Efficiency of Orthogonal Codes for Quasi-passive Wake-Up Radio Receivers using Frequency Footprint IDs

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***Abstract*—This paper introduces robust wake-up IDs for quasi-passive wake-up receivers in an Internet of Things context. These IDs can address single devices and are based on the Hadamard code. Further a novel wake-up threshold is implemented to make the device more sensitive and robust against false wake-ups (FWUs) . The wake-up procedure is simulated with a tap delay line (TDL) model for a line of sight (LOS) channel and a non line of sight (NLOS) channel. In both scenarios sufficient wake-up distances are reached with low false wake-up probabilitys (FWUPs) . Additionally, the system is tested against the influence of an external bandwidth use. Finally, a recommendation for the global system is given.**

I. INTRODUCTION

Seeing data transmission as a process, a solution needs to be found to cut done the non-productive energy consumption. Several techniques have been proposed to find power management for wireless network systems. In 802.11, a power save mode has been designed to lower the consumption. But there is still energy needed for not used duty cycles. Radio-triggered wake-ups with simple OOK have been proposed. The advantage of no energy consumption, when no transmission is required [1], comes on the other hand with shrinking network areas. Suffering from low sensitivity, only small wake-up distances can be achieved. [2] found a way to make the receiver site more sensitive and achieve higher wake-up distances. Using this technique, [3] presented an ID based quasi-passive wake-up receiver (WuRx) for OFDM transmitter. Further they demonstrated a prototype and proved the functionality of the architecture [4]. Especially the power saving aspect has been testified. This work will consider which kind of IDs are practical for this WuRx architecture. To achieve the aim of robust and numerous IDs a Hadamard code is used to find practical IDs. The paper will test the robustness of these IDs by simulating an indoor environment, taking a non line of sight and a line of sight channel into account. Besides it proposes an improvement for the architecture to reduce FWUs : a novel architecture for the threshold is implemented. The threshold is adaptive and can react on channel influences and distance. Further it is no longer fixed and must be set for every channel. In the first section, the Hadamard based IDs are introduced and mathematically validated, followed by the proposed channel models and the implementation of the new threshold. In the third section, the results of the simulation are presented and discussed. Further discussions and the conclusion are found in the final section.

II. WALSH-HADAMARD BASED WAKE-UP IDS

In this scenario, the WuRx is waked up by a unique identification code

$$\boldsymbol{I}_j = [I_{j,1}, \ldots, I_{j,k}, \ldots, I_{j,n}];\ I_{j,k} \in \{0,1\},\ \forall k = 1, \ldots, n. \tag{1}$$

The sent ID for the device $j \in [1, \ldots, m]$ is split on the receiver side into two paths. The direct path D has the same pattern as I

$$\boldsymbol{D}_j = \boldsymbol{I}_j. \tag{2}$$

The complementary path C is the negation of I

$$\boldsymbol{C}_j = \neg \boldsymbol{I}_j. \tag{3}$$

The code is transmitted in a given channel bandwidth by enabling frequencies bands, with a sub bandwidth

$$\Delta f_{sub} = \frac{B}{n}. \tag{4}$$

For the ID I_j in an ideal case the signal is

$$S_j(f) = \sum_{k=1}^{n} I_{j,k} \cdot \hat{s} \cdot \mathrm{rect}\left(\frac{2f}{\Delta f_{sub}} - \frac{2k-1}{2} \cdot \Delta f_{sub}\right), \tag{5}$$

with a transmitted power of

$$\begin{aligned} P_{TX} &= \int_0^{BW} |S_j(f)|^2 \,\mathrm{d}f \\ &= \left(\sum_{k=1}^{n} I_{j,k} \cdot \hat{s} \cdot \Delta f_{sub}\right)^2 \end{aligned} \tag{6}$$

Channels which can be used are given by non-overlapping OFDM-channels, e.g. for 802.11g there are 3 usable channels (Channel 1, 8 and 11) with a channel bandwidth $B = 22\,\mathrm{MHz}$. So, a $n \times m$ matrix is searched in which m is the number of IDs and so the supportable number of devices in one cell. The goal is to get a maximum of m robust codes with a low FWUP and a high-power transmission, to achieve high wake-up distances. [3] gives three conditions for a code:

