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

# ESC 320

## Stochastic Communication Systems

Practical 2 Guide

Last updated on 24 August 2020

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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.

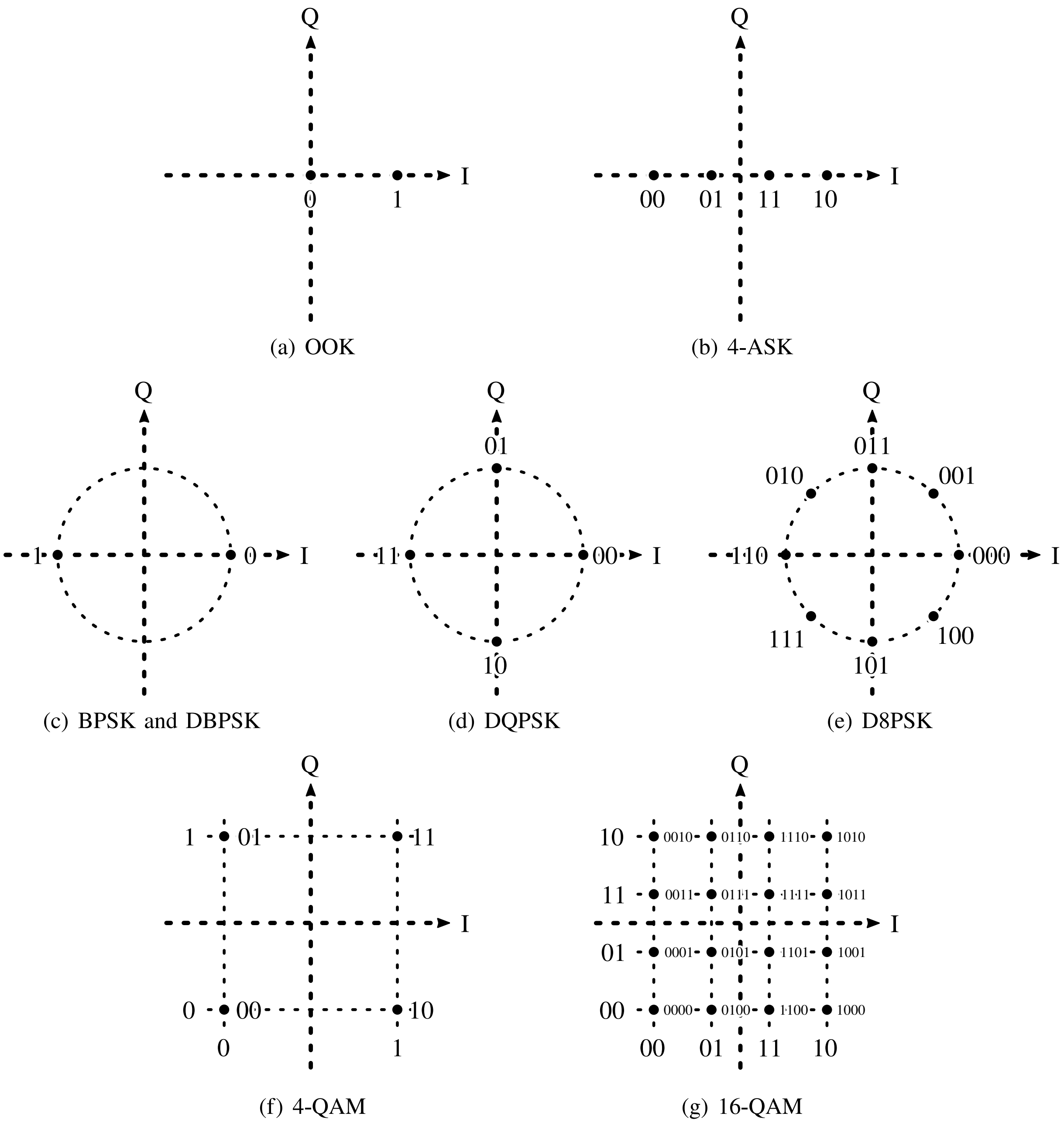
- The carrier frequency is 1.3 GHz.
- The symbol rate is approximately 100 000 symbol/s.
- The modulation schemes used in the transmitted signals are listed below in the order in which they are transmitted in a burst.
  1) on-off keying (OOK)
  2) 4-amplitude-shift keying (ASK)
  3) binary phase-shift keying (BPSK)
  4) differential binary phase-shift keying (DBPSK)
  5) differential quadrature phase-shift keying (DQPSK)
  6) differential 8 phase-shift keying (D8PSK)
  7) minimum shift keying (MSK)
  8) 4-quadrature amplitude modulation (QAM)
  9) 16-QAM
- The constellation diagrams for each modulation scheme are shown in Figure 1. The one exception is MSK, where a 1 and a 0 are represented by the higher and lower frequencies respectively (or equivalently by $\pm 90°$ phase shifts between symbols).
- 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 except MSK, which is implemented by simply switching between two frequencies. 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), respectively.[2] The remaining bits are randomly-generated and will not correspond to ASCII characters except by chance.

