UNIVERSITEIT VAN PRETORIA
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YUNIBESITHI YA PRETORIA
Faculty of Engineering, Built Environment and Information Technology

ESC 320

Stochastic Communication Systems

Practical 1 Guide

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with inputs from ESC 320 assistants

I. Description

A. Receivers

The RTL-SDR software-defined radios (SDRs) issued to students should be used for this assignment. Students will only be allowed to use alternative receivers with written permission from the lecturer.

B. Signal Parameters

The parameters of the signals are provided below.

- The carrier frequency is 1.3 GHz.
- The modulation schemes used in the transmitted signals are listed below in the order in which they are transmitted in a burst.
  1) on-off keying (OOK)
  2) 4-amplitude-shift keying (ASK)
  3) differential binary phase-shift keying (DBPSK)
  4) differential quadrature phase-shift keying (DQPSK)
  5) differential 8 phase-shift keying (D8PSK)
- The constellation diagrams for each modulation scheme are shown in Figure 1.
- There are gaps between each of the bursts during which there are no transmissions.
  – There is a short gap between each burst.
  – There is a long gap (four times as long as the short gap) following the last burst listed above, after which the pattern of bursts repeats.
- The first 10 symbols in each case are the unmodulated carrier.
- A raised cosine bit shape with $\beta = 0.5$ is used for all modulation schemes. It is thus not necessary to apply a matched filter to the signals.
- Each signal starts with a number of 8-bit American Standard Code for Information Interchange (ASCII) characters[1] with the first and last ASCII characters being a caret ("^" which is ASCII character 94) and a dollar symbol ("$" which is ASCII character 36).[2] The remaining bits are randomly-generated and will not correspond to ASCII characters except by chance.

II. Instructions

The objective of this practical is to record transmitted signals using digital receivers and to synchronise the symbols and to decode the transmitted ASCII characters.

The general instructions in Appendix C on pages 9 to 10 of this guide must be followed.

Note that the following tasks are not required for this assignment.

- It is not necessary that the code written for this assignment run in real time. The goal of the assignment is to implement a working system rather than optimising code.
- It is not necessary for the implemented system to automagically determine the start of each burst, and this value may be determined by the user.[3]

[1]These characters contain short jokes obtained from https://onelinefun.com.

[2]The caret and dollar characters are used to denote the start and end of a line in regular expressions.

[3]A well-implemented algorithm should be capable of rapidly locking onto a signal following the gaps between bursts, so the start times of each burst are not strictly necessary for this assignment.

