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Effect of Modulation Format on Signal Strength and Range in CC1101 Wireless Systems

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Abstract- This paper examines the impact of modulation formats on signal strength and communication range in CC1101-based wireless systems. Experiments were conducted with Arduino Nano nodes operating at 433 MHz under line-of-sight (LOS) conditions in a dense built environment. Four modulation schemes OOK/ASK, 4-FSK, MSK, and GFSK were tested with identical parameters, and RSSI values were recorded across increasing distances. Results indicate that while OOK/ASK and 4-FSK achieves more consistent long-range connectivity up to 170 meters, while MSK demonstrates stable signal integrity at moderate distances, whereas GFSK provides strong short-range performance and shows robustness in interference-prone settings but with limited coverage. The study concludes that modulation scheme selection should be application-specific, balancing trade-offs between range, energy efficiency, and reliability.

Keywords: CC1101, modulation schemes, RSSI, wireless systems

Abstrak- Penelitian ini membahas pengaruh format modulasi terhadap kekuatan sinyal dan jangkauan komunikasi pada sistem nirkabel berbasis CC1101. Eksperimen dilakukan menggunakan node sensor Arduino Nano yang beroperasi pada frekuensi 433 MHz dalam kondisi line-of-sight (LOS) di lingkungan padat bangunan. Empat skema modulas OOK/ASK, 4-FSK, MSK, dan GFSK diuji dengan parameter yang sama, dan nilai RSSI dicatat pada berbagai jarak. Hasil menunjukkan bahwa OOK/ASK dan 4-FSK mencapai konektivitas jarak jauh yang lebih konsisten hingga 170 meter, sementara MSK menunjukkan integritas sinyal yang stabil pada jarak menengah, sedangkan GFSK memberikan kinerja jarak dekat yang kuat serta ketahanan pada lingkungan yang rentan terhadap interferensi namun dengan cakupan yang lebih terbatas. Studi ini menyimpulkan bahwa pemilihan skema modulasi harus disesuaikan dengan kebutuhan aplikasi, mempertimbangkan kompromi antara jangkauan, efisiensi energi, dan keandalan.

Kata Kunci: CC1101, modulasi, RSSI, nirkabel

1. Introduction

Wireless communication has become an essential component in numerous modern applications, particularly in fields such as the Internet of Things (IoT), remote sensing, and embedded systems. As the demand for more connected devices increases, optimizing efficiency and performance especially in low-power applications has become imperative [1]. In such systems, maintaining a balance between energy consumption, transmission reliability, and communication range is critical.

Key factors that influence the overall performance of Wireless Sensor Networks (WSN) include modulation schemes, RSSI (Received Signal Strength Indicator), and transmission distance [2]. These networks often rely on battery-powered nodes, so optimizing power use without compromising data integrity or range is an essential design challenge [3]. The RSSI metric is widely used to evaluate link quality, offering immediate feedback on received signal power key in estimating connection robustness and effective communication distance [4].

The CC1101 transceiver by Texas Instruments is favored in many IoT and WSN implementations due to its versatility, low power use, and support for sub-GHz bands (315, 433, 868, 915 MHz) [5]. It supports multiple modulation schemes FSK, ASK, and OOK each with distinct trade-offs in terms of data rate, power efficiency, and noise resilience. Comparative studies have demonstrated that FSK provides superior noise immunity and longer reliable range, while ASK/OOK offer simplicity and energy savings but are more susceptible to environmental interference [6].

Further, research shows that lower data-rate modulations (e.g. FSK) maintain stronger RSSI and extended reach under signal attenuation, compared to higher-rate schemes such as ASK/OOK [7]. Signal propagation is also affected by frequency band, environmental conditions, and antenna design. Lower sub-GHz frequencies provide better penetration and coverage in NLOS or urban scenarios, whereas higher bands (e.g., 2.4 GHz) support greater throughput but attenuate faster.