# II. Instructions

The objectives of this practical are to record transmitted signals using digital receivers, to synchronise with the received signals so that constellation diagrams can be generated from the received signal, and to decode the transmitted ASCII characters.

[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.



(a) OOK (b) 4-ASK

(c) BPSK and DBPSK (d) DQPSK (e) D8PSK

(f) 4-QAM (g) 16-QAM

Figure 1: The constellation diagrams for each signal type.

The general instructions in Appendix C on pages 12 and 13 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]

[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.

### 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?
- A description of the process used to synchronise with the carrier of the received signal. How was the carrier frequency compensated for?
- A plot of the measured constellation diagram of each signal.
- 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 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.

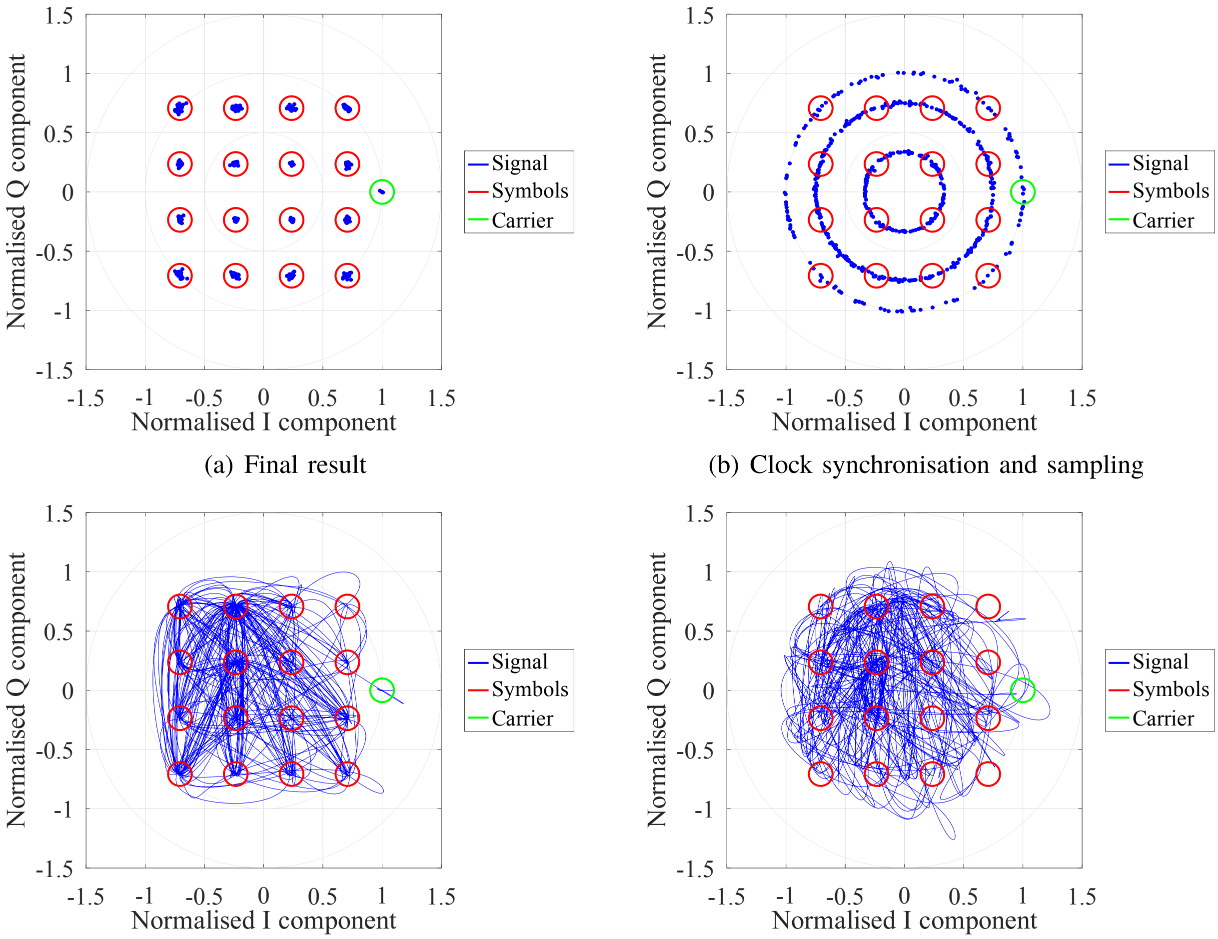
While the primary goals of this practical are to plot measured constellation diagrams and to decode the received data, the key task is synchronisation with the received signal. There are three aspects of synchronisation which both have to be accomplished to obtain the required constellation diagrams. These are

1) coarse tuning to the signal carrier frequency,
2) synchronisation with the transmitted symbols, and
3) synchronisation with the signal carrier.