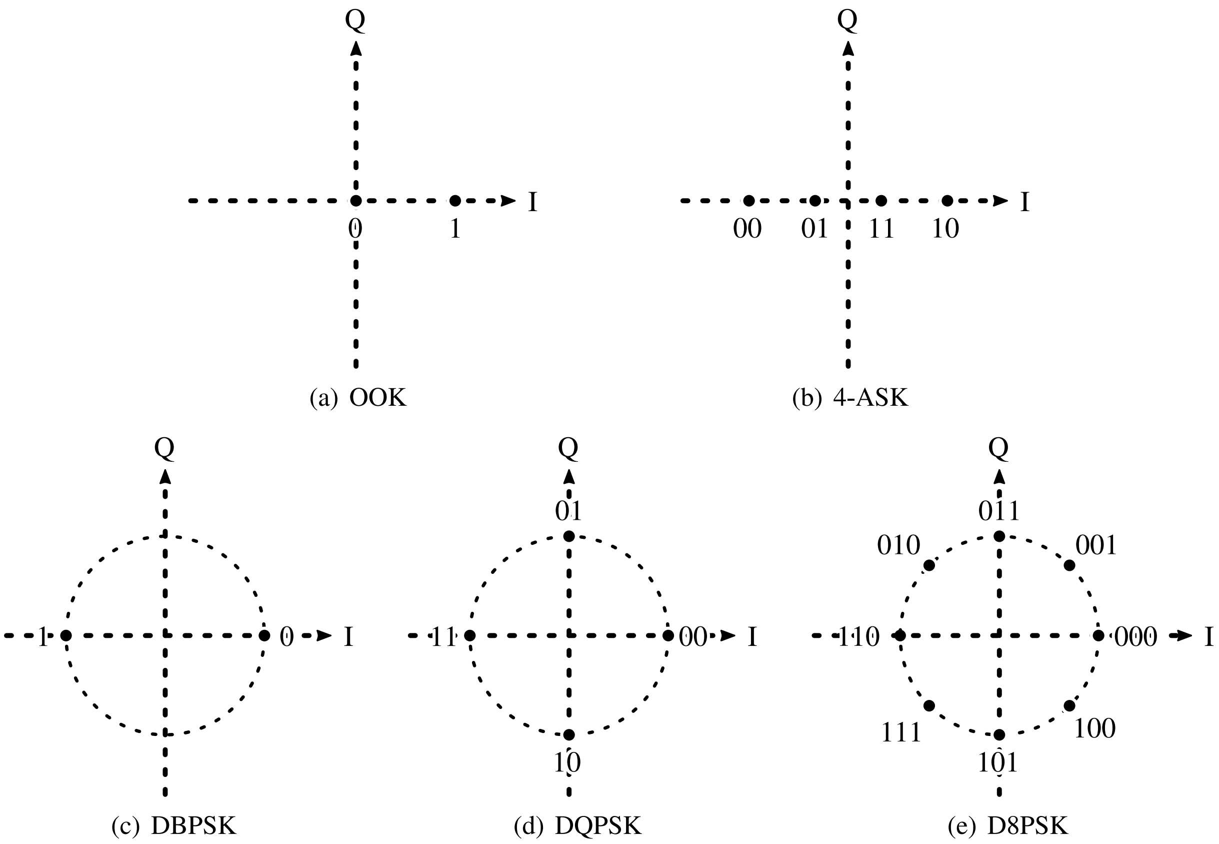


Figure 1: The constellation diagrams for each signal type.

A. Report Content

Each group is required to submit a report providing the information listed below.

- A description of the process used to synchronise with the symbols of the received signal. How was the sampling instant in each symbol determined?
- At least the first 60 demodulated bits must be provided for all signals.
- The decoded ASCII characters for each signal should also be provided.
- Any computer code written used to obtain the results presented in the report should be included in appendices.

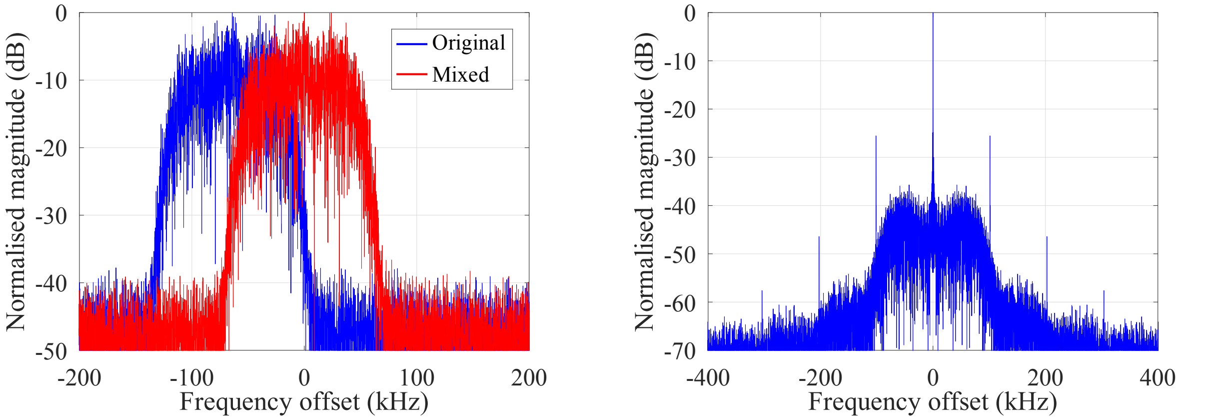
Marks will be awarded primarily on the basis of the explanations and motivations provided. Merely obtaining the correct result is not nearly as important as describing how the result was obtained. The mark allocation for the report is provided in Appendix B.

B. Example of Exceptional Results

Examples of excellent figures are provided in Section III. The plots in Section III correspond to obtaining a high mark,[4] and are not the minimum acceptable standard. Students are also welcome to plot the results in separate graphs rather than in subfigures as in Section III.

