EVM and RSSI Link Quality Measurements in Frequency Selective Fading Channels

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***Abstract*—In this paper, we discuss the suitability of error vector magnitude (EVM) and received signal strength indicator (RSSI) as wireless quality metrics. We evaluate these metrics in a software defined radio testbed and provide detailed measurement results for frequency selective fading channels. We show that EVM is well suited as a packet loss estimator and discuss a case where receiver implementation inefficiencies show up in the EVM.**

I. Introduction

With increasingly dense deployment of wireless networks in urban environments, efficient use of the available frequency spectrum becomes more and more important. Allocating available bandwidth intelligently to communication partners improves the overall system performance. Therefore, it is necessary to estimate the quality of the different wireless links or channels. In the literature it is often assumed to have perfect knowledge of the signal to noise ratio (SNR). This ratio can be used to determine the bit error rate (BER) for a given MCS. In practice, however, obtaining the SNR or BER value is not always straightforward. Both metrics require data-aided algorithms, where a transmitted data sequence has to be known a priori to the receiver. To avoid increasing overhead by including reference data, many SNR estimation algorithms rely on the known parts in a wireless transmission as for example the packet preamble. This restricts link quality estimation to a very small fraction of the packet, leading to imprecise link quality measures or a large number of data packets required.

Many practical systems derive link quality from a so-called received signal strength indicator (RSSI). For the widely used IEEE 802.11 standard, this indicator is not fully specified and highly vendor dependent. Also its calculation is restricted to the header only, with the disadvantages as discussed above. Existing work often refers to the link quality indicator as packet SNR, which usually refers to the case where an SNR value is derived from the RSSI measurement.

Blind estimation techniques are an alternative to RSSI based or data-aided link quality estimation that do not require known data sequences. These techniques make use of the received and reconstructed data signal even though the reconstruction may include errors. By subtracting the received signal from the reconstruction, a measure for the signal error can be found. This measure is called the error vector magnitude (EVM). It is heavily used by network engineers and wireless hardware vendors as a quality measure for practical network equipment, since this measure also accounts for transmitter imperfections. While some efforts have been made to also establish EVM as link quality metric for wireless networks, it is still not very widely used in the literature.

In this paper we measure EVM in a software defined radio (SDR) testbed for an indoor non-line-of-sight frequency selective fading channel. Our SDR testbed is based on an orthogonal frequency-division multiplexing (OFDM) physical layer that resembles the physical layer of the IEEE 802.11a protocol. OFDM splits the available frequency spectrum into so called sub-carriers. Each of them carries its own modulated data stream. While this technique makes the transmission robust to the wireless multipath channel, each sub-carrier will experience a different channel quality in case of frequency selective fading.

In contrast to previous work, we separately calculate EVM for packet header and payload. As the modulation schemes used for header and data part may differ depending on the data transmission rate, this will usually result in two different EVM values. In addition, we record packet SNR link quality measurements. By relating all packet quality measures to detailed packet loss statistics we gain insight into the behavior of the EVM value as link quality metric on frequency selective fading channels. The results show, that EVM is a valuable quality measure as it better allows to infer packet loss than the SNR values that are determined from header data only. Further, it is observed that transmitter imperfections will be reflected in the EVM measurements.

II. Related Work

EVM values not only incorporate channel specific signal degeneration but also include adverse effects introduced by the transmitter. For this reason, EVM measurements are heavily used in transmitter design, evaluation, and engineering. For example, [11] applies fast EVM testing for the manufacturing process of GSM/EDGE chips. Works [5] and [13] derive expressions for the EVM value considering certain transmitter imperfections, such as IQ imbalance, oscillator phase noise, or carrier leakage.

In addition to this engineering centered usage of EVM values, it is also used as a link quality metric. Unfortunately, EVM tends to overestimate the link quality for non-data-aided systems in low SNR environments [3]. For data-aided systems, a relation between BER and EVM is derived in [19]. In [17], it is shown experimentally that this method allows to relate EVM to BER even for non-data-aided optical link transmissions and

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low BER. Further works that analyze the relation between typical link quality metrics and EVM are [10] and [6]. In [10] authors focus on the prediction of BER from peak EVM rate in combination with SNR. In contrast, [6] targets the in-band distortion of non-linear amplifiers and the impact on SNR, EVM and BER.

For OFDM-based wireless transmission, different link quality metrics have been proposed. Due to its simplicity, SNR values derived from RSSI measurements (often called packet SNR) are the most common metric [2]. With respect to the frequency selective fading that affects OFDM systems, two metrics are considered in related works. Effective $E_b N_0$ [15] and ESNR [9] which is derived from channel state measurements. It has been shown in [18] that applying EVM data to the rate selection problem is a worthwhile approach. Rate selection is one of the most important application areas of link quality metrics [8].

