Efficient Access to Radio Spectrum

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ABSTRACT
Congested military spectrum means that next generation communication systems will have to achieve much greater spectral efficiency than their predecessors. In this paper, we consider various examples of approaches that increase the overall spectral efficiency of a communication system. Advanced signal processing techniques provide significant increases in throughput, replacing legacy VHF voice radios with networked systems supporting both voice and data. Multiple antenna technology exploits the spatial diversity in the multipath environments that are typically challenging for military radios, and provides much higher spectral efficiency with the same transmit power. The performance of this new technology can depend on frequency, antenna position and vehicle location, hence adaptivity of data rate and power is a key feature to provide robust communications for mobile platforms. For mobile systems, the properties of the radio channel can change quite rapidly. To achieve the desired quality of service while maintaining spectral and power efficiency, radios should adapt their operating characteristics, in particular, their transmit power and data rate, to make the most of the channel conditions. High spectral efficiency is not just achieved through the choice of modulation or spatial diversity; the overhead costs of feedback and retransmissions must also be taken into account.

1.0 INTRODUCTION

With any essential but limited resource, as demand increases, the price follows until only the very rich can satisfy their needs. In these conditions, it becomes necessary to conserve the resource, to allocate it fairly and to use it as efficiently as possible to maximise the value we receive for it. This applies to the RF spectrum. Modern wireless technology has changed our lives in many ways but the RF spectrum is limited, so all these uses must be fit into the limited available bandwidth. This is especially a challenge for military forces, as there is considerable pressure on national spectrum regulators to release spectrum currently designated for national defence and public safety to the commercial sector, whereby it can be leased to provide significant revenues. The question of how radio devices should be allocated space within the spectrum is the topic of the companion paper [1]; in this paper, we consider how to address the need to maximise the use of the spectrum we are given. The issue of information management is also key to maximising the utility of the RF spectrum, by making sure that every bit carries the maximum amount of information with minimal wastage; this is beyond the scope of this pair of papers but should be an important consideration in application development.

In this paper, we consider approaches to increase the spectral efficiency of communication systems in particular, but the underlying concepts apply equally to many other spectrum-dependent applications. Rather than focussing on theories, this paper gives examples of techniques that have been developed to increase spectral efficiency throughout the communication chain. We consider first the design of the signals themselves, to pack more symbols into the same channel bandwidth. Beyond this primary aspect, spectral efficiency becomes a matter of smart trade-offs. This is illustrated by looking at adaptivity and cross-layer issues, such as the requirement for feedback and the length of signal packets.

2.0 MODULATION

The most basic aspect of maximising spectral efficiency is in the number of bits achieved per unit of channel bandwidth. Continuing advances in digital signal processing capability and on-board memory have enabled the development of sophisticated and complicated signal processing techniques that reduce bit error rates (BERs), hence the transmitted bit rates can be increased while satisfying the applications' error requirements. In this section, we consider an example of how advanced signalling processing enables advanced modulation and coding to achieve large gains in spectrum efficiency, allowing increased support to services without increasing bandwidth.

The existing NATO standard for VHF voice (Stanag 4204) operates in the 30 MHz – 108 MHz band, using uncoded 16 kbps FSK modulation in a 25 kHz bandwidth. Since 2007, the NATO C3 Board's ad-hoc working group for VHF and UHF communications has been working on a new narrowband waveform (NBWF) standard, which is currently in draft form [2].

The new NBWF must conform to the spectral limitations of the legacy equipment so that the new radio equipment can operate in its place without causing interference to neighbouring spectral users. The new waveform uses continuous phase modulation (CPM) that eliminates sudden phase changes between symbols, which constrains the spectral spread of the signal and allows a higher data rate within the same bandwidth [3].

The use of concatenated forward error correction coding provides the possibility for a receiver using iterative detection to achieve very low bit error rates, thereby achieving high spectral and power efficiencies. Concatenated coding means that two simple codes are combined to achieve a good error correction capability without high complexity. In iterative detection, signals are repeatedly decoded and deinterleaved and then re-interleaved and re-encoded, while each time the probability that each bit is either a 1 or a 0 is computed [4]. At the end of the iterations, the most likely option is selected. This has a much higher computational complexity than simpler, linear methods, but it has been seen to achieve good improvements in error rate and the availability of low cost, high-speed processors makes this technique feasible in modern radios.

The new draft provides four operating modes at code rates of 20 kbps, 31.5 kbps, 64 kbps and 96 kbps in the 25 kHz channels. The bit error performances of these modes are shown in Figure 1 along with that of the legacy Stanag 16 kbps waveform [2].

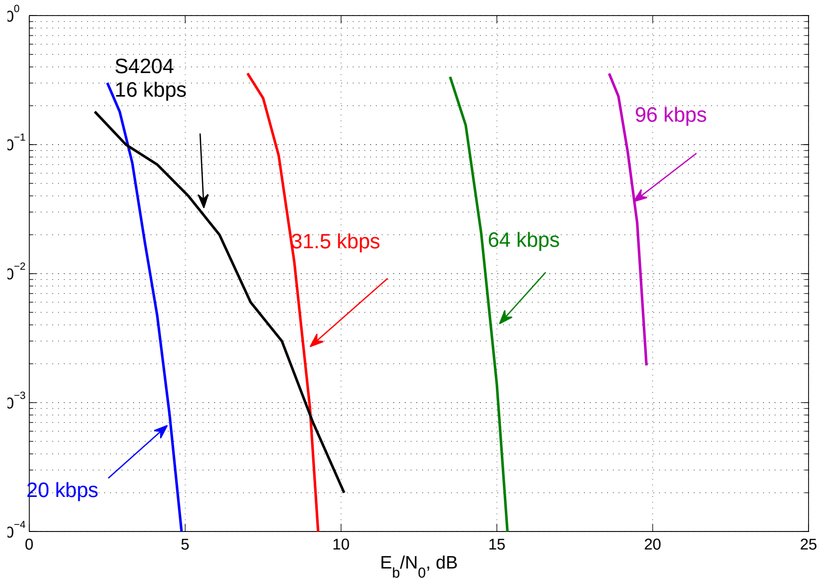


Figure 1: **Error performance of draft Stanag modes, and performance of existing 16 kbps FSK waveform [2]. (Legacy radio performance courtesy J. Nieto, Harris Corp., Rochester, NY, USA. Draft Stanag performance courtesy P. Vigneron, Communications Research Centre, Ottawa, Canada)**

