The Impact of Link Adaptation in Narrowband Frequency-selective Wireless Ad-hoc Networks - Part I: The Physical Perspective

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Abstract—**In this paper, together with its Part II, the impact of relaying and adaptive modulation and coding (AMC) on data throughput in narrowband wireless multi-hop networks is investigated. This part focuses on the physical layer of a single-carrier narrowband time division multiple access (TDMA) transmission in the very high frequency (VHF) band. The transmission chain is designed for a narrowband, long range application with high order quadrature amplitude modulation (QAM) in combination with low-density parity-check (LDPC) codes. The packet error rate (PER) performance is determined for a digital audio broadcast (DAB) VHF channel model. Based on the PER curves for the DAB channel, signal-to-noise ratio (SNR)-thresholds are defined which are required for adaptive selection of different modulation and coding schemes (MCS). These results are further utilized in a system level simulation which studies the impact of relaying and link adaptation in a multi-hop network which is subject of Part II of this paper.**

I. Introduction

Wireless networks have evolved to an important technology in our daily life. Most of the systems currently available rely on cellular networks like GSM, UMTS and LTE. Since a few years, a new area has grown to a major field of interest within the research community: wireless ad-hoc networks. With respect to the great amount of opportunities using wireless ad-hoc networks, several subgroups have arisen for the different fields of application like mobile ad-hoc networks (MANETs), wireless mesh networks (WMNs), wireless sensor networks (WSNs) and vehicular ad-hoc networks (VANETs). These networks become more and more attractive in all areas where no fixed infrastructure is available. Additionally, they are interesting whenever a network needs to be set up within a short amount of time and with a minimum of expenses for infrastructure. These types of networks will become attractive especially for authorities and organizations with security tasks because of their self-organizing behavior and the possibility of fast deployments as required in disaster recovery scenarios. In these scenarios, the communication system should satisfy strict requirements, which differ from the commercial systems [1]. The main differences are in guaranteeing high coverage, robustness against interferences, security, maximum data rate and power efficiency. Related to the requirement on high coverage, a narrowband system shall be able to transmit information up to several kilometers within a sufficient data rate in error-prone wireless channels as opposed to a limited area like in wireless local area networks (WLANs), etc. The results of Takai et al. [2] have shown, that for the evaluation of the overall performance of a communication system (i.e. mainly the 'upper layers'), a detailed and also realistic physical layer simulation is essential. Therefore, we developed and investigated a system level simulation environment, where the complete analysis is divided into two parts: (a) the detailed physical layer simulations and (b) the overall system level simulations including both, an abstract physical layer as well as the upper layers. The overall system simulation, which utilizes the physical layer results to investigate the overall system performance, is subject of Part II of this paper [3].

The focus in Part I of this paper relays on the detailed physical layer simulations. For data transmissions with M-QAM, low-density parity-check (LDPC) codes are used as channel coding and a digital audio broadcast (DAB) channel model is applied for the transmission channel simulation. Hence, we show new reference curves for the packet error rate (PER) over the signal-to-noise ratio (SNR) based on the described model. We compare these results of the DAB channel model with curves for additive white Gaussian noise (AWGN) and for Rayleigh fading channels. Furthermore, we show the impact of interleaving over more than one burst on the PER performance. Another important point of this paper is the derivation of threshold values for an SNR-based link adaptation module used in our system level simulations.

The remainder of this paper is organized as follows: Section II describes the overall context of our investigations. Section III gives an overview on recent related research work and motivations. In Section IV we describe the design of a physical layer transmission chain. The simulation parameters and results of our investigations are given in Section V. Finally, Section VI concludes our work and provides an outlook on our future investigations.

II. Reference Model

The context of our investigations is a wireless ad-hoc network (cf. Figure 1) containing N nodes. Each scenario includes one source (s) and one destination node (d) with fix geographical coordinates. The distance between source and destination node is determined in a way that a communication link can be established employing the most robust modulation and coding scheme (MCS) for comparison purposes. The remaining nodes are limited to relaying (r) data packets on their way from the source to the destination node. These nodes are randomly distributed within the specified simulation area. Based on the scenarios used for our investigations, a data packet could generally take three different ways from a source to a sink node:

(i) Single-hop: Direct transmission from source (s) to destination node (d) by employing the most robust MCS.
(ii) Multi-hop (no AMC): Transmission could occur over relay nodes (r) using a fixed MCS for all hops along the route from source to the sink node.
(iii) Multi-hop (AMC): Transmission considering the conditions on each communication hop along a route from source to destination node. Hence, an AMC algorithm adjusts the transmission parameters for each hop.

