-diversity. This is accomplished by selecting only a single antenna out of a given set. This antenna should offer the most reliable detection.

Selecting antenna is usually accomplished by considering total antenna power. This criterion is unsatisfactory because power is not the only factor that determines the performance of the receiver. In fact, the distribution of the power among carriers is critical as well. For example, take an antenna that has received a giant pulse of power. Most of it emerges in a single carrier. Selecting this antenna while the rest of the carriers suffer low SNR exhibits a high error rate.

This paper provides a simple algorithm for choosing the best antenna from among several. The algorithm improves the reliability of the data recovery process. The central pillar of this algorithm is an information-capacity-like parameter for each of the carriers. Using this parameter, instead of estimating power alone, yields more useful information about the contribution of each carrier. The performance of the receiver, while equipped with each antenna, is predicted by combining the appropriate contributions over all the carriers.

The antenna selection algorithm described in this paper was implemented inside Intel's chipset that handles the IEEE 802.11a standard. The chipset provides wireless connectivity to mobile PCs and also serves Intel® Centrino™ mobile technology.

The paper demonstrates the application of the algorithm by referring to a simplified system consisting of only two carriers. Full treatment of the IEEE standard, which also includes error-correction coding, is beyond the scope of this paper. However, the described principles are very

---

relevant to practical systems. An effort was made to make the contents clear to technical staff who are not directly involved with communication. Thus, terms such as constellation points, Signal-to-Noise ratio, equalization and gain control are demonstrated explicitly in this paper. After mathematically constituting the relevant glossary of terms, the suggested antenna-selection algorithm is introduced. Finally, the algorithm is proved to be successful in predicting the performance of a receiver equipped with an arbitrary characteristics antenna. This is established by numerical simulation of decoding noisy data.

RELEVANT GUIDELINES TO ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

As was previously mentioned, the main idea behind a multicarrier communication system is the division of a given frequency band into smaller frequency sub-bands. Orthogonal Frequency Division Multiplexing (OFDM) is a particular case of a multicarrier communication system, in which the frequency sub-bands overlap. This overlapping is not harmful due to the fact that the carriers are mathematically orthogonal. A good reason for using OFDM is its inherent immunity against narrowband interference. If a specific sub-band is severely disturbed due to multipath fading or interference, error-correction coding can still overcome the disturbance, thus preventing the entire link from failing, as is the case with a single carrier. Another reason for using OFDM concerns the complexity of the equalizer. Assuming that each sub-band is sufficiently narrow, the effect of the channel is taken into account by assigning only a single complex number to each carrier. In comparison to a single-carrier system, this simplifies the implementation of the equalizer to a great extent.

More extensive explanations about the principles of OFDM are documented elsewhere [1]. However, a few more guidelines are presented here to help clarify the information in the remaining part of this paper. Following IEEE standard 802.11a, all carriers that constitute a single data frame are subjected to the same modulation scheme: QAM constellation with a given order. The data is encoded by assigning a specific binary combination to each of the constellation points. This process is demonstrated in the next section. Thus, a single constellation point is determined for each frequency sub-band. Synthesizing the sequence of constellation points into a time domain signal is accomplished by Inverse Fourier Transformation. The inverse process takes place at the receiver. The time domain signal is transformed back to the frequency domain by means of Discrete Fourier Transform. Identifying which constellation point was assigned by the transmitter to each frequency band constitutes the demodulation process. Recognizing the correct point despite the noise and the channel fading is vital for successfully receiving the data. Finally the data is extracted by decoding the constellation points back into binary.

DEFINITION OF A SIMPLIFIED SYSTEM

In order to clarify our strategy, let us assume a simplified multicarrier communication system, which uses only two carriers. That is, the allocated frequency band is only divided into two sub-bands. At each sub-band information is modulated by the well-known Quadrature Phase-Shift Keying (QPSK) method. Figure 1 presents the constellation plane for QPSK and our preferred encoding scheme.

