

PULSEHV: Opportunistic Data Transmissions over High Voltage Pulses for Smart Farming Applications

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Abstract—Wireless Sensor Networks establish the foundation for a revolution in precision agriculture. As an integral part of *smart farming* systems, they can collect detailed information about crop health, air and soil conditions, and other relevant parameters to support agriculturists in their decision-making. Likewise, decentralized actuation (e.g., opening sprinkler valves) becomes possible when embedded sensor and actuator devices are deployed. From a technical point of view, smart farming systems strongly rely on embedded devices with wireless communication interfaces to cater for their convenient deployment. The operation of their wireless radio transceivers, however, often represents a significant energetic burden. This is particularly conspicuous when compared to the low-power microcontrollers that have become ubiquitous on current-generation sensing systems. We mitigate this issue by following an entirely different approach in this work, namely by exploiting the presence of electric fence energizers that are widely used in farming scenarios. Our solution called PULSEHV modulates data onto the high-voltage electric pulses emitted by fence energizers and thus enables broadcast communications at no extra overhead. As electrical fences commonly encircle entire patches of cropland, they act as large sending antennas; a proximity between deployed sensing devices and this antenna is implicitly ensured thereby. We practically demonstrate how PULSEHV accomplishes an effective data rate of $2.7 \frac{\text{bit}}{\text{s}}$ through the application of pulse position modulation. This limited throughput is counterbalanced by the fact that receiving the broadcast transmissions incurs virtually no energy overhead.

I. INTRODUCTION

Smart farming is an emerging application area for Wireless Sensor Networks (WSNs), where networks of embedded sensing systems help to optimize the agricultural yield through, e.g., the precise control of fertilizer use, controlled sprinkling, or the early detection of plant diseases [1]–[4]. The properties of WSNs make them well-suited for this use case, because they allow for distributed sensing on large-scale agricultural areas, without the need for existing infrastructure. However, the energy-efficient operation is a strict requirement to WSNs used in smart farming, particularly when facing challenges like harsh environmental conditions and limited maintainability.

Their energy sources, mostly present in the form of non-rechargeable batteries, are often the key limiting factor for the reliable operation of agricultural WSNs for time spans of months to years [5], [6]. Energy harvesting [7], [8] can be utilized in some scenarios to slightly mitigate this restriction, yet more sophisticated strategies for energy management are

usually inevitable [9]. A common way to enable extended operational times is to minimize the duty cycle of nodes, i.e., the fraction of time their components are active. In practice, duty cycling is predominantly applied to the operation of the radio transceiver device, being one of the most power-consuming parts of a sensor node. Some WSN applications even go as far as relying on secondary low-power wake-up receivers to activate a device’s primary radio transceiver solely when it is needed [10], [11]. Operating such a secondary radio device, however, incurs a corresponding power consumption as well as the cost for additional hardware.

In this work, we present a system design that overcomes this limitation by exploiting the circumstances of many agriculture and farming scenarios, where electric fences are ubiquitous. Such fences are used to protect croplands against boars and other animals, or to keep livestock within the boundaries of their pasturelands. An electric fence energizer periodically applies high voltage pulses onto the fence, which is made from a conductive material. The electric shocks are unpleasant to animals, so even fences with insufficient mechanical stability become effective barriers once the high voltage pulses are being applied regularly. Our system design utilizes the presence of electric fences by converting them into large broadcast antennas for high-voltage pulses, and is consequently named PULSEHV. With only little modifications to the electric fence energizer and only few low-cost components required on the receiver side, data communications become possible. The idea behind PULSEHV can be traced back to the experiences we made during the deployment of our outdoor WSN testbed called *PotatoNet* [12]. On a trial field of a potato crop research station, we observed that pulses of a nearby electric fence coupled into the shielding of the testbeds’s wired connections. By connecting a receiver antenna to an interrupt pin of the sensor platform’s microcontroller, a low-cost and ultra-low power detection of pulses could be achieved in practice [13].

The contribution of this paper goes beyond the simple utilization of triggered pulses for wake-up or synchronization. We demonstrate how the pulses of an electric fence can be modulated and used as a unidirectional broadcast channel to distribute information throughout the network with an almost negligible overhead. Many low-power WSNs can benefit from such an highly efficient secondary channel, e.g., to relay control messages like wake-up schedules [14], clustering infor-

mation [15], or weather forecasts for energy harvesting [16]. We begin our technical contribution by surveying the state of the art in Sec. II. Subsequently, we present insights gained from a preliminary feasibility study in Sec. III. In Sec. IV, the concepts for sender modulation and receiver design are discussed in detail and, moreover, we present a prototypical implementation of PULSEHV. We demonstrate PULSEHV's performance in practice through extensive evaluations in Sec. V and conclude this work in Sec. VI.