This paper examines how different modulation formats specifically OOK/ASK, 4-FSK, MSK, and GFSK impact RSSI and effective communication range when using the CC1101 transceiver, focusing on the trade-offs between signal strength, battery life, and communication reliability in real-world IoT and Wireless Sensor Network (WSN) scenarios. Understanding these dynamics is essential for designing wireless systems that must operate efficiently over varying distances while maintaining low power consumption and stable connectivity.

2. Method

A. CC1101 Radio Frequency Transceiver Module

The CC1101 is a highly versatile RF transceiver operating in the 433 MHz free ISM band, eliminating the need for licensing. Designed for robust and reliable wireless communication, it integrates built-in hardware CRC error detection and address control, ensuring data integrity and secure transmission. This makes it an excellent choice for industrial and embedded applications requiring reliable wireless connectivity [8].

With a maximum data rate of 500 kbps and a minimum of 1.2 kbps, the CC1101 supports multiple modulation schemes, including 2-FSK, GFSK, FSK, and MSK. It also features Clear Channel Assessment (CCA) and a Carrier Sense System, allowing automatic cleanup of transmission channels before sending data. These capabilities enhance its reliability, particularly in noisy industrial environments where frequency stability is critical [9].

The transceiver supports fast frequency hopping, enabled by an advanced synthesizer system, which allows seamless transitions between frequencies. It offers up to 256 programmable channels within a 20 MHz band, providing flexibility for multi-channel operations. Additionally, the 64-byte RX and TX data FIFO buffers help manage data efficiently, reducing the need for frequent microcontroller intervention and improving overall system performance.

Addressing flexibility is another key feature of the CC1101. The device's address can be set via software, ensuring that only data intended for the local address is received and processed. This selective reception, combined with built-in interrupt instructions, allows for easy interfacing with various microcontrollers, simplifying integration into diverse applications.

Performance-wise, the CC1101 boasts high sensitivity, achieving -110 dBm at 1.2 kbps with a 1% packet error rate, making it well-suited for long-range communications. Additionally, its low power consumption ensures energy efficiency, with an average current draw of 20 mA in RX mode and 30 mA in TX mode at 10 dBm output power. This makes it ideal for battery-operated and low-power IoT applications.

Overall, the CC1101 is a powerful and efficient RF transceiver, offering high sensitivity, flexible modulation options, fast frequency hopping, and low power consumption, making it a preferred choice for industrial, automation, and wireless telemetry applications.

B. Received Signal Strength Indicator (RSSI) in CC1101

The Received Signal Strength Indicator (RSSI) refers to the power level of a signal as detected at the receiving antenna. Under ideal transmission conditions, RSSI can be estimated based on the transmit power and the distance separating the communicating nodes. RSSI-based localization methods in wireless sensor networks have established a relationship between signal strength and distance, which is typically modeled using the equation (1) below.

$$RSSI = RSSI_0 - 10.n.\log\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

Where:

- $RSSI_0$ is the signal strength measured at a known reference distance d_0,
- n is the path loss exponent, which characterizes signal attenuation in a given environment,
- X_σ is a Gaussian random variable (in dB) accounting for shadowing effects, with a mean of 0 and a standard deviation σ typically ranging from 4 to 10. A higher σ indicates greater uncertainty in the model due to environmental variability, reflecting more rapid signal fading.

This equation effectively captures the decline in signal strength over distance, adjusted for real-world interference and multipath effects [10].

C. System Architecture

In this study, two nodes are required: a transmitting node and a receiving node. Figure 1 shows the block diagram of the communication system using the CC1101. The transmitting node consists of an Arduino Nano microcontroller connected to a CC1101 transceiver module. Similarly, the receiving node is composed of an Arduino Nano, a CC1101 transceiver module, and an OLED display for visual output. The wiring diagrams for the transmitter and receiver can be seen in Figures 2 and 3.

