An Experimental Study of Controllable Interference Generation Techniques in IEEE 802.15.4 Networks

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***Abstract*—Low power and wireless Ad-hoc sensor networks encounter high-power Cross Technology Interference (CTI) [1] from a wide range of wireless devices sharing the same ISM radio band. To characterize the impact of CTI on low power networks and to mitigate the ill effects of interference on current sensornet protocols, it is important to evaluate the behavior of network parameters in the presence of the interference sources. A widely used technique to generate controllable interference in WSN testbeds is JamLab [2], which effectively augments the sensor nodes present in the testbed to generate interference, which makes this technique low cost and quickly deployable. JamLab uses radio test modes present in CC2420 radios to generate customizable interference patterns. Controllable interference can be generated by using modulated and unmodulated carriers or by using packet storming techniques. However, it is still not clear which technique suites better to generate the complex and diverse interference patterns depicted by the CTI sources. In this paper, we explore three techniques, 1) Packet storming, 2) Tone emission using modulated carriers, 3) Tone emission using unmodulated carriers to generate controllable interference patterns by using TelosB nodes. We evaluate the three methods with respect to timing accuracy, frequency spread, efficiency of jamming and energy consumption. The trade-offs presented by each of methods are evaluated. Based on this study, we suggest which technique should be used for generating a particular interference pattern.**

***Keywords*: CTI, Controllable interference generation, CC2420 radio, Packet storming, Radio test modes, 802.15.4 networks, JamLab.**

I. INTRODUCTION

Low power wireless networks are highly susceptible to CTI sources viz. Wi-Fi access points [3], Bluetooth devices [4], Microwave ovens, FHSS cordless phones, Wireless cameras [1] and many other devices operating in the shared ISM spectrum [5]. These CTI sources are highly unpredictable in nature due to the uncertainty and complexity they induce on 802.15.4 networks. Furthermore, the low transmission power (-25dBm 0dBm) of 802.15.4 devices makes it difficult to mitigate and combat the effects of high power CTI sources, such as 802.11 (WLAN) which transmits at 20dBm peak power, microwave oven at 60dBm and Bluetooth at 4dBm. There has been active research to counteract the interference and communicate effectively in the presence of CTI sources [6]. However, to develop and propose new methodologies, such as interference-aware routing protocols [21], adaptive channel hopping schemes [22], and transmit power adaptation techniques [23], conducting experiments in the presence of controllable interference is essential as simulations are not sufficiently accurate to represent PHY layer parameters such as channel noise level, RSSI, LQI and power consumption.

Controllable and precise interference patterns can be generated by configuring Universal Software Radio Peripheral (USRP) [7] as signal generator. SDR radios are expensive and in large and diverse testbeds such as TWIST [8] and Indriya [9] USRP's are not a viable option. In [2] it is demonstrated as to how a fraction of sensor nodes present in a testbed can be configured to act as active interferers. The experimental results show that the hardware limitations of the sensor nodes are effectively addressed to produce controllable interference patterns. In [10], Oppermann et al. show how automatic configuration of the testbed can be done to select minimum number of nodes to act as jammers. These techniques show the methods to generate controllable interference by using sensor nodes as interferers in an automatically configurable manner. This method is low-cost and quickly deployable in testbeds.

JamLab [2] uses the special radio test modes in CC2420 radios [11] which are compliant with 802.15.4 PHY layer standards. The test modes allow generation of unmodulated and randomly modulated signals which can be used to emulate interference patterns produced by high power CTI sources. The emitted carriers, increase the noise floor of the medium impacting the SNR at the receiver in a controllable manner. Unmodulated carrier, which produces peak power at the center frequency, is used to generate interference patterns similar to background noise in a typical working environment. Modulated carriers are used to generate the precise interference patterns depicted by majority of the high power CTI sources.

Another technique to generate interference patterns is to use continuous packet storming. This technique performs concurrent packet transmissions which affects the PRR at the receiving nodes. Although packet storming has temporal gaps in transmission, typical to packet based transceivers as pointed out in [12], this drawback is not a limiting factor for generating certain interference patterns; it provides better controllability and power efficiency. In comparison, tone emission provides better timing accuracy but the interference patterns which demand narrow band modulated signals results in erroneous CCA readings by the CC2420 receiver radios due to hardware limitations.

