Electromagnetic Interference (EMI) from Consumer Devices and Its Impact on Implantable Pacemakers with AI for Signal Classification

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Abstract

Electromagnetic waves from everyday devices—including smartphones, WiFi routers, microwaves, and electric vehicles—pose potential risks to individuals with medical devices such as pacemakers. Electromagnetic Interference (EMI) can induce mimicking signals, mode switching, signal disruption, and temporary or permanent malfunctions, potentially compromising patient safety and delaying clinical intervention**.** This study investigates the interactions between EMI emitted by common electronic devices and pacemaker operation using a Ventricular Paced, Ventricular Sensed, Inhibited (VVI) pacemaker prototype on a breadboard. Data collected from controlled exposure experiments was analyzed with AI-based signal classification algorithms to identify interference patterns. Results indicate that devices emitting high-frequency electromagnetic waves in close proximity to pacemakers cause the most significant interference. Moreover, AI analysis enhances detection accuracy, enabling proactive mitigation strategies and the potential for real-time device alerts. These findings underscore the importance of integrating advanced signal monitoring and AI-assisted analysis into pacemaker safety protocols to improve patient protection in environments with pervasive electromagnetic exposure.

Introduction

Three million. That is the approximate number of people in the United States who rely on pacemakers to maintain normal heart rhythms. In today's technology-driven world, electronic devices—from smartphones and WiFi routers to electric vehicles—have become ubiquitous, offering convenience and connectivity like never before. Yet, alongside these benefits comes a less visible risk: electromagnetic interference (EMI). Research has linked EMI to biological effects such as headaches, dizziness, and nausea. In some cases, EMI can also cause more serious health concerns. For individuals with implantable medical devices, even minor EMI exposure can disrupt device function, causing unintended mode switching, false sensing, or temporary malfunctions. As technology becomes increasingly pervasive in modern society, the likelihood of such interference rises, highlighting a critical area of concern for both patients and healthcare providers. This study examines the effects of EMI on a VVI pacemaker simulation, leveraging artificial intelligence for signal classification to detect and analyze interference patterns. The ultimate aim is to improve patient safety and device reliability in an increasingly connected world.

History

The modern pacemaker is a small device implanted in the chest that delivers electrical pulses to regulate slow or irregular heart rhythms. Pacemakers are often confused with implantable cardioverter-defibrillators (ICDs), which are also chest implants but function primarily to monitor dangerously high heart rates and deliver corrective shocks through defibrillation. Today, approximately three million Americans live with pacemakers, and about 200,000 new devices are implanted each year.

The history of pacemakers dates back to 1958, when Swedish cardiac surgeon Åke Senning successfully implanted the first fully internalized device. Although that early pacemaker failed within hours, it established the foundation for modern cardiac pacing technology. Since then, designs have evolved dramatically, with devices now lasting 10–12 years, depending on the patient's reliance. Pacemakers also come in several types, including VVI, VVO (Ventricular pacing), and DDD/DDDR (Dual-chamber, Dual-chamber sensing, and Dual-chamber response), each designed to meet specific cardiac needs. This study focuses on the VVI pacemaker, the most basic configuration, as it provides a useful platform for testing electromagnetic interference.

EMI is defined as the disruption of pacemaker function by external electromagnetic signals. EMI can cause false sensing, unintended mode switching, or pacing inhibition. While modern devices are equipped with shielding and filtering mechanisms that make such interference rare, the growing presence of high-frequency electromagnetic fields from consumer electronics raises renewed concerns.

One illustrative case involved an 85-year-old woman with a dual-chamber pacemaker who reported persistent fatigue. Her device, programmed for DDDR pacing, was repeatedly found to have reset into VVI mode, significantly reducing its responsiveness. After ruling out other causes, clinicians discovered that the patient had recently begun using an electric warming blanket during sleep. Once she discontinued the blanket, the pacemaker returned to normal function, and her symptoms resolved.

Although rare, cases like these underscore how the rapid integration of new technologies into daily life can create unforeseen interactions with medical devices. Continued research into EMI effects is therefore critical to ensure pacemaker safety in a technology-saturated environment.

Methods and Circuit Design: Overall Approach

Designing a simple VVI pacemaker simulation on a breadboard required multiple iterations and refinements throughout the project. The final system consisted of four main components: (1) an astable 555 timer circuit; (2) a potentiometer-controlled resistor to adjust the simulated heart rate; (3) an Arduino Uno serving as the pacemaker's processing unit to monitor rhythm irregularities; (4) a monostable 555 timer circuit to generate pacing pulses when triggered by the Arduino.

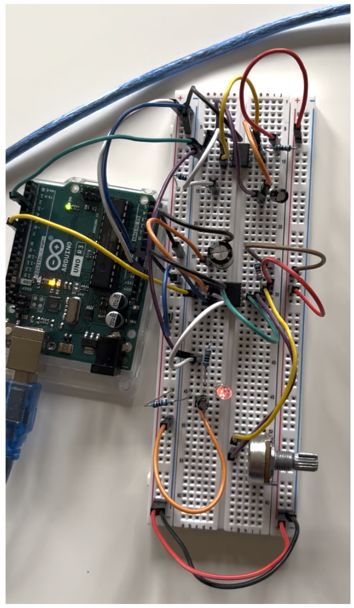


Figure 1: VVI Circuit

To assess EMI susceptibility, the circuit was tested under both shielded and unshielded conditions. Shielding was introduced by placing a layer of aluminum foil over the circuit or between the EMI-emitting object and the pacemaker circuit. In addition, an open probe connected to the Arduino Uno functioned as an EMI detector, enabling measurement of interactions between external electromagnetic fields and the pacemaker simulation.

The table below shows the parts of a real VVI pacemaker mapped to the simulated portions of the VVI pacemaker, along with a brief description of the component's overall function in the pacemaker.

Table 1: Real to Simulated VVI Mapping

Real VVI Pacemaker	**Simulated Arduino Pacemaker**
Pulse Generator (sends electrical signals to the heart)	555 monostable timer (fixed-length pulse, like one used to pace the heart's ventricle, generated electronically)
Heart sensing circuitry/decision-making logic (detects natural heartbeats)	Arduino Uno + code (monitors ventricular activity, decides when to send pulse) → plays the role of the pacemaker's control unit (microcontroller)
Leads, wires & electrodes (sends/receives heart signals from tissue)	Wires connecting Arduino/555s/LEDs (wires/breadboard connections mimic how signals travel out of the pacemaker to the heart; probe attached to Arduino Uno to simulate a lead)
Output to heart	LED

(delivers pacing signals to the heart muscle)	(visualizes pacing output, “stimulating ventricle”)
Heart electrical activity (Ventricular depolarization → causes the ventricles of the lower heart to contract via electrical impulses)	555 astable timer (rhythmic electrical pulses → Electrocardiogram (ECG) signal, simulating beating heart)
Rate sensor/patient input	Potentiometer to vary heartbeats (simulates a person at rest vs exercise, → tests pacemaker logic)
telemetry/diagnostic/data output	Arduino Uno (outputs pulse signals & timing data for EMI analysis)

Heartbeat Simulation

The first step in developing the pacemaker system was to establish a simulated heartbeat. For this purpose, a 555 timer was configured in astable mode, a non-stop oscillator that creates a continuous, adjustable square wave to simulate the natural heartbeat. By experimenting with different resistor-capacitor (RC) configurations, a stable output was achieved at approximately 60 beats per minute (bpm), corresponding to a typical resting human heart rate.