1)
$$\sum_{k=1}^{n} D_{j,k} I_{j,k} - \sum_{k=1}^{n} C_{j,k} I_{j,k} > 0 \tag{7}$$

2)

$$\sum_{k=1}^{n} D_{j,k} \cdot 1 - \sum_{k=1}^{n} C_{j,k} \cdot 1 \leq 0 \tag{8}$$

3)

$$\sum_{k=1}^{n} D_{j,k} I_{j,k} - \sum_{k=1}^{n} C_{j,k} I_{j,k} \leq 0; \forall i \in \{[1,\ldots,m] \setminus i = j\} \tag{9}$$

The Hadamard code always gives a $n \times n$ matrix, where n is $1, 2$ or a multiple 4. The n code lines are orthogonal to each other and they disagree in $n/2$ positions. Thus, the code has a Hamming distance of $d = n/2$. For further simulations, the Hadamard matrices $H_{o,n}$ of the order $n = 4, 8, 12, 16$ are considered, e.g.

$$H_{o,4} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

with the negation

$$\neg H_{o,4} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}. \tag{11}$$

A higher order is directly linked to the filter bandwidth or the overall channel. Considering possible filter bandwidth for a fixed bandwidth, especially for passive bandpass filters, a higher order then $n = 16$ is not worthwhile to regard. For the IDs, a reduced Hadamard matrix H_n is used, since the rows which consists only out of 1 or 0 are not usable. The identifier matrix will be

$$D = I = \begin{bmatrix} H_n \\ \neg H_n \end{bmatrix} \tag{12}$$

and the complementary matrix

$$C = \neg I = \begin{bmatrix} \neg H_n \\ H_n \end{bmatrix} \tag{13}$$

with the order $C, D = \mathbb{N}^{n \times 2(n-1)}$. Solving the three conditions for the Hadamard based codes:

1)

$$\sum_{k=1}^{n} D_{j,k} I_{j,k} - \sum_{k=1}^{n} C_{j,k} I_{j,k} = \frac{n}{2} > 0 \tag{14}$$

2)

$$\sum_{k=1}^{n} D_{j,k} \cdot 1 - \sum_{k=1}^{n} C_{j,k} \cdot 1 = 0 \leq 0 \tag{15}$$

3)

$$\sum_{k=1}^{n} D_{j,k} I_{j,k} - \sum_{k=1}^{n} C_{j,k} I_{j,k} = 0 \leq 0;\ C_j \neq I_i \tag{16}$$

$$\sum_{k=1}^{n} D_{j,k} I_{j,k} - \sum_{k=1}^{n} C_{j,k} I_{j,k} = \frac{n}{2} \leq 0;\ C_j = I_i \tag{17}$$

One can see the Hadamard based IDs fulfil the three conditions.

III. SIGNAL AND CHANNEL MODELLING

A. Transmission

The signal time based on [3] is $T_s = 400$ ¯s and the bandwidth $B = 20\,\mathrm{MHz}$. The coherence bandwidth is set to

$$B_c = \frac{1}{8\tau_{max}} = 1.25\,\mathrm{MHz}, \tag{18}$$

with $\tau_{max} = 100\,\mathrm{ns}$. Since the devices are stationary no Doppler shift occurs. First the transmitted signal $S(f)$ is modulated. The output power

$$P_{TX}|_{\mathrm{dB}} = P_{out}|_{\mathrm{dB}} + P_{margin}|_{\mathrm{dB}}, \tag{19}$$

is equally distributed over the rectangular shaped signal pattern in the given bandwidth. P_{out} is the provided signal power from the transmitter, e.g. $P_{out,max} = 20\,\mathrm{dBm}$. An additional power budget $P_{margin} = 2\,\mathrm{dB}$ is added, which includes antenna gains ($3\,\mathrm{dBi}$ for omnidirectional antennas), device losses e.g. the 3-dB splitter at the receiver site. The signal pattern is given by the Hadamard based IDs. Afterwards the signal is shifted to the carrier frequency $f_c = 2.45\,\mathrm{GHz}$. Further, the well known TDL model is used to model the channels. Based on the TDL, a LOS and a NLOS channel are considered. Further an additional disturbance is added for both Channel models. The Channels are described in the following subsections.