In this paper, we present a comparative experimental analysis of the three interference generation schemes by using TelosB nodes [13]. We compare timing accuracy, frequency spread, efficiency of jamming and power consumed by these techniques. We generate patterns commonly shown by CTI sources such as periodic interference patterns, incremental interference, constant interference, channel hopper and patterns with varied duty cycles to check the timing accuracy. We use Contiki OS [14] for development and tracking the power consumption. The accurary of the generated interference is analysed by recoding the patterns by a USRP N210 with RFX2400 2.3–2.9 GHz Rx/Tx daughter board in a controlled environment. As a reference for typical interference patterns generated by various CTI sources we referred the models and parameters described in [1]. Finally, we suggest which technique to opt for when a particular interference pattern generation is required.

Rest of the paper is structured as follows, in Section II we survey controllable interference generation methodologies. Section III presents experimental setup and tools used for the comparative analysis. Section IV provides detailed study of interference generation by tone emission and the experimental results. In section V we present our observations and results while generating interference patterns by using packet storming. In section VI we present comparison between both the techniques with respect to power consumption, section VII presents the comparative analysis with respect to packet reception ratios in both the techniques followed by discussion and results. We conclude our paper in section VII.

II. EXPERIMENTAL SETUP

The experimental setup consists of 3 TelosB nodes, a transmitter, a receiver, an interferer and a USRP N210 connected to computer running GNU Radio to record the interference patterns as shown in Figure 1.

Carrier	Channel 11	Channel 18	Channel 26
Modulated	18.24mA	18.18mA	18.05mA
Unmodulated	18.04mA	17.98mA	15.54mA

TABLE I
CURRENT CONSUMED WHILE TRANSMITTING MODULATED AND UNMODULATED CARRIERS ON CHANNEL 11, 18 AND 26

To generate and record the interference patterns, only the interferer node and the spectrum analyzer are used. RFX2400 is a transceiver designed for applications in the 2.4 GHz band and is operational in the 2.3–2.9 GHz band. The board provides a bandwidth of 20 MHz and a maximum sampling rate of 25 Mhz. Before running the experiments, the spectrum analyzer output was monitored to select the channel with minimum activity (channel 26) which was used to verify and analyze the interference patterns generated by the interferer node. The RSSI values provided by the spectrum analyzer are plotted against time to verify the timing accuracy of the interference generation techniques and the frequency spread is monitored by analyzing the FFT plots.