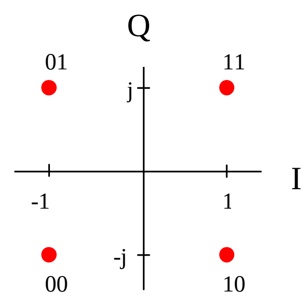

Figure 1: Bits encoding scheme for QPSK constellation

Suppose that the sequence to be delivered is "1110." For simplicity, we assume that no error-correction coding is applied. Encoding this sequence results in two complex numbers: 1+j and 1-j, which comprise the baseband representation of this message. The transmitter combines these two complex numbers into a waveform in the time domain by using the Inverse Fourier Transformation. This waveform finally modulates the amplitude and phase of the RF carrier that is transmitted through the air.

Demodulation and Noise

At the receiver the reverse process is taking place, which results in measured points in the constellation plane. However, the constellation points measured by the receiver are corrupted by noise. This noise cannot completely be avoided, no matter what the quality of the receiver is. Once the message is transmitted the receiver measures two constellation points, (I_1,Q_1) and (I_2,Q_2), in carriers "1" and "2," respectively. Although the exact values $1+j$ and $1-j$ were sent by the transmitter, this would never be the case with the measured values, due to the noise. Since no error-correction coding was applied, demodulation is carried out just by assigning each measured point to its nearest constellation point. That is, demodulation is performed by identifying the quarter in which the points (I_1,Q_1) and (I_2,Q_2) appear. If the noise power is more intensive than that of the signal power, demodulation becomes a random process. In this case successful decoding would happen with a high probability of 0.5. This of course is not satisfactory for constituting a communication link.

We then adopted an approach that makes use of an Ensemble average. This enables us to treat the noise in a statistical manner. Figure 2 represents measurements of (I_1,Q_1, I_2,Q_2) for an ensemble of receivers assuming additive white Gaussian noise.

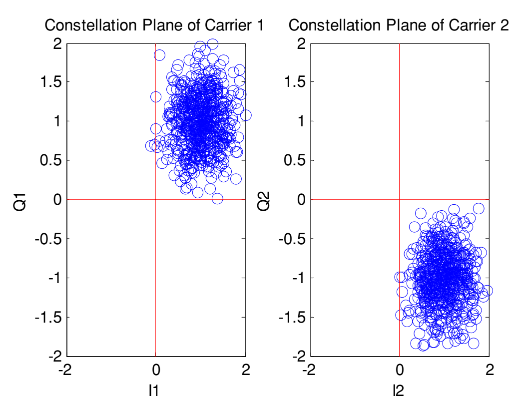

Figure 2: Constellation planes of carriers "1" and "2"

We can see that all measurements are concentrated around the constellation point *1+j* and *1-j* according to the message that was sent. However, the noise shifts the measured values to different locations in the constellation plane. The figure makes visible the fact that each measured point can be described by the sum of two components: the signal component (either *1+j* or *1-j)* and the noise component (n_1 and n_2 for carriers "1" and "2," respectively). This can be mathematically expressed as follows:

$$P_1 = I_1 + jQ_1 = (1 + j) + n_1$$
$$P_2 = I_2 + jQ_2 = (1 - j) + n_2$$

The Ensemble average of the squared-magnitude of the noise components is equal for both carriers, as is evident from Figure 2. It is designated by σ^2:

$$\left\langle |n_1|^2 \right\rangle = \left\langle |n_2|^2 \right\rangle = \sigma^2$$

It is very important to emphasize here that we do not restrict the statistical nature of the noise to any particular kind of noise. Although we used white Gaussian noise in our simulations, this kind of noise does not always have to be used. The mean of the noise, however, should be zero. The SNR is now defined as follows:

$$SNR(\sigma)_{[dB]} = 10Log_{10}\left(\frac{\left\langle |P_1|^2 \right\rangle - \left\langle |n_1|^2 \right\rangle + \left\langle |P_2|^2 \right\rangle - \left\langle |n_2|^2 \right\rangle}{\left\langle |n_1|^2 \right\rangle + \left\langle |n_2|^2 \right\rangle}\right) =$$
$$= 10Log_{10}\left(\frac{2}{\sigma^2}\right)$$

The value of σ for the Gaussian distribution in Figure 2 is *0.5*, which results in an *SNR* of *9 dB*.