The first two tasks are considered in the guide for the first practical for ESC 320 [1], so only the third task will be considered below.

Figure 2 provides idealised examples of the effect of the second two types of synchronisation for a 16-QAM signal to try to clarify the differences between them.

[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.

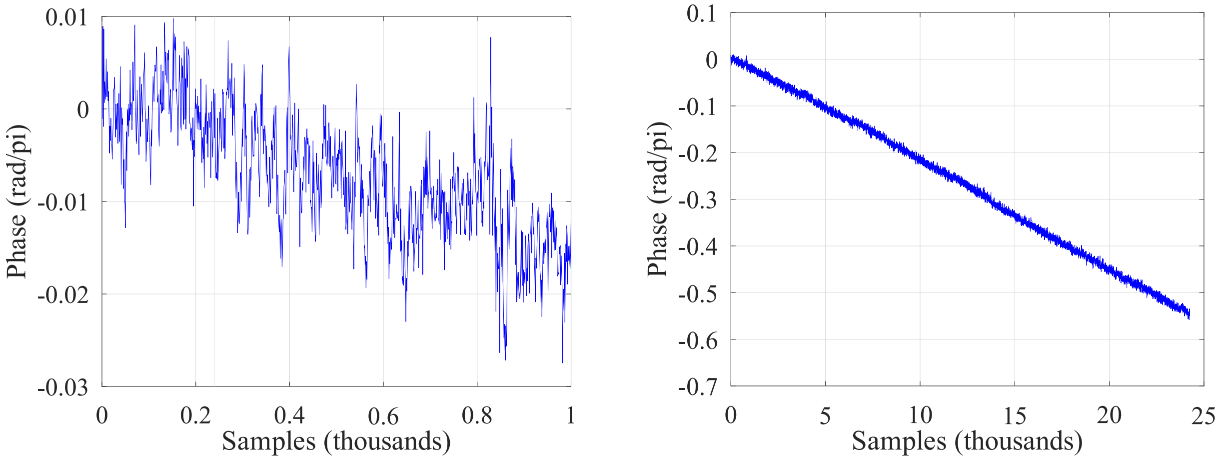



(a) Final result (b) Clock synchronisation and sampling

(c) Carrier synchronisation (d) Initial measurement

Figure 2: The idealised results for various scenarios for 16-QAM with the constellation points and their magnitudes being shown in red and magenta respectively.

- Figure 2(a) shows an example of what is to be expected once the necessary synchronisation has been achieved for a signal with a high signal-to-noise ratio (SNR). Note the initial carrier symbols in the green circle.
- Synchronisation with the carrier deals with compensating for the phase shift which is caused by a non-zero carrier (a frequency offset), and even small variations can have a significant effect. The effect of synchronising with the symbol clock and sampling at the correct times, but failing to compensate for the carrier frequency phase is shown in Figure 2(b). The constellation points in Figure 2(b) are rotating anticlockwise around the centre of the I-Q plane at a rate corresponding to the non-zero carrier frequency because a frequency causes a phasor diagram to rotate.
- Synchronisation with the transmitted symbols and sampling at the correct instants is necessary to remove the transitions between symbol points because these transitions do not contain useful information as the inter-symbol interference (ISI) is only zero at the exact constellation points. The effect of synchronising with the carrier, but neglecting to sample the signal is shown in Figure 2(c). Figure 2(c) shows the entire path between constellation points, and the way the signal overshoots these points during its transitions between them is clearly shown. The constellation points in Figure 2(c) are seen as the points at which transitions begin and end, but the paths between the symbols lead to



(a) All samples (b) Detail of final samples

Figure 3: The effect of estimating the carrier frequency from only the initial samples.

difficulty in determining the transmitted constellation point.

- Finally, Figure 2(d) shows the effect of failing to synchronise with the received signal the carrier and the symbol clock. The full paths between constellation points are included, and the constellation is simultaneously rotating around the centre of the I-Q plane.