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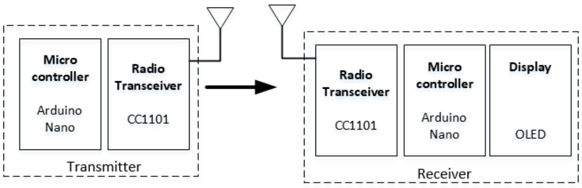

Figure 1. Block Diagram

Both the transmitter and receiver employed quarter-wavelength monopole antennas tuned for 433 MHz, each with a physical length of approximately 17 cm, corresponding to one-quarter of the free-space wavelength at the operating frequency. The antennas were equipped with standard SMA connectors, ensuring low-loss interfacing and stable mechanical attachment to the CC1101 module. The use of a quarter-wavelength configuration provides an optimal compromise between compact form factor, radiation efficiency, and impedance matching to 50 Ω, thereby supporting stable and reliable wireless communication during the experimental measurements.

During the data collection process, the transmitter and receiver are positioned facing each other and aligned in a straight line. The transmitting node is responsible for sending data packets to the receiving node. Upon receiving the packets, the receiver reads the received signal strength (RSSI) at specific distance points.

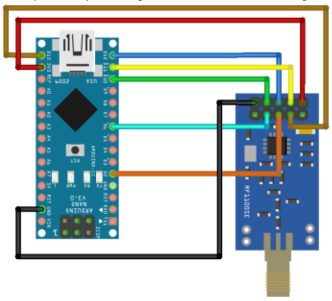

Figure 2. Transmitter

To determine the maximum communication range, the receiving node is gradually moved away from the transmitter. Data is collected at 10-meter intervals, and the process continues until the receiver is no longer able to detect or receive data from the transmitter.

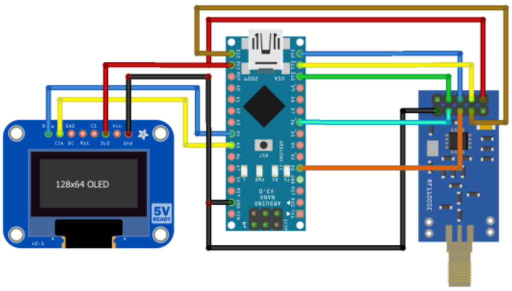

Figure 3. Receiver

D. Data Collection

The data collection procedure in this study was conducted systematically to evaluate the impact of modulation formats on signal strength (RSSI) and communication range using the CC1101 transceiver module. The experimental setup involved two nodes: a transmitting node and a receiving node.

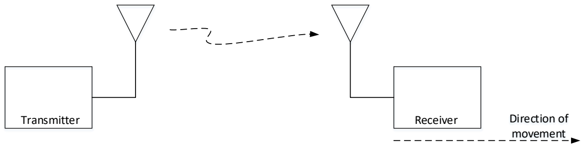

Figure 4. Link Configuration

The transmitting node consisted of an Arduino Nano microcontroller connected to a CC1101 transceiver module and programmed to send data packets periodically. The receiving node was built with the same components but was also equipped with an OLED display to visualize RSSI values in real time.

Before data collection, both nodes were calibrated at a short distance to ensure reliable connectivity, proper synchronization of communication parameters, and accurate RSSI readings. Communication settings such as frequency, data rate, transmission power, and modulation type were configured identically on both nodes. Once the system was validated, the experiment was conducted under line-of-sight (LOS) conditions in a dense environment surrounded by buildings. In such scenarios, the path loss exponent (propagation attenuation factor) can be relatively high due to reflections, diffractions, and scattering effects from the surrounding structures. The distribution of test points used in the experiment is illustrated in Figure 5, where each location is marked with a red dot.

Figure 5. Test Points

Data collection began at a distance of 10 meters, where the transmitter continuously sent data while the receiver recorded the RSSI values of successfully received packets. After each measurement, the receiver was moved an additional 10 meters farther from the transmitter, as illustrated in Figure 4, which shows the measurement link configuration. This process was repeated until the receiver could no longer receive any data, indicating the maximum communication range. To ensure data reliability, each measurement was repeated three times at

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each distance point, and the average RSSI value was used for analysis. The entire procedure was repeated separately for each modulation format being tested, namely OOK/ASK, 4-FSK, MSK, and GFSK.

