Quantifying the Gain of Multi-Connectivity in Wireless LAN

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Abstract—Multi-Connectivity (MC) using multi-link diversity is a promising approach to enable Ultra-Reliable Low-Latency Communications. While recent analytical results about MC already indicate improved reliability compared to a single link, we are interested in the actual gain of implementing MC into an established wireless standard. Therefore, we evaluate inter-frequency MC over independent fading channels for the physical layer of Wireless LAN (WLAN). We compare three combining schemes, namely Selection Combining (SC), Maximal Ratio Combining (MRC), and the recently emerging Joint Decoding (JD), by their respective packet error rates in Monte-Carlo simulations. Our results show that MC outperforms a single link for all of the three combining schemes, even if the total transmit power is not increased but shared among the available links. JD performs best and is found to be considerably less dependent on SNR estimation than MRC and SC. We show that packet synchronization in WLAN causes an error floor in frequency-selective channels which can be effectively mitigated by MC.

Index Terms—Multi-Connectivity, Diversity Combining, Joint Decoding, URLLC, WLAN.

I. INTRODUCTION

Reliable wireless networks with low transmission delays enable new use cases in industry, medicine and autonomous driving. Ultra-Reliable Low-Latency Communications (URLLC) include a class of applications called the Tactile Internet, demanding a round-trip latency of less than 1 ms and application outage probabilities down to $10^{-9}$ [1].

An application example of URLLC is to wirelessly control a robot in a factory hall [2], where the robot receives motion control updates at a regular time interval. If the network fails to deliver an update within the control cycle, the robot must extrapolate its movement from previous data [3]. Depending on accuracy and safety requirements, the robot is configured to stop if the number of consecutively dropped update packets exceeds a certain threshold. An application outage occurs when the robot stops. For instance, if we want to achieve an application outage probability of $10^{-9}$ and define three lost packets as error threshold, we need to ensure that the probability for an individual packet to be dropped does not exceed $\sqrt{10^{-9}} = 10^{-4.5}$, assuming uncorrelated packet errors.

Achieving such low packet error rates (PERs) using just a single wireless link either requires a high signal-to-noise ratio (SNR) or retransmissions. The latter is not applicable to URLLC, because minimizing latency and repeating a transmission are mutually exclusive — we therefore do not consider retransmissions or any other type of time domain diversity. In some cases, increasing the SNR by raising the transmit power may not be desirable either, for example, in order to avoid interfering with other devices, to limit energy consumption, or because of regulatory constraints.

On the contrary, making use of multiple wireless links simultaneously (Multi-Connectivity, MC) by transmitting the same data redundantly (Diversity) can improve reliability in fading channels, even without increasing the total transmit power in the system [4]. In this work, we consider inter-frequency MC on the physical layer using independent channels on distinct carrier frequencies [5], where the receiver merges information from parallel links according to a diversity combining scheme. We evaluate the following three schemes: (1) Selection Combining (SC), picking only the best link in terms of SNR; (2) Maximal Ratio Combining (MRC), weighing all links by their respective SNR and averaging; and (3) Joint Decoding (JD), exchanging information during parallel decoding of all links. SC and MRC are established concepts whose outage probabilities in Rayleigh fading channels are well-covered in literature [6]–[8]. Analytical expressions for the upcoming JD have been derived only recently in [4].

While theoretical outage probabilities provide a lower bound to empirical PERs, system engineers are left in doubt about how actual implementations perform compared to the predicted optimum. We are therefore interested in practical results which give a clue to expectable PERs in real-world systems.

In [9], Awoiyi and Tobagi developed an expression for PERs of orthogonal frequency-division multiplexing (OFDM) receivers such as in WLAN and characterized the impact of frequency-selective fading for a single link. In [10], Panajotović and Drača simulated realizations of a stochastic MIMO channel model, determined the combined SNR for SC and calculated the achievable data rate of such a system. The aforementioned authors considered channels more realistic than Rayleigh fading, but did not take imperfections of a complete physical layer implementation into account. In [2], the authors provided PER results of a complete link-level simulation of WLAN in a frequency-selective channel for different system parameters. They employed up to four links and implemented SC for combining. However, since the authors did not present results for a well-known reference channel model such as Rayleigh fading, it is difficult to determine the impact of WLAN implementation and channel conditions on the PER separately.
Complementing the analytical work in [4], we shed light on the actual gain of MC compared to a single link, considering WLAN as a common standardized wireless system. We provide theoretical context by comparing our simulated PERs to analytical outage probabilities for Rayleigh fading channels. Furthermore, we consider packet synchronization and SNR estimation as examples of imperfections in typical receiver implementations, and quantify their impact on the achieved PER. In addition to the established combining schemes SC and MRC, we also evaluate the recently emerging JD.

