GB4 Final Report

Author: Nick Husic (NH543) College: Homerton Group Members: Haysen, Helen

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Introduction

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Description automatically generatedThis report details the testing and optimisation of the multi-modal communication system we have designed. The aim of this system is to use sound, electrical and molecular communication in series to control a drone using your voice. See appendix item (1) for a graphical overview of the system. The main focus of this project is on the molecular communications, which consists of an electrical sprayer spraying diluted lemon cologne at a gas sensor. This is a continuation of the Interim Report (appendix item 2) that details the conception and initial setup choices made, in particular for the molecular communications part of this project. Figure 1 shows the setup discovered in (2) which produced the best impulse response. This was at 70cm, full mist mode and 75% cologne concentration (in water).

*Figure 1: Original Molecular Communications* Setup

This report will discuss how testing the system using On-Off Keying (OOK) and Pulse Width Modulation (PWM) has forced us to reconsider this setup in order to maximise data transmission rate and error probability.

Testing Molecular Communications

The molecular communications part of the system is the major bottleneck. This is because molecular communication is inherently very slow compared to electromagnetic and sound waves since the molecules take significant time to travel (response time) and disperse (recovery time). The larger the response/recovery time, the more inter-symbol interference (ISI) becomes an issue as you increase data rate. In (2) we found that the main issue was due to the slow diffusion time of the molecules, and adding the fan was key in improving this because it accelerates the particles towards the gas sensor, and also creates turbulent flow around the sensor that disperses them quickly too.

Considering that the end product of this project is controlling a drone to go up or down, the data rate does not need to be high. A reasonably rate at which commands would be issued is 2-4s, limited by the user’s ability to say the words up/down and the time it takes the drone to actually take off and land. The following details how we implemented OOK and PWM to achieve this data rate. For the integrated system, OOK is used because only 2 different messaged as required to be communicated (drone up and down). PWM is only useful if more than two messages are required, so it is investigated to see what the capabilities of the system would be beyond the project specification.

On-Off Keying (OOK) Modulation

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The transmission code was simple to implement, but the decoder code was more complex. The transmitter and decoder computers can not begin running the code simultaneously, but the period is known by both. The decoder must synchronise with the transmitter such that is samples as close to the peaks as possible. Then this sample is compared to a threshold value to determine if it is 1 or 0.

*Figure 2: Sensor Voltage with 10011100 transmitted using OOK. Threshold = 2.2V*

Figure 2 shows a typical OOK transmission. The decoder is run before the transmitter and reads the sensor voltage until the voltage crosses the threshold value (red dot in Figure 1). Since the red dot is on the rise, the code waits a fraction of a second to take the first sample (first green dot in Figure 1) shortly after the peak. It then samples at the same period as the transmitter (green dots). For this to work, the first bit when initiating transmission must be a 1. Ideally the samples would be at the peak, but this is unrealistic using this method because the peak won’t be exactly periodic and if it samples too early, it samples before the very sharp rise, giving a false 0. Therefore, a slight delay is introduced in the sampling, which we found to work with around 0.3s.

There were two attributes of the response that we were looking to perfect through testing:

* **Consistency** in how high the pulse goes when a 1 is transmitted to make transmission without errors feasible.
* **Quick recovery time** to maximise transmission rate.

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Description automatically generatedFigure 3 shows why consistency is important. For a signal to be correctly decoded, the threshold must lie in-between the highest trough (purple dot) and the lowest peak (yellow dot). If the highest trough was higher than the lowest peak, it would be impossible to decode using this method. In this case, it would have to lie between 2.1V and 2.4V. This is not good because a small change in conditions such as the air flow in the room could make these points cross. Compare this to Figure 2 where the interval is about 0.7V, and the peaks and trough are all at roughly the same value. The interval must also remain within roughly the same values to avoid having to recalibrate the system by finding a new threshold. Reducing the period (increasing the transmission rate) always makes this interval smaller.

*Figure 3: Typical response of original setup*

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Description automatically generatedFirstly, after doing some random initial tests, we realised that the original setup (Figure 1) did was not good enough to achieve a period below 4s. We tested it at progressively lower periods, and it failed at a 9s period with the response shown in Figure 4. In this case, the threshold points crosses, as explained above, making decoding impossible. We had to test different combinations of distance, concentration, and spray time to reduce period.

The first major change that worked was lowering the height of the gas sensor and the fan (Figure 5). We believe that this improved the response because it accounts for the fact that gravity causes the molecules to fall as they travel (it is a misty spray of small liquid drops, not a perfect gas), and so more of them reach the sensor. The fan was also lowered because it has no desirable effects unless it is pointing directly at the sensor. The distance was also reduced from 80cm to 70cm.