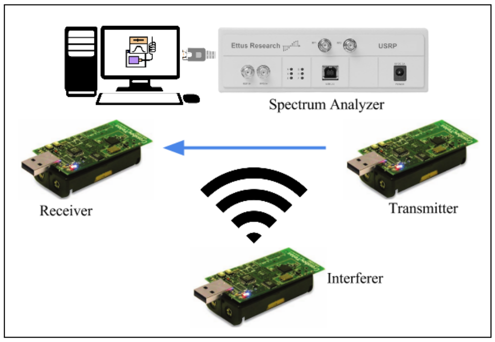


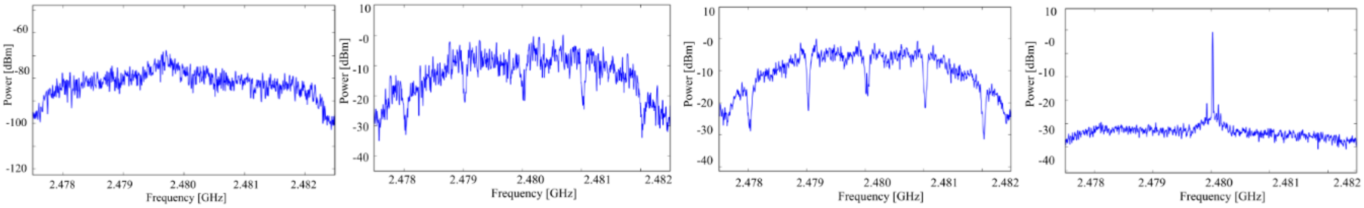
Figure. 1. Experimental Setup

The power consumption is tracked by using a Contiki [14] application, PowerTrace [18]. This provides the power consumed by the CPU in active and low power modes, by the radio while transmitting and receiving the packets and the energy spent in idle listening. The TelosB nodes are USB powered to ensure constant and steady power supply while conducing all the experiments. The transmit power of the interferer node is set to the maximum (0dBm). We calculate the jamming efficiency by transmitting 1000 packets and analyzing the received packets, firstly in absence of any interference and then in the presence of generated interference patterns. The Packet Reception Ratio (PRR) in the absence of any interference was used to normalize the PRR values measured in the presence of generated interference patterns to shadow the channel effects. During reception, we also measured the RSSI values at the receiver, the Signal to Noise Ratio (SNR) and Link Quality Indicator (LQI) for each packet. All the above experiments were also carried out in Cooja simulator [19], to analyze the PRR and the behavior of the interferers in a completely noise insulated environment.

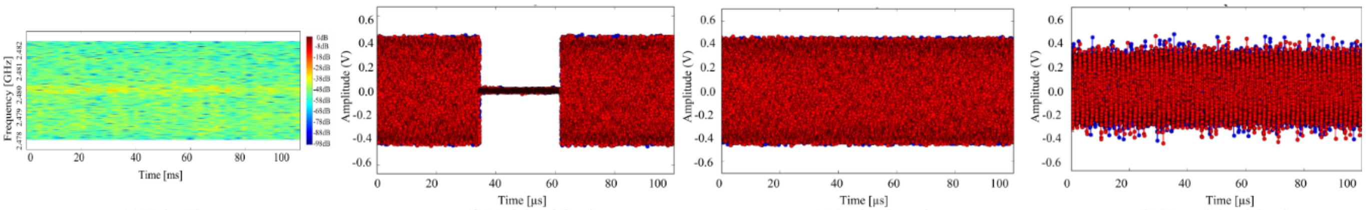
III. RELATED WORK

Radio interference is an actively researched topics today. Anwar et al. [1] present the behavior of CTI and characterize the impact of various CTI sources such a microwave ovens, FHHS and analog phones, wireless cameras, Bluetooth, and WLAN on low power 802.15.4 networks. The channel quality estimation in an 802.15.4 network in the presence of RF smog is studied in [15]. There are several research papers with a detailed study on impact of individual high power wireless technologies on low power networks and their respective mitigation schemes [16] [17].

As increasing number of RF devices are operating in the ISM band, there is need to adapt the existing algorithms and sensornet protocols to operate under interference. Thus, there is a need for low cost and flexible infrastructure to evaluate the performance of protocols in the presence of



(a) Noise Floor (b) Modulated Carrier (c) Packet Storming (d) Unmodulated Carrier



(e) Noise Floor (f) Modulated Carrier (g) Packet Storming (h) Unmodulated Carrier

Figure. 2. Noise floor on channel 26

interference in a testbed setup. There have been some studies on controllable interference generation for 802.15.4 networks in a sensornet testbed. [12] presents controlled interference generation scheme by using Tmote Sky nodes. A detailed study on interference generation by using radio test modes present in CC2420 radios is presented in [2]. An automated tool to select precise number of nodes to act as jammers has been shown in [10]. However all theses studies use modulated carriers to generate majority of the interference patterns. A comparative study using all the schemes of controllable interference generation and evaluating the accuracy, power consumption and efficacy of the three methods is still lacking. We aim to fill this void.

In this paper, we present a detailed comparative study on the three schemes for interference generation namely tone emission techniques (modulated and unmodulated carriers) and packet storming method. We generate the interference patterns by using the radio test modes of CC2420 transceiver with modulated and unmodulated carriers as done in [12]. In addition, we generate exactly the same interference patterns by packet storming. We compare both the schemes with respect to timing accuracy, energy consumption and jamming efficiency.

IV. TONE EMISSION TECHNIQUE

In this section, we present a detailed study on interference generation by continuous tone emission using modulated and unmodulated carriers. CC2420 chipcon radio transceiver can be set to special transmit modes for testing and evaluation purpose. These modes can be used to generate unmodulated carriers in which peak power lies at the center frequency as well as modulated carrier signals which are created by using pseudo random sequences generated by the CRC checker [12]. The maximum spectrum analyzer sensitivity was measured to be -110dBm and all the experiments were carried on channel 26 due to minimum activity (disturbance) on this channel. Figure 2 shows the noise level on channel 26, in the absence of any interference, these readings have been used to normalize the RSSI values to minimize the channel behavior impact on the result of the experiments.

