# A Wireless Spread-Spectrum Communication System Using SAW Chirped Delay Lines

Andreas Springer, *Member, IEEE*, Wolfgang Gugler, Mario Huemer, *Member, IEEE*, Rainer Koller, and Robert Weigel, *Senior Member, IEEE*

***Abstract*—We report on the use of broad-band chirp signals for spread-spectrum communications in indoor and industrial environments. The well-known pulse compression technique associated with chirp signals is exploited to achieve a highly robust communication system. For the generation and compression of the chirp signals, surface acoustic wave delay lines fabricated from an $LiTaO_3$-X112rotY substrate are used. Center frequency, bandwidth, chirp duration, and chirp rate are 348.8 MHz, 80 MHz, 500 ns, and $\pm$40 MHz/$\mu$s, respectively. Different modulation schemes for chirp signals are introduced, the effects of nonlinearities, frequency drift, and temperature drift are addressed, and simulations and measurement results from a hardware demonstrator are presented for the use of $\pi/4$-differential quadrature phase-shift keying (DQPSK) modulation. A data rate of up to 40 Mb/s has been achieved experimentally and shows that the proposed system is highly robust against multipath effects.**

***Index Terms*—Chirp signals, differential phase-shift keying, spread-spectrum communications, surface acoustic waves, wireless communications.**

## I. INTRODUCTION

THE rapid progress in wireless communications technology during the last decade introduced many new applications. The most prominent one is certainly mobile cellular telephony. However, besides that, many other applications have emerged with wireless local area networks (WLANs) being one of them. While the WLAN market expectations in the past years were too optimistic, the finishing of the IEEE 802.11 Standard for the industrial, scientific, and medical (ISM) band at 2.4 GHz [1] brought up a lot of products on the market. In addition, for the European HIPERLAN Type 2 Standard [2] and the IEEE 802.11a Standard [3], both for the 5-GHz band, first releases have been finished. They will support data rates up to 54 Mb/s [4]. The main application for this WLAN systems are the deployment of a wireless network in a limited geographical area, e.g., a campus. By using a WLAN, not only desktop computers can be linked together without any wiring, but also nomadic users can access the network resources, typically via a notebook and a suitable network card with a small antenna. Other applications are the use of WLANs as backbone systems and wireless local loop installations to bridge the last mile to the customers without the need for expensive wires [5].

Another market segment for WLANs are industrial applications, e.g., communication between robots and some type of controller or navigation systems for autonomous vehicles in large factory halls or hospitals, just to name a few. There are at least two specific problems associated with such industrial applications, which are not present to such an extent in an office environment. First, multipath propagation will usually cause many more severe distortions in environments with large halls and lots of objects with metallic surfaces. The average delay spread $\tau_{\mathrm{rms}}$ of the mobile radio-channel characteristic is larger and the coherence bandwidth $B_{\mathrm{C}}$ is smaller than in office buildings. The multipath radio channel features a severe fading characteristic, which causes strong distortions due to intersymbol interference (ISI) in the received signal. Additional interference is to be expected from electromagnetic emissions from any type of machinery. A typical example is, for example, the power electronics for electric drives, which can cause electromagnetic compatibility problems to a much higher extent than in office environments.

A second issue related to industrial applications of WLANs are timing and security problems. Usually, the data to be transmitted in industrial environments are real-time data, and only small delays are acceptable. Closely related to this demand is the transmission of security information. If, for example, on a handheld control device for a robot, an emergency stop button is implemented, its information must be transmitted under all circumstances. Therefore, a wireless transmission can only rely on an active security concept where data are sent steadily in both directions to indicate normal operation. If this data flow is interrupted, the robot automatically performs an emergency stop. This results in the necessity of an extremely robust wireless link to prevent an emergency stop due to bad link quality.

Today's WLAN products are not well suited to deal with both issues described above. The robustness of the physical layer is not high enough to meet industrial demands, despite the fact that it is based on direct-sequence (DS) spread spectrum (SS). SS systems have been well known for many years to provide reliable and secure communication links [6]. The degree of spreading determines the robustness of the SS system against interference. In the IEEE 802.11 based WLANs, a spreading factor of only 11, together with a channel bandwidth of 11 MHz, is applied, leading to a quite limited interference resistivity. Another type of performance degradation is encountered if multiple connections are established over the same

Manuscript received November 8, 2000; revised January 15, 2001.

A. Springer, R. Koller, and R. Weigel are with the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, A-4040 Linz, Austria.

W. Gugler was with the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, A-4040 Linz, Austria. He is now with KEBA AG, A-4040 Linz, Austria.

M. Huemer was with the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, A-4040 Linz, Austria. He is now with DICE GmbH & Co KG, A-4040 Linz, Austria.