### *A. Carrier Synchronisation*

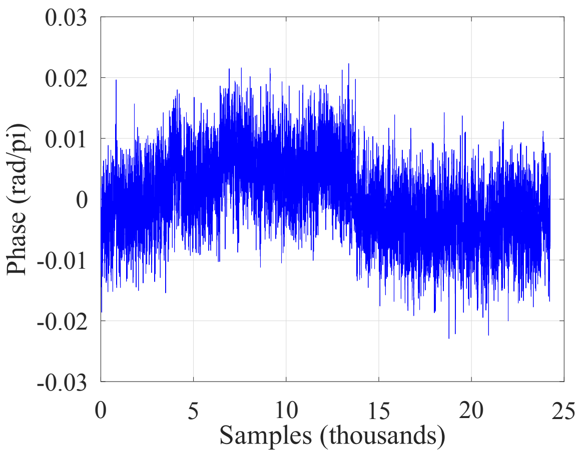
There are a number of possible approaches to achieving synchronisation with the carrier frequency and phase, including phase-locked loops (PLLs), Costas loops, and others. The approach described below should thus not be considered the only, or even the best option. There are a number of seemingly-simple options which have rather significant drawbacks, and the exposition will start by considering some of these.

*1) Issues to Consider:* The first issue is that estimates of the carrier frequency and phase are not accurate over long periods as a result of noise and frequency drift. Figure 3 shows the effect of estimating the carrier frequency and phase using just the first 10 symbols. The initial phase closely matches that of the signal, especially over the first 240 samples (the first 10 symbols) over which the phase correction was computed, as shown in Figure 3(a). However, Figure 3(b) shows that the phase error in the final samples reaches $0.55\pi$, which is easily enough to lead to incorrect decoding of modulation schemes which use phase information. It is thus necessary to calibrate the phase of the receiver over the entire burst.

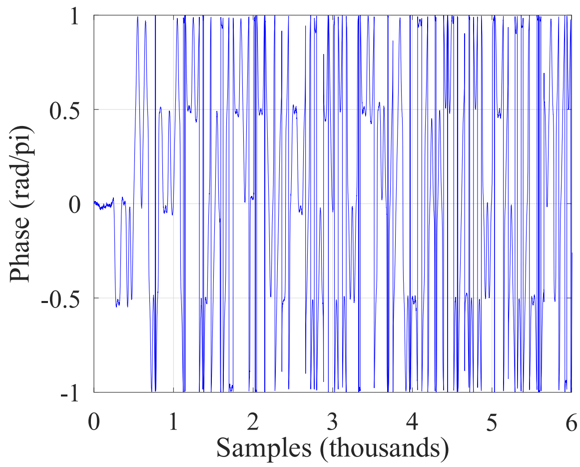
A related problem is shown in Figure 4(a), where the measured carrier phase and a linear fit to the measured carrier phase are compared.[5] Figure 4(a) shows that the linear fit accurately matches the signal carrier, though it is notable that the frequency difference between the transmitter and receiver varies over time.

A far more significant problem is shown in Figure 4(b), where the phase difference to a signal with DQPSK modulation is shown. While the carrier frequency is well compensated, the phase shifts due to the modulation cause the signal phase to change from that of the carrier. More importantly, random data will cause the phase to drift in an unpredictable manner making it impossible to perform a linear fit on the raw phase data. Some form of

[5]Fitting a linear phase to signal phase corresponds to estimating the frequency of the signal.




(a) Unmodulated signal




(b) Modulated signal

Figure 4: The difference between the transmitter and receiver phases for measured signals after accurate frequency synchronisation.

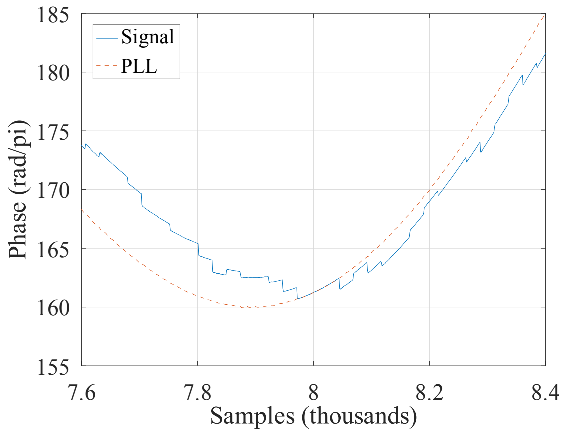
compensation for the phase shift due to modulation is necessary to achieve accurate carrier synchronisation for modulations which vary the signal phase. Additionally, a PLL should be used to continuously track the carrier to ensure that any variations are compensated for.

The effect of applying a PLL is illustrated in Figure 5. Figure 5(a) shows how the phase differences caused by modulation are ignored by the PLL to isolate the carrier signal. The modulation phase steps are also seen when viewing the instantaneous frequency in Figure 5(b), and again, it is clear that the PLL ignores phase changes due to modulation. Figure 5(b) also shows that the PLL does not simply follow the signal frequency, but that the filtering in the PLL smooths the noisy phase of the signal. Finally, Figures 5(c) and 5(d) show the phase of the received signal before and after compensation by the PLL, respectively. Significantly, the phases of the modulation can be directly observed in Figures 5(d).