II. SYSTEM MODEL

Our link-level Monte-Carlo simulations are built on the “MATLAB WLAN System Toolbox” and implement inter-frequency MC which we outline in this section. At first, we present an applicable high-level network topology for this case of MC and define our lower-level physical layer transmission model. We then describe the considered schemes for diversity combining and highlight differences between them. The section is completed by a summary of our channel coding and WLAN configuration being used in the simulations.

1) Network Topology: We consider inter-frequency MC using multi-link diversity in the downlink, where the same data is sent by multiple synchronized access points (AP) to a single mobile station (MS). Fig. 1 shows a corresponding network topology for L wireless links and L senders indexed by \( l = 1, \ldots, L \). In this model, the term sender refers to an AP while receiver refers to the MS.

2) Transmission Model: Let \( \mathbf{d} \) be a vector of bits \( \in \{0, 1\} \) with uniform probabilities, representing a data packet. Each of the L senders transmits the same data and outputs a transmit signal \( s_l \) represented by a vector of complex-valued baseband samples. The transmit signals pass independent channels exhibiting uncorrelated small-scale fading plus additive white Gaussian noise, giving the receive signals \( r_{l1}, \ldots, r_{Ll} \). On the receiver side, the incoming signals from all links are processed in parallel and joined according to a combining scheme, finally obtaining an estimate \( \hat{d} \) of the original data. We distinguish the instantaneous SNR \( \Gamma_l \) of the \( l \)-th link which varies for every channel realization, and the underlying mean SNR \( \bar{\Gamma} \) which we define to be equal for every link. In order to assume uncorrelated fading, the channels must be separated in frequency at least by the larger of the signal bandwidth and the coherence bandwidth [6]. Comparing multi-link to spatial diversity, the considered model can be seen as an \( L \times L \) multiple-input multiple-output (MIMO) system with a diagonal channel matrix.

![Fig. 1. Multi-connectivity topology for diversity in the downlink.](image1)

![Fig. 2. Transmission chain of L independent links, depicting the considered processing blocks in sender (top) and receiver (bottom), and the combining points of SC, MRC and JD within the receiver.](image2)

![Fig. 3. Joint decoding of multiple links at the receiver.](image3)

3) Combining Schemes: SC and MRC join the multiple links at the symbol level, as highlighted in Fig. 2. That is, they combine the receive symbol vectors \( \hat{m}_1, \ldots, \hat{m}_L \) into a single vector \( \hat{m}_{SC} \) and \( \hat{m}_{MRC} \), respectively. Combining of receive symbols requires the transmit symbols to be identical, i.e., \( m_1 = m_L \). While SC selects the symbol vector with the highest SNR, i.e., \( \hat{m}_{SC} = \hat{m}_l \) with \( l = \arg(\max(\Gamma_1, \ldots, \Gamma_L)) \), and MRC weighs the phase-corrected symbol vector of each link with its corresponding SNR and averages them, i.e., \( \hat{m}_{MRC} = \frac{1}{L} \sum_{l=1}^{L} \hat{m}_l \). JD keeps the symbol vectors from all links for individual demapping and decoding. The symbols are demapped to real-valued log-likelihood ratios (LLRs, also known as “soft bits”), representing the probability for an individual bit to equal “0” or “1”. For SC and MRC, the already combined LLRs are passed to a single decoder, whereas for JD, the LLRs of each link are scaled by their underlying channel coding allowing for such processing is described in the following.