In our investigation we assume single-carrier time division multiple access (TDMA) as channel access scheme. As depicted in Figure 1, the communication link quality is impacted by reflection, scattering and path loss.

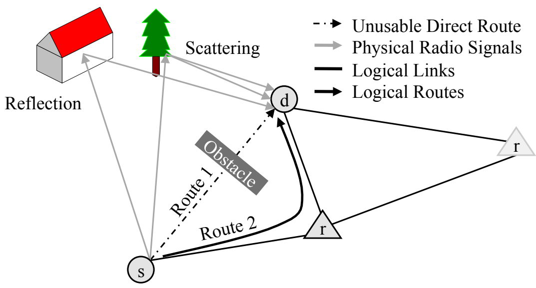

Fig. 1. Influences on a transmission link – (s) source, (r) relay, (d) destination.

III. Related Work

One mechanism to improve the average transmission link quality is relaying. In combination with link adaptation algorithms, negative channel effects, as shown in Figure 1, can be mitigated by adjusting transmission parameters (e.g. modulation, code-rate, transmission power, etc.) according to the actual channel conditions [4], [5]. This approach allows an enhancement in data rate and/or coverage. Therefore an optimal combination of relaying and link adaptation is still an open research issue. In [6], the combination of relaying and link adaptation is investigated in cellular networks with one relay station. [6] reveals that the proposed approach allows substantially higher throughput and lower transmission time than the existing scheme. Mueller et al. [4] investigated the performance of a dual-hop adaptive transmission applying two different scheme selection mechanisms, a SNR-based adaptive modulation and coding (AMC) and a buffer-aware AMC under consideration of the buffer filling level. In their investigation, the physical layer as well as the MAC layer have been covered by numerical analysis. Additionally, a Nakagami-m channel has been assumed. In [4], it is shown that the buffer-aware algorithm achieves a better average packet loss rate with a system transmission efficiency and delay performance, which is nearly identical compared to the SNR-based AMC algorithm. As shown from these results, the utilized AMC algorithm and the channel model have a significant impact on the overall system performance. Especially in the field of cellular networks, many channel models have been introduced. Some of the common channel models are COST, SCM, SCME and WINNER [7]. These models are utilized for cellular networks which are operating in the upper UHF-band with bandwidths in the range of a few MHz. In the VHF frequency band realistic channel models are rare. The most appropriate VHF channel models are specified in ITU-R P.1546-3 [8] and the DAB channel in [9].

The expectation on future research results rely on more realistic assumptions and models. This also includes investigations on cross layer optimizations. Nevertheless, the selected components on the physical layer define the performance (i.e. data rate), which can be provided to the upper layers. Especially the channel coding method has, besides the channel itself, a significant impact on the transmission performance. Baumgartner et al. [10] investigated the performance of the most important forward error correcting (FEC) schemes according to IEEE 802.16e (WiMAX) [11]. Their analysis compared the performance of convolutional codes, convolutional turbo codes (CTC) and low-density parity-check (LDPC) codes. The results show, that the advanced coding techniques like CTC and LDPC are providing a performance gain, especially at higher code-rates like 3/4. In the related literature, BER curves with LDPC are available under the utilization of AWGN and Rayleigh channel models [10], [12].

The literature research above shows the potential of the combination of relaying and link adaptation to improve the transmission quality. The investigation of these mechanisms for long range narrowband application requires reconsidering the approaches and components used in cellular networks. For this purpose, the physical layer has to be designed to satisfy the requirements and restrictions mentioned in Section I.

IV. System Setup

In the following paragraphs the physical layer transmission chain is explained including the used channel model and the AMC algorithm.

A. Components of the transmission chain

The components of the transmission chain on the physical layer are shown in Figure 3. The physical layer receives a number of input bits a_k from the upper layer. The number of input bits depend on the TDMA slot structure which is shown in Figure 2. At the physical layer, the channel encoder/decoder has to support the given number of bits per TDMA slot. The physical layer service data unit (PSDU) contains the payload of the upper layers. In front of the PSDU, training sequences for synchronization and header information on the physical layer complete the physical protocol data unit (PPDU).