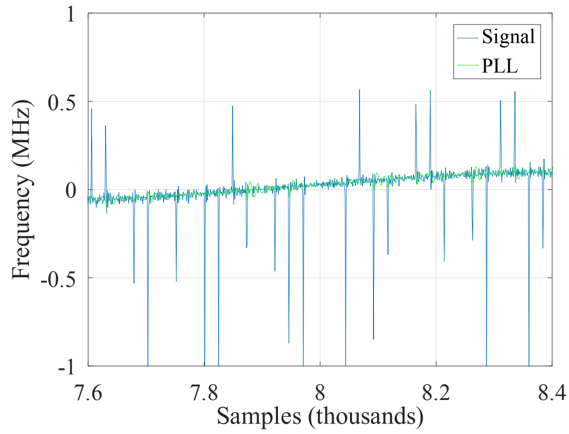
*2) Suggested Implementation:* The amplitude and phase shifts caused by the modulation can be compensated by exploiting knowledge of the constellation for each symbol. The one risk with this approach is that an incorrectly-decoded signal will affect the compensation, which may lead to additional errors.

The first 10 symbols for each of the bursts are simply the unmodulated carrier. This knowledge can be used to initialise a PLL, which then estimates the correction factor that needs to be applied to the eleventh symbol. The eleventh symbol can then be determined by finding the constellation point which is closest to the corrected eleventh received data point. This demodulated symbol can then be used to determine the actual error for the eleventh symbol because the point in the constellation diagram which corresponds to the eleventh data point is now known. As seen in Figure 6, the phase error is computed from the angular difference between the corrected signal point and the constellation point, while the amplitude error is determined from the amplitudes of the corrected signal and constellation points. These errors are fed into the PLL which then computes the correction factor for the twelfth data point. This process is repeated for the remaining symbols.

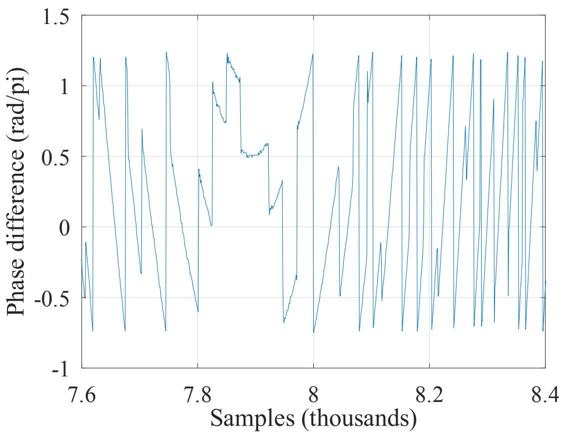
One benefit of this approach is that errors can be detected by plotting the phase for each of the received symbols. The expected phase values should be approximately a straight line (a constant frequency), and a significant deviation from a straight line is probably an indication