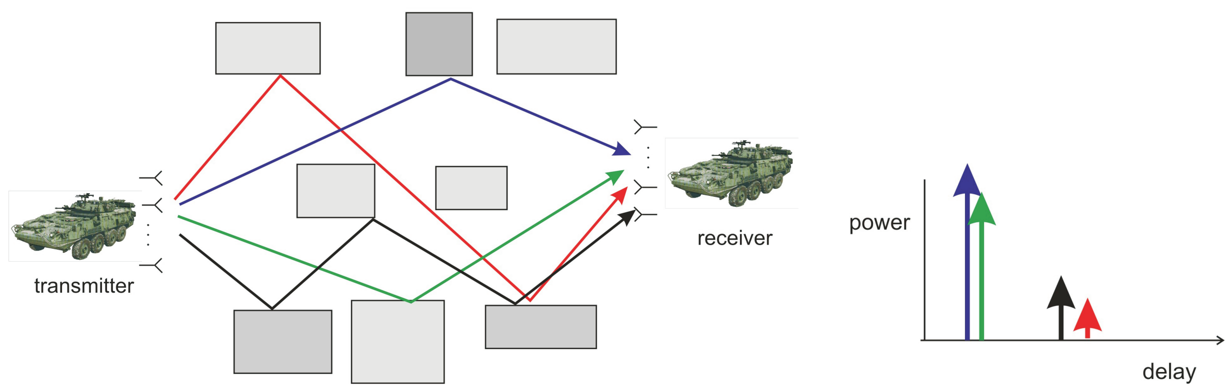
This new Stanag uses the 2.4 kbps NATO Stanag MELPe voice encoder, with the result that the 25 kHz bandwidth can now be used to support both voice and 20–96 kbps data or additional voice channels through the inclusion of a TDMA MAC. Even with networking overhead, the required services can be delivered with no loss of range.

3.0 MIMO

Most military radios are designed for use in propagation environments with limited multipath components. As modern warfare moves into more complex geographical environments such as mountainous or urban areas, the number of multipath components increases. Multipath environments may defeat many legacy military radio systems, which were designed to operate in line-of-sight regions with very low levels of multipath. However, the complex propagation environment introduces diversity into the system, which can be exploited to provide higher spectral efficiencies and increased robustness.

A multipath component is a replicate of the signal propagated through a distinct propagation mode; components arrive at the receiver with different delays and from different directions (Figure 2). Multipath components arriving within a single symbol interval are not distinguishable in time. The combination of signals with different delays means that sometimes the signals add constructively in phase, and sometimes they add destructively – this results in a time-varying amplitude called fast fading. Countering fast fading has traditionally required interleaving and coding, which introduces delays and reduces the data rate.

Multi-input multi-output (MIMO) systems use multiple RF chains at each end of the communications link and are designed to exploit the spatial diversity inherent in a multipath environment. MIMO was proposed as a theoretical concept in the late 1990s, but is only just being integrated into wireless standards such as IEEE 802.11n (wi-fi) and LTE (cellular). To-date there are no known military standards that incorporate MIMO, but it remains one of the most promising technologies for increasing spectral efficiency.



(a) Multipath environment (b) Multipath power delay profile

Figure 2: **Illustration of the multipath environment and the resulting delayed replicates of the transmitted signal.**

Multipath components arriving from different directions may be separable in space by an antenna array with a wide enough aperture. Signal components from different directions have different phase signatures across the array, hence they can be isolated by tuning the amplitude and phase response of each RF chain independently. This tuning is done at the signal processing level, not at the antenna as it would be in a phased array, hence the signals can be processed in different ways at the same time. The signals in each component can therefore be recombined in phase to counter most of the effects of fading. This is receiver *spatial diversity* processing, and it can eliminate the need for strong error correction coding and interleaving.

In MIMO, the idea of spatial processing is extended to the transmitter. Simplistically, distinct signals can be transmitted in different directions, i.e., with different spatial signatures, coinciding with the multipath components. These signals might contain the same information, which would allow reliable detection at very low signal power levels, or they might contain different information streams, which would increase the data rate through the system. In reality, the spatial signatures are more complex, and generally take advantage of several multipath components simultaneously.

In the initial hype about MIMO, it was suggested that a system with N antennas at both the transmitter and receiver would be able to achieve an N-fold increase in the data rate at high SNRs. At lower SNRs, the gain is even more significant. This was based on an assumption of rich scattering, i.e., that the environment is filled with objects that reflect signal energy toward the receiver, so that the multipath components arrive at the receiver with uniformly distributed powers and angles. The result of this is that the channel responses from a single transmit antenna to two adjacent receiver antennas, spaced by only one-half a wavelength, are uncorrelated. This condition is optimum for maximising the possible throughput on the MIMO channel. The maximum spectral efficiency (equivalently, Shannon capacity) achievable at 10 dB is illustrated in Figure 3 for this ideal model (dashed lines), and it is evident that the spectral efficiency more than doubles with each doubling of N at this low SNR.

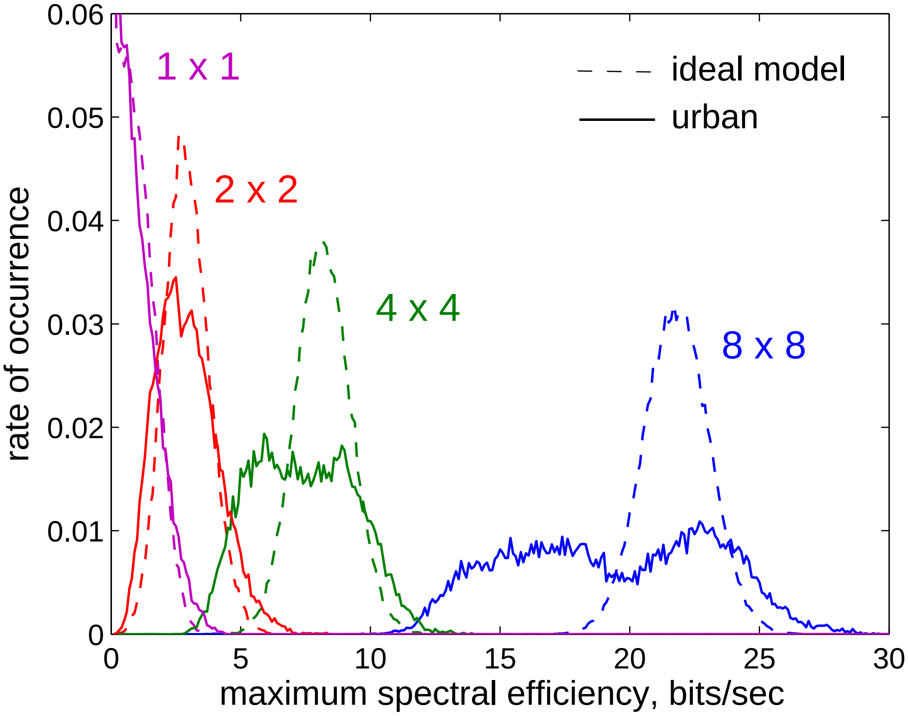


Figure 3: **Ideal and measured maximum spectral efficiencies for $N \times N$ MIMO at 10 dB, 2 GHz.**

Unfortunately, the real operating environment does not match the hypothesised ideal model. In reality, the directions of arrival tend to be clustered, as illustrated in Figure 2(a): this leads to correlation among the channel responses, and reduces the achievable throughput. Figure 3 also shows the maximum spectral efficiency computed from measurements with a static transmitter as the receiver moved along Laurier Ave., in downtown Ottawa (solid lines). It is clear that there are significant gains in throughput, but they are much less than those of the ideal model. Furthermore, there is quite a large spread of gains in the real environment, as the mobile moves through different local conditions.