CHANNEL EFFECT AND EQUALIZATION

Channel Effect

So far only the additive noise was considered as a distraction to demodulation and data extraction. However, any actual signal is disturbed to some extent by channel distortion. Replicas of the signal coming from walls and equipment interfere with the antenna. The result of this interference is the so-called "channel" effect. The total power that appears at the antenna port of the receiver is always smaller than the transmitted power, due to channel losses. However, the channel also distorts the original signal by changing its spectral content. In a multicarrier system, decomposing the received signal back to its spectral component is actually equivalent to measuring constellation points for each of the frequency sub-bands that constitute the system. Under the effect of the channel, these constellation points do not appear at their original location as in the transmitter. Instead, both their magnitude and phase are changed. That is, the channel moves each constellation point to an arbitrary new location, even if noise is completely absent.

Equalization

The channel distortion can be partly overcome by equalization. The data packets are usually preceded by a known training sequence. Thus, the channel distortion can be analyzed and can be taken into account throughout the process of demodulation. Assuming that the frequency sub-bands are narrow enough, the channel influence for each carrier can be expressed with a single complex number. The phase and magnitude of each number describe the transformation that the constellation points undergo in the relevant carrier. These complex numbers are called "channel coefficients." The equalizer coefficients are no more than the reciprocal of the channel coefficients. Multiplying the measured constellation points by the appropriate equalizer coefficients moves them back to their normal place. If the training sequence is long enough and the channel has static characteristics, the estimation error of the channel coefficients can be made as small as it needs to be. Therefore we neglect this noise component and assume ideal equalizer coefficients for the rest of this paper.

Nevertheless, equalization does not completely cancel the impairments of the channel. This is due to the fact that equalization cannot compensate for the intrinsically low SNR in carriers that are suppressed by the channel; in other words, carriers with a magnitude of channel coefficient that is much lower than one. The interplay between the total power of both carriers and the magnitude of their channel coefficients is most relevant to the topic of this paper, that is, antenna selection.

Gain Control

We continue with our double-carriers simplified system. This time we add the influence of a channel. We designate the channel coefficients by C_1 and C_2 for carriers "1" and "2," respectively. Thus, the constellation points measured at the receiver are redefined by

$$P_1 = I_1 + jQ_1 = (1+j)\times C_1 + n_1$$
$$P_2 = I_2 + jQ_2 = (1-j)\times C_2 + n_2$$

Next, we present the concept of Gain Control. While this function is accomplished both analogically and digitally in a rather complicated way in real systems, here we are just concerned with the essence of this feature. Our ideal gain controller verifies that

$$\left\langle |P_1|^2 \right\rangle + \left\langle |P_2|^2 \right\rangle = 4$$

The Ensemble average that appears in the equation above verifies that all the receivers in our ensemble have exactly the same gain. Substituting the explicit expression for the points P_1 and P_2 and recalling that the variance of the noise was defined as σ^2 we get

$$|C_1|^2 + |C_2|^2 + \sigma^2 = 2$$

The magnitudes of C_1 and C_2 can take values either higher or lower than one. An increase in the magnitude of one coefficient occurs at the expense of a decrease in the magnitude of the other. The reader should note that channel coefficients with a magnitude higher than one do not imply increased power in an absolute manner. The magnitudes of the channel coefficients only indicate how the measured power is distributed among the frequency sub-bands and how the relative strength of the signal compares to the noise.

The expression for the SNR in the gain-controlled receiver is modified, since the total signal power is not 4 ($|1+j|^2+|1-j|^2=4$) any more. Instead, it is the Ensemble average of the total power (both signal and noise) that equals 4. Thus, the total SNR, which refers to both carriers together, is

$$SNR_{total}(\sigma)_{[dB]} = 10Log_{10}\left(\frac{2-\sigma^2}{\sigma^2}\right)$$

Equalization and Modified Signal-to-Noise Ratios

After equalization, the original constellation points are restored with modified noise components:

$$P_1^{Eq} = (1+j) + \frac{n_1}{C_1}$$

$$P_2^{Eq} = (1-j) + \frac{n_2}{C_2}$$

The Ensemble averages of the squared-magnitudes of the modified noise components are

$$(\sigma_1)^2 = \left\langle \left|\frac{n_1}{C_1}\right|^2 \right\rangle = \frac{\sigma^2}{|C_1|^2} \quad , \quad (\sigma_2)^2 = \left\langle \left|\frac{n_2}{C_2}\right|^2 \right\rangle = \frac{\sigma^2}{|C_2|^2}$$