II. RELATED WORK

As mentioned in the introduction, a fundamental mechanism to preserve energy in WSNs is duty cycling [17]. Consequently, several Medium Access Control (MAC) protocols that reduce idle listening while ensuring multi-hop communication with low latency have been proposed [18]. For ultra-low power WSNs with potentially very long periods of inactivity, the overhead of such protocols has been demonstrated to have a negative impact on their energy efficiency. As a proposed solution, secondary *wake-up* receivers can be utilized to signal requests to activate the primary radio transceiver only on demand [19], [20]. The power demand of secondary radios is, however, often only slightly lower than when operating the primary wireless transceiver. In an attempt to increase energy efficiency even more, there are also passive wake-up radios, powered by the energy of the received signal directly [21]. However, these passive radios commonly have too short receiving ranges to be useful for smart farming applications.

The idea to utilize external events to trigger events on a sensor node has also been proposed in existing literature. For example, in structural health monitoring, the data collection can be triggered by external vibration events [22]. Similar to the PULSEHV approach presented in this paper, [23] make use of the electromagnetic (EM) emission of regular power plugs, which are used to synchronize sensor nodes to overcome the issue of clock drifts. However, while this approach might be applicable to indoor deployments, for outdoor WSNs it is impractical due to the absence of wall outlets.

Considering the targeted application area of smart farming, common electrical fences can also be used for the purpose of external triggering. In [13], we have already demonstrated that the reception of pulses emitted by an electric fence is feasible with almost no overhead. Thus, we adopt this approach again in this paper. However, instead of relying on the simple functionalities of waking up a node or using the synchronous reception of electric pulses for time synchronization, we present a full system design to accomplish data transmissions from a sending station (the fence energizer) to all nodes in the smart farming WSN. To the best of our knowledge, the only approach towards data transmission via electric fences has been discussed in [24], where nodes were directly attached to the fence. The use of a wired communication channel, however, imposes many limitations on the placement of nodes, and thus leads to numerous disadvantages over the use of wireless devices.

III. PRELIMINARY STUDY

In many smart farming applications, e.g., the ones described in Sec. I, electric fences can be assumed to be omnipresent. By emitting high-voltage pulses of short duration in regular intervals, they are effective means to keep livestock within pasture boundaries or unwanted animals from entering croplands. The pulsed emission of high voltages, however, turns electric fence energizers into transmitters of wireless signals, with the fence acting as a large antenna. Emitted wireless signals can often be received by devices within the entirety of the pasture or cropland they encompass. This intuitively qualifies them as candidates for a transmission of control traffic from a configuration terminal (e.g., a base station) to all deployed smart farming devices in WSNs. In a preliminary study, whose results we present as follows, we target to get an in-depth understanding of the generated electric pulse and explore its usability for such data transfers.

A. Regulations Applying to Electric Fence Energizers

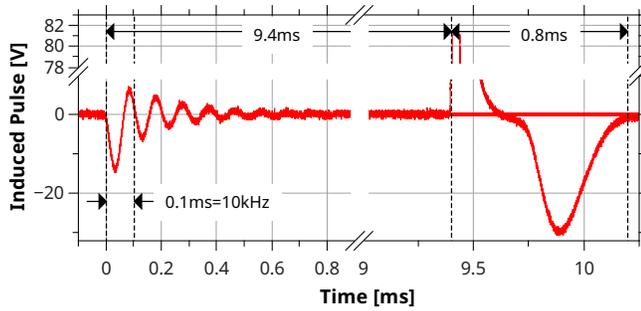
The operation of electric fences is limited by regulatory restrictions in many places, e.g., the IEC 60335-2-76 standard [25], which specifies usage restrictions to electric fence energizers. Most relevant to the scope of this work, the length of high-voltage pulses (at most 10 ms) and the rate at which they can be emitted (at least 1 s between pulses) are defined. While regulations only impose a lower limit on the time interval between pulses, the actual pulse rate is commonly determined by practical aspects: The longer the duration between pulses, the lower the efficacy of the electric fence to keep animals at bay.

B. Experimental Setup

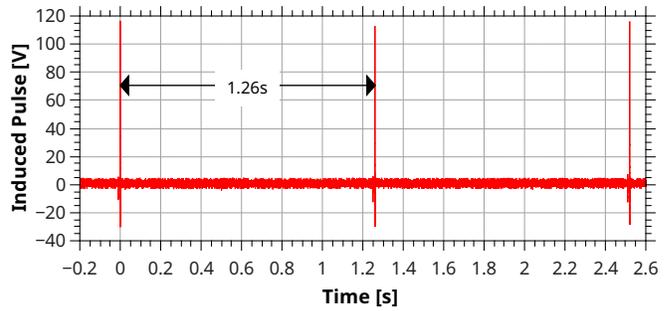
In order to assess how the pulsed electric field emitted by an electric fence energizer can be used to transfer data, we have set up a preliminary indoor lab experiment. For the generation of pulses, an electric fence energizer (model Kemo FG025¹) has been connected to a 12 VDC power supply. According to its specifications, the energizer provides a maximum output voltage of 2400 V, with a pause of at least 1.2 s between pulses. An insulated cable designed to carry voltages up to 12 kV of 5 m length was attached to each of the energizer's terminals. To capture the changing electric field, we have used a stranded wire of approximately 1 m length in this preliminary experiment positioned at about 25 cm from the energizer's cables. A corresponding signal waveform, collected by attaching the wire to an oscilloscope's input, is shown in the screen captures in Fig. 1. Two aspects of noteworthy importance are visible in Fig. 1a, and discussed as follows:

- 1) While the amplitude envelope of the signal initially decreases exponentially, the actual signal is composed of a sinusoidal carrier waveform of approximately 10 kHz frequency.
- 2) A second short peak is observed at a temporal offset of approximately 10 ms with respect to the first pulse. The

¹Data sheet at <https://www.kemo-electronic.de/datasheets/fg025.pdf>



(a) Detailed view of a single waveform's shape and characteristics.



(b) Train of pulses, transmitted at 1.26s intervals.

Figure 1. Signal waveform of the electric fence energizer, as received when using a length of wire as antenna.

source of this spike could be traced back to the driver circuitry, which energizes an internal flyback converter for this amount of time, before removing the applied voltage again. In many cases, the final pulse comes at an even greater amplitude than the initial one.

Moreover, as visible in Fig. 1b, the periodic recurrence of the emitted signals takes place very regularly, with little variance. Our measurements have shown that pulses are emitted every 1.26s, a rate well within the boundaries of the IEC standard. Note that an in-depth analysis of the variability of these intervals is studied in Sec. V-B of this paper.

C. Practical Experiences on Embedded Sensing Systems

Based on our objective to use high-voltage pulses for data transmissions between embedded systems, we study next to what extent these signals can be captured and processed on low-power devices. To this end, we connect the wire antenna to the interrupt pin of a Cortex-M4 based Teensy 3.2² microcontroller board (cf. Sec. IV-C). A software application was developed to provide the following functionality:

- Measure the time that elapses between the last peak of one and the first peak of the subsequent transmission
- Count the number of discernible zero-crossings of the signal after the first pulse peak of each transmission
- Measure the time between the first and the last signal peaks (approximately 10ms in prior experiments; cf. Fig. 1a)

The sender side has been left unmodified, i.e., it only relies on the operation of the unaltered electric fence energizer, connected to two cables which were used as sending antennas.

The operation of our test setup under lab conditions has practically confirmed that a reception of the pulses is possible at high reliability. However, spurious interrupts were frequently triggered due to the fact that the piece of stranded wire used as our antenna has little frequency selectivity. Other electric fields, emitted from the ignition coils of vehicles driven by or other electrical appliances being operated, were thus received in addition to the ones sent by the fence energizer. Through modifications of the software application,

however, it was possible to eliminate most of the outliers through the following filters:

- Pulses which did not arrive close to the time of an expected pulse reception (implemented by means of a temporal window around $1.26\text{ s} \pm 0.4\text{ s}$) were omitted from processing.
- The presence of a sinusoidal carrier wave within the pulse allows us to determine its frequency (by means of counting the zero-crossings). Any signal that does not exhibit a fundamental frequency within the observed limits of the signal (cf. Fig. 1a) is disregarded. The number of discernible zero-crossings depends on the distance between the sending antenna and the receiver. Thus, it may potentially be usable for a coarse-grained distance estimation. Even when operating the system in identical environmental conditions, however, different numbers of zero-crossings within fence energizer pulses were counted throughout the day. Thus, using them as candidates for carrying data appears to be unreliable.

In summary, these results also confirmed the insights gained in our prior work [13], yet in an office environment with many more sources of electric fields, as compared to the outdoor scenario used in the cited publication.

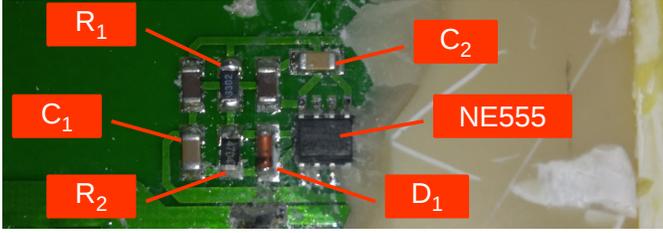
IV. CONCEPT DERIVATION AND PROTOTYPE

Through observing the operation of the prototypical system, we have seen that a reliable transmission of pulses is possible between the sending station and receivers in its vicinity. To increase the usability of our solution, a mechanism to *modulate* data onto the wireless signal is, however, needed. In this section, we thus discuss options to modulate data on the signals emitted by the energizer. Moreover, we present a prototypical system design that utilizes the physical communication channel provided by the fence energizer to transfer actual payloads.