First we generate periodic interference pattern with a period of 2ms, using modulated carrier, fixed transmission power at 0dBm and 1 meter fixed distance from the spectrum analyzer. The pattern is plotted in Figure 4. Figure 5 shows the interference pattern generated by varying the transmit power randomly between [-25dBm - 0dBm], other settings were kept the same as the above experiment. This experiment was conducted to check the behavior of the radio when transmitted power is randomly varied after each period. We generate periodic interference with constant power using unmodulated carrier. Figure 6, shows the interference pattern generated. Figure 7 shows the pattern generated using unmodulated carrier and random power in range [-25dBm 0dBm]. Figure 8 shows incremental interference pattern using the modulated carrier, the same was generated using unmodulated wave but the temporal gaps varied in the range of 2-3ms while incrementing the power. In addition, the power gradually rises in steps of 1.5dBm for a 6dBm power increase in total. Figure 9, shows the generated pattern for a varying duty cycled pattern. As seen from the graph when the ON-time duration is longer, the received power fluctuates between 2-4dBm, and takes 4-6ms for the power to settle to the desired value. The power profile, duty cycle, and the wave period generated by a typical commodity microwave oven was studied [15] and the model was used to emulate the pattern. Figure 10 shows the microwave power profile emulated by using the TelosB node.

The periodic interference pattern is a characteristic of wireless cameras; FHSS cordless phones also depicts a periodic pattern similar to the unmodulated carrier in Figure 7. On the contrary, analog phones transmit a continuous signal at +55dBm [1] whenever it is switched on, as shown in Figure 11.

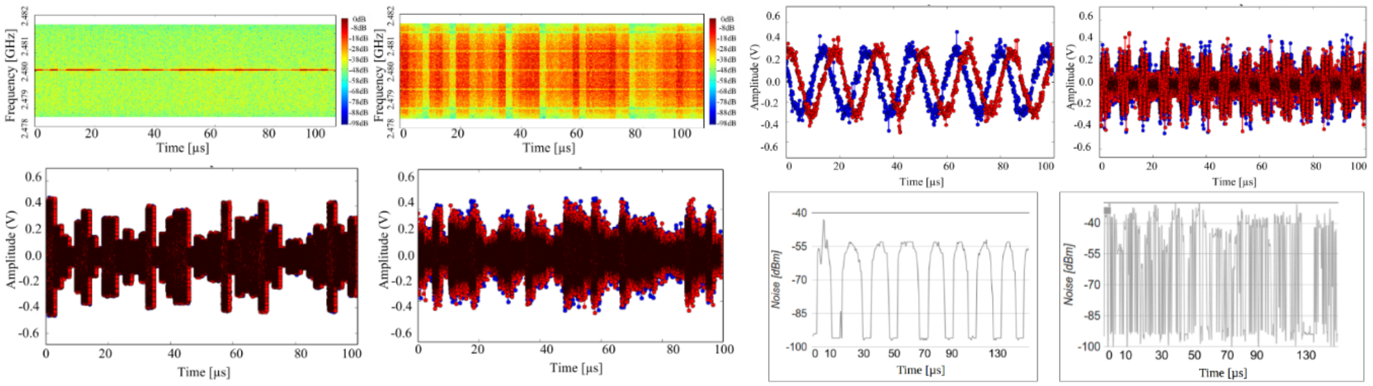


Figure. 3. Noise floor on channel 26

V. PACKET STORMING

In this section, we present a detailed study on interference generation by using packet storming or concurrent packet storming technique. The same experimental setup described in the previous section is used here. We generate the same patterns by this technique which were generated in the above section. To allow the node to transmit packets continuously, without any temporal gaps, we boosted the CPU speed, disabled all the MAC layer functionalities, disabled clear channel assessment (CCA) by pulling down the CCA pin and adjusted the delays between concurrent packet transmission to have minimal effect on continuous interference generation.

Figure 12 shows the constant interference pattern similar to the one generated by analog phone. Figure 12 shows that the packet storming has fewer temporal disturbances. We tried to generate the same pattern with exactly the same parameters but without boosting the CPU speed, the profile obtained is presented in Figure 13. We see that there are many temporal gaps present which vary between 1-3ms, which aligns with study in [12]. Figure 14 shows the profile obtained for incremental interference pattern. As seen from the graph the power profile obtained is smother and gradual as compared to Figure 8. Figure 15 shows the power profile obtained by using packet storming to generate periodic interference pattern. It provides fixed peak power without any fluctuations and temporal gaps.