Publisher Item Identifier S 0018-9480(01)02900-3.

channel. The net throughput, which is specified to be 1, 2, or 11 Mb/s, is then drastically reduced due to the used carrier sense multiple access/collision avoidance (CSMA/CA)-based medium access control (MAC) protocol [7]. This protocol is similar to the Ethernet protocol and controls the access to the channel via carrier sensing and randomly distributed idle times in the transceivers.

Our proposed system tackles the problem of the robustness of the wireless link. We use a different type of SS technique, namely, chirp SS [8]. The transmission of chirp signals and the use of the associated pulse compression technique, well known from radar technology [9], makes the system highly robust against interference and multipath distortions. As with the IEEE 802.11 Standard, the multiple access capability is realized in the MAC layer and not due to user-specific spreading. If necessary, additional coding can be applied to the chirp SS system if CDMA is required in the physical layer [10]. The critical sections in a chirp-based SS system are the generation of the chirp signal in the transmitter and the matched filtering (= pulse compression) in the receiver. Both operations can easily be performed using surface acoustic wave (SAW) devices. Today, SAW filters are widely used in mobile communications as filters and duplexers [11], [12]. They achieve high performance at low costs. The use of chirped SAW delay lines in combination with differential phase-shift keying will be shown to give an extremely robust communication system operating in the unlicensed ISM band at 2.4 GHz with data rates up to 40 Mb/s.

The paper is organized as follows. In Section II, the theory of chirp signals and their use in digital communication systems is described. Our proposed system concept and the simulations performed to validate it are covered in Section III, and in Section IV, a description of the used SAW devices follows. Finally, the realized demonstrator is presented together with measurement results.

## II. Chirp Signals in Digital Communication Systems

In the following, we will consider only linear chirp signals, i.e., signals that have a linearly varying instantaneous frequency. With this, we find the expression for a linear chirp signal centered at $t = 0$ as follows:

$$s(t) = a(t)\cos\left[\Theta(t)\right] = a(t)\cos\left[2\pi f_0 t + \pi\mu t^2 + \varphi_0\right] \quad (1)$$

Here, $a(t)$ is the chirp envelope with $a(t) = 0$ for $|t| > T/2$, $f_0$ is the center frequency of the chirp signal, $\mu$ is the chirp rate, and $\varphi_0$ is a phase constant. The chirp rate $\mu$ is the rate of change of the instantaneous frequency. We define an up-chirp to have $\mu > 0$ and a down-chirp if $\mu < 0$. Usually, the chirp bandwidth $B$, centered at $f_0$, is defined as the range of the instantaneous frequency

$$B = |\mu|T \quad (2)$$

The impulse response of a filter matched to a certain linear chirp signal is the same chirp signal, but with the opposite sign of $\mu$. The output of the matched filter, which is the autocorrelation function $\varphi_{\rm ss}(\tau)$ of the chirp signal, is given by [9]

$$\varphi_{\rm ss}(\tau) = \sqrt{BT}\frac{\sin\left\{\pi B\tau\left(1-\frac{|\tau|}{T}\right)\right\}}{\pi B\tau}\cos(2\pi f_0\tau) \quad (3)$$

for $-T < \tau < T$ if $a(t)$ is a rectangular function with amplitude 1 and duration $T$, and is centered at $t = 0$. The envelope of $\varphi_{\rm ss}(\tau)$ has its maximum value $\sqrt{BT}$ at $\tau = 0$ and the first zeros occur at $t \approx \pm 1/B$. Therefore, the transmitted chirp signal pulse has been compressed in time by its matched filter. If we specify the width of the autocorrelation pulse to be $1/B$, we find $BT$ as the ratio of chirp signal duration to autocorrelation pulsewidth. $BT$ is also known as pulse compression ratio or processing gain. If $a(t)$ is not a rectangular function, the sidelobes of the compressed pulse can be suppressed below the 13 dB [for rectangular $a(t)$] relative to the maximum, but at the expense of broadening the main pulse.

In chirp-based communication systems, the chirp signal $s(t)$ is somehow digitally modulated by the information bits. After pulse compression in the receiver, this digital modulation is detected in the compressed pulse. Any type of frequency shift keying (FSK) is not feasible if chirp signals are generated and processed by means of fixed SAW chirped delay lines, but amplitude shift keying (ASK) and phase shift keying (PSK) remain applicable. While on–off keying (OOK) is not recommended in highly reliable wireless systems, the use of binary orthogonal keying (BOK) is possible, since up- and down-chirp are almost orthogonal. This gives rise to a simple and cost-effective communication system, which has been described in [13]. With BOK, the maximum data rate is low because only 1 b is transmitted with each chirp signal. An enhancement of the data rate can be achieved if the transmitted chirp signals overlap in time. This is possible due to the linearity of the pulse compression. The overlapping and, therefore, the data rate, is limited by the delay spread of the mobile radio channel [13] since all multipath components, which are separated in time at least the width of the compressed pulse, occur in the matched filter output signal as distinct autocorrelation peaks. Another possibility for digital modulation is phase shift keying, which also offers the possibility to transmit more than 1 b per chirp signal. If the phase of the transmitted chirp signal $s(t)$ is modulated according to the data bits, the same modulation appears in the compressed pulse. In conclusion, chirp-based communication systems can be analyzed as any other digital communication system if the chirp signal is used instead of the baseband transmit pulse in conventional systems. In the ideal case, the pulse compression in chirp systems does not change the theoretical bit error rate (BER) behavior compared to other systems for additive white Gaussian noise (AWGN) channels. The only consequence of pulse compression in AWGN channels is the fact that overlapping in time of the transmit chirp signal does not lead to ISI as long as the spacing of the transmit chirps is larger than the width of the compressed pulses. The benefits gained from pulse compression in multipath environments can be significant, as will be described in the following sections.