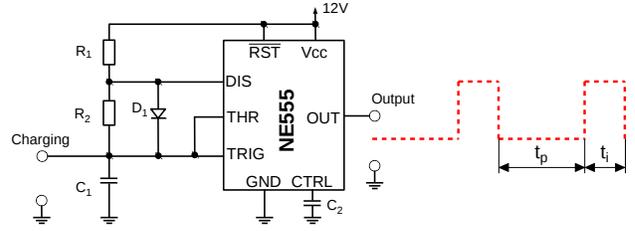
A. Modulation of Data onto Emitted Pulses

In essence, the key objective of our work is to re-purpose electric fence energizers as broadcast transmitters to disseminate configuration information in smart farming applications. Through our in-depth investigation of the nature of emitted pulses in Sec. III, we have gained several insights on the

²Technical specifications at <https://www.pjrc.com/teensy/teensy31.html>



(a) Photo of the electric fence energizer with its case opened.



(b) Connection diagram of the employed NE555 timer IC.

Figure 2. Photography of the printed circuit board and the corresponding schematic diagram of the fence energizer used in our experiments.

viability of using the pulsed electric field for data transmissions. Our experiments have, however, also revealed several limitations with regard to how data can be modulated onto the pulsed signals:

- The pulse amplitude at the receiver shows a strong dependency on the distance to the sending antenna as well as environmental conditions. This lack of amplitude stability renders the use of amplitude modulation (AM) inapplicable as means to carry data.
- The frequency of the sinusoidal waveform following the first pulse (cf. Fig. 1a) is pre-determined through the choice of components in the fence energizer's power amplifier. Its variation is thus not easily possible, which excludes frequency modulation (FM) from the list of candidate modulation schemes to transfer data.
- The number of discernible zero-crossings observed after the initial pulse (cf. Fig. 1a) depends on the strength of the received signal. Thus, modulation schemes like on-off keying (OOK), where the data to be transferred is encoded in the length of an active signal (as determined through the number of zero-crossings), cannot be applied.

By opening the case of the fence energizer (see Fig. 2a), it was visible that its pulse timings are determined through the use of an NE555 timer IC. Its timings are determined through an external network of two resistors, a capacitor, and a diode, as schematically shown in Fig. 2b. This opens up a different possibility for the modulation of data onto the emitted electric field: The defined variation of the pauses between pulses, i.e., the application of a pulse position modulation (PPM).

The application of PPM merely requires a modification of the NE555's timings and thus keeps the required hardware modifications of the fence energizer to a minimum. At the same time, it allows variations of the pulse lengths (t_i) as well as the lengths of the pauses in-between pulses (t_p) for the modulation of data. These time constants are defined by Eqs. (1) and (2).

$$t_p = \ln(2) \cdot R_2 \cdot C_1 \quad (1)$$

$$t_i = \ln(2) \cdot R_1 \cdot C_1 \quad (2)$$

Thus, with components dimensioned as $R_1 = 33 \text{ k}\Omega$, $R_2 = 4.7 \text{ M}\Omega$, and $C_1 = 470 \text{ nF}$ (as per the parts in the energizer), the timings visible in Fig. 1a result: $t_p = 1.53 \text{ s}$ and $t_i = 12.3 \text{ ms}$. The reason for the deviation of these values

from the measurements presented in Sec. III-B lies in the input impedance of the NE555 chip. As currents on the order of $2 \mu\text{A}$ are sunk by its inputs and R_2 has a comparably large value, an effective pulse interval of $t_p = 1.26 \text{ s}$ results.

Based on these equations, it also becomes clear that enlarging the capacitor size linearly increases the interval between pulses as well as the pulse duration. Note that a reduction of the capacitance has not been considered to ensure compliance with the minimum pulse interval defined in the IEC 60335-2-76 standard [25]. Given the ratio between resistors R_1 and R_2 , the duration of the inactivity interval t_p experiences increments 142 times as large as the increase of the pulse duration t_i . Based on our practical measurements, the connection of 15 nF additional capacity leads to an increment of the pulse interval by roughly 30 ms . Thus, a viable means to realize the pulse position modulation in practice has been found. Note that we have intentionally decided not to control the pulse generation entirely in software, such that the functionality of the electrical fence is even given in case the modulation unit encounters an error and stops emitting pulse signals.