1) NLOS Channel : The NLOS channel uses the ITU pathloss model with a factor $N = 34$, for the reduction of the overall signal power [5] [6] with

$$P_{PL}|_{dB} = 20\log_{10}(f_c) + N\log_{10}(d) - 27.6 \tag{20}$$

Further a multipath channel after Jake and Clark's is added with $L = 11$ taps, to provide comparable statistical solutions [7]. The time impulse response is given as,

$$h(t) = \sum_{l=0}^{L} h_l \cdot \delta(t - \tau_l), \tag{21}$$

with the Fourier transformation

$$H(f) = \sum_{l=0}^{L} h_l e^{-2\pi j(\tau_l f)}. \tag{22}$$

The Amplitude $h_l$and time delay τ_l of each tap is randomly distributed. For the last tap, the delay time is $\tau_L = \tau_{max}$. The first delay component is adjusted by the K-Factor, so that

$$K = \frac{P_{LOS}}{P_{NLOS}} = \frac{\hat{h}_0^2}{\left(\sum_{l=1}^{L-1} \hat{h}_l\right)^2}, \tag{23}$$

where P_{LOS} is the power of the LOS components and P_{NLOS} is the power of the NLOS components. The K-Factor states occurrence and the strength of the LOS path. The K-Factor set to $K = 0$, to provide perfect NLOS conditions and therefore no LOS path exists and the effective number of delay taps is $L = 10$. This is known as a Rayleigh fading channel. The channel impulse response is normalized, so that $|H(f)| = 1$.

2) LOS Channel: The LOS channel uses the ITU indoor path loss model with a factor $N = 28$. Again the TDL is used for channel modelling, with $L = 10$. However, a K-Factor with $K \geq 1$ is used. Therefore a LOS path is given and a Rican fading channel is simulated. As above the channel impulse response is normalized, so that $|H(f)| = 1$.

3) Additional disturbance: In an ongoing scenario an additionally disturbance, e.g. another Wi-Fi access point, is simulated. Therefore, a unified distributed signal over the channel bandwidth BW with a power P_{add} is received. The signal power P_{add} is added at the receiver side

$$P_{RX,add} = P_{RX} + P_{add}. \tag{24}$$

B. Reception

The receiver side is based on the device in [4]. The received signal is divided by a 3-dB splitter in to a direct path, with a filter structure as the ID I_j and a complementary path with a negated filter structure C_j. Each filtered signal is transformed in to a power level P_D of the direct path and P_C of the complementary path. Further they are subtracted to get the power level

$$P_{trigger} = P_D - P_C. \tag{25}$$

If the power level $P_{trigger}$ is lower than the sensitivity P_{sens}, the power level will equals the sensitivity. Next $P_{trigger}$ and a threshold are compared. In this paper, a novel adaptive threshold is used, where the sum out of the power of the direct path P_D and complementary path P_C, attenuated by a factor a, gives the power level of the threshold

$$P_{t,ad} = a(P_D + P_C). \tag{26}$$

A wake-up is achieved, when

$$P_{RX} = P_D + P_C \tag{27}$$

is greater than the threshold $P_{trigger} > P_{t,ad}$. Solving (25) and (26) for (27) gives the equation:

$$P_D > \frac{1+a}{1-a} P_C \tag{28}$$

For the ongoing studies, a factor $a = 0,9$ has been chosen. Thus, after (28) the condition for a wake-up is set to:

$$P_D - P_C > 12.79\,\mathrm{dB} \tag{29}$$

Note that the occurring white Gaussian noise can be neglected, due to a long broadcast time of $T_s = 400\,^{-}\mathrm{s}$ in time domain and the power detection over filter structures in the frequency domain.