As stated previously, please remember that marks will primarily be awarded for the motivations for what was done rather than just what was done. For example, the procedure to

[4]That said, some of the fonts in the figures in Section III are on the small side, and some of the legends could be better.



(a) Signal spectrum

(b) Rectified signal spectrum

Figure 2: The power spectral densities (PSDs) of (a) a DQPSK signal and (b) a rectified DQPSK signal.

synchronise with the received carrier ensures that the constellation points do not rotate around the centre of the diagram, and a description of how this was achieved is more important than the fact that it was achieved.

III. Guide

This section provides a brief guide to how the practical can be approached. The suggestions below are not the only ways to achieve the required outcomes, and other, better approaches may exist.

While the primary goal of the practical is to decode the received data, the key task is synchronisation with the transmitted symbols. There are two primary tasks that both have to be accomplished to decode the received data. These are

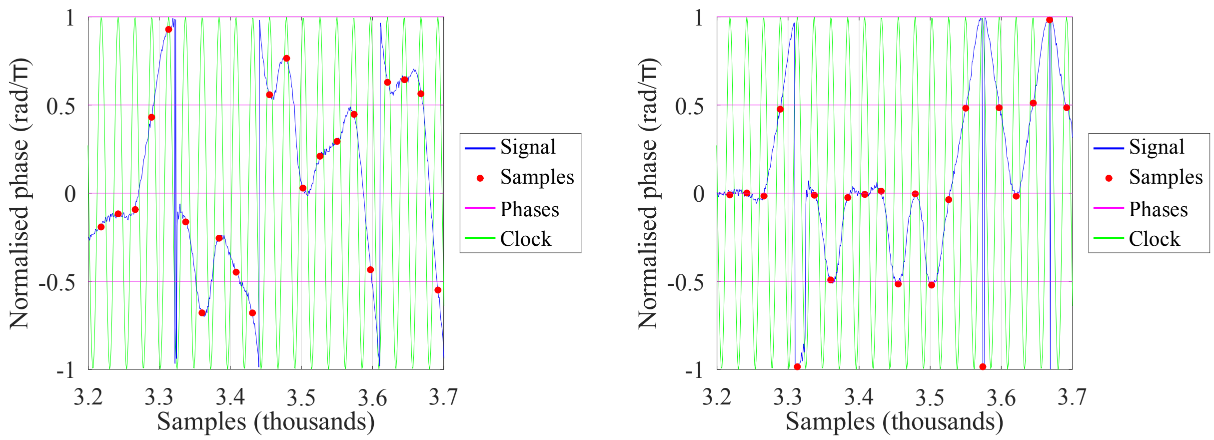
- coarse tuning to the signal carrier frequency, and
- synchronisation with the transmitted symbols.

The first task is achieved by tuning the receiver to the known carrier frequency, and needs to be performed in order to receive the desired signal.

A. Frequency Offset

The first step in demodulating a signal is normally to remove any frequency offset in the received signal. An example of such an offset is shown in Figure 2(a) for a DQPSK signal, where it can be seen that a frequency offset was originally present, but has been removed.

Even small frequency offsets can cause significant errors as shown in Figure 3. In Figure 3(a), it can be seen that the three signal samples around 3 400 samples and the four signal samples between 3 500 and 3 600 samples appear to have similar phase differences. However, this is not the case a shown in Figure 3(b), where the 32-kHz offset – an error of a mere -0.0024% or -24 parts per million (ppm) of the centre frequency – has been removed from the signal. The three signal samples around 3 400 samples actually have the same phase, while the four signal samples from 3 500 to 3 600 samples differ by $90°$ – a full symbol in DQPSK.



(a) Frequency offset

(b)

Figure 3: The effect of (a) the case with a frequency offset compared to (b) the case when the frequency offset has been removed.

Despite the rather dramatic effect of the frequency offset in Figure 3, it is worth noting that modulation schemes with large phase differences between symbols (e.g. DBPSK) and/or low modulation rates can be successfully demodulated with small frequency offsets. The key to successful demodulation is that it must be possible to distinguish whether symbol phases have changed between symbols, and if so by how much.