In this study, four different modulation schemes were implemented and tested using the CC1101 RF transceiver module to examine their effect on RSSI and communication range. The modulation schemes included On-Off Keying (OOK/ASK), 4-Level Frequency Shift Keying (4-FSK), Minimum Shift Keying (MSK), and Gaussian Frequency Shift Keying (GFSK). Each modulation type offers distinct characteristics in terms of power efficiency, signal robustness, and range performance, making them suitable for different wireless application scenarios.

To configure these modulation schemes in the Arduino IDE, we used the ELECHOUSE_CC1101 library, which allows for easy initialization and setting of the modulation parameters. The modulation is controlled through the setModulation() function, which takes an integer value corresponding to the desired modulation type:

a) OOK / ASK (On-Off Keying / Amplitude Shift Keying):
This is a simple and power-efficient modulation scheme. It is set by calling `ELECHOUSE_cc1101.setModulation(2);`. This modulation works well for ultra-low-power systems but is more prone to noise.

b) 4-FSK (4-Level Frequency Shift Keying):
This scheme allows encoding two bits per symbol, improving data throughput. It is set with `ELECHOUSE_cc1101.setModulation(3);` though note that not all libraries support 4-FSK natively, so direct register configuration may be required in some cases.

c) MSK (Minimum Shift Keying):
Known for its continuous-phase nature, MSK provides good spectral efficiency and noise resilience. It is selected using `ELECHOUSE_cc1101.setModulation(4);`. MSK is ideal for long-range applications with better signal integrity.

d) GFSK (Gaussian Frequency Shift Keying):
GFSK is a form of FSK that uses Gaussian filtering to reduce out-of-band emissions, improving performance in crowded frequency environments. It is configured via `ELECHOUSE_cc1101.setModulation(1);`. This modulation is widely used in Bluetooth and similar applications.

For each modulation type, other parameters such as frequency, transmission power, and data rate were kept consistent to allow for fair comparison. In the CC1101 configuration, the frequency was set using:

```
ELECHOUSE_cc1101.setMHZ(433.00);
```

This command sets the operating frequency of the CC1101 transceiver to 433.00 MHz, which is part of the ISM (Industrial, Scientific, and Medical) frequency band. This band is commonly used for low-power wireless communication such as telemetry, sensor networks, and remote control applications.

While the transmission power was configured with:

```
ELECHOUSE_cc1101.setPA(12);
```

This command configures the Power Amplifier (PA) output level. A value of 12 corresponds to approximately +12 dBm (about 15.8 mW) transmission power, according to the Elechouse CC1101 driver documentation. This parameter determines how strong the transmitted signal is, directly impacting communication range and energy consumption.

Similarly, the data rate was specified by:

```
ELECHOUSE_cc1101.setDRate(99.97);
```

This sets the data rate (bit rate) of the communication link to 99.97 kbps. The data rate defines how fast information is transmitted over the channel. Higher data rates allow faster transmission but can reduce range and increase susceptibility to interference, whereas lower data rates improve range and robustness at the expense of speed.

As discussed earlier, the CC1101 transceiver was configured to operate at a center frequency of 433 MHz with an output power level of 12 dBm and a target data rate of approximately 100 kbps. To achieve reliable communication under this specification, the modulation deviation and channel filter bandwidth were carefully selected based on the recommended register settings in the CC1101 datasheet and SmartRF Studio. A modulation deviation of 47.60 kHz was configured by setting the DEVIATION_M = 0x51 register value, which ensures sufficient frequency separation between symbols for high-rate FSK communication. Additionally, the receiver channel filter bandwidth was configured to 203.125 kHz, corresponding to the MDMCFG4 = 0x2D register setting. This bandwidth provides an optimal trade-off between sensitivity, selectivity, and noise performance when operating near 100 kbps. These numerical parameter values were directly applied to the CC1101 modem configuration registers to ensure consistent performance during the entire telemetry communication experiment.

Through this modular setup, the same code structure was reused while altering only the modulation type to evaluate signal strength and communication distance for each configuration under controlled test conditions. All collected data were compiled into tables and plotted as graphs for comparative analysis. This analysis aimed to provide deeper insights into the trade-offs between signal strength, power efficiency, and communication range associated with each modulation format used in low-power wireless systems based on the CC1101 transceiver.