The circuit consisted of two resistors in series paired with a capacitor, forming the RC timing network that governed the output pulse frequency. The resulting periodic square wave served as the intrinsic electrical activity of the heart.

Figure 2 below illustrates the astable circuit on the breadboard, currently being powered by a 9-volt battery. The resistor values initially used were 10 k ohms as R1 and 100 k ohms as R2. The capacitor value was 10 microfarads. The LED in Figure 2 that is lit serves as the visual signal of the heart rate and will later also be used as the visual output for the pacemaker’s pulses. The components in Figure 2 consist of two resistors, a capacitor, and one red LED, all powered by a 9V battery.

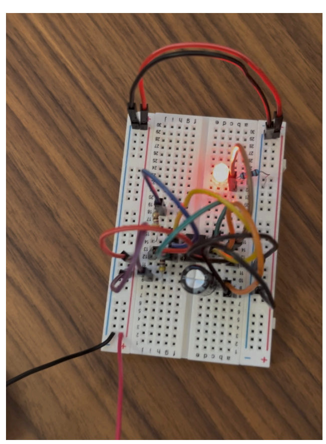


Figure 2: Astable 555 timer

Rate Variation

After configuring the heartbeat simulation, R2 was switched out on the astable 555 timer for a 100k ohm potentiometer to tune the oscillation frequency and allow a change in the bpm of the heartbeat. The potentiometer functions by limiting the amount of current able to pass through at a given moment. The potentiometer tuned for higher resistance will result in a slower heart rate, while a lower resistance will result in a faster heart rate. The 100k ohm potentiometer's maximum resistance value is 100k ohms. This feature was implemented to allow testing of the pacemaker's ability to respond to bradycardia (slow heart rate), and tachycardia (fast heart rate).

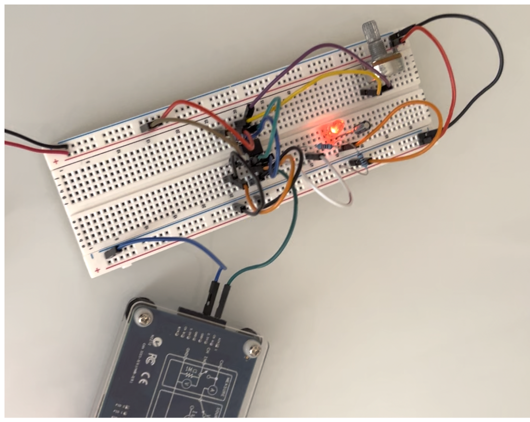


Figure 3: Astable 555 timer with potentiometer

Monitoring and Pacing

Once the heartbeat and a method to test the functionality of the pacemaker logic were established, the pacemaker logic needed to be implemented. The output of the 555 astable timer was connected to an Arduino Uno input pin. The Arduino was programmed to monitor the time between successive pulses, compare this to a preset threshold of 80 bpm, detect missed beats or prolonged pauses, and trigger an external pulse through the monostable 555 timer if any anomalies are detected. The functionalities listed above are congruent with the VVI pacemaker logic, which monitors the ventricles and delivers pacing when the heart rate drops below the pacemaker's programmed rate.

The monostable 555 timer was set up such that the Arduino Uno's output pin was fed into the monostable 555 timer's input pin, and the output pin of the monostable 555 timer connected to the LED. Figure 4 below depicts the astable 555 timer (circled in yellow) next to the monostable 555 timer. The monostable setup ensured each triggered pulse had a fixed, stable width, independent of trigger duration. The combination of the monostable configuration and the LED visual output effectively simulated the pacing function of a clinical pacemaker. The loose wires will be attached to an Arduino Uno.

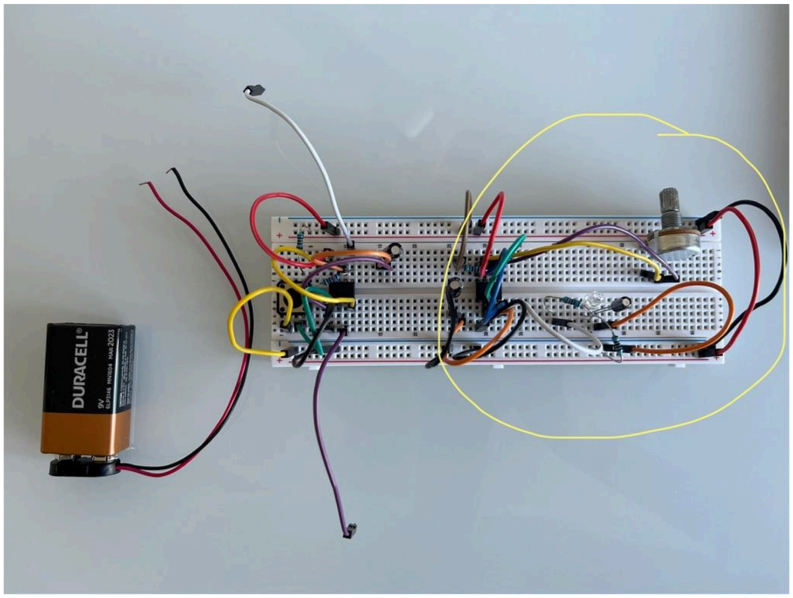


Figure 4: Astable (right) and monostable (left) 555 timers

Coding VVI Logic

The Arduino Uno was coded using the Arduino Cloud IDE. The pinIn and pinOut functions were defined on the Arduino Uno and were connected to the astable and monostable 555 timers, respectively. A constant was utilized to keep track of the interval threshold of 80 bpm in milliseconds — about 750 milliseconds — and declared as a global variable that keeps track of the last beat time in milliseconds.