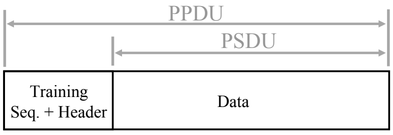

Fig. 2. Structure of a TDMA slot.

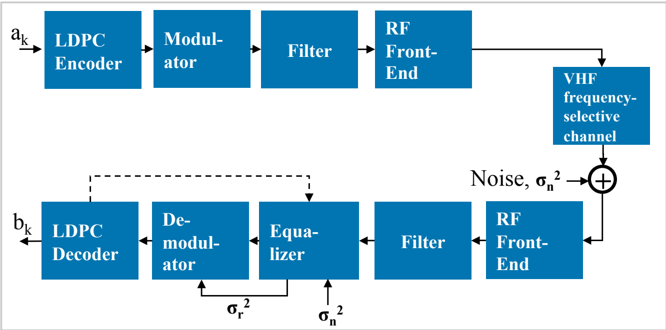

Fig. 3. Physical layer transmission chain; a_k = Input Bits, b_k = Received output Bits.

1) LDPC Channel Encoder / Decoder: Based on the previously explained benefits of LDPC coding with respect to performance and complexity, we decided to implement an irregular quasi-cyclic LDPC encoder and decoder, as defined in IEEE 802.16e (WiMAX) [11]. Based on this standard, the following code-rates are supported: 1/2, 2/3, 3/4, 5/6.

2) Modulator and Demodulator: In our transmission chain low and high order linear modulation schemes such as BPSK, QPSK, 16-QAM and 64-QAM are considered. The lowest modulation order (i.e. BPSK) is essential to achieve wide area coverage even in worst case channel conditions. The remaining noise variance ${\sigma_r}^2$ estimated by the equalizer is used in the demodulator to calculate the log-likelihood ratio of the received bits.

3) Transmitter and Receiver Filter: As mentioned earlier, the applied transmission chain has been designed for long range communication in the VHF band. The transmission chain contains a root raised cosine (RRC) transmitter and receiver filter for single carrier transmissions. Note that for long range communications together with high order modulation schemes the effects of frequency selectivity can not be ignored.

4) Channel Model: The channel model is one of the major components in the simulation environment. The channel influences the transmission by multipath fading which occurs due to reflection and scattering as shown in Figure 1. Additionally, the transmitted frames are influenced by a distance-dependant path loss model as well as an uncorrelated log-normal fading (sometimes referred to as 'slow fading', 'shadow fading', or 'long-term fading') and white Gaussian noise (AWGN) at the receiver. This paper focuses on narrowband transmissions for long range applications which are mainly using the VHF and the lower part of the UHF band. The most detailed and well-known channel model in the VHF-Band from our point of view is the DAB channel (174 - 240 MHz). The DAB channel is modeled as a wide sense stationary uncorrelated scattering (WSSUS) process, which exactly represents any given scattering function as depicted in [9]. The channel impulse response of a WSSUS is determined by [13]:

$$h(\tau, t) = \lim_{N\to\infty} \frac{1}{\sqrt{N}} \cdot \sum_{n=1}^{N} e^{j(\theta_n + 2\pi f_{D_n} t)} \cdot \delta(\tau - \tau_n) \qquad (1)$$

whereby, each echo is characterized by a uniformly distributed phase θ_n $(0 \leq \theta_n < 2\pi)$, a delay τ_n $(0 \leq \tau_n \leq \tau_{max})$ and a Doppler shift f_{D_n} $(-f_{D_{max}} < f_{D_n} < f_{D_{max}})$.