3. Result and Discussions

A. RSSI and Distance Measurement

Table 1 presents the measured average RSSI values for four modulation schemes OOK/ASK, 4-FSK, MSK, and GFSK across increasing distances ranging from 10 to 170 meters. The data clearly illustrate the gradual signal attenuation experienced by all modulation formats as distance increases, with each scheme exhibiting distinct performance characteristics.

Meanwhile, Figure 6 displays a line graph illustrating the relationship between Received Signal Strength Indicator (RSSI) in dBm and Distance in meters for various modulation methods. The x-axis represents distance in meters, ranging from approximately 10 m to 170 m, while the y-axis represents RSSI in dBm, ranging from -50 dBm to -25 dBm.

Table 1 Average RSSI Measurements for Different Modulation Schemes at Various Distances

Distance (m)	RSSI (dBm) OOK/ASK	4-FSK	MSK	GFSK
10	-35	-33	-32	-28
20	-37	-39	-36	-30
30	-38	-41	-47	-34
40	-40	-43	-46	-36
50	-42	-40	-40	-48
60	-43	-43	-47	-46
70	-45	-43	-43	-44
80	-46	-46	-46	-46
90	-47	-44	-49	-47
100	-44	-45	-44	-48
110	-46	-47	-46	-
120	-47	-45	-47	-
130	-45	-42	-	-
140	-45	-46	-	-
150	-48	-45	-	-
160	-45	-	-	-
170	-48	-	-	-

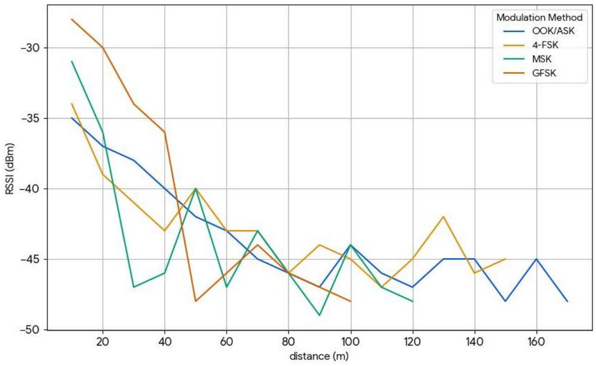

Figure 6. RSSI vs distance

The graph presents data for four different modulation methods, each represented by a distinct color: OOK/ASK (Blue line), 4-FSK (Orange line), MSK (Green line) and GFSK (Red line).

An overall inverse correlation between Received Signal Strength Indicator (RSSI) and distance is observed across all modulation schemes. Consistent with the fundamental principles of wireless communication, RSSI values tend to diminish (become more negative) as the transmission distance increases, indicating progressive signal attenuation. However, the decline in RSSI is neither linear nor uniform. Noticeable fluctuations and abrupt dips are present along the measurement curves, likely attributable to environmental influences such as multipath fading, physical obstructions, or electromagnetic interference [11]. These irregularities are characteristic of empirical signal propagation in real-world scenarios.

B. Performance Comparison of Different Modulation Format

The comparative analysis of the RSSI performance across different modulation techniques reveals unique signal attenuation patterns as distance increases. As expected in wireless communication systems, an inverse relationship between RSSI and distance is consistently observed, where signal strength weakens (i.e., RSSI becomes more negative) with greater separation between transmitter and receiver. However, the degree and pattern of this degradation vary significantly among the modulation schemes tested.

Starting with OOK/ASK, the signal strength begins at around -35 dBm at a 10 meter distance and decreases steadily, reaching approximately -40 dBm at 40 meters. A noticeable dip occurs near 50 meters, where the RSSI drops to -42 dBm. Although there is a brief recovery, the values continue to fluctuate at greater distances. Beyond 100 meters, OOK/ASK maintains an RSSI between -45 dBm and -48 dBm, with a prominent decline at 150 meters. The final data point is recorded at 170 meters with an RSSI of around -48 dBm, indicating a consistent yet modest degradation profile across the range.