Interference Pattern	Technique
Continuous Interference	Modulated Carrier
Periodic Interference	Unmodulated Carrier
Incremental Interference	Packet Storming
Interference with Random Power	Modulated Carrier
Microwave Oven	Modulated Carrier
Controlled Duty Cycle	

TABLE II
MY CAPTION

For generating the pattern with random power, we transmit subsequent packets with the transmit power randomly selected in the range [-25dBm 0dBm]. The profile obtained as seen in Figure 16 shows that, there are temporal gaps and peak power fluctuations, the power increment or decrement is not as gradual as Figure 5. As seen in Figure 14, the power increment is gradual as the transmit power is incremented in small steps of 4dBm which does not lead to many fluctuations. Figure 17 shows the power profile obtained by transmitting packets while emulating microwave oven power profile. As seen from the graph the power increment and decrement is gradual but with some temporal disturbances and peak power fluctuations. On the contrary to this the profile obtained by continuous tone transmission is smooth and gradual.

VI. POWER CONSUMPTION

In this section we compare the power consumed by the interferer node while pattern generation using all the techniques. The power consumption is calculated by using the PowerTrace application and the Energest [18] module available in Contiki to monitor per component power consumption. The Energest module keeps track of the radio operation and counts the total timer ticks when the radio is transmitting, receiving the packets and the time elapsed in doing idle listening.

The CPU current consumption while operating in active mode is 2.2mA, while in low power mode it is 0.00169mA, the radio consumes 17.2mA while doing packet storming, with all the MAC layer functionalities switched off and the total radio receiver current consumption is 33.6mA, including idle listening [11]. The current consumed while transmission of modulated and unmodulated carriers on channels 11, 18 and 26 is shown in table 1. All the values are at full transmit power; 0dBm [20]. We calculate the total power consumption according to equation 1 for packet storming, equation 2 for modulated carrier transmission and equation 3 for unmodulated carrier transmission.

$$\frac{((CPU \times 2.2) + (LPM \times 0.00169) + (TX \times 18.05) + (RX \times 33.06)) \times 3}{RTIMER\_ARCH\_SEC} \quad (1)$$

where, CPU corresponds to total rtimer ticks for which CPU is in active mode, LPM corresponds to total rtimer ticks for which CPU is in low power mode, TX corresponds to rtimer ticks for which radio is in transmit mode, RX corresponds to rtimer ticks for which radio is in receive mode including idle listening, RTIMER _ARCH _SEC corresponds to timer resolution total number of RTIMER ticks equivalent to one second. By dividing rtimer ticks by RTIMER _ARCH _SEC, we are able to obtain the time in seconds.

Figure 18 shows the power plot while continuous pattern generation with packet storming after boosting the CPU speed to avoid any temporal gaps in the pattern. We show the total power consumption including the CPU power consumption in active and low power modes, by transmitter and receiver. We observed that the CPU active power consumption increases steadily with time, while CPU never went in to low power mode was as it is continuously occupied by the packet generation task. The power consumed by the radio transmitter also showed gradual increase, however the receiver power consumption was increasing by negligible amount due to idle listening. In comparison the power consumption by modulated carrier for continuous interference generation is less, as over clocking is not required to produce constant power profile. Figure 19 shows power consumption while generating periodic interference pattern. Due to ON and OFF cycles, the overall power consumption is much lower as compared to Figure 18, during the off periods, the CPU goes in to low power mode which further contributes to less power usage and gradual increase in the total power consumption.In the next step, we calculate power consumption while generating periodic interference with exactly the same rate as with modulated carrier. The values stay almost identical as for packet storming. However, in case of unmodulated carrier as seen in Figure 20, the power consumption is less compared to both techniques due to less current required by the radio. In Figure 21, we show the power plot obtained when generating incremental interference by using packet storming. We observed that the energy consumed was less compared to modulated carrier when used to generate the same pattern. Next, we find the power consumption behavior for interference patterns generated by randomly varying the transmit power. Figure 22 shows the power consumption using modulated carrier. We also observed that the power profile has sudden peaks when the subsequent power levels are apart from each other by +6dBm or more when the same pattern was generated using packet storming, which contributed to higher power consumption. We get similar profiles for patterns with different duty cycles, although we noted that when the ON time is greater than 20ms, the radio takes 3-5ms to settle down to the required power level when the radio is OFF. On the contrary, when a particular duty cycled pattern is generated using modulated or unmodulated carriers, the radio instantly settles to the power level when radio is off and CPU goes to low power mode. We observed similar characteristics when emulating the power profile of microwave oven. The total energy consumed by modulated carrier was lower and the curve is gradual as compared to packet storming technique. The power plot of modulated carrier generating microwave pattern is presented in Figure 23. We ignore the minor power consumption difference in different channels.