The power delay spectrum (PDS) of the DAB hilly terrain (HT) 1 profile, as worst case scenario, contains three exponential distributions with a maximum total delay of around 90 μs [9], shown in Figure 4. Each of these echo peaks are factorized by a_{echo}, which have been determined in [9]. The superposition of N echoes results in a Rayleigh distributed amplitude. Considering the factor of the echo peaks, the exponential function in (1) results in:

$$h(\tau, t) = \lim_{N\to\infty} \frac{1}{\sqrt{N}} \cdot \sum_{n=1}^{N} \sqrt{a_{echo}} e^{j(\theta_n + 2\pi f_{D_n} t)} \cdot \delta(\tau - \tau_n) \qquad (2)$$

The delay τ_n is distributed according to equation (3) in which T is the time constant from the power delay spectrum [9], [13] and u_n is a uniformly distributed random number in the interval of [0,1).

$$\tau_n \approx -T \cdot \log_e(1 - u_n) \quad \text{for} \quad \tau_{max} \gg T \qquad (3)$$

The equation of the Doppler shift f_{D_n} assumes a two-dimensional isotropic scattering

$$f_{D_n} = f_{D_{max}} \cdot \cos(2\pi u_n) \qquad (4)$$

whereby, $f_{D_{max}}$ is the maximum Doppler frequency shift [13]. The Doppler power spectrum of a two-dimensional isotropic scattering is Jakes distributed as shown in Figure 4.

$f_{D_{max}}$ is determined by the carrier frequency f_c, the velocity v and the speed of light c_0:

$$f_{D_{max}} = \frac{f_c \cdot v}{c_0} \qquad (5)$$

Figure 4 illustrates the simulated scattering function $S(\tau; f_D)$ of the implemented DAB HT1 channel model. The scattering function is obtained by the Fourier transformation of (2) with respect to t.

The coherence time t_c of the channel is approximated by:

$$t_c \approx \frac{1}{2 f_{D_{max}}} \qquad (6)$$

If $t_c > T_{Slot}$, then the channel can be assumed as time-invariant during a TDMA Slot.

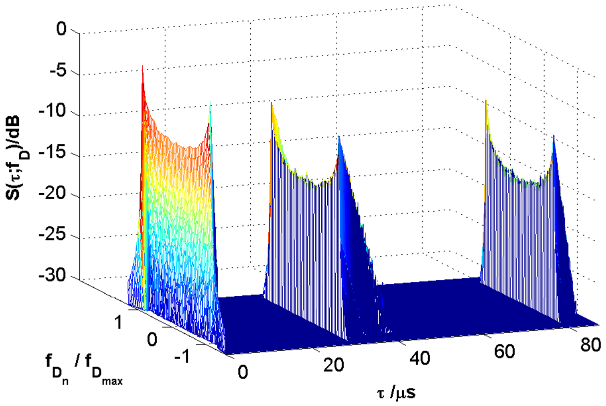

Fig. 4. Scattering function DAB HT1 channel.

5) Equalizer: To compensate the effects of intersymbol interference caused by the frequency selective VHF DAB channel, we employ a T/2-spaced finite-impulse-response (FIR)-minimum mean-square error (MMSE) decision-feedback equalizer (DFE). Thereby we assume the equalizer has an optimal knowledge of the channel impulse response including the noise variance ${\sigma_n}^2$ and is optimally synchronized.

B. Adaptive Modulation and Coding Algorithm

To apply link adaptation, different modulation and coding schemes (MCS) are utilized. AMC algorithms have received a lot of attention in the past years, especially for WLAN or cellular mobile communication standards as GSM, LTE, etc. [14], [15]. Thereby, four major metrics are distinguished to determine the channel quality:

- Received Signal Strength Indication (RSSI)
- Signal-to-Interference-plus-Noise Ratio (SINR)
- Packet-Delivery Ratio (PDR)
- Bit-Error Rate (BER)

As Vlavianos et al. [16] mentioned, the SINR metric has been considered to be the most appropriate metric for quantifying the quality of a link. Related to this evaluation, we decided to implement an algorithm, which selects the MCS level based on previously defined SNR thresholds. The SNR thresholds for our proposed algorithm are determined from the PER-curves achieved by the simulation of the physical layer to satisfy a PER $\leq 10^{-2}$. The determination of the SNR at the receiver can be subject to strong deviations, caused by the channel variations. To prevent oscillations between two MCS levels near a threshold, the SNR thresholds are defined as a hysteresis. The thresholds for switching each MCS level are shown in Figure 7.

V. Simulation Results

The following results of the physical layer are based on simulations in MATLAB®. The required simulation parameters for this purpose are shown in Table I.

Figure 5 compares PER curves under the utilization of a DAB and AWGN channel model for different modulation and code rates. The curves show the significant impact of Rayleigh fading (sometimes referred to as 'fast fading' or 'short-term fading') in the DAB channel model on the PER. However, the DAB channel achieves a better PER performance compared to a 1-Tap Rayleigh channel model as depicted in Figure 6.