In contrast, GFSK demonstrates the strongest initial signal, with an RSSI of approximately -28 dBm at 10 meters, suggesting better short-range performance. However, the signal strength drops sharply to -34 dBm within the first 30 meters and continues declining to -36 dBm by 40 meters. A significant dip is observed at 50 meters, reaching -48 dBm the lowest among all schemes at that range. The recorded RSSI values between 50 and 100 meters generally range from -44 dBm to -48 dBm. Its final available data point at 100 meters registers approximately -48 dBm, demonstrating competitive signal resilience within its range despite the limited dataset.

Moving on to MSK, this scheme starts at -32 dBm at 10 meters and exhibits a steep drop to -40 dBm by 22 meters. Over subsequent distances, the RSSI remains generally between -40 dBm and -48 dBm, similar to the pattern observed in OOK/ASK. However, a particularly sharp decline occurs at 90 meters, where the signal drops to around -49 dBm, indicating a possible vulnerability to interference or environmental obstructions. The final measurement for MSK is recorded at 120 meters with an RSSI of -47 dBm, confirming its overall stable yet slightly less robust long-distance performance.

Finally, 4-FSK presents a slightly different profile due to fewer and less continuous data points, especially at longer distances. Beginning at -33 dBm at 10 meters, it shows a relatively smooth attenuation up to 20 meters, reaching -36 dBm. Similar to GFSK, 4-FSK also

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experiences a significant dip around 40 meters but recovers thereafter. Interestingly, 4-FSK exhibits a resurgence in signal strength around 130 meters, peaking at -42 dBm. This brief recovery highlights its potential for intermittent performance improvements under certain conditions. The modulation concludes its trend at 150 meters with an RSSI of about -45 dBm, aligning it with the long-range performance of OOK/ASK.

In the dense built environment where the test was conducted, several physical obstructions likely contributed to the observed RSSI dips at specific distances. At around 50 meters, the GFSK signal degradation coincides with the presence of building corners and metallic structures that can cause significant multipath fading and signal shadowing. Similarly, the notable RSSI drop for MSK at approximately 90 meters aligns with a cluster of taller buildings and vegetation that partially blocked the line of sight between transmitter and receiver. These environmental factors plausibly explain the 'dead zones' identified in the measurements, reinforcing the interpretation that signal performance is strongly influenced by the surrounding physical landscape.

In summary, while all modulation schemes exhibit the expected RSSI degradation with increasing distance, 4-FSK offers superior performance at shorter ranges, whereas OOK/ASK and MSK provide relatively consistent long-range behavior. GFSK, although underrepresented at longer distances, shows potential for stable communication. These variations underscore the importance of selecting an appropriate modulation method based on the specific range and environmental conditions of a wireless telemetry application.

C. Comparative Analysis and Implications

The comparative analysis of the modulation methods reveals several key insights regarding their performance in wireless telemetry applications. To begin with, GFSK demonstrates the strongest initial signal strength, particularly within the 10 to 20-meter range, making it potentially advantageous for short-range communication scenarios. This early advantage may be attributed to its modulation characteristics, which allow for efficient energy concentration at closer distances.

As the distance increases, all modulation methods exhibit the expected trend of signal attenuation, though determining a clear overall winner in terms of maintaining the highest RSSI is challenging due to significant signal fluctuations. In this regard, OOK/ASK and 4-FSK appear more extensively tested, with data extending to 170 meters and 150 meters, respectively. This suggests their suitability for long-range applications, or at the very least, that they were prioritized in the longer-range evaluation during experimentation [12].

Despite their individual strengths, none of the modulation techniques maintains consistently stable RSSI values throughout the entire measurement range. The considerable variability across all methods underscores the influence of environmental factors such as multipath fading, obstructions, or interference, which affect signal robustness [13]. Therefore, no single modulation method can be deemed universally superior in all scenarios.

Interestingly, each modulation scheme seems to exhibit distinct "sweet spots" and "dead zones" along the distance spectrum. For example, 4-FSK shows a performance spike around 130 meters, while OOK/ASK fares better at 160 meters. In contrast, GFSK and MSK experience noticeable signal degradation at 50 and 90 meters, indicating regions of reduced reliability. These fluctuations highlight the importance of context-specific modulation selection based on environmental characteristics and deployment requirements.