One restriction applies, however, due to the internal operation of the NE555 device. Depending on the moment the capacitance value is altered during the capacitor's charging phase, the length of the pause varies. To achieve repeatable and accurate results for the pulse positioning, it is thus mandatory to make such changes of the capacitance value at deterministic points in time. To simplify this process, we have attached a signal connection to the NE555's output pin. This pin toggles between a high logic state (when the output driver is active) and a low logic state (during the pause in-between pulses). It is interfaced to the microcontroller by means of a simple

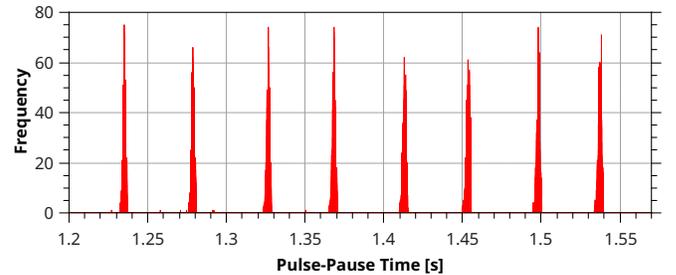
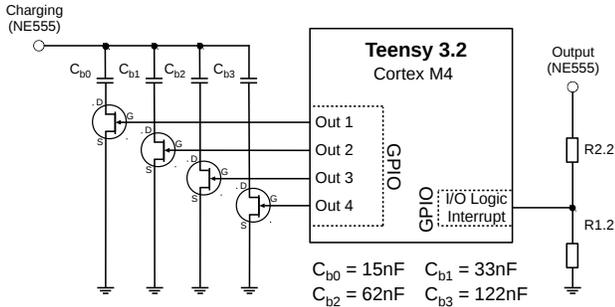
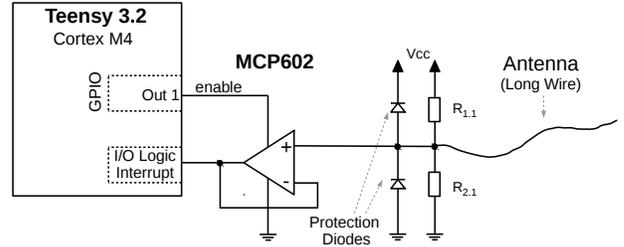


Figure 3. Histogram of interval durations when between 0–7 additional capacitors of 33 nF are added each.



(a) Schematic diagram of the sender-side hardware realization.



(b) Schematic diagram of the receiver-side hardware realization.

Figure 4. Schematic diagrams of sender and receiver peripheral devices to realize PULSEHV on the Teensy 3.2 microcontroller.

voltage divider to convert its 12 V level down to the 3.3 V signal levels used by the microcontroller. Through these two additions to the electric fence energizer, namely the possibility to increase its capacitor value and tapping into its output trigger, the foundation for a practical application of PPM for data transfers between embedded systems has been laid.

In order to confirm the linearity of the timings in practice, we have conducted another preliminary experiment, in which we have increased the capacitance by connecting up to seven additional capacitors of 33 nF each in parallel to C_1 . To visualize the impact of these changes, we show the distribution of resulting values for t_p in Fig. 3. The diagram primarily shows distinct and equally spaced groups of pulses that have been transmitted using the same pause duration. It also becomes apparent that there is no overlap between pulse arrival times. This indicates that there is even potential for optimization through the use of intermediate values for time t_p that elapses between transmitted pulses.

B. Sender Implementation

As highlighted above, pulse positions can be altered by enlarging the capacitor used to determine the NE555's timings. Thanks to the linear impact of the capacitor's size on the pulse timings (cf. Eq. (2)), precise increments can be achieved easily. In particular, by connecting a set of switchable capacitors of different capacity values to the NE555, an exponential number of resulting pulse positions can be attained. In our sender implementation, we have thus decided to connect four capacitors to the NE555 circuit, using a series of exponentially growing values for their capacitances. By placing MOSFET transistors in series with the capacitors, they can be individually connected and disconnected from the NE555, controlled by the microcontroller.

Based on the slightly varying length of the time between beginning and end of each pulse (cf. Fig. 1a), we have decided to implement a minimum pulse position increment of about 30 ms between different capacitor configurations. Thus, we have selected 15 nF as the minimum capacitance to add, and approximately doubled this value for each additional capacitor. In our prototype implementation, the concrete values measured using a calibrated RLC meter were 15 nF, 33 nF, 62 nF (nom-

inally 63 nF), and 122 nF (nominally 120 nF). Through all combinations of the four capacitors, 16 different capacitance values can be realized, and pulse intervals ranging from 1.26 s to 1.73 s be accomplished in practice. Thus, one four-bit symbol can be encoded in each pulse interval. At the same time, the primary functionality of the electric fence energizer, i.e., emitting regular electric pulses for farming applications, is not impacted. To increase the throughput further by encoding longer data words, the extension of the capacitor bank by a fifth value would have seemed meaningful. However, in order to allow for the correct distinction between pulses, the upper limit of the interval t_p is bounded by double the minimum pulse interval (i.e., 2.52 s in our case). Adding an additional capacitor, which would have to be double the capacity of the largest existing capacitor (i.e., 240 nF) would have violated this criterion. A schematic visualization of the sender-side circuitry is shown in Fig. 4a.