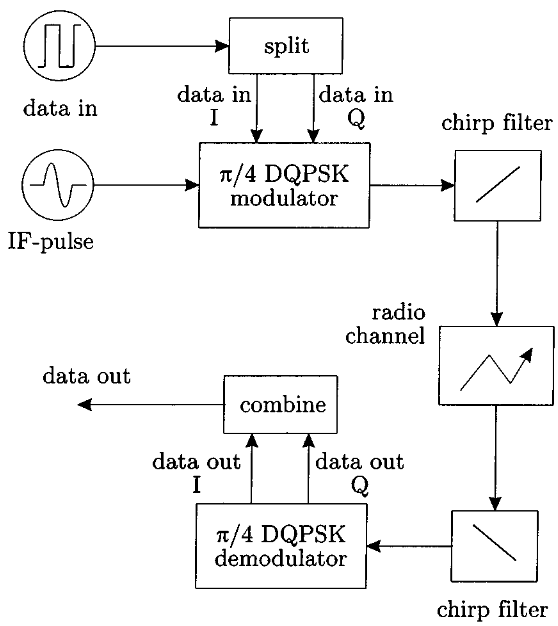


Fig. 1. Schematic block diagram of the chirp-based $\pi/4$-DQPSK communication system.

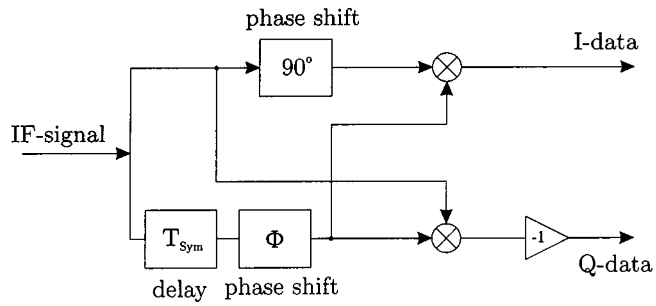


Fig. 2. Schematic block diagram of the $\pi/4$-DQPSK demodulator.

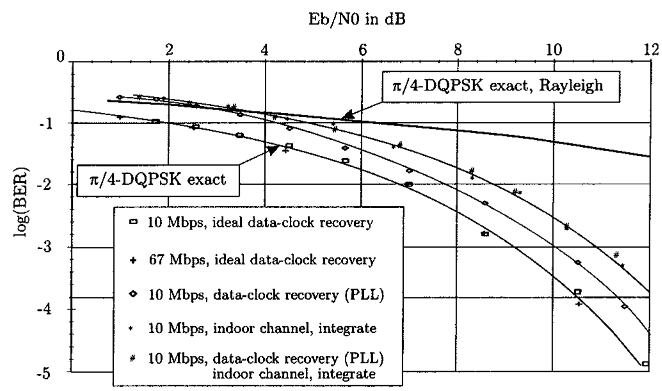


Fig. 3. Simulation results for the BER of the SAW-based $\pi/4$-DQPSK communication system.

## III. SAW-Based Chirp $\pi/4$-DQPSK System

### A. System Concept

We decided to use the well-known $\pi/4$-DQPSK technique [14] to avoid phase synchronization problems. A schematic diagram of the chirp-based $\pi/4$-DQPSK system is shown in Fig. 1. Instead of modulating the IF signal, as in conventional systems, the signal stimulating the SAW chirp filter is phase modulated. The excitation signal consists of a short IF pulse at the center frequency of the chirp filter. This pulse is phase modulated according to the $\pi/4$-DQPSK scheme and stimulates the SAW filter, thereby generating the phase-modulated chirp signal at IF. After up-conversion to RF and amplification, the signal is transmitted. In the receiver, pulse compression is performed after low-noise amplification and down-conversion to IF by passing the received signal through the matched filter. The compressed pulses are fed to the $\pi/4$-DQPSK demodulator, shown in Fig. 2. The phase shifter in the lower path of the demodulator has to account for the phase shift introduced by the delay element, which is necessary to compare the phases of the actual and previous pulse. Both phase shifters and delay can also be implemented as SAW devices. The only assumption necessary for correct operation of the system is that the mobile radio channel does not change significantly during one symbol period. This is usually true in indoor environments at high data rates.