Finally, in terms of long-range performance, OOK/ASK and 4-FSK stand out due to their extended coverage in the test results [6]. This not only reflects their potential for distance communication but also suggests greater resilience in maintaining signal detectability at farther ranges. On the other hand, MSK and GFSK display shorter testing coverage, with data points ceasing before reaching the 130-meter mark, possibly indicating limitations in their long-range applicability or reduced testing focus. Together, these findings offer valuable guidance for selecting appropriate modulation schemes in wireless telemetry systems depending on distance, environment, and application needs. The comparison of signal strength, sensitivity, and range across OOK/ASK, 4-FSK, MSK, and GFSK modulation formats is summarized in Table 1.

Table 2 Signal Strength, Sensitivity, and Range Analysis for Various Modulation Type

Modulation Format	Signal Strength & Sensitivity	Range
OOK/ASK	Moderate initial RSSI; variable under noise; slightly improved stability in ASK over OOK.	Tested up to 170 m; performs better at far end (160 m) despite susceptibility to interference.
4-FSK	Good RSSI stability; performance spike around 130 m.	Tested up to 150 m; strong short-to-mid range with notable peaks in specific zones.
MSK	Stable RSSI due to continuous phase modulation; reduced distortion in noisy conditions.	Data coverage ends before 130 m; theoretical potential for longer range at higher data rates.
GFSK	Strongest initial RSSI at 10–20 m; Gaussian filtering improves robustness in interference-rich areas.	Comparable to MSK; tested up to <130 m; strong in multipath environments.

D. Implications of Modulation Format Choices

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The choice of modulation format has significant implications for wireless system design, particularly in IoT and WSN applications:

1. **Energy Efficiency vs. Range**
   OOK/ASK is simpler and energy-efficient but more susceptible to interference, making it more suitable for short to medium-range systems in low-noise environments [14]. In contrast, MSK and GFSK, although more power-intensive, offer enhanced robustness and spectral efficiency, ideal for denser deployments. This aligns with findings on energy consumption trade-offs in IoT modulation schemes [15].
2. Application-Specific Suitability
   For applications demanding short bursts of high reliability, such as industrial monitoring within confined areas, 4-FSK's strong short-range performance is valuable. For long-distance agricultural telemetry, OOK/ASK offers better end-to-end reach despite higher variability.
3. **Environmental Adaptability:**
   GFSK, with its filtering advantages, demonstrates resilience in multipath-rich or interference-prone environments, such as urban settings. Thus, it may be preferable in scenarios where spectrum congestion is a concern.
4. **Design Trade-offs:**
   The fluctuating performance profiles of different modulation formats suggest the necessity of adaptive systems capable of dynamically switching modulation types based on distance and interference conditions, ensuring optimal balance between energy consumption, range, and data reliability [16][17].

Overall, the results highlight that modulation scheme selection cannot be generalized but must be tailored to specific application requirements, deployment conditions, and performance trade-offs.

4. Conclusion

This study analyzed the effect of different modulation formats (OOK/ASK, 4-FSK, MSK, and GFSK) on signal strength and communication range using the CC1101 transceiver module. Results demonstrate that while all modulation formats exhibit predictable signal attenuation with increasing distance, each modulation type presents distinct strengths. OOK/ASK and 4-FSK excels in long-range communication, , MSK offers continuous phase stability, and GFSK provides strong short-range performance and shows robustness in interference-prone environments.

The findings emphasize that no single modulation format is universally optimal. Instead, modulation scheme selection should consider application-specific factors such as required range, environmental conditions, energy efficiency, and tolerance to interference. These insights are particularly relevant for IoT and WSN deployments, where trade-offs between power consumption, range, and communication reliability are critical.

Future research directions can explore hybrid modulation techniques, adaptive modulation schemes, and machine-learning-assisted parameter optimization to further enhance CC1101-based system performance under varying operational conditions.

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