The figure also shows the pulse feedback pin on the right-hand side. It signals an interrupt to the microcontroller whenever a high-voltage pulse has been emitted, and thus indicates the moment when changes to the capacitor configuration can be made without any negative impact on the timing accuracy. The set of active capacitors is determined through mapping the next four bits of input data to the switching transistors of the capacitor bank. A logic high level leads to the capacitor being connected to the circuit, a logic low level to its disconnection. The 15 nF capacitor corresponds to the least significant bit and the 122 nF capacitor to the most significant bit of the four-bit data word.

C. Receiver Implementation

In analogy to the sending side, we have designed the receiver devices based on the Teensy microcontroller. However, without loss of generality, any other low-power microcontroller device with accurate timestamping abilities can be used to receive data sent through the electric fence. The electric field is captured using a length of wire, which is connected to the input of an operational amplifier in voltage follower configuration for impedance matching. The large input impedance of an operational amplifier is required to minimize signal distortions. The Microchip MCP602 low-power rail-to-rail operational

amplifier device is specified to consume only $230\mu\text{A}$ of quiescent current per channel, and offers an input impedance of $10^{13}\Omega$. By connecting the operational amplifier’s power supply to an output pin of the microcontroller, it can be selectively enabled when transmissions are expected to occur. Besides conserving power during the remaining time, this also allows for extended sleep cycles of the microcontroller which reacts to incoming pulses through interrupt handlers. The choice of a long piece of wire instead of more sophisticated antenna options (e.g., a ferrite cores) is based on the fact that electric fence energizers emit a purely electrical field. Without the presence of electromagnetic field components, inductive antenna components are inapplicable to receive the signals. We have supplementally run an experiment to compare the received signal strengths for these two different antenna types, and confirmed that the quickly changing potential between the fence and ground can be captured best using a length of wire.

V. EVALUATION

After having presented the design and implementation of PULSEHV on both sender and receiver devices, we evaluate several important properties of the system next. We focus on the assessment of three crucial aspects of our system design. Firstly, an important factor for the practical applicability of PULSEHV is to have a consistent duration of pauses (t_p) over time, in order to allow for a reliable detection of the transmitted data words. Secondly, we quantify the achievable throughput and the likeliness of bit errors to occur during transmissions. Thirdly and lastly, we demonstrate the low energetic overhead when running PULSEHV on receiver devices in practice.

A. Evaluation Setup

To evaluate PULSEHV, we have deployed a single sender device and a single receiver device (configured as shown in Fig. 4) in our laboratory. The distance between the sender’s antenna and the receiver was approximately 1 m. The software implementation on the sender device modulates pre-determined data words through modifying the pulse positions, as described in Sec. IV-A. On the receiving devices, a software implementation is executed to determine the length of the time intervals between the final peak of the preceding high-voltage pulse and the initial peak of the next pulse.

PULSEHV’s detection whether a pulse originates from the fence energizer is based on the fundamental frequency of the waveform following the initial pulse. Any signal that does not oscillate at a frequency of approximately 10 kHz (cf. Fig. 1a) is disregarded. To further reduce the number of false-positive pulse detections, no interrupts are recorded for about 800 ms after a detected pulse. As mentioned above, this filtering is valid as the pulses from the electrical fence energizers have unique characteristics, by which they can be distinguished from other sources of pulsed electrical fields.

B. Consistency of Detected Pulse Intervals

To practically confirm the consistency of the pulse intervals of our PULSEHV sender design (cf. Sec. IV-B), we performed

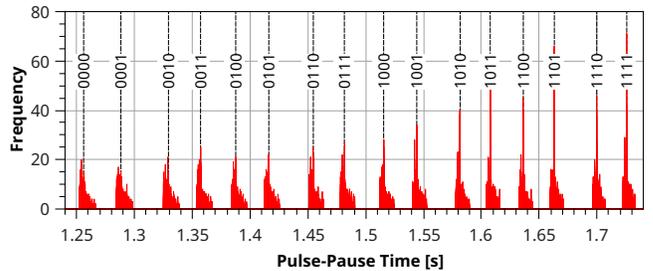


Figure 5. Histogram of practically measured pulse interval durations.

a continuous transmission test over a period of more than 20 hours. The sender device has randomly selected a four-bit word for each transmission, and modulated it onto its emitted high-voltage pulse via PPM. During the test, about 350,000 events were triggered at the receiver device, and about 55,000 valid data words detected. The difference between triggered events and valid data word detections is caused by the detection of the actual pulse as a combination of several zero-crossing events occurring at approximately 10 kHz, followed by the final pulse at a temporal displacement of around 10 ms (cf. Fig. 1a). A visualization of the pulse intervals is given in Fig. 5, with a detailed analysis of the distributions of pulse intervals provided in Table I.