Accordingly,

$$SNR_1[dB] = 10Log_{10}\left(\frac{2}{[\sigma_1]^2}\right)$$
$$SNR_2[dB] = 10Log_{10}\left(\frac{2}{[\sigma_2]^2}\right)$$

ANTENNA DIVERSITY

Suppose the receiver is equipped with two antennas: antenna *A* and antenna *B*. During signal detection the receiver switches back and forth between these two antennas. The gain controller sets the gain such that the condition $<|P_1|^2>+<|P_2|^2>=4$ is fulfilled for the highly energized antenna. Thus, saturation of the receiver's amplifier is avoided no matter which antenna is attached. Once the gain is set, the receiver estimates two sets of channel coefficients. Each set refers to a different antenna and consists of two channel coefficients, a single coefficient for each carrier. As soon as estimations are completed, the receiver has to select either antenna *A* or antenna *B*, in order to receive the rest of the data. Which one should it select?

Power Considerations

Suppose that antenna A is the one with the higher total power. The gain controller sets the gain such that

$$|C_1^A|^2 + |C_2^A|^2 + \sigma^2 = 2$$

Indexes *A* and *B* are attached to the channel coefficients of antennas *A* and *B*, respectively. Assuming that the signal power in antenna *B* is reduced by a factor of *X* we get

$$X \left[\left|C_1^B\right|^2 + \left|C_2^B\right|^2 \right] + \sigma^2 = 2$$

Note that at this antenna, it is only the signal power that is reduced by *X* and not the noise power. Thus, the noise level σ^2 is the same no matter which antenna is selected. This statement is valid since the amplifier gain is set just before the beginning of the antenna selection process.

Symmetry and Asymmetry

As will be evident soon, the performance of the receiver is optimal when the signal power is homogenously distributed between the two frequency sub-bands. We define an antenna whose channel coefficients are identical (the same for both carriers) as a symmetric antenna. In contrast, an asymmetric antenna is one with different channel coefficients. If the higher power antenna is also a symmetric one, then selecting the best antenna becomes a trivial task. However, the decision becomes more complicated if the high-power antenna is asymmetric, and the low-power antenna is symmetric. We focus our discussion on the latter. Since we defined antenna *A* to be the one with the higher power, we extend its definition and declare it asymmetric. In order to take into account the asymmetry property in a quantitative manner, we define the asymmetry parameter *S* as follows:

$$S = \frac{|C_2|}{|C_1|}$$

Thus, $0 \le S < 1$ for antenna *A* whereas $S=1$ for antenna *B*. When selecting the antenna only the parameters *X* and *S* should be taken into account; these describe power reduction in *B* and the asymmetry of the carriers in *A*, respectively. The values of these two parameters are accessible to the receiver since they can be ascertained once the channel coefficients are estimated.

Simulation of Bits Error Rate

In order to realize the effect parameters *X* and *S* have on receiver performance, we simulated the entire simplified system following the structure we described so far. We emphasize again that we do not restrict the statistical nature of the noise to any particular kind. Although we used white Gaussian noise in the simulations, this should not always be the case. If the statistical nature of the noise is known in advance, the Bits Error Rate (BER) can be predicted analytically. However, because we do not assume any specific statistical distribution we use a numerical attitude instead of an analytical one. Furthermore, in practical communication systems, interleaving and error-correction coding are probably applied, making the BER analytical prediction too complicated. Thus, the numerical exploration of the simplified communication system, along with an empirical construction of the antenna selection algorithm, actually provides a complete methodology that is applicable to practical systems as well.