III. Packet Quality Measures

In this section we give a short overview of different link quality metrics. They can be divided in two main categories: data-aided and non-data-aided.

A. Data-aided SNR Estimation

As in typical packet based systems the preamble is the only known data part, there exist a number of receiver-based SNR estimators that solely rely on this part of the packet. The basic idea of these methods is to relate an estimate for the signal power $\hat{S}$ to an estimate of the noise power $\hat{W}$ to obtain an estimate for the SNR value p.

$$p = \frac{\hat{S}}{\hat{W}} \tag{1}$$

One example of a popular SNR estimator is the MMSE estimator. It makes use of the orthogonality between the channel frequency response estimation and the signal estimation error. The MMSE estimates for signal $\hat{S}_{MMSE}$ and noise power $\hat{W}_{MMSE}$ are as follows.

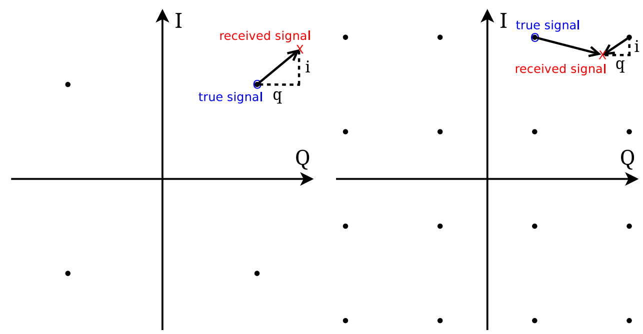
$$\hat{S}_{MMSE} = \frac{1}{M} \sum_{m=0}^{M-1} |Y_{hdr}(m)C(m)|^2 \tag{2}$$

$$\hat{W}_{MMSE} = \frac{1}{M} \sum_{m=0}^{M-1} |Y_{hdr}(m)|^2 - \hat{S}_{MMSE} \tag{3}$$

Hereby, Y_{hdr} are the received header symbols under assumption of perfect synchronization and $C(m)$ are the known preamble symbols. M is the number of subcarriers in the system. A more detailed overview of data-aided preamble SNR estimators can be found in [20].

B. Packet SNR

The packet SNR value derived from RSSI measurements is one of the most widely used metrics [2]. However, it suffers from several drawbacks. First, in the context of IEEE 802.11 networks, the RSSI measurement mechanism is not specified in the standard [1]. The implementation of the RSSI measure is only restricted by the maximum value for the RSSI and the condition that the measurement shall be conducted only over the packet header. Granularity, accuracy, and range of the RSSI value is left to the IEEE 802.11 hardware vendors. This leads to significant differences and inaccuracies in RSSI based link quality measures.



(a) EVM of a QPSK signal (b) Biased EVM of a QAM16 signal

Fig. 1. Example of EVM calculation

C. Error Vector Magnitude (EVM)

The EVM value for a modulated quadrature carrier denominates its complex error vector at the receiver. The EVM value for a QPSK signal is shown in the left graph of Figure 1(a) as the complex vector (i, q) between the mapped constellation point (blue circle) and the equalized received QPSK constellation point (red cross).

In case of a non-data-aided transmission system, the EVM calculation may be biased to lower error values in case of wrong constellation mapping. When the equalized signal is mapped to a wrong constellation point, the error vector is calculated with respect to the wrong constellation point. This means that the maximum EVM value is bounded by half the distance of the modulation scheme's constellation points. Figure 1(b) visualizes this effect for a 16-QAM modulation. The received signal (red cross) is mapped to the closest constellation point, leading to smaller (i, q) error vector than that of the actually transmitted constellation point (longer arrow). Without data aid it is, however, not possible to determine the right constellation point for the calculation.