The challenge is then that the original techniques that were proposed to take advantage of the spatial diversity in ideal MIMO channels do not generally work in these correlated channels, and an alternative approach is needed that takes into account the actual conditions experienced in real channels.

3.1 Precoding

There are many MIMO signalling strategies to take advantage of the spatial characteristics of the multipath channel. In this paper, we focus on linear precoding schemes, which are particularly well suited for the mobile networked environment typical of military tactical communications. There are two specific precoding schemes: *linear feedback precoding* (LFP) [5] and *orthonormal diversity-multiplexing precoding* (ODMP) [6]. Both of these can operate in conjunction with OFDM, so we need to consider only a frequency-flat fading channel. In both cases, we assume that the transmitter has N_t antennnas and the receiver has $N_r \geq N_t$ antennas. Standard signal processing techniques are used to separate the symbol streams at the receiver. Note that the MIMO mode of LTE is a form of LFP.

In precoding, one or more symbols are transmitted simultaneously from the set of N_t transmit antennas, and each is given a different spatial signature so that it takes a different path through the environment. In LFP, M symbols are transmitted in a single interval, where $M = 1, \ldots, N_t - 1$, giving a rate of M symbols per interval. The spatial signatures used by each of the symbol streams are selected by the receiver, which computes an estimate of the matrix channel response, i.e., the attenuation and phase response on each of the $N_r \times N_t$ links from the N_t transmitter antennas to the N_r receiver antennas. From this channel estimate, the receiver determines the transmitter precode that has the best match to the channel characteristics, and feeds back the index corresponding to that precode to the transmitter. Thus, if there are 16 possible transmitter precodes, 4 bits are required to pass that information. The feedback rate must be sufficiently fast that the transmitter changes precodes to keep up with changes in the channel characteristics as the transmitter and receiver move.

The concept of ODMP is to exploit the spatial diversity in the channel without knowing the specific multipath component directions. To do this, $M = 1, \ldots, N_t - 1$ data symbols are transmitted L times with different spatial signatures. The spatial signatures of each of the M symbols are maximally separated to minimise their interaction. Different data rates are achieved by varying the number of times ($L = 1, \ldots, N_t - 1$) each symbol is transmitted, and each retransmission uses a different spatial signature. In this way, each symbol is transmitted in L different directions, increasing the probability that it can be detected correctly. In contrast to LFP, the precodes are fixed by the rate selected. The receiver uses the information available about the channel, selects the optimum rate for the required quality of service, and feeds back only the rate information to the transmitter. The range of rates possible is given by M/L; thus for $N_t = 4$, the rate can vary from a minimum of $1/3$ to a maximum of 3.

The gains obtained by taking advantage of the channel's spatial diversity is illustrated in Figure 4 using real channel parameters, obtained using CRC's MIMO channel sounder in downtown Ottawa. The transmitter was parked at the side of Lyon St., just south of Laurier Ave., and the receiver was driven up Kent St., from just south of Nepean St. to north of Gloucester St. Bit error rates are shown in Figure 4 for rate 1 signalling using LFP ($M = 1$) and ODMP ($M = L = 3$) both with $N_t = N_r = 4$ antennas. For comparison, a rate 1 signal using a single antenna at transmitter and receiver ($N_t = N_r = 1$) is also shown – this conventional mode is known as single-input single-output (SISO). The same totally transmit power is considered for each case. We can see that the MIMO systems outperform the SISO system. The ODMP and LFP perform similarly: note that the overhead cost of feedback required for LFP is not included in computing the data rate at this point. Note also that these results have been generated using a BPSK modulation, but that MIMO systems can, and should, employ bandwidth efficient modulations such as that described in Sec 2.0 to further increase their spectral efficiency.

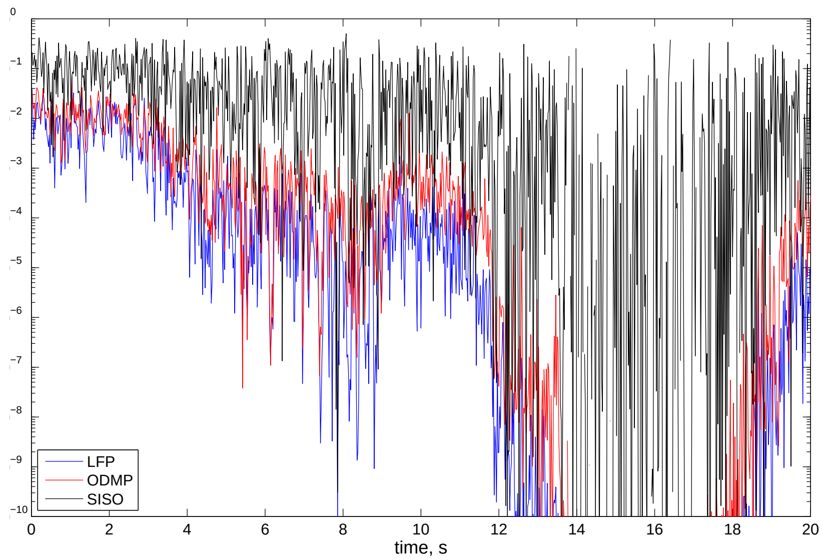


Figure 4: **Bit error rates of precoded MIMO and SISO systems along Kent St. at average SNR 8 dB, 2 GHz.**

All the systems show significant local variation in BER; this is expected as there are rapid fluctuations in the channel structure. Most BER performance curves are shown as averages, with no indication of the variations that might be expected. The variation of the channel characteristics limits the length of a data packet because the channel response can change significantly, meaning that the channel estimates become out-of-date. It was seen in [7] that in urban areas, the channel statistics are typically consistent over distances as short as 2 m, or less than 0.25 s at 30 km/h. This is particularly challenging for systems that use sophisticated signal processing. When the variations in BER are large or the data packets are too long, the system loses robustness: even though the average received power is large enough to expect a satisfactory average BER, more packets of data are not detected correctly and must be re-sent. This has a cost to the overall spectral efficiency, as will be seen in Section 5.0.