*Figure 4: Original Setup, 9s period, 111111100 transmitted*

*Figure 5: Modified Setup for Improved Consistency*

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Description automatically generatedNext, we tested the effect of lowering the concentration from 75% to 45% and 30%. The effect of this was more evident when doing PWM tests, so see the next section for more details. Overall, we sound that 30% was too low and reduced consistency, but 45% worked very well. In addition, previously the sensor would max out voltage with a 0.4s spray duration at 75%, but with 45% the spray duration had to be increased to 0.8s to max out the sensor. It is desirable to max out the sensor because it means that the peaks occur at roughly the same value, improving consistency. However, spraying for too long saturates the sensor, causing a step response rather than impulse.

In the end, we found that the optimal setup was 45% concentration, 60cm away and 0.8s spray duration. Using this setup, the system managed to reliably communicate with a 4s period and no errors in our tests (Figure 6). Using a 3s period would produce 1-2 errors when transmitting 16 bits, so we decided to stick with a 4s period. Therefore, the maximum reliable transmission rate is 15bits/min

*Figure 6: 10101110 with 4s period using optimal setup*

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Description automatically generatedPulse Width Modulation (PWM)

With PWM, different messages are sent by spraying for different durations of time. This results in differing amplitudes of pulses at the gas sensor. For example, spray 0.01s for 0 and spray 0.4s for 1. Figure 7 shows what the sensor response should look like for PWM to work. Unlike OOK, PWM can be used to send more than two unique messages per transmission. In this section, the investigation concerns the transmission of only two messages, 1 or 0, because this allows for a better comparison between OOK and PWM.

*Figure 7: 10101010 using PWM*

Conveniently, the code used to sample and decode the bits for OOK also works for PWM when only sending two messages. See the OOK section for details on how it works. This is because when using PWM with only two messages, you are essentially just using a higher signal value for a 0.

However, PWM has 3 attributes that must be perfected for optimal transmission:

* **Consistency** in how high the pulse goes when a 1 or 0 is transmitted.
* **Quick recovery time** to maximise transmission rate.
* **Large difference in amplitude for different messages** to reduce probability of error

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The first two are explain in the OOK section, but the third is unique to PWM. A large difference in amplitude of small and large pulses is required so that the interval to place the threshold in is consistent. Figure 7 shows an example where this condition is not satisfied. This interval is between the lowest peak for a 1 (purple dot) and highest peak for a 0 (red dot). This gives an interval of only about 0.15V in which the decoding would work, which is very hard to predict. Figure 8 on the other hand has an interval of about 0.6V which is must easier to work with. Again, this is all very similar to OOK. Also, when reducing the period between transmissions, the main issue is when you do a 1 0 transmission. This is because the signal may not have enough time to decay and, even if the 0 pulse is small, it will go above the threshold due to ISI.

*Figure 8: 101010 using PWM*

The aim of our tests was to consistently make the large pulse max out the voltage every time, and for the small pulse to be as small as possible, enabling minimal ISI and maximum transmission rates. This involved varying the distance, concentration, and spray durations.

After all our tests, we converged on an optimal setup of 70cm distance, 30% concentration and sprays of duration 0.01s and 0.8s. The main thing we discovered was that concentration is very important when doing PWM. This is because if the concentration is too high, it was impossible to get the small pulse to be consistently small. For example, in Figure 9, at 45% concentration you can see how the first 0 is much larger than the third 0. On the other hand, in Figure 10 you can see how even lowering the concentration slightly to 30% reduced the size of the small pulses, while retaining the height of the big pulses.

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*Figure 10: 10101010 using 30% conc.*

*Figure 9: 10101010 using 45% conc.*

In addition, reducing the concentration reduced the average amplitude of the big pulses too. In order to ensure that the big pulse gets close to maxing out the sensor each time, we increased the big spray during from 0.4s to 0.8s. This also improves consistency.

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Description automatically generatedNext, we reduced the period to see how high we could get the transmission rate. When minimising the period, it become clear why a small amplitude for the short pulse is very important, since the time allowed for recovery is not long. Using the setup above, the shortest period we could achieve without getting any errors was 4s, surprisingly the same as OOK. Figure 11 shows a typical response for a 4s period. The interval for the threshold starts to become too small, and this is why reducing the period to 3s yielded many errors, typically 3-4 errors per 16 bits transmitted.