In the setup method, the pinMode and digitalWrite were utilized to configure the Arduino Uno's idle state, start the Serial Monitor, and delay it to allow the circuit to establish a rhythmic heartbeat before counting the time between beats. An anomaly that occurred was having the digital write respond to the opposite call, meaning if the output of the 555 monostable timer is to be off until a specific call, the digital write would need to be HIGH for the output pin, not LOW. This syntax continued in the loop method, where the program would first check whether a beat is detected, and inhibit pacing thereof. Next, the code checks whether too much time has passed without a beat by subtracting the total amount of milliseconds the code has been running from the recorded milliseconds of the last beat time, and comparing the result to the interval threshold. If too much time has passed, the digital write function is used to set the pinOut LOW, then HIGH, and ends by resetting the last beat time to the number of milliseconds the circuit is currently at. Finally, the code concludes by setting up the serial plotter display and finishes with a delay of 200 milliseconds for the pacemaker to debounce any of its own pacing. You can find the code here: https://github.com/giabhatia/VVI_Pacemaker

Shielding & EMI Detection Setup

To replicate shielding on real pacemakers, aluminum foil was wrapped around portions of the circuit while testing EMI. Tests both with and without shielding were conducted, and the results of both were compared to roughly determine the efficiency of EMI shielding against EMI.

Figure 5 below shows a makeshift probe (circled in yellow), placed on the Arduino Uno to detect external EMI around the circuit and receive visual input on the serial plotter. This feature served to detect variations in waveform amplitude and frequency when exposed to different sources. The probe simulates a lead on a pacemaker, which is also susceptible to EMI, displayed in the image on the right.

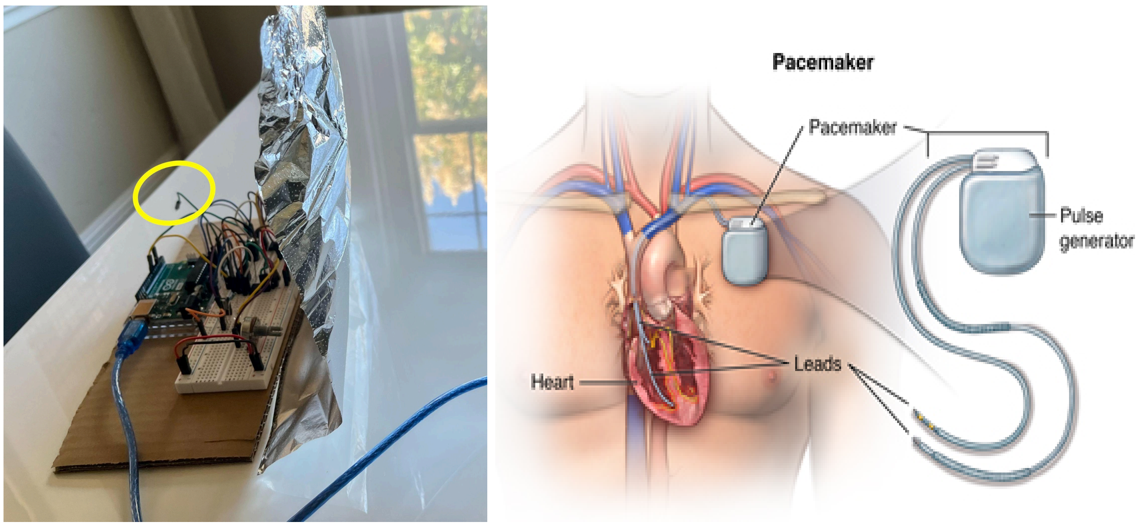


Image of completed circuit with the probe circled in yellow next to an image of a pacemaker with leads taken from Johns Hopkins Medicine.

Figure 5: Circuit with probe (left) and pacemaker with leads (right)

The VVI pacemaker simulation circuit was brought near EM emitting objects, where data points were recorded from the following:

- Apple MacBook Air
- Apple iPhone Mini 13
- GE Microwave
- High EMI desk setup: sit-stand desk, table lap, and study timer
- Airpods 1st Generation
- WiFi Router
- Tesla Car Model Y

Data Collection & Trials

Waveforms from the pacemaker circuit were observed and logged via the Arduino Uno IDE serial plotter. In each trial, the circuit was exposed to an EMI source up to a maximum distance of 4 meters away from the circuit. Simultaneously, screen recordings were taken of the serial plotter for analysis, as well as utilizing the serial monitor, which outputted numeric data to be later fed into artificial intelligence (AI) models for data analysis. Interference, such as missed beats, extra pacing pulses, or signal distortion, was analyzed in the following trials. The Arduino Uno does not measure in units on the y-axis, but utilizes milliseconds on the x-axis.

The laptop was connected to the Arduino Uno, providing both power and ground connections via USB. Upon connecting the probe to the Arduino Uno, the laptop's EMI was immediately detected and picked up significant interference. The graphs below show the difference in interference picked up on the serial plotter when the probe was attached versus when it was not attached to the Arduino Uno. The single spikes are the pulses the VVI pacemaker is sending to the LED, while the approximately steady pulse is the astable 555 timer's pulse to the LED, turning it on.

Laptop EMI before the probe: **Laptop EMI after the probe:**

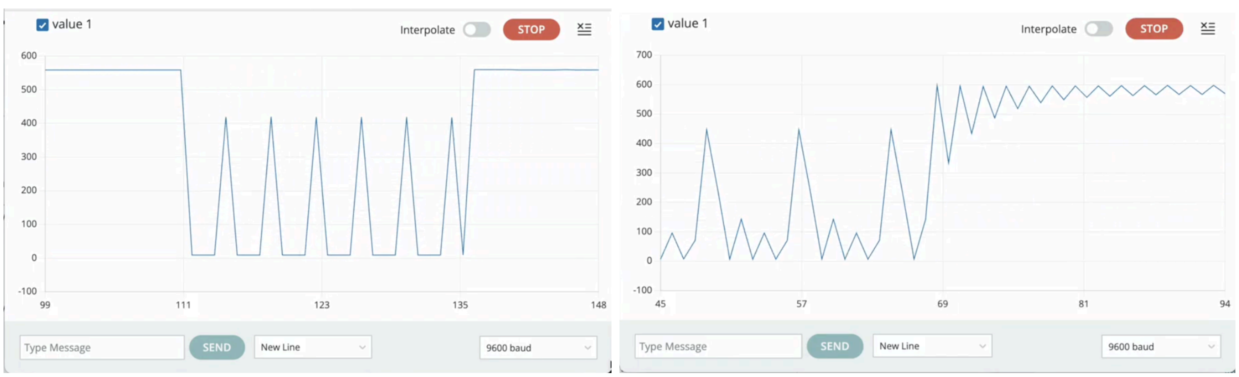


Figure 6

The spikes are caused by the Arduino Uno being electrically grounded to the laptop, as the USB cable provides both power and ground to the Arduino. The interference shown is expected as the laptop's ground can be noisy due to power supply switching, USB bus chatter, and processor activity. Therefore, even when the shielding was applied, the same level of interference appeared on the serial plotter, as the EMI is not just being radiated by the laptop, it is also injected through the USB cable. As a result, when the data was analyzed, it was based on the interference of the laptop being present at all times.

<u>iPhone Calling EMI (Information about the Shielding vs Non-Shielding Oscillation Data)</u>

The iPhone EMI was recorded by placing an iPhone about two inches from the probe with its speakers facing the probe. A call was placed on the iPhone set on speaker mode to see if the vibrations could cause interference.