Figure 4 shows there are significant improvements in BER for all systems in the regions 5–8 s and 14–18 s. In these intervals, the receiver is passing through the intersections with Nepean St. and Gloucester St., which results in increased received power arriving along those streets. The improvement is greatest in the second intersection because the receiver is closer to the transmitter. In between the intersections, signal power arrives at the receiver from along Kent St., which means it must be reflected and diffracted into the street at the corners, and is subsequently reflected off the buildings along the sides of the street, and hence is additionally attenuated.

This effect is a reminder that power is the most important factor in system performance – spatial diversity helps to support higher data rates and reduced BER, but a strong line-of-sight signal, with minimal spatial diversity, would always be preferred. This fact is often overlooked in the literature, where the channel responses are normalised to remove the power variations. However, for practical systems, the link budget is a key consideration. For the route shown in Figure 4, using power adaptation to keep the quality of service within 1% of BER 10^{-3}, only 23% of the total power is required for the ODMP compared to the SISO case, and only 18% for the LFP. In these cases, the rate could be increased, while maintaining the same error performance, without exceeding the power budget.

Another factor that is often overlooked is that in practical systems, the receiver cannot have perfect channel estimates. Errors in the estimates arise from short training periods, received in a noisy environment, as well as from changes in the channel response itself as the transmitter and receiver move. This is discussed in more detail in Section 5.0.

3.2 Operating environment

Although MIMO systems are intended to provide gains in rich multipath environments such as urban and complex terrain, they also achieve gains in less rich environments. In particular, in the extreme case of line-of-sight communications, a MIMO system should be able to revert to adaptive antenna behaviour. In this case, beamforming at the transmitter and receiver increases the received signal power in the desired direction, while minimising interference to and from other users in the same geographic area.

The impact of changing local conditions was shown in Figure 4 for an urban environment. Even in sparse scattering environments such as suburban areas, significant gains are achievable using MIMO systems. Figure 5 shows the distribution of maximum spectral efficiencies for the urban route along Laurier Ave. (solid lines) and for a suburban route in Kanata, west of Ottawa (dashed lines). The gain for the suburban route is lower than the urban, due to less spatial diversity as a result of a less rich environment. However, there is still a significant gain with $N_t = N_r = 8$ at SNR 10 dB . Measurements from a non-line-of-sight rural environment were also analysed, and the distribution of spectral efficiencies was found to be quite similar to the suburban one.

3.3 Antenna position

It is clear from the results shown in the previous section that the location of the transmitter and receiver affect the characteristics of the channel, and thereby the performance of the communication system. Most scientific work to-date on the measurement of MIMO channels has used optimally-spaced, omni-directional antennas located on the roof of the measurement vehicles. This approach removes the effect of the vehicle, as much as possible, from the observations of the channel, to allow modelling of the propagation channel. This is problematic for military vehicles, as antennas must be positioned away from other equipment mounted on the top, such as weapons.

Work at CRC has investigated the effect of positioning the antennas elsewhere on the vehicle. In particular, patch antennas were placed on the sides of the vehicle, as illustrated in Figure 6 [8]. These antennas have a 10 dB beamwidth of $134°$, and typically receive 6–10 dB less power than the roof-mounted antennas. In situations where one side of the vehicle is oriented toward the transmitter, shadowing by the vehicle itself results in a difference in power between the two side arrays of about 20 dB. Overall, the power range observed at the side arrays is greater than that on the roof.

Signal components that arrive at the antennas on the side of the vehicle are more likely to have interacted with other vehicles in the environment (the roof-mounted antennas are above most vehicles except city

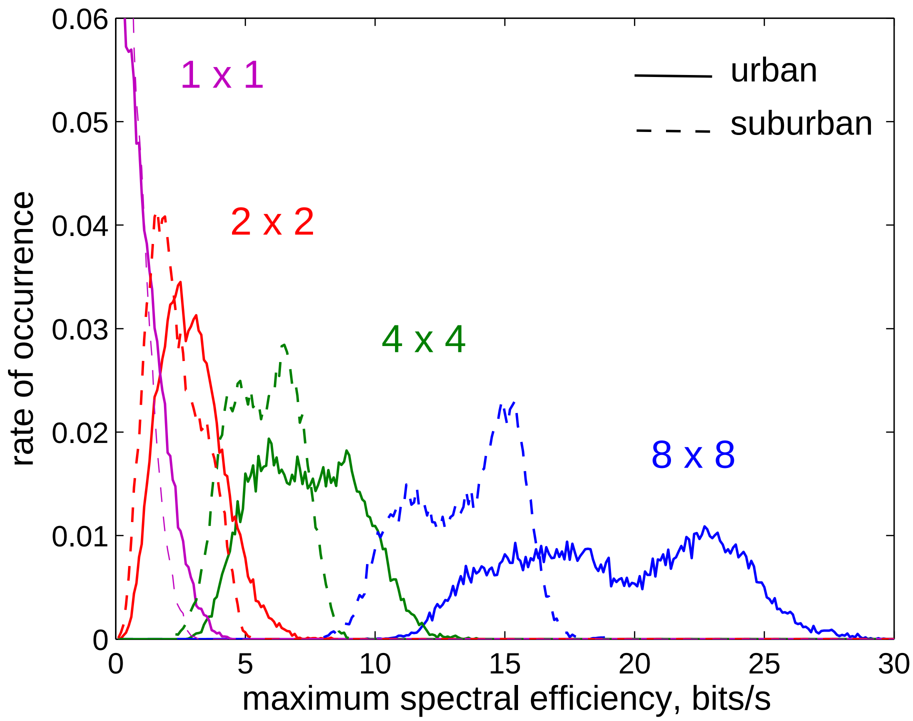


Figure 5: **Measured maximum spectral efficiencies for $N \times N$ MIMO in urban and suburban environments at 10 dB, 2 GHz.**

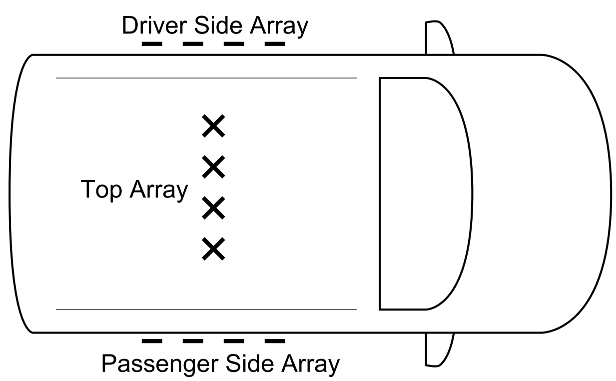


Figure 6: **Position of antennas on receiver vehicle [8].**

buses and trucks). This means that the power in these components may be lower, but also the signal is more likely to arrive from a wider range of angles.