VII. RESULTS AND DISCUSSION

We compare the jamming efficiency of both the techniques by comparing the PRR values in the presence of the generated interference patterns. We programmed the transmitter to transmit 1000 packets of 127 bytes at 23dBm on channel 26, and measured the received packets. In addition, we also measured the RSSI at the receiver in the presence of the interferer. We observed that the pattern of the RSSI and noise level followed approximately similar to the interference patterns described in section III and IV, although with minor power level fluctuations and temporal gaps. Power level of 23dBm was chosen as the jamming is effective only if the interferer's power is +3dBm greater than the ongoing communication [2]. We verified this in case of incremental transmit power interference pattern, microwave and random transmit power pattern. It is observed that whenever the power level of the interferer goes below 19dBm, the transmitted packets are successfully received at the receiver, accompanied with dropping of the noise level and LQI values increase. The PRR values followed the interference pattern curves presented in section III and IV. Although, in the presence of continuous interference pattern generated by packet storming, packets were being received after 3-5ms, this is due to the temporal gaps lying in the pattern because of the time taken for packet construction by the C2420 radio. All the experiments were conducted by keeping the distances fixed. The transmitter and receiver were kept 5 meters apart and the interferer was placed at exactly 3 meters from the midpoint of the line joining the transmitter and receiver as depicted in Figure 1.

We now discuss the suitability of different interference generation techniques for generating a certain interference. The suitability is based on a balanced trade-off between accuracy of the generated pattern and power consumption. The results show that tone generation method using modulated carrier suits better for generating continuous interference pattern, due to absence of any temporal gaps in the generated pattern and moderate power consumption. For generating a pattern with similar efficacy using packet storming method, CPU should be boosted leading to more power consumption. For generating periodic interference with periods in the range 3-8ms, continuous tone emission with unmodulated carrier performs better, because no power fluctuations is observed at the peak power and the energy consumption is more efficient compared to the other techniques. For generating gradual incremental interference pattern, packet storming technique is preferred due to its steady peak power, less power consumption, and gradual power level increase as compared to the tone emission techniques. We suggest to employ modulated carrier for pattern which require random transmit power levels, due to less energy consumption and lower peak power fluctuations and temporal gaps as compared to packet storming technique. The same scheme is also suggested for emulating microwave oven interference pattern. For controlled duty cycle pattern, we select packet storming due to gradual changes, less power consumption and lower peak power fluctuations. We summarize the interference pattern and technique to be used in table 2. In addition to this, we observed that by over-clocking the CPU speed to 11MHz, we are able to generate interference on 4 subsequent channels, with a time gap of 10ms for channel shift. This is useful in scenarios when actual impact of wide-band interferer's needs to be studied (e.g., Channel 1 of WiFi overlaps with channels 11-14 of IEEE 802.15.4). However, this is limited to networks in which channel hopping by the interferer's takes place after a gap of 10ms.

VIII. CONCLUSION

In this paper, we compared three techniques for controlled interference pattern generation, which are packet storming and continuous tone emission using modulated and unmodulated carriers. We performed experiments to generate various interference patterns by all techniques in a controlled environment and analyzed the accuracy of the generated patterns in terms of timing, temporal gaps, and power fluctuations. We also checked how the power levels are incrementing or decrementing by monitoring the gradual or steep changes in the patterns. Further, by using PowerTrace [18] we calculate the power consumed in generating each interference pattern. Based on the above criterion, we suggest which technique to employ to generate a particular pattern, to achieve a balanced tradeoff between accuracy and power consumption.

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