Across all transmitted words, the interval timings detected at the receiver were within ± 7 ms around the mean durations of t_p , with standard deviations consistently around ± 3 ms. An important observation to make is that the intervals are non-overlapping, i.e., a confusion between transmitted words is excluded by the choice of our capacitor sizes.

C. Throughput Limits and Communication Errors

Through the application of the pulse position modulation, the time to transmit a word varies between 1.253 s (0000) and 1.733 s (1111). This is due to the used modulation of pulse lengths (cf. Table I). Assuming a uniform distribution of data

Table I
PULSE INTERVALS FOR ALL POSSIBLE COMBINATIONS OF THE CAPACITOR BANK, DETERMINED THROUGH PRACTICAL MEASUREMENTS.

Input	NE555 capacitor	t_p [s]	$\min(t_p)$ [s]	$\max(t_p)$ [s]
0000	C_1	1.256 ± 0.0031	1.253	1.266
0001	$C_1 + 15\text{ nF}$	1.289 ± 0.0032	1.285	1.298
0010	$C_1 + 33\text{ nF}$	1.329 ± 0.0030	1.325	1.339
0011	$C_1 + 48\text{ nF}$	1.358 ± 0.0031	1.354	1.367
0100	$C_1 + 62\text{ nF}$	1.388 ± 0.0029	1.384	1.397
0101	$C_1 + 77\text{ nF}$	1.416 ± 0.0030	1.412	1.425
0110	$C_1 + 95\text{ nF}$	1.455 ± 0.0028	1.451	1.463
0111	$C_1 + 110\text{ nF}$	1.482 ± 0.0029	1.478	1.491
1000	$C_1 + 122\text{ nF}$	1.516 ± 0.0027	1.512	1.524
1001	$C_1 + 137\text{ nF}$	1.544 ± 0.0027	1.541	1.553
1010	$C_1 + 155\text{ nF}$	1.581 ± 0.0026	1.578	1.590
1011	$C_1 + 170\text{ nF}$	1.608 ± 0.0026	1.604	1.616
1100	$C_1 + 184\text{ nF}$	1.636 ± 0.0025	1.633	1.644
1101	$C_1 + 199\text{ nF}$	1.663 ± 0.0025	1.660	1.671
1110	$C_1 + 217\text{ nF}$	1.700 ± 0.0024	1.696	1.707
1111	$C_1 + 232\text{ nF}$	1.726 ± 0.0024	1.722	1.733

Table II
STATISTICAL ANALYSIS OF TIME BETWEEN ERRORS.

Min.	Lower quantile 25%	30%	Median	Upper quantile 60%	75%	Max.
0.13 s	1.54 s	5.26 s	62.58 s	183.61 s	398.83 s	4147.85 s

words leads to an average data rate of one 4-bit word every 1.493 s. Thus, the achievable bandwidth for communication is $C = \frac{4 \text{ bit}}{1.493 \text{ s}} \approx 2.7 \frac{\text{bit}}{\text{s}}$.

Messages larger than 4 bits in size are fragmented into multiple 4-bit words, and sent in a consecutive manner. If messages are sent in fragments, however, the probability of transmission errors increases with the number of fragments. We have thus analyzed the frequency and distribution of erroneous pulse detections through the log files of received signals. In the test, the operational amplifier was always powered on to allow the system recovery after erroneous receptions. Our analysis has shown that the median of the measured times between two erroneous pulse detections is 62.58 s. It has furthermore shown that most errors occur in bursts. During periods without errors, the inter-error interval commonly ranges from several minutes to over an hour. More statistical features of the error distribution are summarized in Table II.

A second analysis was performed to prove that errors per 4-bit word are independent from the chosen message lengths. To prove this, we measured the error probability for message lengths of 1, 4, 8, and 16 4-bit words. Fig. 6 shows the measured error probability for different message lengths.

If the probability of errors per word is statistically independent from the message length, we can model the error probability for a message as follows: $P_m(n) = 1 - (1 - P_w)^n$ (where P_w is the error probability for one word and n the length of the message m). The probability of errors for this model is also depicted in Figure 6. A correlation coefficient of $r = 0.9923$ between the model and the measured values proves that message lengths do not affect the error probability per word.

D. Receiver Energy Overhead

A mains connection or a dedicated power supply is mandatory for the operation of an electric fence energizer due to its power demand. We thus solely focus on the additional energy requirement of the receiver-side terminal when running PULSEHV. Particularly as sensing platforms are often limited to tight energy budgets, minimizing their power demand is crucial for their long-term practical deployment.