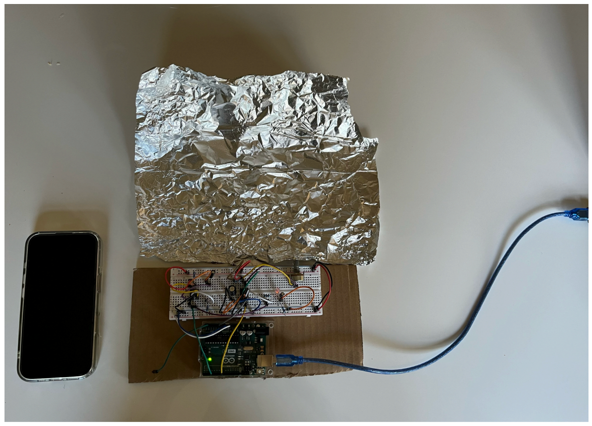


Figure 7: iPhone EMI Testing

The serial plotter depicted both EMI signs when tested with shielding and not shielding. A key finding includes there being a spike during both shielding and non-shielding trials between the monostable and astable timer transition. Comparing the trials both with and without shielding, there appears to be roughly the same number of spikes. This shows that the shielding did not fully block EMI from the surroundings. Upon close inspection of the serial plotter, there appears to be a little less interference concerning the astable 555 timer portion, as there is less interference seen in the stable line. The spike would appear in other EMI tests as well — some occurred during all the transitions from the monostable 555 to the astable 555 timer, while others did not occur as frequently. This spike could have also come from hardware issues. However, since the spike was not consistent and did not occur for each test, it is reasonable to consider this a sign of EMI.

iPhone EMI no shielding with the spike: **iPhone EMI no shielding without the spike:**

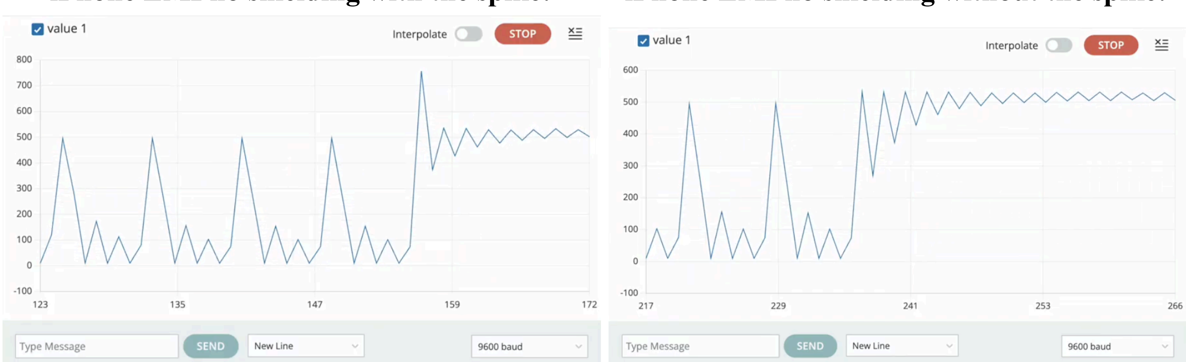


Figure 8

iPhone EMI shielding with the spike: **iPhone EMI shielding without the spike:**

Figure 9

The AirPods trial resulted in very little interference, as shown by the serial plotter, other than the occasional spike. Minimum interference by the AirPods is expected, as they emit high-frequency EM waves, and the probe may not be that sensitive to higher-frequency EMI. However, upon comparing the serial plotter's data concerning shielding and no shielding, the spike appeared much more when the circuit was shielded than when it was not. This led to some concern as the shielding is meant to reduce EMI on the circuit. For this reason, the verification of the hardware components in the circuit was necessary. Noting that the hardware was in order, human error could have occurred, such as the aluminum foil resting on the probe during the shielding tests, thus causing the sensitive circuit to spike upon contact.

Upon close inspection of the microwave used for testing, there appeared to be a Faraday cage encapsulating the internal box of the microwave. Faraday cages are often used to replicate the encapsulation of pacemakers as well. Therefore, when conducting the microwave trials, no EMI effects were expected to be seen, which was the case for the no-shielding trial, but a spike was seen for the shielding trial. Yet again, this brought up the question of whether this was a hardware issue or another human error. Seeing no issues with the hardware, this could have occurred due to improper shielding placements. Possible scenarios could be due to not covering the entire circuit with aluminum foil, or EMI from nearby EM-emitting objects, such as the fridge and oven. That being said, not all microwaves have a built-in Faraday cage to contain EM waves, as some older or worn-out microwaves could experience some leakage with their Faraday cage, thus potentially posing a threat to EMI.

WiFI EMI (Information about the Shielding vs Non-Shielding Oscillation Data)

The WiFi router's serial plotter output was as expected. When the circuit was not shielded, there was distinct interference compared to when shielding was utilized– mainly seen in the astable part of the visual output. This is accounted for, as the WiFi router radiates substantial EMI to surrounding objects, in this case, seemingly affecting the amount of noise the Arduino Uno receives from the astable 555 timer.

WiFi EMI no shielding astable 555 configuration: **WiFI EMI shielding astable 555 configuration:**

Figure 10

Tesla Car Seat EMI (Information about the Shielding vs Non-Shielding Oscillation Data)

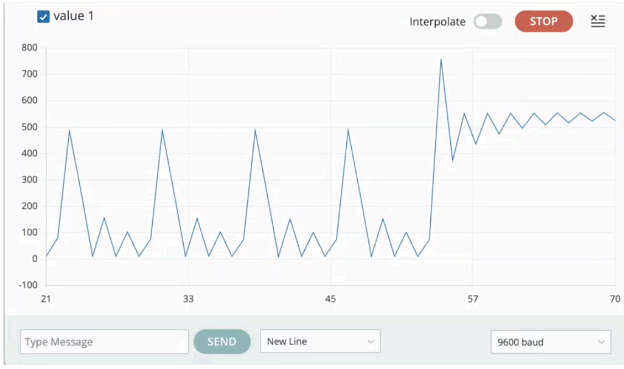
Both front and back-seat EMI were tested in the Tesla Car, during which the spike was observed again. The Tesla car was parked in the garage when the tests were conducted, not charging, the AC was on at 69 degrees, and had the internal car lights on to illuminate the circuit. Furthermore, the circuit was placed in the middle console when tested in the front, and the middle seat when tested in the back. Based on the Model Y the circuit was tested on, the battery of the car is in a "skateboard" platform, meaning the battery was distributed roughly equally throughout the car. There are known to be batteries in the frunk of the car, and overall more electrical components towards the front of the car, such as the control panel touch-screen.