C. Simulation

For one given channel (NLOS, LOS) each signal based on the Hadamard code

$$S = \begin{bmatrix} H_{o,n} \\ \neg H_{o,n} \end{bmatrix} \tag{30}$$

is transmitted to every filter structure j of the IDs

$$I = \begin{bmatrix} H_n \\ \neg H_n \end{bmatrix}. \tag{31}$$

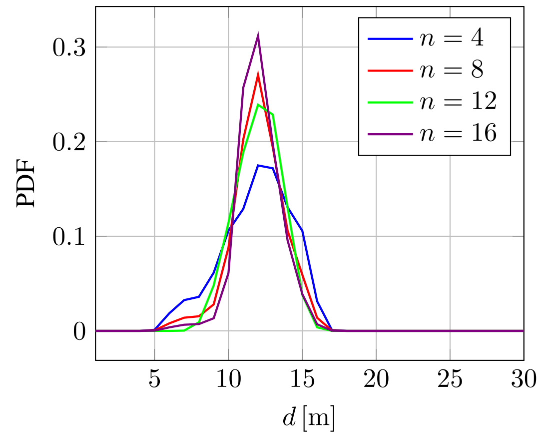

Figure 1: PDF of d_{max} for different H_n and $\tau_{max} = 50\,[\mathrm{ns}]$

A sent ID with a received power level $P_{TX} \geq P_{sens}$ or $P_{TX} \geq P_t$ will be defined as a wake-up. If a wake-up is happening by another signal then the ID, it will be called a FWU .

IV. RESULTS

A. NLOS Channel

In the first simulation, the maximum delay for the channel model is set to $\tau_{max} = 50\,\mathrm{ns}$. To compare the $2(n-1)$ filter structures of each H_n based ID matrix, $n_C = 1000$ statistical independent channels have been simulated. Therefore the number of channels which have the same maximum distance d_{max} are counted and normalized by n_C.

Fig 1 shows the probability distribution function (PDF) of the maximum received distance d_{max} for $n = 4, 8, 12, 16$. By increasing n, the probability of reaching larger distances d_{max} decreases slightly. However the operation realm d_{true}, where the cumulative distribution function (CDF)$>$ 0.9, increases marginally Thus, the reachable distance is more predictable. But even for $n = 4$ in $90\,\%$ of the cases, a wake-up is achieved with $d_{max} > 8\,\mathrm{m}$.

B. LOS Channel

The IDs are now tested in an LOS scenario as described above. The ID order is set to $n = 8$, the maximum delay is $\tau_{max} = 100\,\mathrm{ns}$ and the K-Factor is set to $K = [1, 5, 10, 30]$. The resulting CDFs are displayed in Fig. 2. For the LOS channel the wake-up distance is increased compared to NLOS channel, due to the pathloss. Further with increasing K the maximum reachable distance is decreasing, due to missing amplification of single subbands. However the reliable operation realm d_{trust} is wider.

C. Additional Disturbance

Last the signal robustness against an external Wi-Fi use in the operated channel is simulated. A signal with the power $P_{add} = [-100\,\mathrm{dBm}, -60\,\mathrm{dBm}, -50\,\mathrm{dBm}, -40\,\mathrm{dBm}, -30\,\mathrm{dBm}]$ is added. The order $n = 8$ is used with $L = 10$, a pathloss factor $N = 34$ and $K = 1$. The channel has a maximum

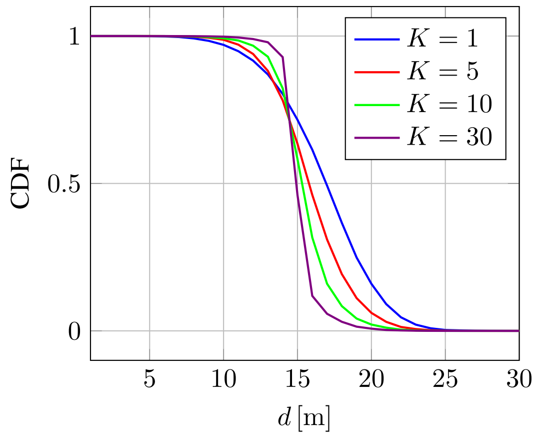

Figure 2: CDF of d_{max} for H_8 and LOS conditions

delay of $\tau_{max} = 50\,\mathrm{ns}$. As seen below the added external channel use influences the receiving distance strongly, when the disturbance is greater then $-50\,\mathrm{dBm}$.

For for stronger external power the wake-up distance is reduced. Considering $P_C = 0$, when an ID is send, the condition of (28) will be:

$$P_D > \frac{a}{1-a} P_{add} \tag{32}$$

So with a factor $a = 0.9$ the attenuated received power of a sent ID $P_{trigger} = P_D$ has to be

$$P_{trigger} - P_{add} > 9.54\,\mathrm{dB} \tag{33}$$

to achieve a wake-up. Since the receiver sensitivity is $P_{sens} = -50\,\mathrm{dBm}$, P_{add} has to be under $-60\,\mathrm{dBm}$ to not disturb the wake-up transmission. The additive power has no influence on the FWUP, because it will set the threshold higher and therefore prevent FWUs.