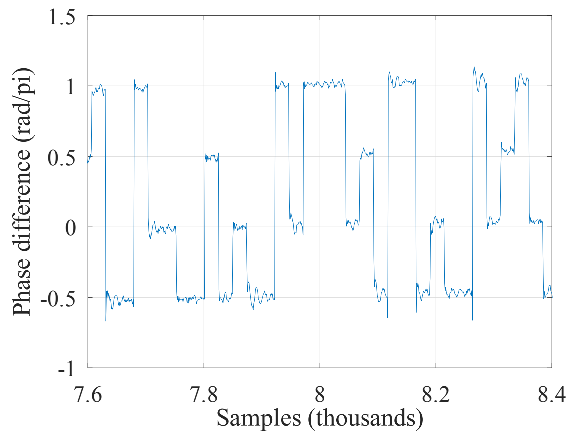

(a) Unwrapped phase




(b) Frequency

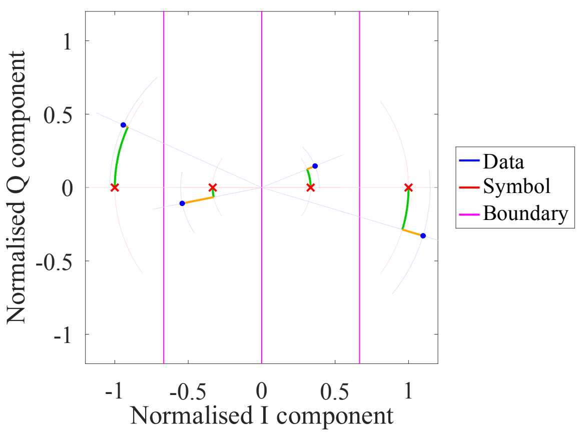



(c) Signal phase

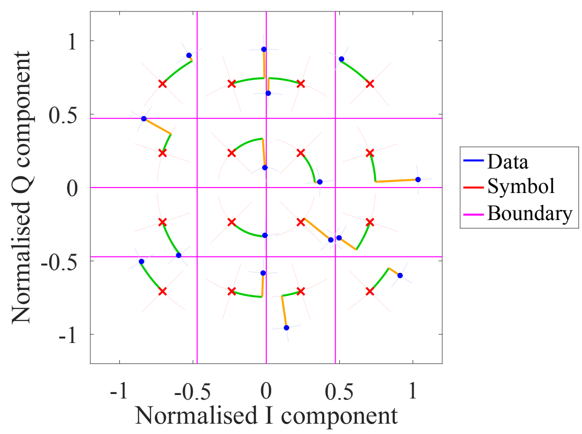



(d) Signal phase with carrier removed

Figure 5: The effect of applying a PLL to a modulated signal.

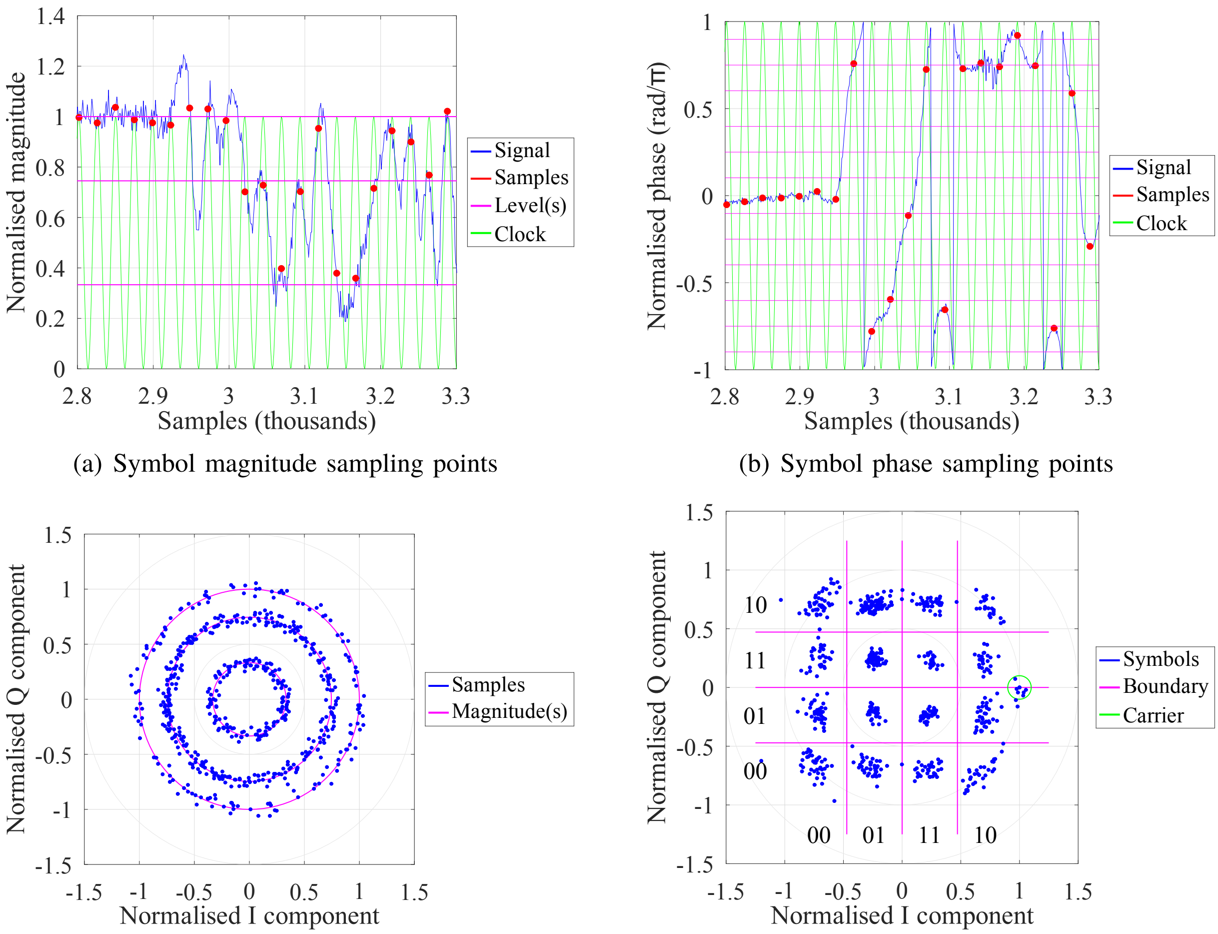



(a) 4-ASK




(b) 16-QAM

Figure 6: Constellation diagrams showing the amplitude (orange) and phase errors (green) between the expected and received symbols.