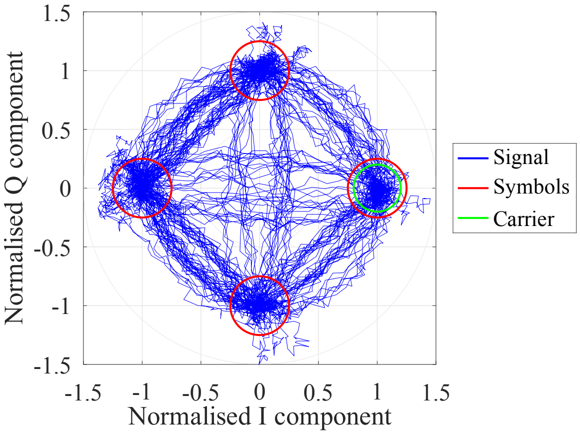
While there are many ways of estimating a frequency offset, using the median of the phase difference between samples should work here. The primary benefit of the median is that it ignores outliers, so the steps caused by phase wrapping are automatically ignored. This is not the case when using the mean, where outliers can significantly affect the result.

B. Symbol Synchronisation

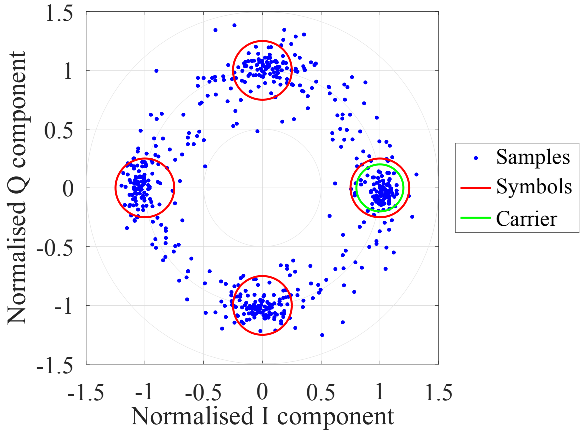
The need for symbol synchronisation is shown in Figure 4(a), where a DQPSK signal is plotted on the I-Q plane. The full signal in Figure 4(a) moves along various paths between the symbols, making it essential to avoid sampling the signal during these transitions between symbols. For example, Figure 4(b) shows the same signal sampled with inaccurate estimates of the symbol times. The sampling inaccuracies lead to the symbol samples that do not clearly correspond to any of the symbols, thereby causing demodulation errors. By comparison, using accurate estimates of the symbol times to sample results in samples that are clearly distinguished as shown in Figure 4(c).

The process of synchronising to the symbols and determining the appropriate sampling points described below is based on the recommendation to rectify the signal provided in Section 7.5.2 of the prescribed textbook [1].

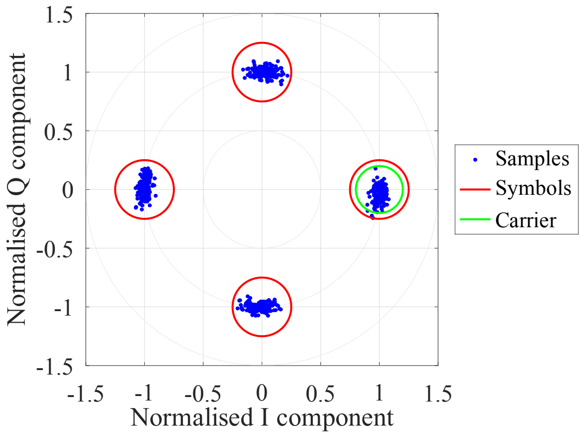
A possible mathematical implementation of full-wave rectification is the absolute value operator as it computes the magnitude of the signal. The reason this approach is reasonable here is that the phase varies over time both due to the modulation of the signals and the carrier frequency offset. Computing the magnitude of the received signal will remove all phase shifts producing a signal which has a clear repeating component at the symbol rate. Furthermore, the peak of this repeating signal will be at the sampling instant because the signal magnitude reach its largest value at the sampling instant. There are numerous ways to extract the symbol



(a) Full signal



(b) Inaccurately sampled signal



(c) Sampled signal

Figure 4: The (a) full path, (b) inaccurate symbol samples, and (c) accurate symbol samples of measured DQPSK signal on the I-Q plane after frequency compensation.

clock, including filtering, phase-locked loops (PLLs), Fourier transforms, and others, once the received signal has been rectified.