Revisiting the receiver-side circuitry, as shown in Fig. 4b, we can observe that only one active component has been added to the sensor platform, namely the operational amplifier. To maintain the low-power operation of the platform, a low-power operational amplifier model with a nominal current draw of only 230 μA per channel has been selected. A two-channel device has been chosen because of an initial idea to operate different antenna realizations in parallel; after gaining insights

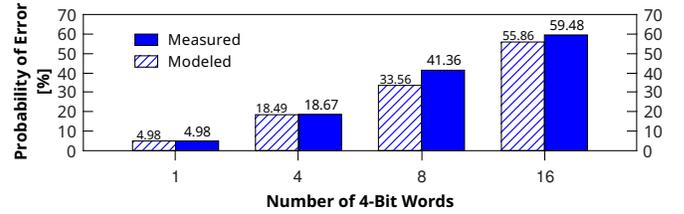


Figure 6. Evaluation of the probability of error for different message lengths.

on the inadequacy of ferrite core antennas (briefly discussed in Sec. IV-C), however, we have dismissed this option. Practical measurements have confirmed its total power consumption to be at most $P_O = 2 \text{ mW}$, even during phases of signal amplification. Besides the operational amplifier, a second source of power dissipation is visible in the figure: The resistor network connected to the input terminals of the operational amplifier leads to a constant current flow between the supply voltage's terminals. Given the $2 \text{ M}\Omega$ total resistance, a quiescent power dissipation of $P_R = \frac{(3.3 \text{ V})^2}{2 \text{ M}\Omega} = 5.445 \mu\text{W}$ is observed. Through the connection of the operational amplifier's supply voltage terminal to an output pin of the microcontroller, the energy consumption model shown in Eq. (3) can be derived.

$$E_{total} = P_R \cdot t_{total} + P_O \cdot t_{active} \quad (3)$$

While t_{total} refers to the entire duration of a word transmission, i.e., between 1.253 s and 1.733 s, time t_{active} only contains the fraction of time during which the operational amplifier needs to be active, which depends on the transmitted data word. For example, when transmitting the word 0000, the operational amplifier can remain inactive for 1.253 s after the previous pulse, and only needs to be powered for at most $t_{active} = 0.013 \text{ s}$ to reliably detect the word (see Table I). Even in the worst case, i.e., the transmission of 1111, where the operational amplifier must be turned on during the 16 receiver slots (cf. Fig. 5) with $t_{active} = 196 \text{ ms}$ across an entire interval of 1.733 s length, the duty cycle of the operational amplifier is only 11.3%. Using above values in the computation, the reception of the shortest word 0000 leads to an energy demand of $E_{total} \approx 27.3 \mu\text{J}$ (with $t_{total} = 1.27 \text{ s}$ and $t_{active} = 10.2 \text{ ms}$). In contrast, receiving the longest word 1111 represents the worst case energetically and requires at most 401.4 μJ (with $t_{total} = 1.733 \text{ s}$ and $t_{active} = 196 \text{ ms}$).

E. Data Transmission Test Case

For a sample transmission, two messages with contents related to smart farming applications were chosen. Firstly, messages with weather forecast information were encoded into packets to let distributed sensor nodes with energy-harvesting components know about their expected future energy intake. Weather forecast statistics included minimal temperature, maximum temperature, chance of rain, amount of rain, chance of sunshine, wind speed and air pressure. Secondly, parts of the DCF77 time signal [26] were re-combined to transmit information on the current hour and minute. Both packets were combined into a compact representation of 66 bits in total, such

that they can be sent through a sequence of 17 data words. In order to increase the reliability of the transmission, parity bits were added to different subparts of the message as well as the whole transmission, resulting in a 72 bit long package which can be transmitted by means of 18 4-bit-words. The test was carried out with one sender and one receiver device and conducted in a laboratory environment. To cater for the synchronization between sender and receiver and signal the beginning of a transmission, a preamble preceding the message has been used. The chosen data preamble was 1110-0001-1110 as neither any of the containing data words nor the preamble as a whole are of valid parity. Thus any reception of these values as data words would be disregarded due to the parity error. The transmission was continuously repeated in order to allow for a reception of the message by devices that failed to synchronize to beginning or encountered reception errors. Any duration in excess of 2 s without a pulse reception was interpreted as a missing data word and therefore the received message was dismissed.

The sample transmission could be recognized in about 75 % of cases. Furthermore, most cases of failed transmissions could be traced back to an incomplete preamble, resulting from a delay in the reception of the previous message instead of a channel error.

VI. CONCLUSIONS

We have presented PULSEHV, a novel way to accomplish broadcast transmissions of control data in smart farming scenarios. Relying on widely used electrical fences, we have demonstrated how data can be modulated onto the high-voltage pulses emitted from the fence energizer at little overhead. Through the application of pulse position modulation, a broadcast communication system with low data rate, yet also very low receiver-side energy consumption, has been created. In practical experiments, we could show that an encoding of 4 bits per pulse interval leads to a data rate of $2.7 \frac{\text{bit}}{\text{s}}$, with very low channel errors. In the future, we plan to increase PULSEHV's robustness against channel errors even more by including ways for sender-side data coding.

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