*Figure 11: 10101110, 4s period*

Drone Control and Speech Recognition

The aim of this project was to create a multimodal communication system that allows the users to speak the words ‘up’ or ‘down’ in order to control a drone using acoustic, electrical, and molecular signals.

The drone used was very simple. The command that we were able to electrically communicate to the drone was essentially just a toggle to either take off and hover, or land. Allowing the drone to free-fly was forbidden, so it was anchored to a metal plate using a string. The string was not long enough to let the drone stabilise when trying to hover, so all tests conducted were with the drone stationary (held down in place) and we would observe if the propellers were spinning or not.

The receiver computer communicated with the drone via a digital Arduino pin connected to a relay module, which is then connected to the drone controller. To toggle the state of the drone, a 1 must be applied for a short time. Through testing, we found that the 1 must not be applied for more than 0.5s, and at least 6s must pass between toggles for each toggle signal to be recognised.

The acoustic signal part of this system uses a pretrained neural network model based on auditory spectrograms to process the audio signal detected by a microphone, and display is as the word ‘up’, ‘down’ or ‘unknown’. The words detected are then encoded as 1s and 0s and communicated to the electrical sprayer via an Arduino. The main issue was surrounding noise when testing this part of the system. The group was working in a large room, usually filled with at least 10 other people speaking, which would get picked up by the microphone and sometimes picked up as an ‘up’ or ‘down’. This means all tests had to be conducted in a silent room. See Helen’s report for more information on this part of the system.

Communication Scheme for the Drone Control

The drone functions using toggle commands. This means that there are only two messages to be communicated: toggle or do not toggle. Hence, OOK is more suitable for PWM because it is more reliable when only two messages need to be transmitted due to the amplitude difference between 1 and 0 signals being bigger. Therefore, we used the optimal setup determined in the OOK section: 60cm distance, 45% concentration, 0.4s sprays and full mist mode.

The transmission code was written such that it always knows what state the drone is in. When the user speaks, the neural network tells the transmission code, and it determines whether the user is trying to change the drone state (toggle) or not. If toggle, it sprays, otherwise it does not spray. Essentially, a spray is used to communicate a change in state, rather than a particular state. If the user repeats the previous command, it does not spray. This is the optimal way to communicate in order to minimise sprayer fluid used.

On the other end, the decoding algorithm had to be redesigned from the one used when investigating OOK and PWM. In those previous sections, the goal was to maximise transmission rate when periodically sending bits, so the decoder and transmitters had to be synchronised. Now, synchronisation was not required because the sprayer sprays whenever the user wanted to change state.

The new decoder was much simpler than the other one. It consists of an infinite while loop that samples the voltage from the sensor continually until it goes above a threshold value. This means a pulse has been sent, so it sends a toggle signal to the drone, and wait 6s before resuming the voltage monitoring. This wait of 6s is required because the drone will not toggle again if the second toggle is sent before 6s have elapsed.

The optimal setup for OOK was able to communicate using a 4s period without any errors. Here the worst case scenario is a period of 6s, so it is virtually impossible for an error to occur in the molecular part of the system. Overall, the system worked very well when integrated, with the user being able to command the drone with a response time of 1-2s from the words being uttered to the propellers spinning (or stopping spinning).

Conclusion

In conclusion, this investigation into the viability of molecular communication has been very insightful. Molecular communication is fundamentally very different to using EM waves. It is much slower but can be more reliable and secure. Using an electrical sprayer and gas sensor, we were able to achieve a transmission rate of 15 bits/min with negligible bit error rate using OOK and PWM. This rate is fundamentally limited by the long time that it takes for the molecules to disperse, resulting in ISI if the rate is too high. Using an artificially created air-flow such as a fan can be used to improve this, but it will always be tricky to control due to random nature of air flow. In a room with carefully controlled air flow and more sensitive sensors, this transmission rate could certainly be pushed much higher than achieved here.

Using the optimised setup for OOK, we managed to create a very reliable drone control system that uses acoustic, electrical, and molecular signals. The user could command the drone to go up or down using their voice with a response time of 1-2s. In this application, the transmission rate requirements were not high, so the molecular part of the system managed to keep up well enough. Further investigations could involve using a more controlled environment, or multiple sensors to achieve more accurate detection.

References

* References are referred to with square brackets [].

*[1] Farsad, N., Kim, N. R., Eckford, A. W., & Chae, C. B. (2014). Channel and noise models for nonlinear molecular communication systems. IEEE Journal on Selected Areas in Communications, 32(12), 2392-2401.*

Appendix

* Appendix items are referred to with circular brackets ().

Item 1

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Item 2 – Interim Report

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