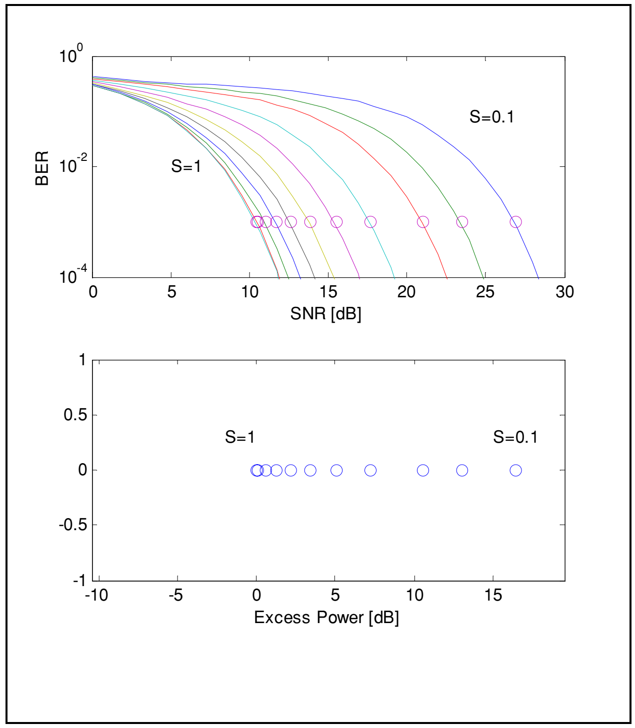

Figure 3: BER results for different values of the asymmetry-parameter, *S*

The plot at the top of Figure 3 presents BER results for our double-carriers system, which relies on QPSK modulation. Demodulation was carried out, as was explained earlier, by identifying to which quarter the measured constellation points belong.

The horizontal axis of the figure shows SNR_{total} in a logarithmic scale. Its definition is repeated here again for the convenience of the reader:

$$SNR_{total}(\sigma)_{[dB]} = 10Log_{10}\left(\frac{2-\sigma^2}{\sigma^2}\right)$$

Each colored line in the figure describes BER results for different values of the asymmetry-parameter, *S*. The furthest right is the case of *S=0.1* with the worst performance, as expected. The furthest left is the case of *S=1* with the best performance. In between, *S* displays intermediate values.

The empty circles at the figure denote the intersection of the curved lines with an invisible horizontal line, which crosses the vertical axis at the BER value of 10^{-3}. These circles are plotted again at the lower part of the figure with a modified horizontal axis. The modification incorporates a shift of the zero to be just below the furthest left circle. Thus, the value that fits each circle in the new scale is just the distance from the furthest left circle. The reader should realize that the furthest left circle actually represents the symmetric antenna *B*. Therefore, the rest of the circles specify the amount of excess power that should be added to the asymmetric antenna *A*, in order to achieve the same BER result of 10^{-3}. This excess power depends on the value of the asymmetry-parameter, *S*, as the figure shows.

ANTENNA SELECTION

In constituting the antenna selection algorithm we follow these logical steps:

- Understand qualitatively why excess power is required for compensating for asymmetry.
- Based on this understanding, suggest an algorithm that predicts receiver performance for given values of *X* and *S*.
- Validate the algorithm and tune its free parameters. This is done by reconstructing the dependence of the excess power on the symmetry parameter *S*, as depicted in Figure 3.
- Verify proper antenna selection for any combination of asymmetry parameters S_A, S_B, and power difference *X*.

Therefore, why is excess power required for compensating for asymmetry? Increasing asymmetry while keeping total power constant causes Signal-to-Noise Ratio (SNR) degradation in one carrier and SNR improvement in the other. In other words, decreasing *S* gradually from 1 to lower values increases the spread of equalized points in one constellation and decreases the spread in the other. Thus, more and more points move to a wrong quarter in the constellation plane of one of the carriers while at the same time spreading is reduced in the other carrier. However, if spreading is initially small and a good communication link can be established for $S=1$, reducing the spreading further has no benefit at all. In contrast, the SNR degradation at one of the carriers will finally shift points to the wrong quarter and the communication link will fail. Applying more and more power while asymmetry increases keeps all constellation points inside the quarter they really belong to.

Based on this explanation we propose a grade for each carrier, based on its effective SNR. The grade is calculated based on the fact that the benefit from high signal power is saturated beyond a certain SNR value. In the same way, decreasing the grade for defective carriers should be restricted if SNR goes below another value. The antenna is therefore selected by following these steps:

- Grade each carrier according to its SNR.
- Add up all grades to get a total score.
- Select the antenna with the highest score.

"Kapasity"

The missing building block for the algorithm above is the function by which grades are calculated, versus the SNR. We already indicated what should be the asymptotic behavior of that function for high and low values of SNR. This kind of asymptotic behavior is similar to the information-capacity of a channel [2]. Indeed, estimating channel capacity can be a useful tool for predicting receiver performance. However, we are not going to make any explicit use of information theory here. The function we are looking for is an empirical one, with free parameters for tuning the receiver performance. Despite all that, we named the total antenna score "Kapasity," after the well-known phrase.