Another consideration in the implementation of side-mounted antennas is that the channel models that have been developed using roof-mounted arrays may not be applicable. The multipath components that arrive at the driver side array, for example, are different to those arriving at the passenger side. In contrast, all antennas in the roof-mounted array see the same multipath components.

The maximum spectral efficiencies at 10 dB for three different antenna configurations are shown in

Figure 7 for a route along Bank St. in downtown Ottawa. The transmitter had $N_t = 4$ antennas at one-wavelength spacing, and was parked on Lyon St. This was on the driver's side as the vehicle moved north. The blue line shows the distribution for two antennas on each side of the vehicle, placed three wavelengths apart. The green line shows the distribution for all four antennas positioned on the driver's side, at one-wavelength spacing. The red line shows the distribution for a similar configuration on the passenger side. All receiver elements were vertically polarised patch antennas, mounted approximately 1 m above street level. The driver's side achieves the highest spectral efficiency, but note that if the vehicle were driving in the opposite direction, these antennas would be on the other side, resulting in the lowest spectral efficiency. The configuration with two antennas on each side achieves a good spectral efficiency at all locations along the route.

There are certainly advantages to mounting the antennas on the sides, and possibly front, of the vehicle. Signal energy along urban streets tends to be fairly directional, notably along the direction of the street itself, except in intersections, as noted in Section 3.1. A set of antennas that is exposed to different physical aspects of the environment will be more likely to be able to sustain a consistent minimum received power, which will support a more uniform quality of service.

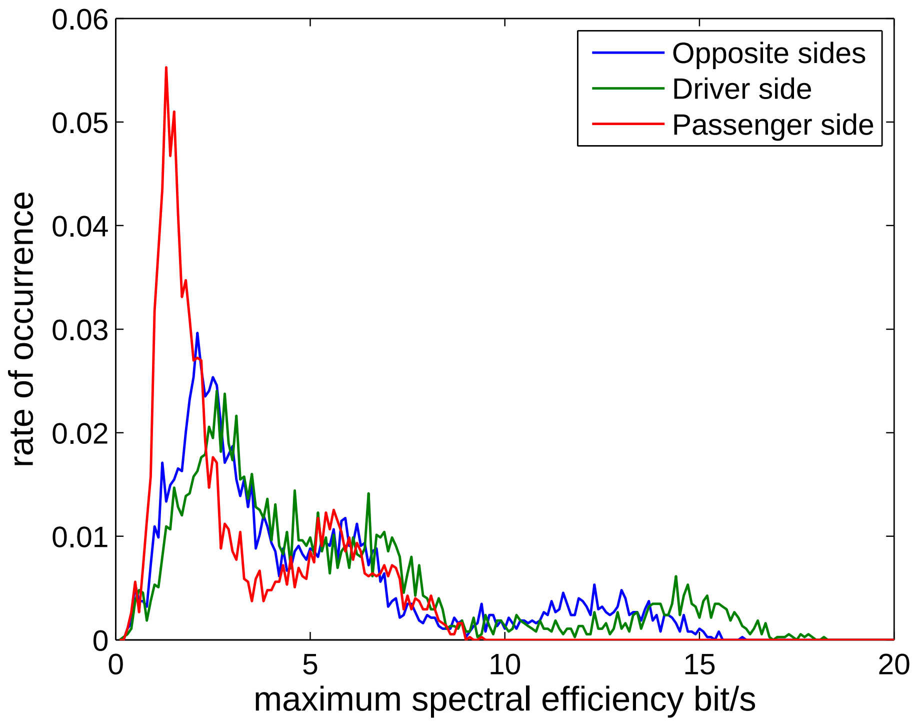


Figure 7: Measured maximum spectral efficiencies for different arrangements of $N_r = 4$ receive antennas on Bank St. at 10 dB, 2 GHz.

4.0 ADAPTIVITY

The narrowband waveform discussed in Section 2.0 has four operating modes, providing different data rates at different SNRs (Figure 1). The existence of a suite of waveforms, along with variable transmission power, provides the capability to support different throughputs over a wide operating range, as shown in Figure 8. This capability allows the user to adapt the waveform and power parameters to achieve the desired quality of service without wasting resources.

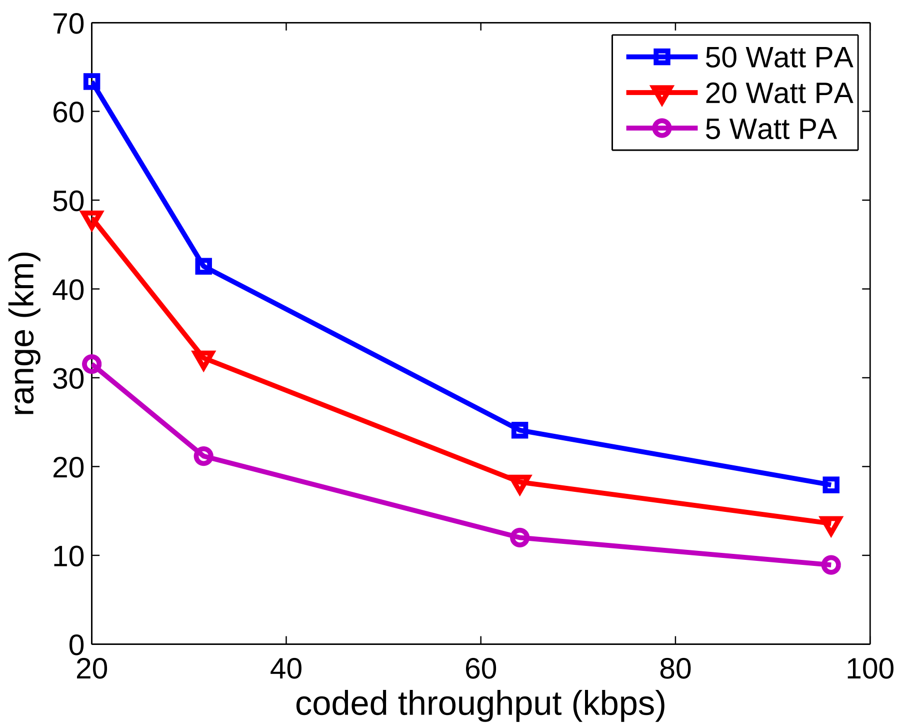
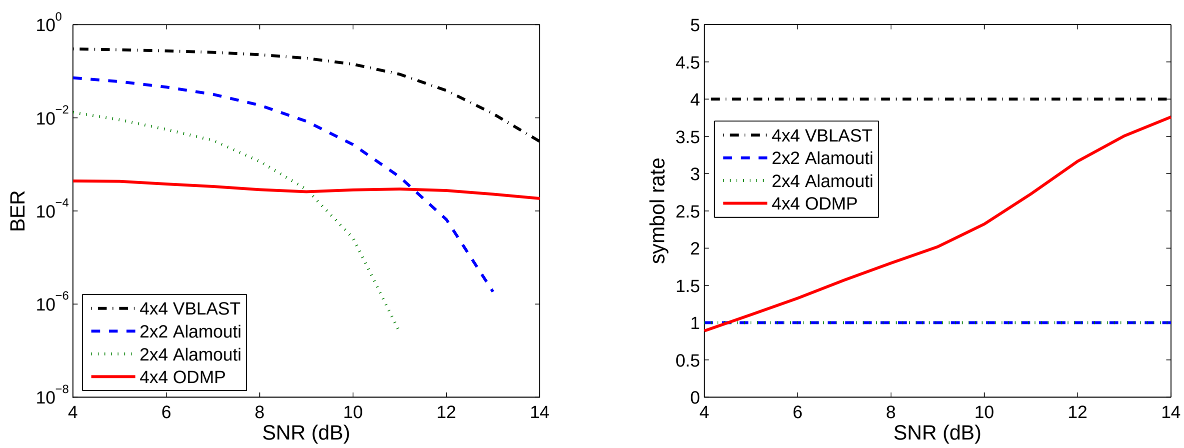