Tesla Car backseat no shielding: **Tesla Car backseat shielding:**

Figure 11

The "no shielding" image shows how the spike is present, and the output pulses are higher than expected, which is greater than 500. The same follows for "with shielding,". The spike was constantly seen during the transition of the Arduino output, the monostable 555 timer, to the Arduino input, the astable 555 timer. During the trials with shielding, the spike was seen less consistently, though still present.

Tesla Car front seat no shielding:



Tesla Car front seat shielding:

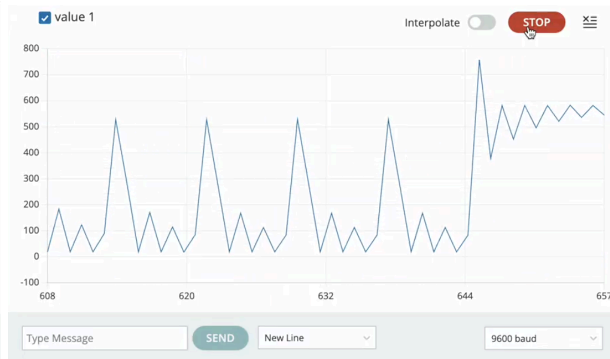


Figure 12

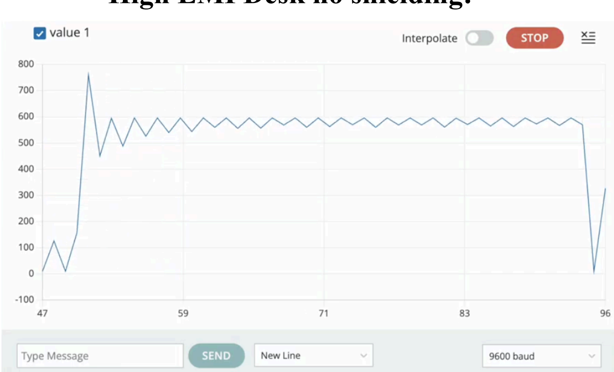
The images above show that the shielding trials resulted in a higher output pulse (greater than 500) compared to the non-shielding trials, and the spike that occurs both with and without shielding. The input astable configuration appears relatively undisturbed compared to the output Arduino pulses and the monostable pulses, as the period when the astable timer was measured was quite stable.

Surprisingly, the shielding trials for both front and back seats showed a much higher record of EMI. This can be explained, as the shielding could have acted as a resonant cavity due to improper grounding. It may be hypothesized that, rather than blocking EMI, the shielding causes the waves to be trapped and reflected within it, thereby increasing the total electromagnetic field strength.

These trials highlight that shielding is a necessary component for pacemakers to block electromagnetic interference, but the Tesla trials demonstrate how the shielding must be done currently, as an incorrect implementation could result in increased EMI.

The High EMI desk setup consisted of the circuit placed in the center of the sit-stand desk, occasionally moving up and down, a table lamp to its side in the lowest mode, and a stopwatch, all operating simultaneously. The spike was prominent in both shielding and non-shielding, continuously showing up between the transition from the Arduino's output to the astable 555 timer's output.

High EMI Desk no shielding:



High EMI Desk shielding:

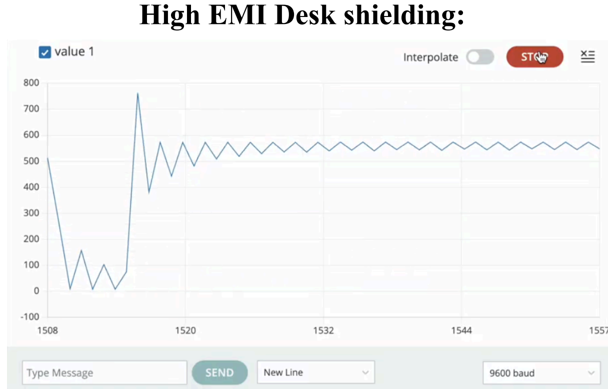


Figure 13

Once these trials were conducted, the data from the serial monitor were input into AI models for data processing.

Artificial Intelligence Implementation

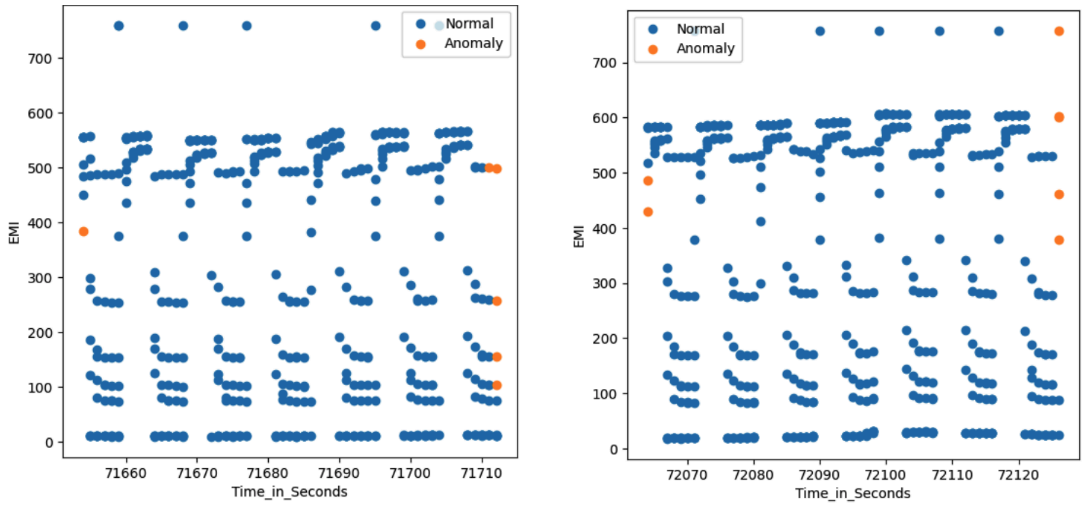
The AI models used for data analysis include Isolation Forest, Random Forest, and Autoencoder Anomaly Detection Neural Networks. Due to the high volume of data from the serial monitor and time constraints, only the Tesla Front Seat, WiFi, and iPhone inputs were sorted into data sets. All the EMI data sets from the serial plotter are available in the GitHub repository.

Creating the data sets included extracting the EMI and time in milliseconds and converting them to seconds, from the serial monitor. The 5-number summary –consisting of the minimum, quartile one, median, quartile two, and maximum– was taken for the EMI data points, and the frequency of the occurrences of EMI data points within these categories was noted. Furthermore, the low and high outdoor temperatures, as well as the garage temperatures, were recorded. These values were held constant in their respective category (low or high). The same was true for the outdoor dewpoint and the garage dewpoint. Dewpoint and temperature were considered to see if these values impacted the pacemaker's functionality. Finally, the blood pH of a healthy human (values ranging between 7.35 to 7.45) and the elevation above sea level were recorded from low to high and high to low, respectively, in two columns. These last two values were considered as the blood pH could mimic internal human body conditions within the heart and provide a chemical element, while the elevation above sea level could affect breathing and blood pressure. In essence, these conditions were used to determine how this pacemaker would function in the human body.