The Fourier transform of the absolute value of the received rectified signal will thus have peaks corresponding to the symbol rate as shown in Figure 2(b) where the symbol rate is 101.3 kHz. Note that the signal in Figure 2(a) does not show components at the symbol rate. The precise magnitudes of these peaks will vary depending on the modulation scheme used, but there will be a component at zero frequency (the mean of the rectified signal is non-zero) and components at positive and negative frequencies corresponding to the symbol rate (±101.3 kHz in Figure 2(b)). Further harmonics will also be present and may be visible above the noise, with harmonics at ±202.7 kHz and ±304.0 kHz being visible in Figure 2(b) before disappearing below the noise.

One of the ways of obtaining a more accurate estimate of the clock frequency is interpolating the discrete Fourier transform (DFT)[5] of the signal as shown in Figure 5. This can easily be achieved by adding zeros to the end of the signal, and then performing the DFT on the resulting

[5]Note that DFT is the name of transform, while fast Fourier transform (FFT) is the name of a class of algorithms to compute that transform. So the transform is the DFT, not the FFT.

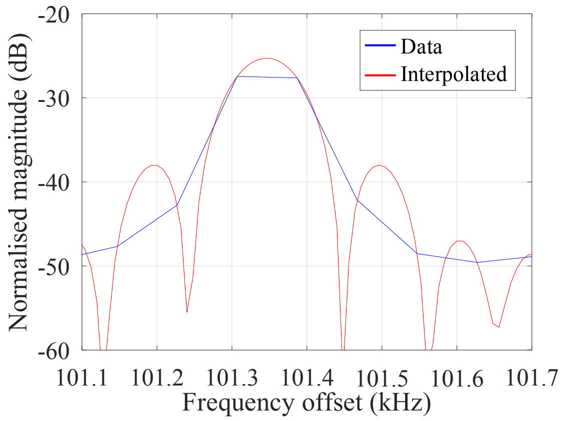


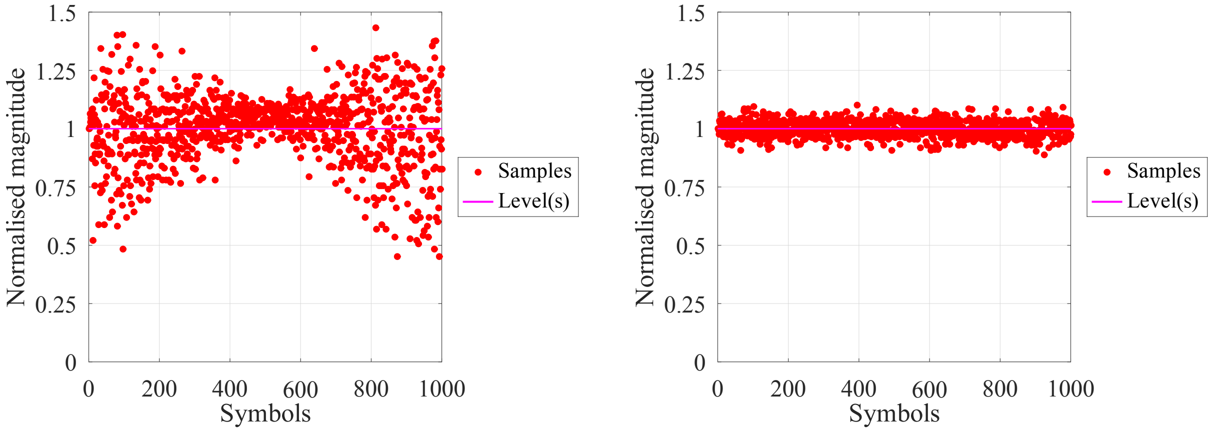
Figure 5: The portion of the spectrum of the rectified signal from Figure 2(b) around the symbol frequency showing the effect of interpolation.

longer signal. This computation is sufficiently common that many software packages allow the length of the DFT to be specified by the second argument to the relevant function with the time-domain samples being zero-padded to that length (e.g. `fft(signal,1024)` to zero-pad `signal` to 1024 samples before computing the DFT in Octave and MATLAB). As can be seen in Figure 5, the interpolation can lead to a significantly more accurate estimate of the clock frequency. It is important to note that this zero-padding process does not mean that new information is added to the spectrum as the zeros added to the time-domain signal contain no additional information about the signal. This process merely interpolates the existing spectrum information, and any other valid interpolation would produce the same result. The benefit of this approach is that efficient FFT algorithms exist to rapidly compute long DFTs.