### B. Simulation Results

The proof of the proposed system concept was done using system simulation. Where appropriate, the simulations were carried out in baseband. The chirp filters were implemented as transfer functions in the frequency domain. Their characteristics are described in Section IV. For the simulations, we used measured data of prototype SAW filters.

In Fig. 3, the simulation results in terms of BER versus $E_b/N_0$ are plotted. The term $E_b/N_0$ is the ratio of energy per bit and noise power spectral density. For transmission over an AWGN channel and ideal chosen sampling points, the system performance exactly matches the theoretical one, even for data rates up to 67 Mb/s. In this case, 17 consecutive chirp signals are overlapping, while for 10 Mb/s, three chirp signals are transmitted simultaneously. The theoretical performance of any $\pi/4$-DQPSK system in terms of bit-error probability $P_e$ is given by [15]

$$\begin{aligned} P_e &= \frac{1}{2}(P_{eI} + P_{eQ}) \\ &= \frac{1}{2}\left[1 - Q\left(\sqrt{\frac{E_b}{N_0}(2+\sqrt{2})}, \sqrt{\frac{E_b}{N_0}(2-\sqrt{2})}\right)\right. \\ &\quad \left. + Q\left(\sqrt{\frac{E_b}{N_0}(2-\sqrt{2})}, \sqrt{\frac{E_b}{N_0}(2+\sqrt{2})}\right)\right]. \end{aligned} \tag{4}$$

Here, $Q$ is the Marcum $Q$-function. If data clock recovery by means of a simple phase-locked loop (PLL) is included in the simulations, the results in Fig. 3 show a loss of about 1 dB. The introduction of a multipath channel results in an additional loss of approximately 1 dB. The channel was modeled according to the IEEE 802.11 standardization body [1]. The magnitude of the implemented channel impulse response is depicted in Fig. 4. As can be seen, there is a nonline-of-sight (NLOS) condition (i.e., no direct path between transmit and receive antenna exists), and even for a data rate of 10 Mb/s, ISI is occurring. To improve the detection, both outputs of the demodulator were integrated over the duration of one symbol and sampled according to the data clock recovery. Thus, a summation of the energy of all radio-channel paths during one symbol period occurs. Compared to a

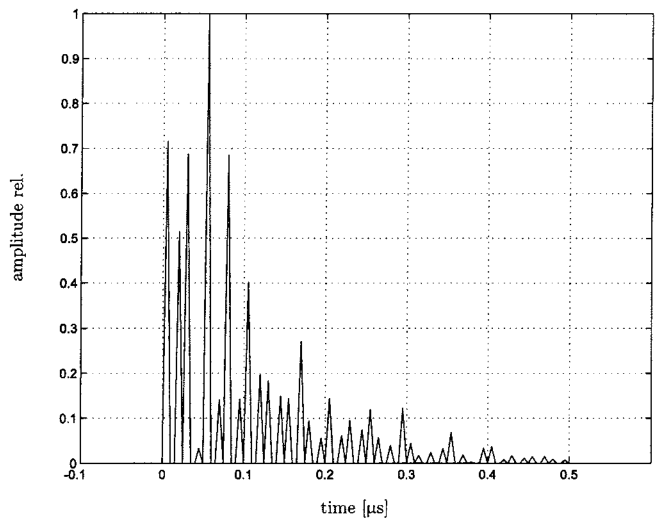


Fig. 4. Magnitude of the impulse response of the indoor radio-channel model used in the simulations.

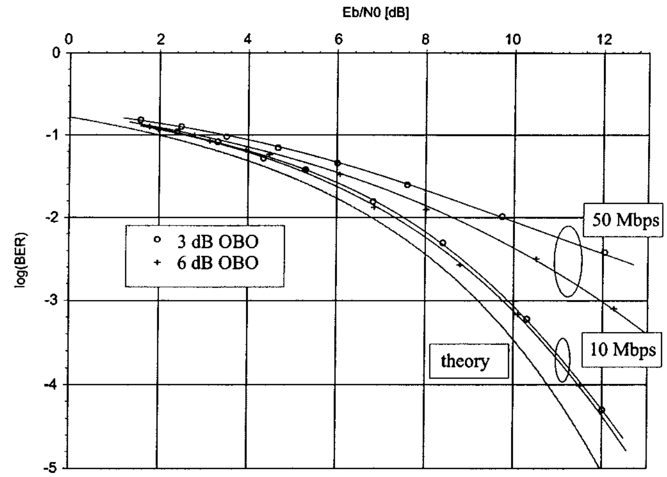


Fig. 5. Simulated BER for the SAW-based $\pi/4$-DQPSK communication system with a nonlinear transmit amplifier.