Since the blood pH and elevation above sea level had data points that varied over time, these were analyzed in graphs against EMI. An estimate of 100 trees, 0.01 expected proportion of anomalies, was used across all models, consisting of 500+ rows of data. The variance between the number of anomalies pointed out shows why multiple models run the same data– to avoid any bias.

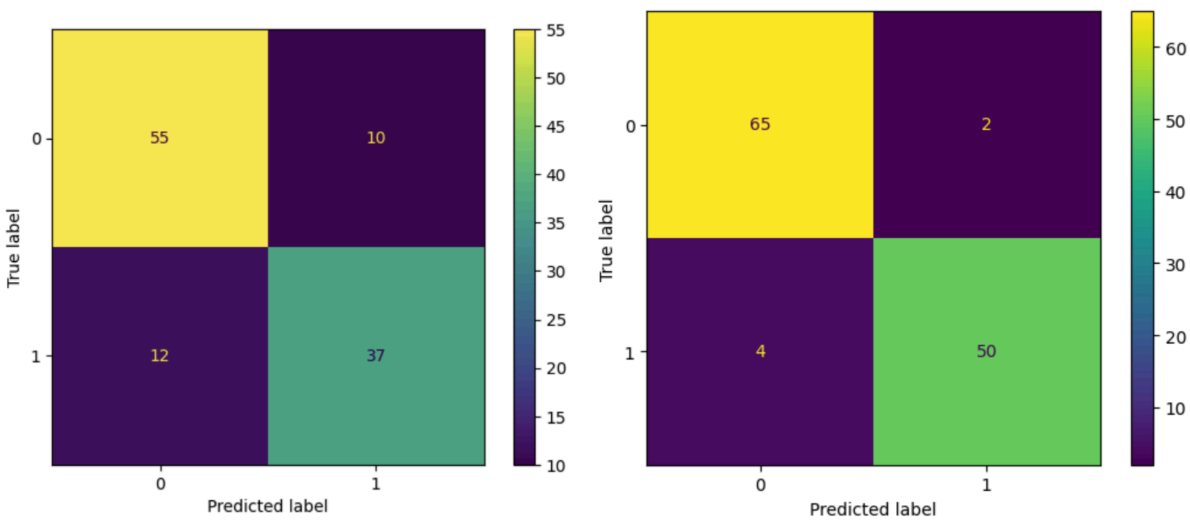
Table 2: Tesla Car Front EMI

AI Models	**No Shielding Anomalies**	**Shielding Anomalies**
Isolation Forest	6	7
Random Forest	22	6
Autoencoders	19	28



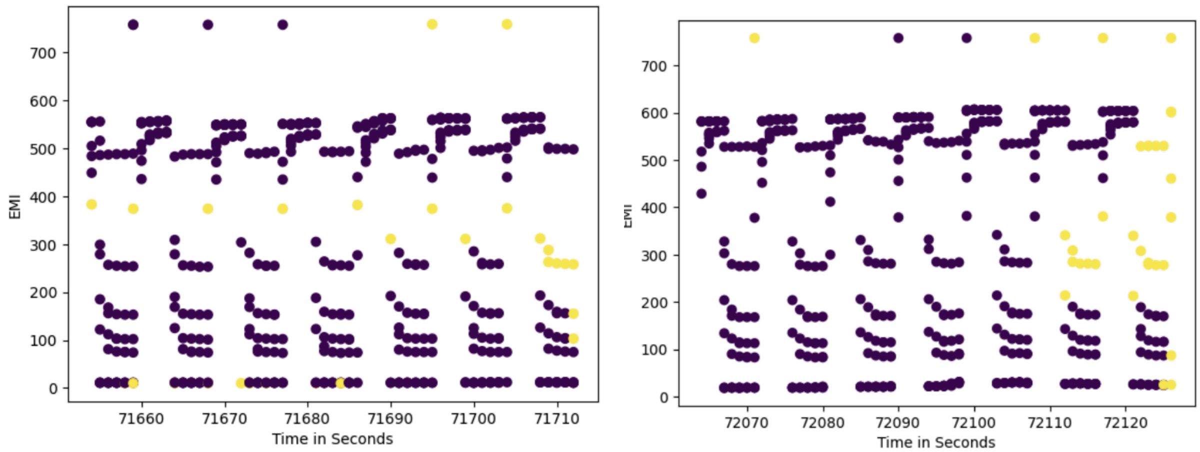
The results of EMI over time in seconds for the non-shielded data set (left) and the shielded data set (right).

Figure 14: Isolation forest



False positives are in the top right, false negatives are in the bottom left. True positives are in the top left, false positives are in the bottom right.

Figure 15: Random forest



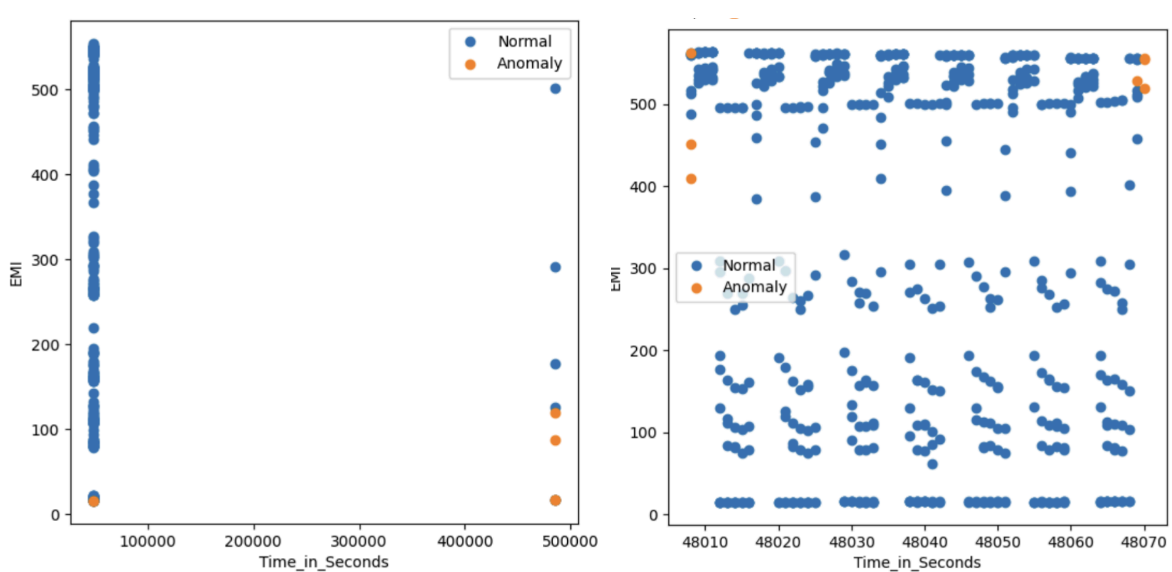
The results of EMI over time in seconds for the non-shielded data set (left) and the shielded data set (right).