4) Distributed Turbo Coding: Distributed Turbo coding (DTC) is one particular realization of JD; others use Low Density Parity check codes [11] or Polar codes [12]. Following the proposed architecture in [13], we replaced the default channel coding in WLAN with two concatenated memory-1
convolutional codes which are separated by an interleaver and are both to be decoded by the BCJR algorithm [14]. A non-systematic non-recursive code with rate 1/2 constitutes the outer code, while the inner code is a punctured systematic-recursive code. Combining the two avoids the error floor otherwise common to Turbo codes [15]. Each sender uses said coding chain, but interleaves the data bits with a pattern unique to the sender, thereby producing different transmit symbols for the same data. The receiver contains a decoding chain for each link. The LLRs from each link are deinterleaved according to the pattern used by the respective sender. Using BCJR enables joint iterative decoding of multiple links as parallel Turbo code, as the algorithm allows information on coded bits to be exchanged between the decoding chains of each link [13]. The right-hand part in Fig. 3 shows the connected decoders (Soft Dec) and the final decision turning real-valued soft bits into binary hard bits (Hard). For meaningful comparison of the combining schemes, we use these decoders also for SC and MRC, i.e., decoding of the already combined LLRs of SC and MRC corresponds to executing the aforementioned coding chain for just one link.

5) WLAN Configuration: The physical layer implementation of WLAN was configured with the “High Throughput” profile of IEEE 802.11n for 20 MHz channel bandwidth. This corresponds to an OFDM system with 52 usable subcarriers of which 48 carry data and 4 are used as pilots. Each OFDM symbol is 3.2 μs long, plus a 0.8 μs cyclic prefix. The preamble contains signaling information and multiple training fields, including 2 symbols of 12 subcarriers for coarse synchronization (Short Training Field, STF) and 2 symbols using all 52 subcarriers for channel estimation and fine synchronization (Long Training Field, LTF). The parameters given in Tab. I apply, unless noted otherwise.

III. SIMULATION AND COMPARISON TO THEORY

Firstly, we evaluate the performance of MC in WLAN under optimal conditions, i.e., with accurate SNR knowledge available to the combining schemes and error-free synchronization. In order to legitimate the obtained results, we compare the simulated PERs to the analytical outage probabilities (OPs) for frequency-flat Rayleigh block fading, a mathematically convenient and well-studied channel model [4], [6]. The OP expressions for SC, MRC and JD are given in [4, 11, 18, 28]. Fig. 4 shows said OPs and our simulated PERs as function of the mean SNR $\Gamma$ per link. Unless noted otherwise, simulations use Binary Phase Shift Keying (BPSK) for constellation mapping, allocating one bit per symbol. The gap of 5-7 dB between the PER and OP graphs reveals the limitations of the considered implementation, in particular the small constraint length of the channel code, and the inaccurate equalization for low SNRs due to noise in the preamble. Nevertheless, for high SNRs, the graphs exhibit the same slope, thus indicating the same diversity gain. We can conclude that all of the combining schemes make use of the diversity from multiple links by decreasing the PER, as predicted in previous theoretical work [4]. We see that JD slightly outperforms MRC and SC in terms of PER.

IV. SHARING THE AVAILABLE TRANSMIT POWER

To emphasize the advantage of MC over a single link, it comes in useful to consider equally dividing the available transmit power across all links so that adding a link does not increase the system SNR $\Gamma_{\text{sys}} = L \cdot \Gamma$. Fig. 5 shows PER results for up to $L = 4$ links with respect to the system SNR. The graph for $L = 3$ is omitted for clarity. Note that the graphs equal the results for the SNR per link, but are shifted in positive direction along the SNR axis by the number of links in dB. If we consider two links for example, the shift amounts to $10 \cdot \log_{10}(2) \approx 3$ dB.

The gain of multiple links becomes apparent as (a) the reduction of PER for a given SNR, and (b) the reduction of SNR $\Delta \Gamma$ (equivalent to reducing the transmit power) for a given PER. Some readings are presented in Tab. II. For instance, JD using four links allows for a 10.6 dB lower transmit power while retaining a PER of 1%.

V. TRADE-OFF BETWEEN RELIABILITY AND DATA RATE

Reliability and data rate are opposite key performance indicators in a wireless system. The MC improvement in reliability can be traded for enhanced data rates, as we illustrate

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<th>Table I: Simulation Parameters</th>
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<tr>
<td>Channel Bandwidth</td>
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<th>Table II: Transmit Power Reduction Compared to Single Link</th>
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in the following. For instance, the higher-order constellation mapping 16-QAM maps 4 bit to one symbol, as opposed to BPSK, where a symbol represents only 1 bit. Since 16-QAM allocates more bits per symbol and the PER depends on the received energy per bit, 16-QAM needs a higher SNR to reach the same PER as BPSK. However, MC reduces the required SNR for a given PER. By using MC, we can increase the data rate by switching to a higher-order constellation mapping and maintain a certain PER without increasing the SNR.