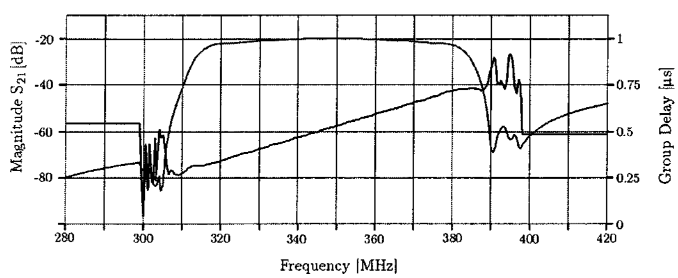


Fig. 6. Measured magnitude of the frequency transfer function and group delay of the fabricated SAW up-chirp filter.

conventional narrow-band $\pi/4$-DQPSK system under Rayleigh fading conditions (according to [15]), a significant improvement even for the described bad indoor channel with ISI is achieved due to the SS-type transmission. When the data rate is chosen so that no ISI occurs after pulse compression and the energy of all paths is gathered, we are able to reach the theoretical BER. The limiting factor for the data rate of the chirp-based system is, therefore, only the time dispersion due to the mobile radio channel.

Since the overlapping of the chirp signals introduces a non-constant envelope of the transmit signal, the effect of nonlinearities in the transmitter was investigated. A nonlinearity was introduced according to the Rapp's model [16]

$$g(A) = \frac{vA}{\left(1 + \left(\frac{vA}{A_0}\right)^{2p}\right)^{1/2p}}. \tag{5}$$

Here, $A$ is the amplitude of the input signal, $v$ is the gain, $A_0$ is the saturation value, and $p$ is the variable that characterizes the nonlinearity of the model. For the simulations, $p$ was chosen to be two and we assumed an AWGN channel and ideal data-clock recovery. The results are shown in Fig. 5. The output backoff (OBO), which is the ratio of output saturation power of the amplifier to the mean output power of the transmit signal, was chosen to be 3 and 6 dB. Since the amplitude variations increase with the data rate (= overlapping), the deterioration of system performance due to nonlinearities also becomes more pronounced. Therefore, for high data rates (50 Mb/s), an increase in the OBO clearly improves the performance, while at 10 Mb/s, almost no difference between 3- and 6 –dB OBO was found. Considering peak-to-average values of up to 15 dB of the transmit signal with overlapping chirp signals, the OBO values are quite low. Hence, chirp-based communication shows good resistance against nonlinear distortions.

## IV. SAW Chirped Delay Lines

For the hardware demonstrator, SAW chirped delay lines (up- and down-chirp) have been fabricated from $LiTaO_3$-X112rotY substrate using a standard optical lithography technique. The weighting of the magnitude of the frequency transfer function was optimized for improved sidelobe rejection, while keeping the compressed pulse narrow. In Fig. 6, the measured magnitude of the frequency transfer function and the group delay of the up-chirp filter is shown. The filter has a center frequency of 348.8 MHz, a bandwidth of 80 MHz, and a chirp duration of about 500 ns. This results in a chirp rate of $\pm 40$ MHz/$\mu$s and a time-bandwidth product or processing gain of 16 dB [17].

Since the described SAW-based communication system heavily relies on the generation and matched filtering of the chirp signals, any imperfections in the SAW devices will affect the system performance. Production tolerance and temperature drift are the most important mechanisms that change the desired device characteristics. From measurements [18], a temperature coefficient of 85 ppm/K was determined for our SAW filters. This results in a frequency shift of the filter transfer function of about 4 MHz over the temperature range from $-45$ °C to $+85$ °C. A small frequency shift translates only to a time shift $\tau_s$ of the compressed pulse [19], which is computed according to

$$\tau_s \approx \frac{f_d}{\mu}. \tag{6}$$

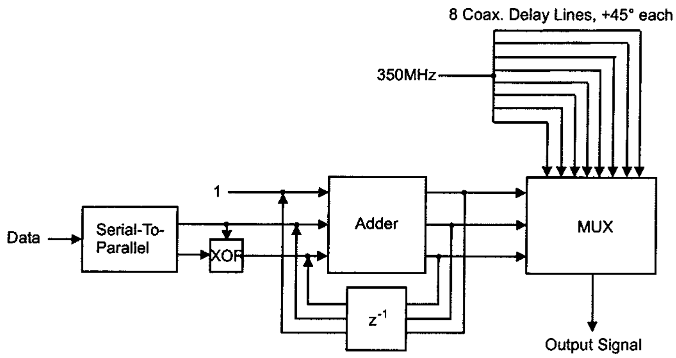


Fig. 7. Principle of $\pi/4$-DQPSK modulator implemented in the hardware demonstrator.