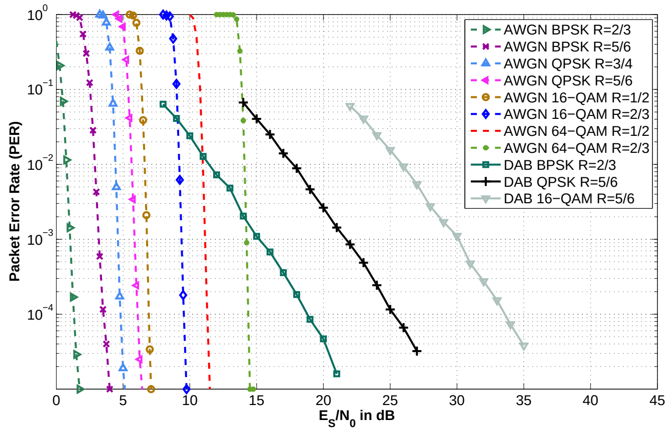

Fig. 5. PER curves AWGN compared with DAB HT1 under different code-rates for a TDMA slot duration with interleaving within one TDMA slot.

An additional mechanism to achieve a significant improvement in the PER performance is interleaving over different TDMA slots. In Figure 6, the data packets are interleaved over three TDMA slots in the DAB channel model. Interleaving over three TDMA slots reaches an over 5 dB performance improvement compared to a single packet transmission. However, this gain costs delay. At the receiver all three bursts have to be received correctly for the deinterleaving. The impact of the increased delay is less on data transmission but significant in real time services as voice transmissions.

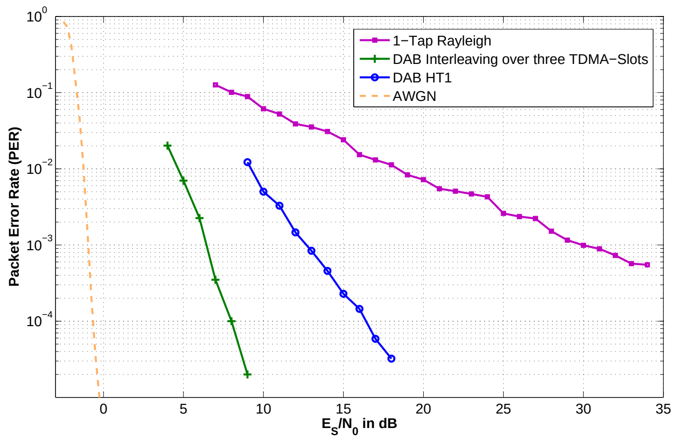

Fig. 6. PER curves BPSK R=1/2 for AWGN compared with DAB HT1, Rayleigh and DAB with interleaving over three TDMA slots.

Based on the determined curves under the utilization of a DAB channel model, the MCS schemes in Figure 7 are defined. The AMC algorithm determines the MCS, based on the SNR-thresholds on each hop in a multi-hop network. Thereby, the thresholds are optimized to provide a minimum PER $\leq 10^{-2}$.

TABLE I
LAYER-SPECIFIC SIMULATION PARAMETERS

Layer	Parameter	Value
Physical	Bandwidth (B)	25.0 kHz
Physical	Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Physical	Code rate (R)	1/2, 2/3, 3/4, 5/6
Physical	Carrier Frequency (f_c)	240 MHz
Physical	Transmit- / Receive Filter Roll-off factor	0.25
Physical	Number of interfered delays per echo peak (N)	1000

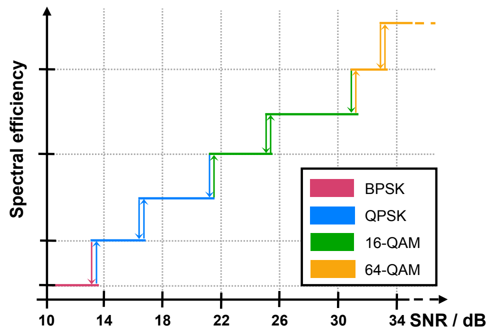

Fig. 7. Qualitative AMC SNR thresholds for the DAB channel model, based on PER $\leq 10^{-2}$ and a hysteresis of 0.3 dB.