D. *False wake-ups*

The FWUP for different set-ups is shown in Tab. I. The FWUP is only detected for $n = 12$ and $n = 16$ with $\tau_{max} = 50\,\mathrm{ns}$ and $n = 8$ for $\tau_{max} \geq 100\,\mathrm{ns}$. The FWUP increases with higher ID order n and high delayed channel impulse responses. Nevertheless for any case, the FWUP is ≤ 0.0021 and therefore neglectable The reason for FWUs are in the frequency selectivity of the channel. If whole subbands of a signal are strongly attenuated, e.g. with the pattern of the complementary path, with a higher power then the sensitivity, will lead to a FWU. As shown in (29) the attenuation of the complementary compared to the direct subbands must be $12.79\,\mathrm{dB}$ to get a FWUs. For shorter distances the FWUP is higher, since with greater distance FWU signals, are not received any more. FWU signals have a lower transmission distance, due to double attenuation of path loss and frequency selectivity.

V. Conclusion

The Hadamard based IDs have been successfully implemented and tested for their robustness. Combined with the adaptive threshold a robust system has been found. For both channel models, the order has no big impact on the transmission distance. But a slightly better transmission has been found for higher order in both models. The main advantage of a larger order is of course given by the number of supportable wake-up devices. Comparing the two channel models, with LOS wider operation realm are accomplished. With $K = 30$, and so perfect LOS conditions, distances about $14\,\mathrm{m}$ can be reached. By using directional antennas on the receiver side, which spatially filters components outside the antenna beamwidth, side paths can be reduced [5]. Therefore even larger distances can be achieved, with an increased antenna gain and a decreased τ_{max}. Also the influence of external channel users is reduced, since these transmitters usually can not be found on the LOS path. But even NLOS transmission can be considered in small cells with a maximum transmission distance up to $8\,\mathrm{m}$. The Hadamard based IDs can handle high tap delays on costs of the wake-up distance. Still set-ups with highly delayed tabs should be avoided.

τ_{max}	H_n	FWUP
50 ns	H_{16}	0.0018
50 ns	H_{12}	0.0017
100 ns	H_8	0.0021
200 ns	H_8	0.0007

Table I: FWUP occurrence for different set-ups

References

[1] L. Gu and J. A. Stankovic, “Radio-triggered wake-up for wireless sensor networks”, *Real-Time Systems*, vol. 29, no. 2-3, pp. 157–182, 2005.

[2] H. Kim, H. Cho, Y. Xi, M. Kim, S. Kwon, J. Lim, and Y. Yang, “Cmos passive wake-up circuit for sensor network applications”, *Microwave and Optical technology letters*, vol. 52, no. 3, pp. 597–600, 2010.

[3] F. Hutu, A. Khoumeri, G. Villemaud, and J.-M. Gorce, “A new wake-up radio architecture for wireless sensor networks”, *EURASIP JWCN*, vol. 2014, no. 1, p. 177, 2014.

[4] F. Hutu, D. Kibloff, G. Villemaud, and J.-M. Gorce, “Experimental validation of a wake-up radio architecture”, in *Radio and Wireless Symposium (RWS), 2016 IEEE*, IEEE, 2016, pp. 155–158.

[5] I.-R. WP3K, “Propagation data and prediction models for the planning of indoor radio communication systems and radio local area networks in the frequency range 900mhz to 100ghz”, *Draft ITU-R P. 1238*, 1999.

[6] T. Chrysikos, G. Georgopoulos, K. Birkos, and S. Kotsopoulos, “Wireless channel characterization: On the validation issues of indoor rf models at 2.4 ghz”, *First Panhellenic Conference on Electronics and Telecommunications (PACET)*, pp. 20–22, 2009.

[7] C. Xiao, Y. R. Zheng, and N. C. Beaulieu, “Novel sum-of-sinusoids simulation models for rayleigh and rician fading channels”, *IEEE Transactions on Wireless Communications*, vol. 5, no. 12, 2006.