We define the Kapasity function $f(\sigma)$ as

$$f(\sigma) = \frac{1}{1+\exp\left(\frac{\sigma - d}{q}\right)}$$

Note that *f* is defined in terms of σ instead of SNR, which should make the equations that follow easier to understand. However, the variance of the noise for each carrier (σ^2) and the *SNR* of each carrier are related, as was explained previously. It is easy to verify that *f* has the required asymptotic behavior, as σ approaches either zero (i.e., high *SNR*) or infinity (i.e., low *SNR*). The explicit form of the function *f* can be chosen in many other ways, if the correct asymptotic behavior is kept. For hardware implementation, any piecewise linear approximation of the function *f* can fit as well. The parameters *d* and *q* are free parameters that should be tuned in order to optimize the antenna selection process. Factors that affect the optimized values of *d* and *q* are the type of error-correction coding and the available hardware resources for Kapasity calculations. However, it is easy to guess what should be the value of the parameter *d*. Notice that $f=0.5$ when $\sigma=d$. At this point the gradient of *f* is maximal, and minor changes of σ result in major changes in the Kapasity. This tendency also exists with the demodulation error rate, as the noise standard deviation approaches half of the distance between two adjacent constellation points. Thus, the likely assumption is that the optimal value of *d* for our QPSK constellations should be around 1. We will see soon that this is really the case. The value of *q* determines the slope of *f* around $\sigma=d$. The higher the value of q the lower the slope of f is at that point.

VALIDATION OF THE ALGORITHM

Figure 3 describes the excess power required for an asymmetric antenna compared to a symmetric one, in order to keep both antennas performing at the same level. This illustrates one scenario for antenna selection where $S_B=1$ and the Kapasity is equal for both antennas. We follow this trend and speculate what should be X for each value of S_A. Formulating this mathematically in terms of Kapasity we get

$$f\left(\sigma_1^A\right)+f\left(\sigma_2^A\right)=2f\left(\sigma^B\right)$$

The superscripts A and B indicate which antenna σ belongs to, and the subscripts 1 and 2 relate to carriers 1 and 2, respectively. Because we assume that antenna B is symmetric, both its carriers have the same value of σ. Therefore, from now on we omit the subscripts for antenna B.

As soon as we express σ_1^A ,σ_2^A and σ^B in terms of X and S, we can insert them into the Kapasity equation above. We go back to the mathematical model of the simplified system. Recall that after equalization the noise component in each carrier can be characterized by an effective variance, which depends on the relevant channel coefficients

(*) $$\left(\sigma_1^A\right)^2=\frac{\sigma^2}{\left|C_1^A\right|^2} \quad , \quad \left(\sigma_2^A\right)^2=\frac{\sigma^2}{\left|C_2^A\right|^2} \quad , \quad \left(\sigma^B\right)^2=\frac{\sigma^2}{\left|C^B\right|^2}$$

Extracting C_1^A and C_2^A (in terms of S and σ) from the equations that define gain and asymmetry,

$$\left|C_1^A\right|^2+\left|C_2^A\right|^2+\sigma^2=2 \quad , \quad S=\frac{\left|C_2^A\right|}{\left|C_1^A\right|}$$

and inserting them into (*), we get

$$\sigma_1^A=\sqrt{1+S^2}\ \sqrt{\frac{\sigma^2}{2-\sigma^2}}$$

$$\sigma_2^A=\sqrt{\frac{1+S^2}{S^2}}\ \sqrt{\frac{\sigma^2}{2-\sigma^2}}$$

Extracting C^B (in terms of X and σ) from the equation that defines X,

$$\left|C_1^B\right|^2+\left|C_2^B\right|^2=2\left|C^B\right|^2=\frac{2-\sigma^2}{X}$$

and inserting it into (*), we get

$$\sigma^B=\sqrt{2X}\ \sqrt{\frac{\sigma^2}{2-\sigma^2}}$$

From Figure 3 we derive σ and S for each circle and insert both of them into σ_1^A and σ_2^A above. Thus, the left-hand side of the equal-Kapasity equation is calculated for each empty circle in Figure 3. All that is left is to extract X, which only appears at the right-hand side of the equation.