Figure 8: **Operating range for draft Stanag 4204 waveforms at different transmit powers (Courtesy P. Vigneron and C. Brown, Communications Research Centre, Ottawa, Canada).**

For the MIMO precoding discussed in Section 3.1, a suite of precodes providing different data rates is also available to provide the required quality of service in a range of operating conditions. Figure 4 showed the variation in BER as the mobile receiver moved along Kent St.; BER below those required by the application are a waste of resources. Adaptivity provides a mechanism to maximise throughput where the conditions allow, and to reduce the throughput otherwise, to maintain a fixed quality of service, e.g., a prescribed BER. One approach would be to maintain a fixed data rate, and to vary the power. An alternative is to vary the data rate. As illustrated above, varying both power and data rate provides a great deal of flexibility to the user. For $N_t = N_r = 4$, ODMP provides seven distinct rates. An eighth rate, 4 symbols per interval, is available by using full spatial multiplexing, i.e., transmitting one symbol per antenna in a single interval. Hence, only 3 bits of feedback are required for rate selection

The advantages of adaptivity are illustrated by a simulation run over the Kent St. measurement. The target BER was set at 10^{-3}, and the rate was adapted to meet that goal. The resulting mean BER over the Kent St. route is shown in Figure 9(a) for different average SNRs. The comparison curves are non-adaptive MIMO signalling techniques: VBLAST [9] and Alamouti coding [10]. VBLAST uses each of the N_t transmit antennas for a different signal stream, and therefore achieves a rate of$N_t = 4$ symbols per interval. The Alamouti code uses only $N_t = 2$ transmit antennas, but can be received by one or more antennas. Curves for $N_r = 2$ and $N_r = 4$ are shown: clearly the BER is improved by extra receive antennas, this improvement is 3 dB at high SNR, due to the noise reduction achieved by doubling the number of receive antennas. However, as see in Figure 9(b), the rate is not increased by increasing the number of receive antennas.

At average SNRs below 9 dB, neither of the alternative systems can achieve the required BER. The VBLAST system requires much higher SNRs to achieve this target. However, even below 9 dB, when the Alamouti 2×4 system achieves a BER of 10^{-3}, the ODMP system can adapt to the local conditions to provide a robust throughput. While the Alamouti scheme provides a fixed rate of one symbol per interval regardless of the SNR, the ODMP exploits the available spatial diversity to increase the symbol rate as the signal power increases. By an SNR of 14 dB, the ODMP is achieving nearly 4 symbols per interval, as much as the VBLAST system, but at a BER that meets the required target.



(a) mean BER (b) mean BER

Figure 9: Mean bit error rate and adapted error rate along Kent St. for ODMP and two fixed code rate schemes.

5.0 ROBUSTNESS

There is more to achieving high spectral efficiency than just the modulation, number of antennas or adapting to the local environment. Designing communication systems for spectral efficiency in mobile environments requires that we take into account the impact of imperfect channel knowledge and changes in the channel characteristics over time. We will see that robustness is important to overall spectral efficiency.

To illustrate the importance of considering the overall communication system, we will consider MIMO, as in Section 3.0, but the general concepts apply also to SISO. We consider first the impact of channel estimation from a training sequence, and then the impact of the channel response changing over the length of a data packet.

5.1 Training sequence length

For coherent communications, a good estimate of the channel is required at the receiver. In the academic literature, it is often assumed that the receiver (and sometimes the transmitter) have perfect channel knowledge. In some sense, this provides an “upper bound” on the expected performance of a real system, however, imperfect channel knowledge can in fact have an catastrophic impact on the system performance, so this upper bound may not be very informative. In reality, perfect channel knowledge is impossible, even if the channel response remains constant, because the received signal is corrupted by noise.

Our work has shown that it is possible to increase the robustness of the system to counter the effect of this imperfect information by taking into account the expected change over the packet length: the interested reader is referred to [11], [12].

The usual method for estimating the channel response is to transmit a known sequence that can be processed at the receiver to extract the desired parameters. This sequence is typically placed at the start of the data packet, although training symbols may be placed at the start and end of the packet, or even be spaced throughout, in order to update the channel estimate over time. For simplicity, we consider here only the case where the transmit symbols are at the start of the data packet; the other cases address some of the concerns to some degree, at the cost of additional complexity, but do not solve the problems we will discuss.

Within a data packet, a long training sequence is desirable to reduce the impact of noise and to obtain a good channel estimate. However, training symbols replace data symbols in the transmission, so the longer the training sequence, the lower the total spectral efficiency. Hence, there is a trade-off between channel estimate accuracy and data throughput; the improvement in performance with training sequences is not usually linear, hence this trade-off is system dependent.