In our case, this time shift is about 25 ns. Due to the long time constants of the temperature variations, this can easily be tracked in the receiver and does not degrade the system performance. Other system imperfections can also be modeled by a frequency shift of the received signal. These are Doppler shift and drift of the receiver's local oscillator. If we assume a movement of the mobile station with 300 km/h, the time shift $\tau_s$ of the autocorrelation peaks evaluates to 62.5 ps, which is much smaller than the duration of the compressed pulse. Therefore, our system is extremely robust against Doppler shift.

## V. Demonstrator and Measurement Results

To validate the simulation results, we designed and built a hardware demonstrator consisting of a $\pi/4$-DQPSK modulator, a SAW chirp filter excitation circuit, an up-conversion and RF stage, and a receiver containing a low-noise amplifier (LNA), down-conversion, and the compressor SAW filter. The equivalence of phase offset and delay led to the realization of the phase modulator for the IF burst stimulating the SAW chirped delay line by means of coaxial delay lines. Fig. 7 shows the principle. The IF signal with a frequency of 348 MHz is fed through eight coaxial delay lines with delays corresponding to phase shifts of 45°, 90°, 135°, $\cdots$, 315°. The one-to-eight line driver and the 3-b multiplexer to chose the signal path with the delay corresponding to the coded data are implemented in 100-K emitter coupled logic (ECL) technology. The $\pi/4$-DQPSK modulator to generate the multiplexer control signals was realized in cheap fast transistor–transistor logic (TTL). This was possible due to the incremental structure of the modulator, which allows a simple hardware coding algorithm that only needs four logic blocks, keeps the overall switching time low, and avoids timing problems. The maximum data rate that can be coded is about 80 Mb/s. This corresponds to the theoretical maximum data rate that can be achieved with a 80-MHz bandwidth excitation burst at 348–MHz center frequency (these bursts must not overlap). The phase shifted continuous wave (CW) output signal of the $\pi/4$-DQPSK modulator is gated in a following circuit stage to yield an IF burst signal of sufficient bandwidth and passed to the expanding chirp SAW filter. Afterwards, the DQPSK modulated IF chirp signal is up-converted to the 2.4-GHz ISM band, amplified, and transmitted.

The received signal is bandpass filtered, amplified, down-converted, and, after automatic gain control (AGC) amplification, compressed in the receive SAW chirp filter. This compressor filter has the same characteristic as the expanding filter, but with the opposite sign of the chirp rate $\mu$. The demodulation is accomplished using a vector signal analyzer (VSA).

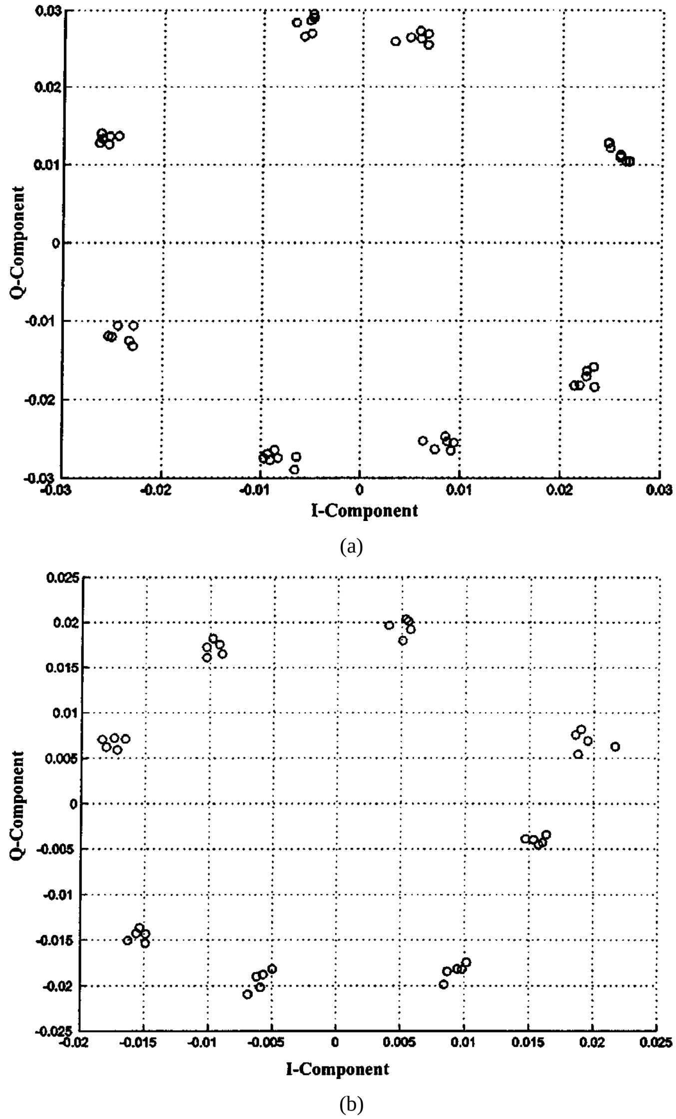


Fig. 8. Constellation diagram. (a) 10 Mb/s. (b) 40 Mb/s.