An important point to bear in mind is that clocks can drift over long periods as a result of estimation errors, noise, and frequency drift. Figure 6 shows the effect of the accuracy of the estimate the clock frequency and phase for D8PSK with a high signal-to-noise ratio (SNR). The Fourier transform computes average results over all the samples considered, and Figure 6(a) shows how a relatively poor estimate of the clock parameters leads to sampling points that are accurate over a portion of the time interval considered (roughly samples 400 to 600), but inaccurate elsewhere. The resulting symbol samples are shown in Figure 4(b), and it is not possible to unambiguously demodulate many of the symbols. By comparison, Figure 6(b) shows that using a more accurate estimate of the clock phase and frequency (interpolation was applied) is able to accurately estimate the correct sampling points. Using an accurate symbol-rate estimate results in the symbol samples shown in Figure 4(c), where accurate demodulation is easily performed. Ideally, the clock should be tracked by a separate PLL to ensure that the estimated sampling instants are accurate even if the clock varies.

C. Demodulation

As carrier synchronisation is not implemented in this practical (apart from compensating for frequency offsets, which is a form of carrier synchronisation), the phase of the received signal cannot be determined relative to the carrier. The only available option is thus to compare the phase of each symbol to that of the previous symbol to determine the difference between them. As can be seen in Figure 3(b), the phase differences are clearly apparent as long as the carrier frequency is removed. The simplicity and effectiveness of this approach are some of the reasons for the use of differential modulation schemes such as DQPSK.



(a) Poor estimate

(b) Good estimate

Figure 6: The effect of errors in the estimation of the clock frequency.

TABLE I: Demodulated data from Figure 3(b)

Description	Symbol 1	2	3	4	5	6	7	8
Phase change	+90°	+90°	180°	−90°	+90°	0°	0°	−90°
Data	01	01	11	10	01	00	00	10
ASCII character	$\underbrace{\hspace{6em}}_{\wedge}$				$\underbrace{\hspace{6em}}_{\text{B}}$			

The first samples on the left of Figure 3(b) are the final samples of the initial ten symbols that that contain the unmodulated carrier. These initial symbols are provided to allow initial carrier synchronisation and thus correspond to a zero phase as seen in Figure 3(b). As this is a quadrature phase-shift keying (QPSK) signal, the remainder of the symbols are demodulated on the basis of their phase difference to the previous symbol and the constellation shown in Figure 1(d). The result is shown in Table I for the first 8 symbols, which correspond to 16 bits and two ASCII characters.

References

[1] B. P. Lathi and Z. Ding, *Modern Digital and Analog Communcation Systems*, 4th ed. Oxford, UK: Oxford University Press, 2010.

[2] W. P. du Plessis, *ESC 320 – Practical 1 Guide*, University of Pretoria, 28 Jul. 2020.

Appendix A
Abbreviations

AL	Assistant Lecturer
ASCII	American Standard Code for Information Interchange
ASK	amplitude-shift keying
D8PSK	differential 8 phase-shift keying
DBPSK	differential binary phase-shift keying
DFT	discrete Fourier transform
DQPSK	differential quadrature phase-shift keying
FFT	fast Fourier transform
OOK	on-off keying
PLL	phase-locked loop
ppm	parts per million
PSD	power spectral density
QPSK	quadrature phase-shift keying
SDR	software-defined radio
SNR	signal-to-noise ratio

Appendix B
Report Mark Allocation

The mark allocation for the report for this practical is shown in Table II.

Please take note of the following points.

- Methodology should include all theory, calculations, and code flow diagrams used to obtain the results. Where information is reused, referring to the relevant section of the report is acceptable.
- Results should include all obtained results and figures corresponding to those in the practical guide.
- Discussion should include thorough, critical analyses of the obtained results. Observations, and especially anomalies, should be discussed and explained.
- All code that is used to obtain and output the results should be attached as an appendix to the report. Code should be easy to read and well-commented.
- For the formatting, the following points need to be adhered to:
  - a table of contents, introduction and conclusion should be present,
  - the required plagiarism declaration should be added,
  - correct spelling and grammar should be used,
  - figures should be labelled correctly and each figure should be introduced, and
  - all information obtained from external sources (including figures) should be referenced using in-line referencing.