Figure 16: Autoencoders Anomaly Detection Network

The models suggest that shielding introduces conditions that lead to irregularities in both blood pH and elevation readings. This is noted as more outliers are pointed out in general for the shielded tests, and blood pH, as well as elevation levels, tend to be skewed toward one side. This could imply faulty shielding setups.

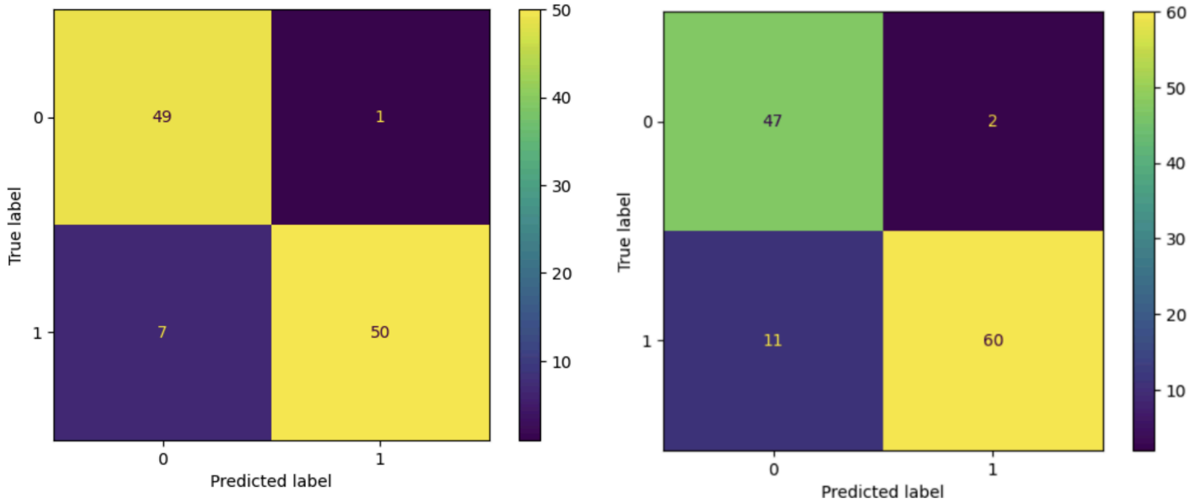
Table 3: WiFi Router EMI

AI Model	**No Shielding Anomalies**	**Shielding Anomalies**
Isolation Forest	6	7
Random Forest	8	13
Autoencoders	0	0



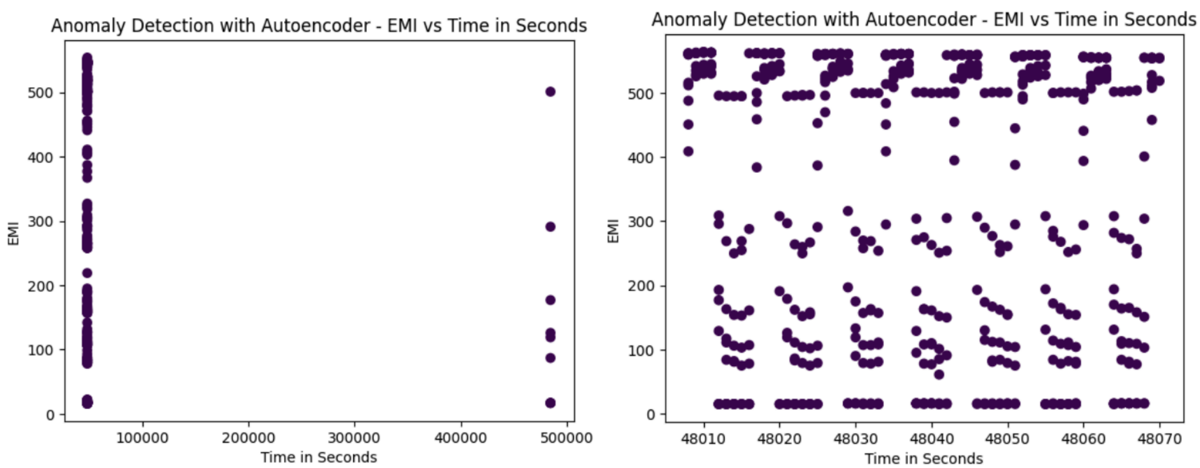
The results of EMI over time in seconds for the non-shielded data set (left) and the shielded data set (right).

Figure 17: Isolation forest



False positives are in the top right, false negatives are in the bottom left. True positives are in the top left, false positives are in the bottom right.

Figure 18: Random forest



The results of EMI over time in seconds for the non-shielded data set (left) and the shielded data set (right).

Figure 19: Autoencoders Anomaly Detection Network

The graphs above show a very high skew to the left in the non-shielded data, and a relatively consistent spread in the shielded data. For blood pH and elevation above sea level, the models are skewed to the upper and lower ends, with outliers above an EMI of 300. For the WiFi data set, we see that shielding was a benefit as it improves consistency and reduces skew, but high EMI levels, anything greater than 300, still cause detectable disturbances. This is a good example of how shielding mitigates, but does not completely eliminate EMI. This data set has an unusual graph for both the autoencoder and isolation forest models for the non-shielded data sets. This could be explained by the threshold value being calculated to over- or under-fit the data.

Table 4: iPhone Calling EMI

AI Model	**No Shielding Anomalies**	**Shielding Anomalies**
Isolation Forest	6	5
Random Forest	7	7
Autoencoders	18	13