Table 1 shows the mean square error of the channel response estimate for different training sequences for $N_t = N_r = 4$. The mean square error is computed as follows: if h_{ij} is the complex channel response from transmitter antenna j to receiver antenna i, and the estimated value is $\hat{h}_{ij}$ then the squared error is $|e_{ij}|^2 = |\hat{h}_{ij} - h_{ij}|^2$. The mean square error is then the averaged over many estimates and $i, j = 1, \ldots, N$, where $N = 4$ for this example.

Table 1: **Mean square error due to training sequence length in noise for $N_t = N_r = 4$.**

Training length, N_T	5 dB	10 dB
8	0.16	0.05
24	0.053	0.017
48	0.026	0.008

Figure 10 shows the impact on BER of different training sequence lengths, N_T, for rate $3/2$ ODMP on a portion of Kent St. For each data packet, the channel response is assumed to remain constant. At low SNR, not only are the data symbols more affected by noise than at higher SNRs, but also the channel estimate is more corrupted, which further worsens the BER. The improvement in BER obtained by increasing the training sequence from $N_T = 8$ to $N_T = 48$ is almost an order of magnitude at 12 dB. Note also that there are diminishing returns from increasing N_T.

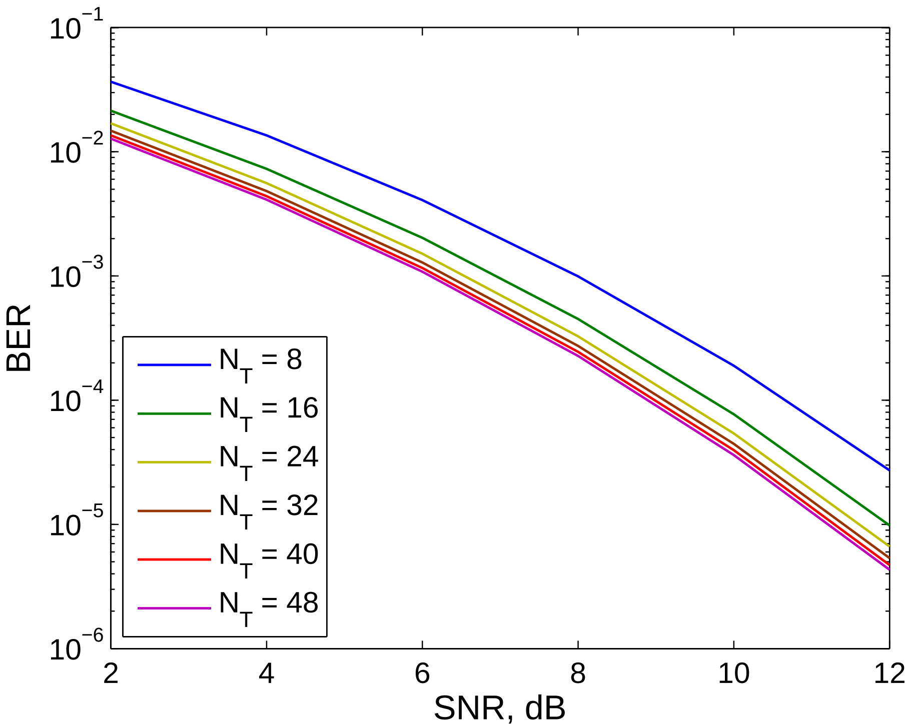


Figure 10: **BER for different training sequence lengths on a portion of Kent St. at 2 GHz (channel responses assumed constant over each data packet).**

5.2 Packet length

The results above suggest that it is worth using a training sequence that provides a good quality channel estimate, and then to mitigate the effect on spectral efficiency by using a long data packet. However, in mobile environments, the channel response changes over time, and the channel response estimate becomes outdated. In this case, to maintain the error performance, it is necessary to insert another training sequence, or equivalently, send a new packet.

Figure 11 shows the change in the channel response in two locations on Kent St., at two different frequencies. The mean square change is computed as follows: if $h_{ij}(t)$ is the complex channel response from transmitter antenna j to receiver antenna i at time t, then the change over a time interval τ is given by $e_{ij}(\tau) = h_{ij}(t+\tau) - h_{ij}(t)$. The mean square change is then the averaged over t and $i, j = 1, \ldots, N$, where $N = 4$ for these results.

Note that the rate of change in the channel response is much greater at 2 GHz than at 370 MHz. This is because the multipath fading scales with the inverse of the wavelength, hence is faster at 2 GHz. Notice also that the local environment plays a significant role in the rate of change of the channel response. The channel changes faster in the mid-block region between the Nepean St. and Gloucester St. intersections than in the intersection with Gloucester St. This is because of the strong components arriving from along the intersecting street, which stabilise the channel response. In the mid-block region, the signal energy is arriving after being reflected from both sides of the street, and these components change quite rapidly.

Comparing Figure 11 and Table 1, it can be seen that at 10 dB for $N_T = 24$, the changing channel response is more significant than the training error for delays τ in excess of 0.3 ms at 2 GHz, and in excess of 3.5 ms at 370 MHz.

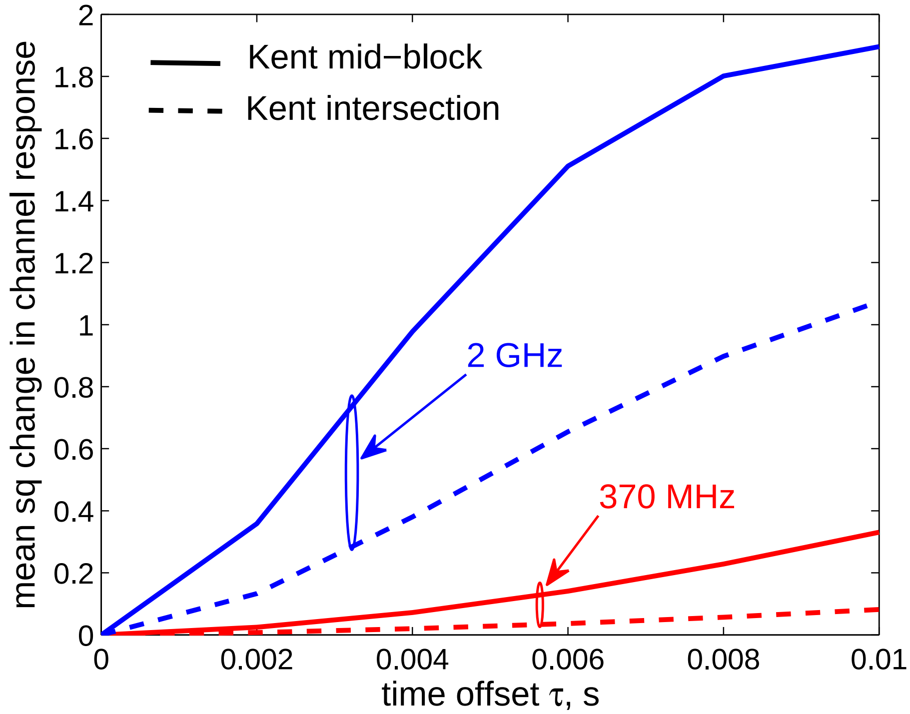


Figure 11: **Size of average change in channel response on portions of Kent St. for 370 MHz and 2 GHz.**