In the following, we consider the EVM value as a packet based measure in an OFDM based transmission system. It also is an estimate for the overall error energy of th packet. $\hat{W}_{EVM}$ therefore, is the sum of all EVM values for every symbol that is transmitted on any sub-carrier in one OFDM packet.

$$\hat{W}_{EVM} = \frac{1}{KM} \sum_{k=0}^{K-1} \sum_{m=1}^{M} |Y_{eq}(kM+m) - Y_m(kM+m)|^2 \tag{4}$$

Here, K is the number of OFDM symbols per packet, $Y_{eq(n)}$ is the received and equalized n-th symbol of the packet, and $Y_m(n)$ is the constellation point the system maps the n-th symbol to. M is the number of OFDM sub-carriers. According to Equation 1, the EVM value can be related to the SNR value in the same way as it is done with data-aided mechanisms. However, it is necessary to provide a value for the signal energy $\hat{S}$. In case of a blind estimation system, the signal energy has to be estimated from the mapped received symbols as shown in Equation 5.

$$\hat{S}_{EVM} = \frac{1}{KM} \sum_{n=0}^{K-1} \sum_{m=1}^{M} |Y_m(kM+m)|^2 \qquad (5)$$

The estimated SNR value can be considered the packet's SNR value. In contrast to RSSI based SNR values, the EVM based one takes into account noise effects of the channel, as well as hardware noise influences, as described in [5]. Furthermore, an EVM based SNR calculated from the payload EVM values includes the complete signal and interference influence throughout the whole packet. In contrast, header based estimators might provide lower precision in case of signal quality changes throughout the payload part. At the same time, due to wrong symbol mapping for high EVM values, this metric tends to overestimate the SNR for low signal levels.

IV. Measurement Setup

We use the Wireless Open Access Platform (WARP) [14] to conduct a series of link quality measurements on a frequency selective fading non-line-of-sight channel. WARP is an FPGA based software defined radio (SDR) platform that provides software access to almost every component of the physical layer (PHY) implementation.

Our measurements use the WARP reference implementation of an IEEE 802.11a-style OFDM PHY layer. The OFDM PHY uses a channel with 10MHz bandwidth and has 64 subcarriers out of which 49 can be used for data transmission. The remaining subcarriers are assigned according to the IEEE 802.11a specification.

Every packet starts with a preamble and training symbol sequence that is needed to correct a potential frequency offset and is used to determine signal quality. Among these, data-aided signal quality metrics include received signal strength and channel state information (CSI). The RSSI value is estimated from the receiver's amplifier gain, set by the automatic gain control during the packet preamble detection. The value is given as a dBm value. Nonetheless, it is denoted as packet SNR as for example in [4]. After the training sequence follows a packet header encoded with a robust MCS (QPSK with code rate 1/2) that transmits information such as the payload MCS, source and destination addresses, packet length, and CRC. The rest of the packet contains the payload data, encoded with the payload MCS.

In addition to the header based signal quality metrics we also consider non-data-aided EVM information measured over the whole packet. WARPs EVM value is calculated as the sum of the complex magnitudes of the equalized signal deviations as described in Section III-C. As header and payload symbols might be encoded with different modulation schemes, we split this sum into a header part and a payload part for further analysis. Note that in WARP, the header EVM sum is calculated non-data-aided. To derive SNR values from the EVM value (see III-C), also the signal energy is measured as sum of the symbols' complex magnitudes.

For the measurement we use the WARPnet framework [7] that allows to easily transfer large amounts of measurement data from the WARP boards via Ethernet to a processing PC system. There, data analysis can be done without the restrictions of WARP's embedded FPGA environment.

As shown in Figure 2, our experiment setup is divided into the WARPnet MAC layer running on the embedded WARP system, data co-processors, and a python experiment control script. We use two WARP boards, one acting as sender and one as receiver. The sender's MAC layer receives commands from the control script via Ethernet for transmission configuration. At the receiver, the MAC layer sends the received data together with logged values via Ethernet to the WARPnet co-processors which aggregate information and hand it to the control script.

