LOW-POWER VOTING DEVICE FOR USE IN EDUCATION AND POLLS
EMPLOYING TI’S CC2530 RF CHIP

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ABSTRACT

HSRvote is a teaching tool that allows teachers to visualize the progress of their students. It brings the prickle and the glamour of a quiz show into the classroom. Tests are becoming a game and the fun factor is guaranteed. The devices for the students contain a battery-driven CC2530 (uC with RF frontend) and four push-buttons for the answer options. On pressing the push-button, a short 802.15.4 radio telegram of less than a millisecond is delivered to the RF receiver sitting in a USB dongle on the teachers PC.

1. MOTIVATION

In an effort to engage more young people into the field of engineering, many institutions on all continents have started programs to foster STEM (science, technology, engineering, and mathematics) or MINT (mathematics, information sciences, natural sciences, and technology) interest. The University of Applied Sciences in Rapperswil has selected 50 high-schools that will receive a classroom set containing 30 devices each in order to promote the idea of designing and producing hardware in Switzerland. Striving to create an interdisciplinary project the device housing is manufactured at HSR by the Institute of Material Science and Plastics Processing [6]. The design of the housing was developed within the scope of a project thesis at HSR [5].

2. BENEFITS

The physics faculty at the University of Colorado found a substantial increase in class attendance after introducing the similar, commercially available, iclicker system. The figures increased from 60% - 70% attending class to 80% - 90% by interactively incorporating students into lecture [4]. Similar effects were reported by other universities after introducing a Classroom Response System (CRS).

3. HARDWARE

The hardware is arranged as a set of 30 transmitters and one receiver, although the number of transmitters can be increased within certain limits to suit larger classes. The back link used implies that both devices to transmit and receive radio packets. For clarity we therefore define the transmitter as the hand-held device used by the participants and the receiver as the device connected to the USB port of the lecturers computer.

The basis of both, transmitter and receiver, is Texas Instruments’ RF SOC CC2530, which provides radio transmission in the license free 2.4 GHz ISM band [1] [2]. An overview of the physical-layer parameters is given in Table 1. On the transmitters, four push-buttons allow the user to choose one of up to four given answers. The power is supplied by a CR 2016 coin-cell battery, which should last up to 8 years for a typical usage case of one game a day. On the receiver side an additional USB controller provides connectivity to the host computer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>2.41 GHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>250 kBit/s</td>
</tr>
<tr>
<td>Spreading gain</td>
<td>8</td>
</tr>
<tr>
<td>Modulation</td>
<td>OQPSK</td>
</tr>
<tr>
<td>Chip rate</td>
<td>2 MChips/s</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 MHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>4.5 dBm</td>
</tr>
</tbody>
</table>

Table 1: Overview of physical layer parameters.
3.1 Link Budget

The transmit power of the CC2530 is configured to the maximum of 4 dBm for transmitter and receiver. The transmitter uses a folded dipole designed onto the circuit board with a gain of 2 dBi. Due to size limitations a ceramic chip antenna is used on the receiver side. Assuming a favorable receiver-orientation the receiver-side gain is assumed as -4 dBi. With a typical RF sensitivity of -97 dBm, the maximal path loss is

\[ P_{\text{Lmax}} = P_{\text{tx}} - P_{\text{rx}} + G_{\text{tx}} + G_{\text{rx}} = 4 \text{dBm} + (-97 \text{dBm}) + 2 \text{dBi} + (-4 \text{dBi}) = 99 \text{dB} \]  

Assuming open field propagation with transmitter and antenna both placed at a height of 1 m results in a path loss according to Figure 2. The theoretical maximal path length according to Fig. 2 therefore is \( \approx 300 \text{ m} \). The results of a outdoor field test have shown that the useful range indeed exceeds 150 meters. The propagation conditions for indoor usage certainly are more demanding with a multipath channel rather than an open-field situation. The results nevertheless indicate that the available link budget presumably is sufficient even for a use in a larger auditorium.

3.2 Collision

The back-of-the-envelope calculation of the collision probability can be carried out as follows. Assume \( T \) as the uniformly populated (by the \( N \) devices under observation) activity window (default 5s). The slot length is assumed to be \( t = 384 \mu\text{s} \). Because the slots are not aligned, a collision might occur if another devices starts a transmission within less than \( t \) prior to the first device’s slot. So, essentially each device occupies \( 2t \) of the activity window. The chance of collisions happening within the activity window (one or several) can thus be expressed as

\[ p_{\text{collision}} = 1 - \prod_{n}^{N-1} (1 - \frac{2t}{T} n). \]  

Both results are collected in Fig. 3

4. MESSAGE STRUCTURE

To reduce transmission overhead, the MAC layer is not used and the physical-data-service unit (PDSU) only contains the necessary payload. For a net payload of 4 Bytes this results in 12 Bytes being transmitted on the physical layer. For the CC2530 RF chip used, this results in the medium being occupied for 384 \( \mu\text{s} \). The content of the payload is shown in Fig 4. Only the "Data" part is user-defined the rest is generated by the chip. The first two Bytes contain the "ID Class", that is used to distinguish transmitters from different sets. Byte 2 contains the transmitter ID which usually ranges from 1 to 30. Byte 3 contains information about the message type (PID), the acknowledge delay, and the button pressed. The PID is used to mark a message either as an (asynchronous) initial request, a resynchronization request, or the notification of a button press. The randomly generated acknowledge delay defines the slot in which the acknowledge packet is expected by the transmitter.