Fig. 6 displays the PER graphs of two links using 16-QAM and a single link using BPSK. The intersections of the single link and the dual link graphs represent the aforementioned trade-off. For example, at an SNR of 16 dB, MC using MRC enables fourfold data rate compared to the single link, retaining a PER of 4%. Additionally, we can see from Fig. 6 that the offset between the different combining schemes grows bigger for higher-valued symbols. This confirms theoretical findings described in [4]. Regarding MC in practice, the choice of the combining scheme becomes more relevant for high data rate applications.

VI. IMPACT OF SNR ESTIMATION

The considered combining schemes rely on the knowledge of each link’s instantaneous SNR. In practical receiver implementations, the relative noise power is estimated from training data in the preamble. Shorter preambles reduce the overhead for transmission of short payloads as in industry applications, but deteriorate estimation accuracy [16]. Fig. 7 shows results for the worst case when no SNR estimate is available at all.

Without SNR knowledge, SC can only select a link at random, thereby falling back to the performance of a single link. MRC without SNR weighting before averaging becomes Equal Gain Combining [6], causing a slight SNR degradation of less than 1 dB but retaining its diversity gain. Interestingly, JD is almost not affected by missing SNR weighting. Considering the point of combining in the processing chain, this finding seems reasonable and underlines an important difference between the combining schemes. While SC and MRC combine the received symbols in an irreversible way by selection and averaging, respectively, JD maintains separate LLR vectors for each link and combines them gradually. During iterative BCJR decoding, LLR magnitudes increase for reliable bits and decrease for undecided bits. Given sufficient iterations, this scaling is equivalent to the weighting by SNR.

VII. IMPACT OF PACKET SYNCHRONIZATION

Likewise dependent on preamble design, packet synchronization is a major concern for WLAN receivers in frequency-selective channels [17]. We found that it may set a lower PER limit independent of the SNR. Fig. 8 shows PER results for a frequency-selective channel described by the TGn model “F” with a 6 dB line-of-sight component and a delay spread of 150 ns, representing a large hall [18]. We observe the error floor as flattening for increasing SNRs.

Since packet synchronization runs before any other receiver function, it is independent of any downstream signal processing such as equalization, constellation demapping and
decoding. If the coherence bandwidth of the channel is smaller than the considered signal bandwidth, that is, if the channel is frequency-selective with respect to the transmit signal, the preamble may get distorted up to a point where synchronization is impossible. The frequency-selectiveness of the channel does not change with SNR, therefore the preamble distortion persists even if the transmit power is increased.

Our results show that the performance bottleneck due to synchronization can be effectively mitigated by MC, as every additional link reduces the error floor significantly. The probability that none of the links detects a packet is given by the product of each link’s probability not to detect a packet, since detection is independent for each link. Hence, every additional link reduces the combined error probability and the error floor scales with the power of $L$, which can be observed in Fig. 8. For instance, the single link exposes an error floor at approximately $5.7\%$. For $L = 2$ links, this PER bound is lowered to about $(5.7\%)^2 \approx 0.32\%$.

The findings above provide a strong argument for using MC in wireless systems exposed to adverse channel conditions. It is worth to note that by letting senders and receivers use multiple channels simultaneously, PER performance is significantly improved without modifying the packet preamble format. Since adherence to the standard allows for greater component reuse in practical implementations, MC might provide a cost-effective option to enhance PERs in existing infrastructure.

VIII. Conclusion

In this work, we quantified the gain of Multi-Connectivity in terms of decreased packet error rates and increased data rates. Physical layer simulations of Wireless LAN using Selection Combining, Maximal Ratio Combining and Joint Decoding confirm theoretical results for Rayleigh fading, albeit with an SNR offset attributed to the specific channel coding implementation. We found that Joint Decoding is tolerant of unavailable SNR estimation as opposed to the other combining schemes, an advantage not known from theoretical work before. We identified packet synchronization in frequency-selective channels as an essential bottleneck to achieving low error rates. The inevitable error floor due to synchronization can be effectively mitigated by the use of multiple links. We conclude that despite the additional bandwidth needed for multiple senders and receivers, Multi-Connectivity is a suitable technology to enable Ultra-Reliable Low-Latency Communications. Insights on practical deployment challenges and the impact on higher layers shall be given in a future publication.

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