The described demonstrator was tested in an indoor laboratory environment with isotropic antennas at transmitter and receiver. The resulting constellation diagram after demodulation by the VSA is shown in Fig. 8 for the case of 10 [see Fig. 8(a)] and 40 Mb/s [see Fig. 8(b)]. The absolute positions of the detected constellation points do not exactly match the ideal $\pi/4$-DQPSK constellation. This is due to imperfections in the modulator circuit mainly caused by standing waves and crosstalk on the coaxial delay lines, which introduce a systematic phase error of maximum 10° per branch. This systematic error can be compensated for if distortions due to noise and multipath effects are limited. Furthermore, this error will be significantly lower in an optimized commercial product. The difference in the constellation diagram between 10 and 40 Mb/ps is only a phase rotation of 90° due to imperfect analyzer triggering. The spreading of the constellation points around the ideal symbols is only small for both cases, showing good receiver performance and sufficient signal-to-noise ratio. Therefore, the performance of the receiver does not depend on the data rate as long as ISI is avoided.

## VI. Conclusions

In this paper, we have presented a SS system using SAW chirped delay lines for indoor environments. Overlapping chirps and $\pi/4$-DQPSK modulation were used to achieve a high bit rate and to eliminate the difficulties of carrier recovery of traditional QPSK systems. Production tolerances, temperature drift, drift of the local oscillators, and Doppler shift have been shown to cause only a time shift of the compressed pulse. Simulations reveal that our system almost attains the theoretical BER limit for the AWGN case in indoor environments. Therefore, the used wide-band transmission technique is robust against multipath channel fading without the need for sophisticated digital signal processing. A hardware demonstrator proved the technical feasibility and allowed high-speed data transfers up to 40 Mb/s, even under bad transmission conditions. The system is, therefore, well suited for cost-effective wireless high date-rate communication in industrial environments.

## References


[1] *Local and Metropolitan Area Networks*, IEEE Standard 802.11, 1997.

[2] "HIPERLAN Type 2 Physical Layer," ETSI, BRAN, ETSI TS 101 475 V1.1.1 (2000-04), 2000.

[3] *Draft Supplement to Standard for Telecommuncations and Information Exchange Between Systems—LAN/MAN Specific Requirements—Part 11: Wireless LAN Medium Access (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer in the 5 GHz Band*, IEEE Standard P802.11a/D7.0, July 1999.

[4] R. van Nee, G. Awater, M. Morikura, H. Takanashi, M. Webster, and K. W. Halford, "New high-rate wireless LAN standards," *IEEE Commun. Mag.*, vol. 37, no. 12, pp. 82–88, Dec. 1999.

[5] S. McClelland, "Europe's wireless futures," *Microwave J.*, vol. 42, no. 9, pp. 78–108, Sept. 1999.

[6] R. C. Dixon, *Spread Spectrum Systems with Commercial Application*, 3rd ed. New York: Wiley, 1994.

[7] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Commun. Mag.*, vol. 35, no. 9, pp. 116–126, Sept. 1997.

[8] W. Hirt and S. Pasupathy, "Continuous phase chirp (CPC) signals for binary data communication—Part I: Coherent detection and part II: Noncoherent detection," *IEEE Trans. Commun.*, vol. COM-29, pp. 836–856, June 1981.

[9] C. E. Cook and M. Bernfeld, *Radar Signals—An Introduction to Theory and Application*. New York: Academic, 1967.

[10] M. Kowatsch and J. T. Lafferl, "A spread-spectrum concept combining chirp modulation and pseudonoise coding," *IEEE Trans. Commun.*, vol. COM-31, pp. 1133–1142, Oct. 1983.

[11] Y. Yamamoto, H. Kawahara, N. Sakairi, Y. Takahashi, R. Kajihara, T. Tsuda, and S. Yoshimoto, "Intermediate frequency SAW filters for mobile phone application in Japanese markets," in *Proc. IEEE Ultrason. Symp.*, Tahoe, CA, Oct. 1999, pp. 333–340.

[12] M. Hikita, N. Matsuura, N. Shibagaki, and K. Sakiyama, "New SAW antenna duplexers for single- and dual-band handy phones used in 800-MHz and 1.8-GHz cellular-radio systems," in *Proc. IEEE Ultrason. Symp.*, Tahoe, CA, Oct. 1999, pp. 385–388.

[13] A. Springer, M. Huemer, L. Reindl, C. C. W. Ruppel, A. Pohl, F. Seifert, W. Gugler, and R. Weigel, "A robust ultra-broad-band wireless communication system using SAW chirped delay lines," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2213–2218, Dec. 1998.

[14] Y. Okunev, *Phase and Phase Difference Modulation in Digital Communications*. Norwood, MA: Artech House, 1997.