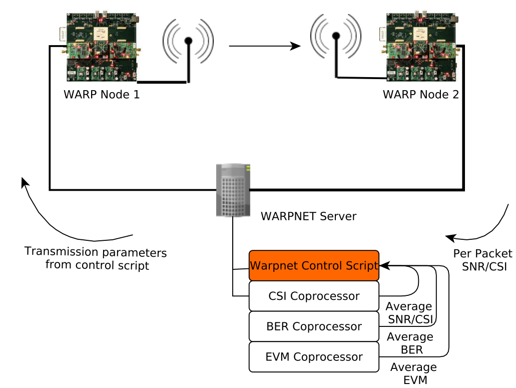


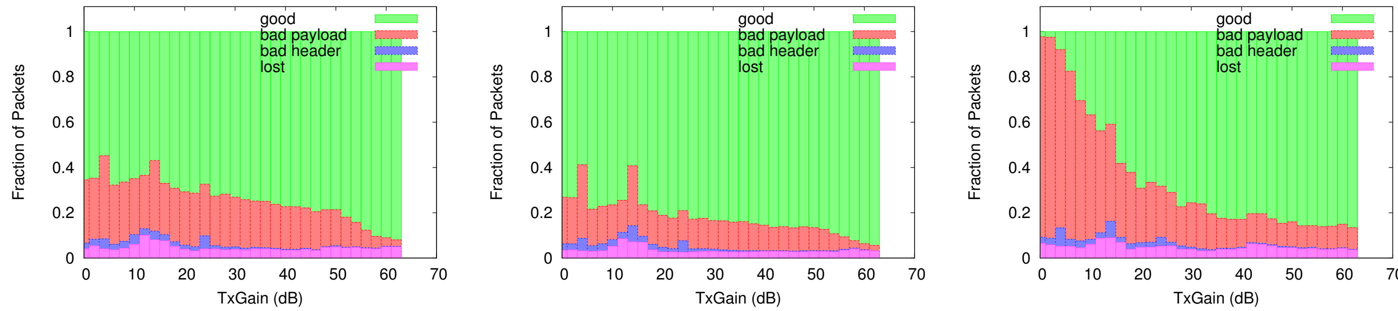
Fig. 2. Experiment setup

We place the nodes in two neighboring rooms without line-of-sight and perform measurements when those rooms are unused. Hereby we use a antenna configurations for which the channel estimation shows heavily faded sub-carriers. We continuously log the channel state information to verify that the fading pattern does not change over the duration of an experiment.

The measurement is done for 10 seconds of continuous packet transmission per configuration, where a configuration is given by the transmit gain as well as the modulation and coding scheme. The values for every time slot are averaged, as the estimated channel coefficients and detected SNR might vary slightly due to noise that affects the preamble detection process. The available modulation schemes are BPSK, QPSK and 16-QAM and the convolutional coder supports rates of 1/2, 2/3, 3/4, and no coding.

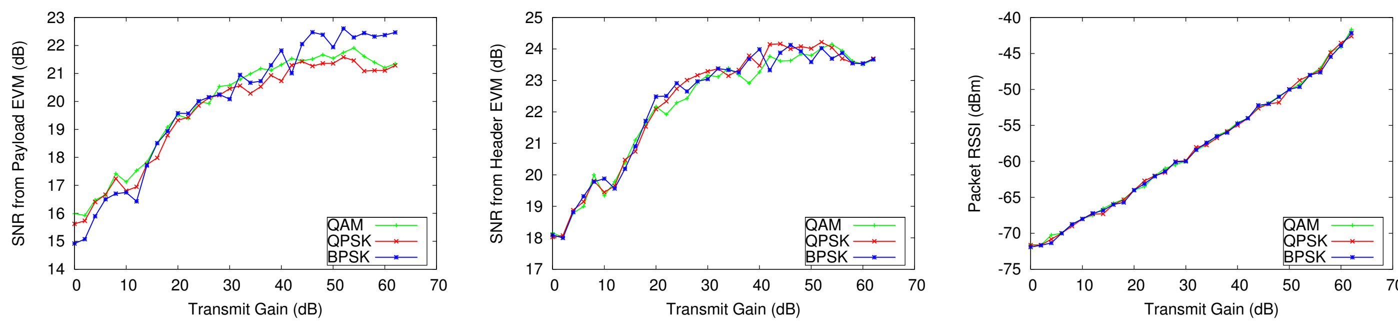
V. Measurement Results

Figure 3 gives an overview over package reception rates for all three uncoded modulation schemes over all possible transmit gains. The plots show the fraction of correctly received packets (green), packets with data errors and hence a wrong CRC value (red), packet loss due to header errors (blue), and packets that were entirely lost due to lack of signal detection (purple). The latter packets were not detected by WARP's



(a) BPSK (b) QPSK (c) 16-QAM

Fig. 3. Packet reception statistic for different modulation schemes



(a) SNR from payload EVM (b) SNR from header EVM (c) RSSI

Fig. 4. Packet quality metrics for different transmit powers

preamble detection algorithm. It is remarkable that there is relatively constant floor of lost packets that is independent of the transmit power. We attribute this effect to timing issues in WARP's packet detector. In order for the detector to be sensitive to strongly attenuated packets, the preamble detection process might erroneously start correlation on a noise peak. If the preamble of a real packet is received at this stage, the correlation will not trigger and the complete packet is lost even in case of sufficient signal quality.