(a) Symbol magnitude sampling points

(b) Symbol phase sampling points

(c) Sampling output

(d) Constellation diagram

Figure 7: The results obtained for 16-QAM.

of an error. The magnitude can be calibrated using a similar approach, where the magnitude of the expected magnitudes of the received symbols are used to correct the system gain.

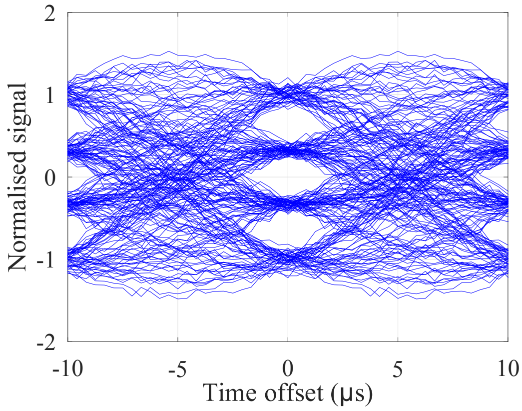
The constellation diagram plotted using the received symbols compensated by the correction factors should be single points corresponding at the positions of the constellation points. A more realistic approach is to plot the received signals compensated by the estimated correction factors because these points were used to determine the symbols.

### *B. Results*

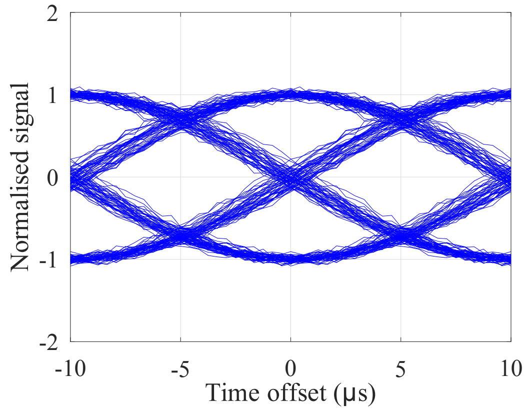
The results obtained when applying the above processes to a measured 16-QAM signal are considered below.

The clock signal, the sampling points deduced from the clock signal, and original signal are shown in Figures 7(a) and (b). The sampling instants are at the peaks of the clock signal, and it is seen that the resulting samples are close to the ideal positions.

While the positioning of the sampling points in Figures 7(a) and (b) is not perfect, Figure 7(c) shows that the sampling is sufficiently accurate to separate the symbols into the three amplitudes produced by 16-QAM, even before symbol phase is considered.



(a) 4-ASK



(b) MSK

Figure 8: Eye diagrams.

Finally, Figure 7(d) provides the constellation diagram that results when full synchronisation with the received signal is achieved. Note that the estimated correction factors were used to show the constellation points used during symbol decoding as described in Section III-A2. The constellation diagram in Figure 7(d) agrees well with the ideal case shown in Figure 1(g), illustrating that the synchronisation used is effective.

### C. *Eye Diagrams*

While not required for the assignment, it is possible to plot eye diagrams for the data. The key issue here is that only the real part of the overall phasor actually exists, with the projections of the I and Q components of the constellation onto the real axis being visible as the phasor rotates at the carrier frequency. Additionally, it is essential to match the carrier as closely as possible to avoid having the constellation points positions change as the phase difference due to the carrier varies.

Two eye diagrams are shown in Figure 8. Figure 8(a) shows the eye diagram for 4-ASK, with the symbol amplitudes and the transitions between symbols being clearly visible. The eye diagram in Figure 8(b) is for MSK, and it should be noted that the double sets of lines are due to timing inaccuracies at the sampling instants.

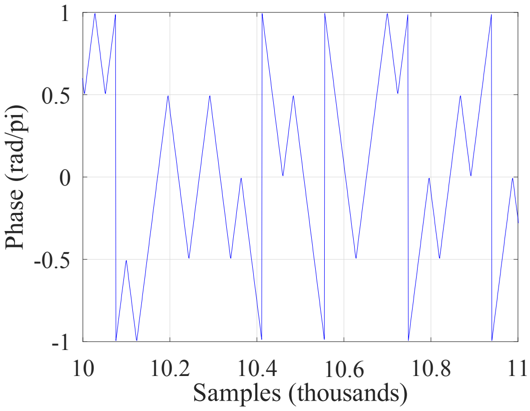
It is initially somewhat surprising that an eye diagram is formed in Figure 8(b) because the amplitude of an MSK signal is not supposed to vary. The explanation can be found by noting that a modulated signal can be written as