VI. CONCLUSION

In this paper, we investigated a transmission chain and a physical simulation environment for a narrowband long range transmission, employing a single-carrier TDMA transmission scheme. We explained an approach of an overall more realistic simulation environment for investigations on the upper layers of the OSI model. The given PER results achieved by assuming a DAB channel model show the significant impact of Rayleigh fading and the benefits of interleaving over more than one TDMA slot. Based on the achieved PER curves, a novel MCS for wireless fading channels has been determined, which is used in part II of this paper for the investigation of the performance of link adaptation and relaying in multi-hop wireless network scenarios.

A. Future Work

Our future investigations will focus on AMC algorithms. Therefore a more detailed physical layer model including synchronization and channel estimation is required. The results based on this more detailed model will be provided to the overall system level simulation for iteratively achieving a more realistic complete system environment. This environment will be used for further evaluation of the performance of upper layer mechanisms, especially under additional scenarios including mobility.

REFERENCES

[1] G. Elmasry, "A comparative review of commercial vs. tactical wireless networks," *IEEE Communications Magazine*, vol. 48, no. 10, pp. 54–59, 2010.

[2] M. Takai, J. Martin, and R. Bagrodia, "Effects of wireless physical layer modeling in mobile ad hoc networks," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, ser. MobiHoc '01. New York and NY and USA: ACM, 2001, pp. 87–94.

[3] S. Helmle, M. Dehm, M. Kuhn, D. Lieckfeldt, and D. Pesch, "The Impact of Link Adaption in Narrowband Frequency-selective Wireless Ad-hoc Networks - Part II: The Network Perspective: Accepted for publication," 2012.

[4] A. Müller and C. Y. Hong, "Dual-hop adaptive packet transmission systems with regenerative relaying," *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 234–244, 2010.

[5] M. Hasna and M. S. Alouini, "Harmonic mean and end-to-end performance of transmission systems with relays," *IEEE Transactions on Communications*, vol. 52, no. 1, pp. 130–135, 2004.

[6] C. H. Cho, T. K. Kim, and H. Y. Youn, "Mobile multi-hop relay system using AMC for multicast broadcast service over mobile WiMAX," in *Wireless Telecommunications Symposium, 2008. WTS 2008*, 2008, pp. 46–52.

[7] M. Narandzic, C. Schneider, R. Thoma, T. Jamsa, P. Kyosti, and Z. Xiongwen, "Comparison of SCM, SCME, and WINNER Channel Models," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, 2007, pp. 413–417.

[8] *ITU-T Recommendation P.1546-3: Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz*. International Telecommunication Union, 2007.

[9] H. Schulze. (1995) Digital Audio Broadcasting: Das Übertragungssystem im Mobilfunkkanal. [Online]. Available: http://www.fh-meschede.de/public/schulze/docs/dab-seminar.pdf

[10] B. Baumgartner, M. Reinhardt, G. Richter, and M. Bossert, "Performance of Forward Error Correction for IEEE 802.16e," 2005.

[11] "IEEE standard for local and metropolitan area networks part 16: Air interface for broadband wireless access systems amendment 3: Advanced air interface," *IEEE Std 802.16m 2011*, pp. 1–1112, 2011.

[12] H. Tatsunami, K. Ishibashi, and H. Ochiai, "On the Performance of LDPC Codes with Differential Detection over Rayleigh Fading Channels," in *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, vol. 5, 2006, pp. 2388–2392.

[13] P. Höher and A. Steingaß, "Modeling and emulation of multipath fading channels using a "controlled randomness"," *Proc. ITG-Fachtagung Wellenausbreitung bei Funksystemen und Mikrowellensystemen*, 1998.

[14] J. C. Bicket, "Bit-rate selection in wireless networks," 2005.

[15] S. H. Y. Wong, H. Yang, S. Lu, and V. Bharghavan, "Robust rate adaptation for 802.11 wireless networks," in *Proceedings of the 12th annual international conference on Mobile computing and networking*, ser. MobiCom '06. New York, NY, USA: ACM, 2006, pp. 146–157.

[16] A. Vlavianos, L. Law, I. Broustis, S. Krishnamurthy, and M. Faloutsos, "Assessing link quality in IEEE 802.11 Wireless Networks: Which is the right metric?" in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, 2008, pp. 1–6.