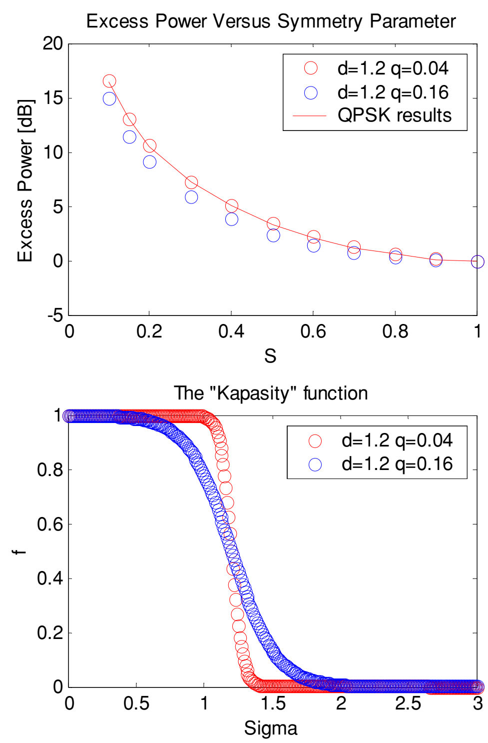

Figure 4: Excess Power calculated by using the Kapasity function, versus the asymmetry-parameter, *S*

The empty circles at the top plot in Figure 4 describe the Excess Power versus S as calculated by the Kapasity model. Red and blue circles illustrate the results while using ($d=1.2$, $q=0.04$) and ($d=1.2$, $q=0.16$), respectively. The shape that the Kapasity function takes using each set of parameters is depicted at the lower part of Figure 4, keeping the same convention of colors. The red continuous line in Figure 4 represents the Excess Power versus S derived from the open circles in Figure 3. It is clear that using the Kapasity model with ($d=1.2$, $q=0.04$) accurately predicts the results of the numerical experiment. We consider this to be proof of the validity of the antenna selection algorithm. It is also evident that the initial guess of d≈1 is very close to the actual value. The other set of d and q, which isn't a good fit in Figure 4, is discussed in the last section of this paper.

FINAL VALIDATION OF THE ALGORITHM

The algorithm is formulated following these steps:

- Calculate the total Kapasity for each of the relevant antennas (might be more than two) by summing up Kapasity contributions over all carriers (probably much more than two): $Kapasity = \sum_n f(\sigma_n)$
- Chose the antenna with the highest Kapasity.

Although the excellent fit between the red circles and the continuous line in Figure 4 validates the algorithm, we would like to demonstrate its applicability in a broader sense. In the previous section, we focused on the case where $S_B=1$. In this section we consider the general case in which both S_B and S_A have arbitrary values between 0 and 1.

Let us focus again on the results of the numerical experiment presented in Figure 3. We depicted the performance of our double-carriers system in terms of *BER* versus $SNR_{total}(\sigma)$ and the asymmetry parameter *S*. This time we consider the entire set of continuous lines in Figure 3 (instead of only considering the set of open circles). Recall that each line shows how the *BER* is changed with $SNR_{total}(\sigma)$, for each definite value of *S*. Thus, for final validation of the algorithm, we should reconstruct the complete BER diagram of Figure 3 in terms of Kapasity. Figure 5 presents exactly that.

The left-hand plot shows the value of [*2-Kapasity*] versus $SNR(\sigma)$ and *S* using ($d=1.2$, $q=0.04$). The right-hand plot shows [*2-Kapasity*] versus $SNR(\sigma)$ and *S*, using ($d=1.2$, $q=0.16$). Replacing the Kapasity with its complement of 2 is just for producing a monotonic decreasing function instead of an increasing one. This makes easier the comparison between Kapasity plots and *BER* plots. Each colored line in Figure 3 is transformed into a line with the same color in Figure 5. The open circles show how points with a definite *BER* value in Figure 3 appear in the Kapasity diagram. It is clear that an absolutely horizontal line exists, which separates circles of different colors. Thus, points with the same *BER* in Figure 3 become points with the same Kapasity in Figure 5. This finally completes the validation of the proposed antenna selection algorithm.