$$x(t) = \mathcal{R}e\left\{a(t)\, e^{j\omega(t)t + j\phi(t)}\right\} \tag{1}$$

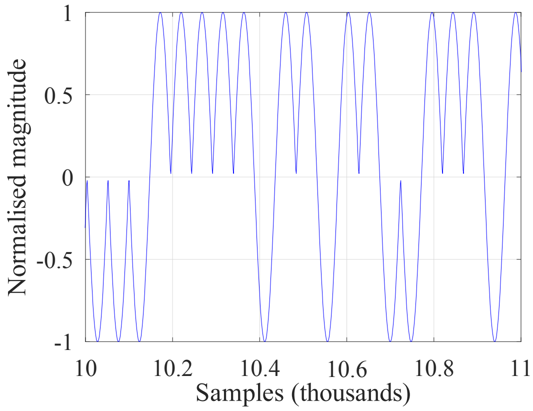
$$= \mathcal{R}e\left\{a(t)\, e^{j\omega(t)t} e^{j\phi(t)}\right\} \tag{2}$$

where $x(t)$ is the signal, $a(t)$, $\omega(t)$, and $\phi(t)$ are the time-varying amplitude, frequency, and phase of the signal respectively. Defining $\omega_c$ as the carrier frequency allows $f(t)$ to be written as

$$\omega(t) = \omega_c + \Delta\omega(t) \tag{3}$$




(a) Phase




(b) Real part

Figure 9: Diagrams showing how an eye diagram is formed from the phase of MSK.

where $\Delta\omega(t)$ is the time-varying frequency due to the frequency modulation. This allows (2) to be rewritten as

$$x(t) = \mathscr{Re}\left\{a(t)\, e^{j[\omega_c + \Delta\omega(t)]t} e^{j\phi(t)}\right\} \tag{4}$$

$$= \mathscr{Re}\left\{a(t)\, e^{j\omega_c t} e^{j\Delta\omega(t)t} e^{j\phi(t)}\right\} \tag{5}$$

which is the equation defining phasors. When the carrier frequency is zero ($\omega_c = 0$), this becomes

$$x_t(t) = \mathscr{Re}\left\{a(t)\, e^{j\Delta\omega(t)t} e^{j\phi(t)}\right\} \tag{6}$$

$$= a(t) \cos\left[\Delta\omega(t)\, t + \phi(t)\right] \tag{7}$$

$$= a(t) \cos\left[\Delta\omega(t)\, t + \phi(t)\right] \tag{8}$$

$$= a(t) \big( \cos\left[\Delta\omega(t)\, t\right] \cos\left[\phi(t)\right] - \sin\left[\Delta\omega(t)\, t\right] \sin\left[\phi(t)\right] \big) \tag{9}$$

which demonstrates that phase variations ($\Delta\omega(t)t$ and $\phi(t)$) are transformed to amplitude variations with sinusoidal scaling. Note that this transformation occurs for all modulations which vary the phase of a signal.[6]

Figure 9 shows how the phase and real part of an MSK signal are related. Noting that the sampling instants are at the peaks extreme values and zeros of the curve in Figure 9(b) ($-1$, 0, and 1) explains how the eye diagram in Figure 8(b) is formed.

## References


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

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

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


[6]Bear in mind that frequency variations also vary the phase of a signal through $\Delta\omega(t)t$.

## Appendix A
## Abbreviations

| | |
|---|---|
| AL | Assistant Lecturer |
| ASCII | American Standard Code for Information Interchange |
| ASK | amplitude-shift keying |
| BPSK | binary phase-shift keying |
| D8PSK | differential 8 phase-shift keying |
| DBPSK | differential binary phase-shift keying |
| DQPSK | differential quadrature phase-shift keying |
| ISI | inter-symbol interference |
| MSK | minimum shift keying |
| OOK | on-off keying |
| PLL | phase-locked loop |
| QAM | quadrature amplitude modulation |
| 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 I.

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 I: Practical 2 Report Mark Allocation

| Topic | Total | Results | Discussion |
|---|---|---|---|
| Methodology | 30 | | |
| OOK | 4 | 2 | 2 |
| 4-ASK | 4 | 2 | 2 |
| BPSK | 6 | 2 | 4 |
| DBPSK | 5 | 2 | 3 |
| DQPSK | 5 | 2 | 3 |
| D8PSK | 5 | 2 | 3 |
| MSK | 7 | 3 | 4 |
| 4-QAM | 7 | 3 | 4 |
| 16-QAM | 7 | 3 | 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_2_{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 2` → `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 [2], this document [3], and the guide for the first practical [1]. 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.[7] 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).

[7]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.