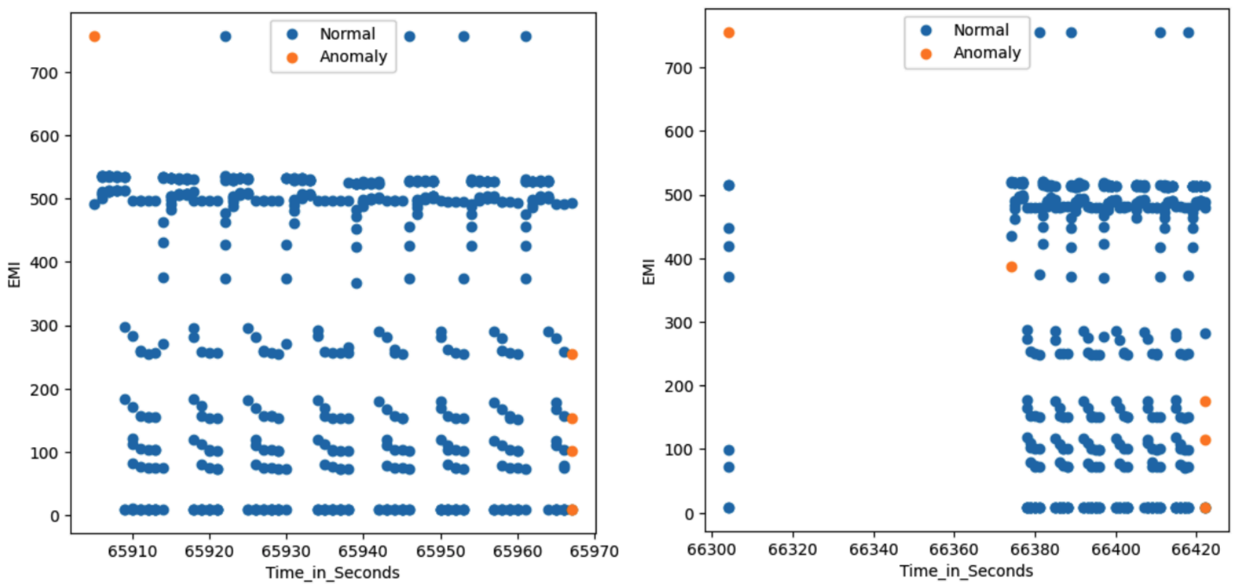
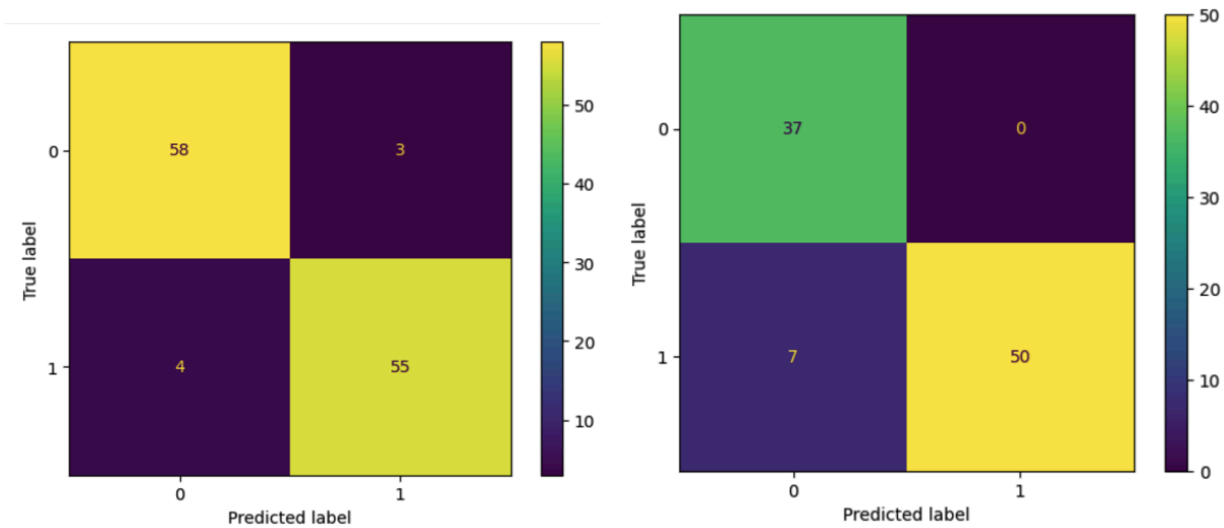
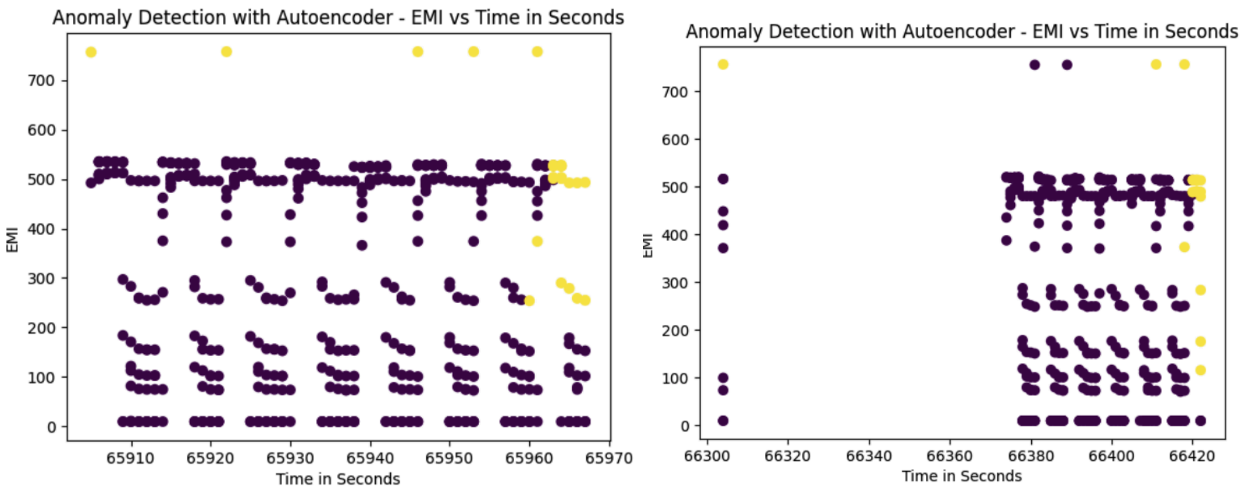


Figure 20: Isolation forest



False positives are in the top right, false negatives are in the bottom left. True positives are in the top left, false positives are in the bottom right.

Figure 21: Random forest



The results of EMI over time in seconds for the non-shielded data set (left) and the shielded data set (right).

Figure 22: Autoencoders Anomaly Detection Network

The findings for this data set indicate more outliers identified as time goes on, as well as a skew for the shielded data set towards the upper end of the graph. This could be due to the threshold factor once again. The trend in blood pH and elevation followed the ongoing trend of outliers skewed to the extremes. In essence, this indicates that as time goes on, more EMI is picked up, possibly due to cumulative EMI effects or threshold limitations. Furthermore, the upper skew of the shielded data implies that while shielding alters the data distribution, it does not eliminate the effects entirely– it could also shift or delay its effects.

Conclusion

Electromagnetic (EM) waves are ubiquitous, and they affect our daily lives without our knowledge. As technology further intertwines with modern society, the implications of EMI on critical medical devices such as pacemakers are all the more susceptible. This research examined the effects of EMI generated by common consumer devices on a simulated VVI pacemaker, including the integration of AI-assisted signal classification to improve detection and analysis. The results of the experiments further indicate that pacemakers may be distressed as a result of EMI from most devices, though not portraying the full scope of the interference, as the shielding of the pacemaker was not underneath human tissue, and not a complete emulation of pacemaker shielding. However, this study underscores the importance of robust shielding and fail-safe design in implantable medical technologies as technology is further integrated into present-day society.

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