[15] L. Miller and J. Lee, "BER expressions for differentially detected $\pi/4$-DQPSK modulation," *IEEE Trans. Commun.*, vol. 46, pp. 71–81, Jan. 1998.

[16] *OFDM for High Speed Wireless Networks*, IEEE Standard P802.11-97/123, 1997.

[17] A. Springer, W. Gugler, M. Huemer, L. Reindl, C. C. W. Ruppel, and R. Weigel, "Spread spectrum communications using chirp signals," in *Proc. Eurocomm'2000*, pp. 166–170.

[18] W. Gugler, A. Springer, and R. Weigel, "A robust SAW-based chirp—$\pi/4$ DQPSK system for indoor applications," in *Proc. ICC'2000*, New Orleans, LA, pp. 773–777.

[19] D. P. Morgan, *Surface-Wave Devices for Signal Processing*. Amsterdam, The Netherlands: Elsevier, 1985.


**Andreas Springer** (S'90–A'97–M'99) was born in Linz, Austria, in 1966. He received the Dipl.-Ing. degree in electrical engineering from the Technical University of Vienna, Vienna, Austria, in 1991, and the Dr. techn. (Ph.D.) degree from the Johannes Kepler University of Linz, Linz, Austria, in 1996.

From 1991 to 1996, he was with the Microelectronics Institute, Johannes Kepler University of Linz. Since 1997, he has been an Assistant Professor at the Institute for Communications and Information Engineering, University of Linz. He has been engaged in research on GaAs integrated millimeter-wave transferred electron devices (TEDs), monolithic microwave integrated circuits (MMICs), and millimeter-wave sensor systems. His current research interests are focused on simulation of wireless communication systems, SS communications, linearization of power amplifiers, direct conversion architectures, universal mobile telecommunications systems (UMTSs), orthogonal frequency division multiplexing (OFDM), and radio-frequency integrated circuits (RFICs).

Dr. Springer is a member of the IEEE Microwave Theory and Techniques (IEEE MTT-S) and the Communications Societies.

**Wolfgang Gugler** was born in Amstetten, Austria, in 1970. He received the Dipl.-Ing. and Dr. techn. (Ph.D.) degrees from the Johannes Kepler University of Linz, Linz, Austria, in 1996 and 2000, respectively.

From 1996 to 2000, he was with the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, where he was a Research and Teaching Assistant. He is currently with KEBA AG, Linz, Austria, where he is involved with wireless communications for industrial applications.

**Mario Huemer** (S'97–M'99) was born in Wels, Austria, in 1970. He received the Dipl.-Ing. and the Dr. techn. (Ph.D.) degrees from the Johannes Kepler University of Linz, Linz, Austria, in 1996 and 2000, respectively.

From 1997 to 2000, he was with the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, as a Research and Teaching Assistant. He is currently with DICE GmbH & Co KG, Linz, Austria, where he is involved with signal processing for GSN.

**Rainer Koller** was born in Linz, Austria, in 1975. He received the Dipl.-Ing. degree from the Johannes Kepler University of Linz, Linz, Austria, in 1999, and is currently working toward the Ph.D. degree n the field of high efficiency power amplifier modules for wireless communications handsets at the University of Linz.

In 2000, he joined the Institute for Communications and Information Engineering, University of Linz.

**Robert Weigel** (S'88–M'89–SM'95) was born in Ebermannstadt, Germany, in 1956. He received the Dr.-Ing. and Dr.-Ing.habil. degrees in electrical engineering and computer science from the Munich University of Technology, Munich, Germany, in 1989 and 1992, respectively.

From 1982 to 1988, he was a Research Engineer, from 1988 to 1994 a Senior Research Engineer, and from 1994 to 1996, a Professor of RF circuits and systems at the Munich University of Technology. In Winter 1994–1995, he was a Guest Professor of SAW technology at the Vienna University of Technology, Vienna, n Austria. Since 1996, he has been Director of the Institute for Communications and Information Engineering, Johannes Kepler University of Linz, Linz, Austria. In August 1999, he co-founded Danube Integrated Circuit Engineering (DICE), Linz, Austria, an Infineon Technologies Development Center, which is devoted to the design of mobile radio circuits and systems. In 2000, he was appointed a Professor of RF engineering at the Tongji University, Shanghai, China. He has been engaged in research and development on microwave theory and techniques, integrated optics, high-temperature superconductivity, SAW technology, and digital and microwave communication systems. Within these fields, he has authored or co–authored over 200 papers and has given over 120 international presentations. His review work includes European research projects and international journals.

Dr. Weigel is a member of the Institute for Components and Systems of The Electromagnetics Academy, the Informationstechnische Gesellschaft (ITG), and the Austrian Engineering Society (ÖVE). Within the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), he is chair of the Austrian IEEE COM/MTT Joint Chapter, Region 8 coordinator, regional distinguished microwave lecturer, and chair of MTT-2 Microwave Acoustics.