  Students are advised to consider using LaTeX it addresses many of these issues are automatically.

TABLE II: Practical 1 Report Mark Allocation

Topic	Total	Methodology	Results	Discussion
OOK	15	7	4	4
4-ASK	17	7	5	5
DBPSK	16	8	4	4
DQPSK	16	8	4	4
D8PSK	16	8	4	4
Language and formatting	10			
Code	10			
Total	100			

Appendix C
General Instructions

This appendix contains general instructions which are applicable to all assignments.

- While no specific format is prescribed, this is a formal report so the requirements for formal reports should be followed (e.g. numbered sections, introduction and conclusion, numbered figures and tables, etc.).
- Only ONE student in each group should submit the report because TurnItIn will flag reports as having 100% similarity if more than one student submits a group report.
- Reports must be submitted via the ESC 320 ClickUP page. Do not email reports to the lecturer or Assistant Lecturer (AL) as emailed reports will be considered not to have been submitted.
- The names of submitted files must have the format shown below.
  `esc320_prac_1_{student number 1}_{student number 2}.{extension}`
- No late assignments will be accepted. No excuses for late submission will be accepted.
- Each student must do their own work. Academic dishonesty is unacceptable and cases will be reported to the university Legal Office for suspension.
- The report must include the standard declaration of originality for group assignments provided in the General Study Guide of the Department of Electrical, Electronic and Computer Engineering.
- All information from other sources must be clearly identified and referenced.
- Any computer code used to obtain the results presented in the report should be included as appendices.

A. *Submission*

Reports should only be submitted via the

- `Practicals` → `Practical 1` → `Report`

links on the ESC 320 ClickUP page. Only assignments submitted in via ClickUP will be accepted. Do not email reports to the lecturer or AL as emailed reports will be ignored.

The names of submitted files must have the format shown below.

```
{course code}_prac_{practical number}_
                    {student number 1}_{student number 2}.{extension}
```

Late submissions will not be accepted! Accepting late submissions is extremely unfair on those students who submit their work timeously because their tardy colleagues are effectively given additional time to complete the same work. Students are advised to submit the day before the deadline to avoid inevitable problems with ClickUP, internet connections, unsynchronised clocks, load shedding, hard-drive failure, computer theft, etc.. Students who choose to submit close to the deadline accept the risk associated with their actions, and no excuses for late submissions will be accepted.

Students will be allowed to submit updated copies of their assignments until the deadline, so there will be no excuse for submitting late. Rather be marked on an incomplete early version of your assignment than fail to submit anything.

B. Academic Dishonesty

Academic dishonesty is completely unacceptable. Students should thus familiarise themselves with the University of Pretoria's rules on academic dishonesty summarised in the study guide and the university's rules. Students found guilty of academic dishonesty will be reported to the Legal Office of the University of Pretoria for suspension.

Students are required to include the standard originality declaration for group assignments provided in the General Study Guide of the Department of Electrical, Electronic and Computer Engineering as part of their reports. This standard originality declaration includes a statement that the group submitting the report is aware of the fact that academic dishonesty is unacceptable and a statement that the submitted work is the work of that group. Failure to include this declaration of originality will mean that the submission will be considered incomplete.

While students are encouraged to work together to better understand the work, each group is required to independently do their own work (including recording signals, processing signals, writing the report, etc.). No part of any group's work may be the same as any part of another group's work.

Students should clearly indicate material from other sources and provide complete references to those sources. Examples of commonly-used sources include the textbook [1], this document [2]. Note that this does not mean that students may reuse code and/or information found in books, on the internet (e.g. GNU Radio), or in other sources as students are required to complete the tasks themselves.[6] Reusing code to perform ancillary tasks such as interfacing with a SDR, reading files, and plotting images is acceptable as long as the portions of the code which are reused are clearly marked (normally comments indicating the start and end of such code, along with its source are sufficient).

[6]The objective of all academic assignments is fundamentally that students learn by completing the assignments. Merely reusing code and/or information found elsewhere defeats this objective because a key part of the learning process is performing the tasks oneself.