It is evident from the left-hand side plot of Figure 5 that hardware implementation of Kapasity calculations demands an extremely large number of bits. Otherwise the antenna-selector will not be able to choose between the antennas. However, the parameters $d=1.2$ $q=0.16$ enable binary representation of the Kapasity using less bits, as shown in the right-hand side plot in Figure 5. This results, however, in a reduction in the efficiency of antenna selection. It is evident from the fact that the separating line between same color circles is not a straight horizontal line anymore. Thus, there is a tradeoff between antenna selection efficiency and hardware cost.

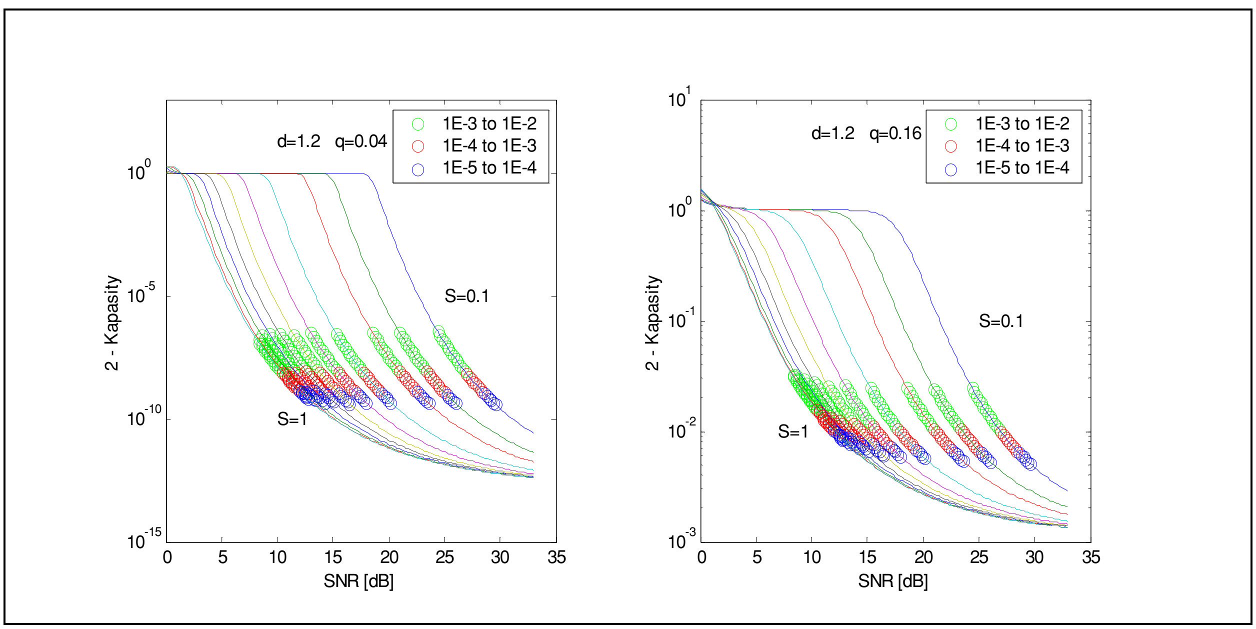

Figure 5: Kapasity versus $SNR(\sigma)$ and S

CONCLUSION

We reviewed the basic principles of multicarrier communication systems and explained how channels can modify power distribution among carriers and how equalization might affect the noise component in each carrier. We described an antenna selection algorithm developed in Intel. Although the algorithm was applied to a simplified communication system, the described methodology was found to be applicable for practical systems as well. Hence it was implemented inside Intel's Orthogonal Frequency Division Multiplexing (OFDM) modem that provides wireless connectivity for mobile PCs.

REFERENCES

[1] R. Van Nee and R. Prasad, *OFDM For Wireless Multimedia Communication*, Artech House, Boston-London, 2000.

[2] J. G. Proakis, *Digital Communications*, McGraw-Hill, 4th ed., Boston, 2001.

AUTHOR'S BIOGRAPHY

Yuval Finkelstein joined the wireless Digital Signal Processing team in the Intel Development Center in Haifa in 2000. He has prior industrial experience in the areas of electro optics and solid-state physics. He received his Ph.D. degree in physics from the Israel Institute of Technology, the Technion, in 1997. His e-mail is yuval.finkelstein@intel.com

For further information visit:

developer.intel.com/technology/itj/index.htm