For a large number of devices (>100), collisions happen with a high probability as can be seen from Fig. 3. In order to establish the number of dropped packets, we compute the probability of failed packets as the complementary of the normalized throughput in an ALOHA access scheme [3]

\[ p_{\text{failed}} = 1 - \exp\left(-\frac{2t}{T} N\right). \]  

Both results are collected in Fig. 3
4.1 Collision Avoidance

To minimize the risk of collisions, a slotted protocol is used. During the first transmission a transmitter synchronizes to the receiver’s slot timing. Following transmissions are then performed synchronized. The synchronization is maintained by periodical re-synchronization. The re-synchronization frequency entirely depends on the accuracy of the sleep-timers clock source. To limit the resynchronization rate an external 32.768 kHz crystal with a frequency stability of 20 ppm is used. The duration of a slot is defined as 32 crystal ticks which equals 977 µs. Figure 6 shows that the beginning of the physical header is synchronized to the center of the slot. The reason for synchronizing on the beginning of the physical header is that the receive interrupt is generated at this instant during the reception of a packet. The maximally allowed timing bias is defined as 250 µs, including a slight margin. Re-synchronizing every

\[ T_{\text{SYNCmax}} = \frac{250 \mu s}{\sqrt{(20 \text{ ppm})^2 + (20 \text{ ppm})^2}} = 8.84 \text{ s} \]  

(4)

therefore ensures that all transmissions occur within the time-slot bounds. After a button press the synchronization is maintained by periodical re-synchronization. A re-synchronization packet is transmitted every \( T_{\text{SYNCmax}} \) or every time a button is pressed. If no further button press is registered for a predefined time interval the transmitter stops synchronizing itself and enters deep-sleep mode (See Fig. 5).

![Image](image_url)

Figure 5: Illustration of the synchronization / re-synchronization procedure.

4.2 Retransmission

In case that a transmission is not acknowledged by the receiver, the transmitter will retry in a random slot within a predefined time-window.

In earlier firmware versions the reception of a packet was not acknowledged by the receiver. Collision detection was based on optical feedback on the presentation screen via a separate reception indicator per participant. Using acknowledge and retransmission increases the energy consumption on average by a factor of \( \approx 3 \).

4.3 Clear-Channel Assessment

The built-in clear-channel assessment (CCA) feature of the CC2530 is not used. The CCA, also known as listen before talk, activates the radio in receive mode to check if the channel is available for transmission before transmitting. The CCA increases the energy demand per transmission by \( \approx 10\% \). The simulation results in Sec. 5.2 show that the expected increase in energy demand due to retransmission is lower for average transmitter-sending rates > 1 second. From an energetic standpoint the use of CCA is therefore not worthwhile in the assumed scenario.

5. SIMULATION

To get an estimate of the system’s reliability, the probability of all 30 devices’ signals being successfully received was analyzed with a Monte-Carlo simulation.

5.1 Simulation Parameters

The transmissions of each transmitter are assumed to occur periodic. The delay between two subsequent transmissions is modeled as Rayleigh distributed

\[ f(t, \sigma) = \frac{t}{\sigma^2} e^{-t^2/(2\sigma^2)}, \quad t \geq 0. \]  

(5)

The random retransmission delay follows a uniform distribution

\[ f(n) = \frac{1}{n}, \quad n \in \{1, \ldots, n_{\text{max}}\}, \]  

(6)

where \( n \) is the number of slots to wait before retransmission.

The simulation scenario assumes 30 transmitters participating in the quiz. The mean of the Rayleigh distribution \( m \) is varied from 50 ms up to 10 s.

5.2 Probability of Successful Transmission

Fig. 7 shows the probability of a successful transmission with a certain number of retransmissions depending on \( m \). For \( m = 1 \) s the probability that a packet must be retransmitted once before being successfully received is eight percent. It can be seen that the benefit of increasing the maximal retransmission count \( r \) rapidly decreases as \( r \) increases. The probability of a packet not being received even after the maximal number of retransmissions is represented by the dotted line at the bottom. Again for \( m = 1 \) s and \( r = 10 \) the packet-error-rate (PER) is \( 1 \cdot 10^{-7} \). The probability of a successful transmission is shown by the dotted line at the top. The PER is well below \( 1 \cdot 10^{-4} \) for \( m \geq 0.4 \) seconds.

6. FURTHER WORK

Using the built-in AES co-processor an alternative with a secured transmission is currently being looked at. Using encryption however massively increases energy demand due to additional processor load and an increased amount of data to transmit. Another area of interest is the ability to harvest
the energy needed for transmission from, if possible, a single button press. For this approach only a minimalistic one way transmission is used since energy is very limited and does not allow the usage of a protocol.

7. CONCLUSIONS

A low-power voting system based on TI's CC2530 system-on-chip has been presented. The simulation results show its transmission reliability in conjunction with the presented protocol.

REFERENCES