To evaluate the impact of these changing channel conditions, consider a system with packets of length 5 ms, bandwidth 100 kHz, and training sequence lengths $N_T = 24$. As seen above bit errors are more likely at longer delays. For illustrative purposes, we set the threshold for defining a packet error as a BER exceeding one error in the last 10% of the packet: with these parameters, the BER threshold is 0.02. This is simulated by computing the BER for ODMP using the channel conditions at the end of the packet, and comparing it to this threshold. When the BER exceeds this level, the packet must be retransmitted.

Figure 12 shows the CDFs of the number of transmissions required for each packet on Kent St., for ODMP rate $3/2$ at 6 dB. As expected from Figure 11, the packets at 370 MHz require few retransmissions, with less than 0.2% of packets needing retransmission in the mid-block region, and a negligible number in the intersection. In contrast, at 2 GHz, the number of retransmissions is quite high, particularly in the mid-block region, where almost 10% of packets require 5 or more transmission attempts.

It is clear from these results that trade-offs are necessary to ensure that striving for high spectral efficiency in the design of signal packets does not have a significant detrimental impact on robustness. When packet-level spectral efficiency is high, i.e., long data streams with short training sequences, packet failure rates may increase, requiring costly retransmissions, and a much lower overall system spectral efficiency.

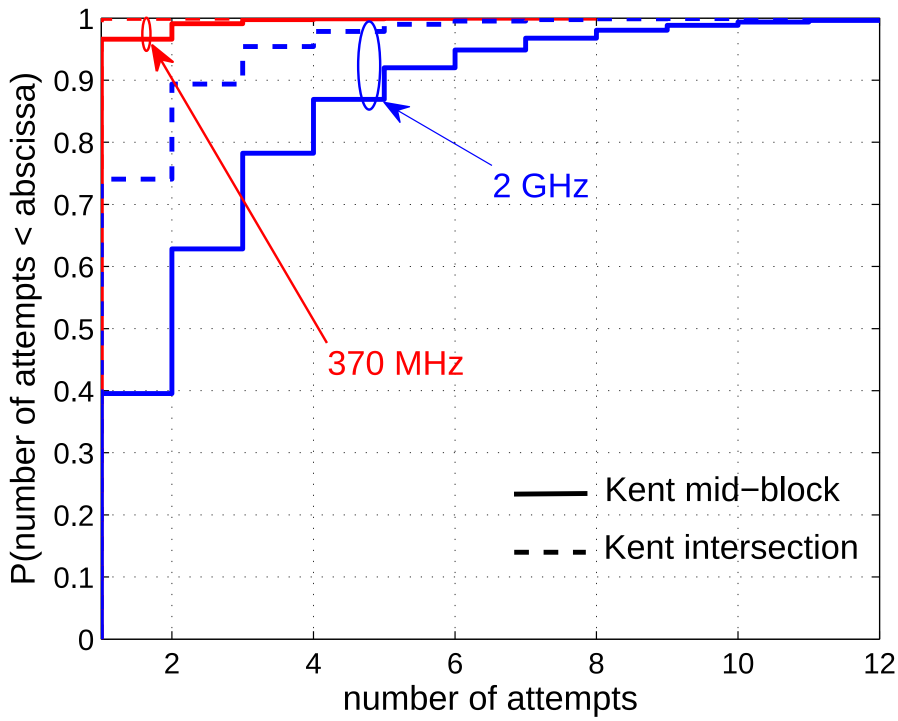


Figure 12: CDF of number of packet transmission attempts for successful detection using rate $3/2$ ODMP, on portions of Kent St. at average SNR 6 dB, 370 MHz and 2 GHz.

6.0 CONCLUSIONS

In this paper, we have looked at various approaches to increasing the spectral efficiency of communication systems. The first step is to ensure that the on-air signal achieves as high a throughput as possible to provide the required quality of service. This can be achieved by selecting an appropriate modulation in conjunction with high-performance coding and signal processing. Diversity provides an opportunity for increasing the spectral efficiency by exploiting additional signal information at the receiver – in complex propagation environment such as urban areas, this can be achieved using multiple antennas to exploit spatial diversity; in environments with less multipath, diversity can often still be found through signal polarisation. These diversity capabilities should be provided in conjunction with spectrally-efficient modulations to maximise the throughput in a given bandwidth.

Regardless of the approach used to increase the spectral efficiency, adapting the radio parameters is an important consideration to maintain the required quality of service without wasting resources. For example, using a higher power than is required to provide the necessary data and error rates wastes the available transmitter power, which may be provided by batteries, and may cause interference to other users on the same frequency, which reduces the overall spectral efficiency. For non-real-time applications, adapting the data rate to take advantage of local conditions makes more efficient use of the bandwidth available.

The cost of adapting the radio parameters should be taken into account when evaluating the overall spectral efficiency. This includes feedback to the transmitter from the receiver; this feedback must be often enough to ensure the information available to the transmitter is timely, but not so often that the cost of the feedback is cumbersome. Long packets are often considered ideal, because each packet requires a certain amount of overhead, such as addressing and training sequences. However, in a mobile environment, channel estimates can go out-of-date quickly, resulting in unacceptable error rates which necessitates packet retransmissions, and hence a reduction in overall system spectral efficiency.

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ABBREVIATIONS AND ACRONYMS

BPSK	binary phase shift keying
BER	bit error rate
CRC	Communications Research Centre Canada
FSK	frequency shift keying
LFP	linear feedback precoding
LTE	3GPP long term evolution
MAC	medium access control
MELPe	mixed-excitation linear predictive (enhanced)
MIMO	multiple-input, multiple-output
NBWF	narrowband waveform
ODMP	orthonormal diversity multiplexing precoding
OFDM	orthogonal frequency division multiplexing
RF	radio frequency
SIR	signal-to-interference ratio
SNR	signal-to-noise ratio
TDMA	time division multiple access
UHF	ultra high frequency (300 MHz – 3 GHz)
VBLAST	vertical Bell Labs space time
VHF	very high frequency (30 MHz – 300 MHz)