A second interesting effect is visible for a transmit gain between 10 and 20 dB. For all three modulation schemes there is a noticeable increase in entirely lost packets. According to [16] there is a flaw in the preamble detection process for low to medium signal quality ranges due to insufficient precision in the packet correlation variables.[1]

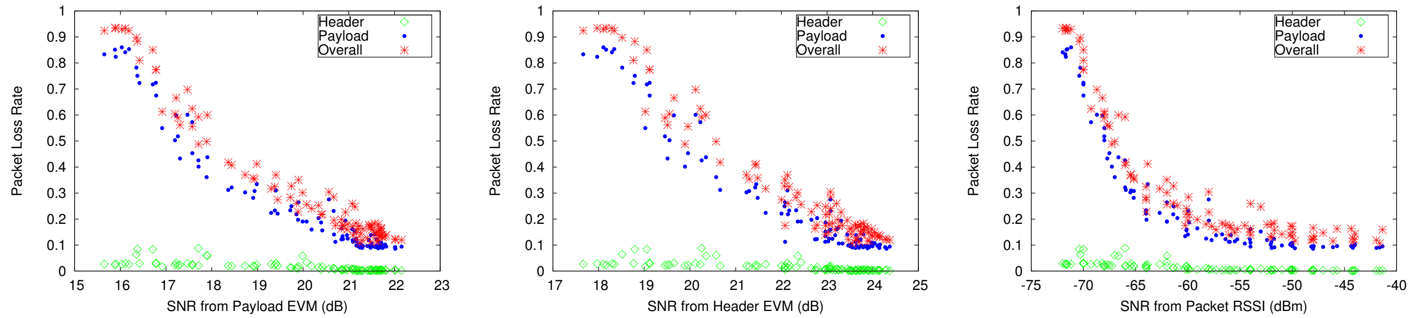
Also, note that the packet loss rates for BPSK are higher than for QPSK. This is related to the fact that we use the same payload length of 624 bytes for all modulation schemes. This results in a different number of OFDM symbols per modulation scheme with BPSK packets being roughly twice as long as QPSK packets. Even though BPSK is the most robust modulation scheme, due to the longer packet length there is higher probability of accumulating bit errors. This effect is well known and is discussed in various publications, e.g., [12].

In Figure 4, we show the variation of packet quality measures over the transmit gain range. It is interesting to observe that SNR values derived from header EVM (Figure 4(b)) as well as from payload EVM (Figure 4(a)) show the same SNR decrease in the transmit power range between 10 and 20 dB. This is a strong indication that the aforementioned entire packet losses are indeed caused by receiver implementation inefficiencies, which EVM takes into account [3]. In contrast, the RSSI metric does not show this effect. On the other hand it is interesting to observe that for higher transmit powers, EVM derived SNR values do not increase linearly with the transmit gain. We believe this effect as well to be created by transmitter imperfection in relation with the noisy and frequency selective fading channel. Small deviations in channel estimation due to the header being impacted by noise will result in constant EVM floor due to imperfect channel equalization.

Figure 5 relates packet loss rate with the three packet quality measures. The overall loss rate combines lost packets due to failed CRC in any packet part and entirely lost packets. It is first worth mentioning that failed header reception does not correlate very well with any of the used quality measures. This is due to the fact that very few broken header events are recorded at all since headers use QPSK 1/2 which is very robust compared to the 16-QAM that is used for the payload. Further, we observe that the RSSI indicator maps a wide range of RSSI based SNR values to a small range of low loss rates. At the same time, for low RSSI based SNR values the precision of loss rate to SNR mapping is quite imprecise.

In contrast, EVM calculated SNR values have an almost linear mapping to loss rates. It is noticeable that the SNR

[1] This flaw is supposedly solved in the newest software version release (OFDM reference design v18).



(a) Payload EVM SNR Correlation (b) Header EVM SNR Correlation (c) RSSI Correlation

Fig. 5. Relationship of packet loss rates and different packet quality metrics

values from payload EVM scatter less over the range of SNR values. Here, payload EVM values provide more accurate information about the signal quality since they are calculated over a much larger number of symbols.

VI. Conclusion

In this paper we investigated the performance of different packet quality metrics. In particular, we were interested in EVM as a quality metric, since EVM can be calculated in a non-data-aided manner for each symbol of the packet, rather than just known header information as is the case with the widely used RSSI metric. This not only allows to detect changes in channel quality more rapidly and even during the course of a packet, but also allows to detect transmitter and receiver implementation inefficiencies. Such a case was in fact detected by our EVM measurements and we confirmed with the device vendor that these imperfections were indeed due to a faulty packet detection implementation. We further show that EVM is well suited to be used as a packet loss rate estimator.

We intend to extend this line of work to use the EVM metric as a basis for opportunistic packet scheduling and other wireless resource allocation mechanisms.

Acknowledgments

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